ADVANCED VEHICLE TECHNOLOGY ANALYSIS AND EVALUATION ACTIVITIES

VEHICLE TECHNOLOGIES PROGRAM

Less dependence on foreign oil today, and transition to a petroleum-free, emissions-free vehicle tomorrow.

2007

annual progress report

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

U.S. Department of Energy
Vehicle Technologies Program
1000 Independence Avenue, S.W.
Washington, DC 20585-0121

FY 2007

Annual Progress Report for
Advanced Vehicle Technology Analysis and Evaluation Activities

Submitted to:
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Vehicle Technologies Program
Advanced Vehicle Technology Analysis and Evaluation

Lee Slezak, Technology Manager

CONTENTS

I. INTRODUCTION

On behalf of the U.S. Department of Energy's Vehicle Technologies (VT) Program, I am pleased to submit the Annual Progress Report for fiscal year 2007 for the Advanced Vehicle Technology Analysis and Evaluation (AVTAE) team activities.

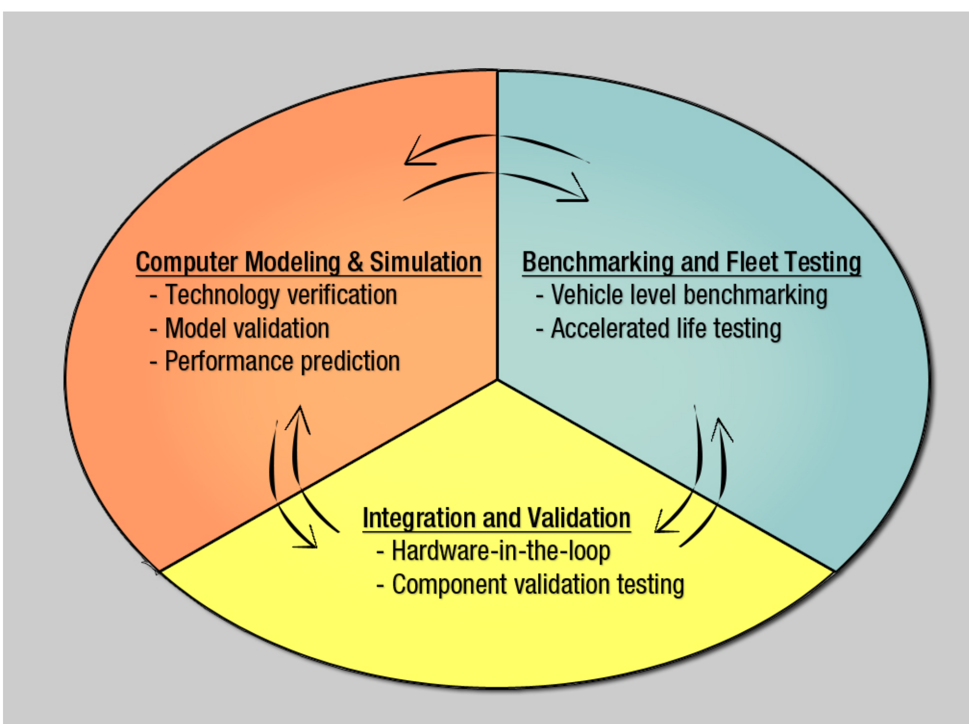
Mission

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

Objective

The prime objective of the AVTAE team activities is to evaluate VT Program targets and associated data that will enable the VT technology R&D teams to focus research on areas that will maximize the potential for fuel efficiency improvements and tailpipe emissions reduction. AVTAE accomplishes this objective through a tight union of computer modeling and simulation, integrated component testing and emulation, and laboratory and field testing of vehicles and systems. AVTAE also supports the VT Program goals of fuel consumption reduction by developing and evaluating enabling vehicle system technologies in the area of light vehicle ancillary loads reduction.

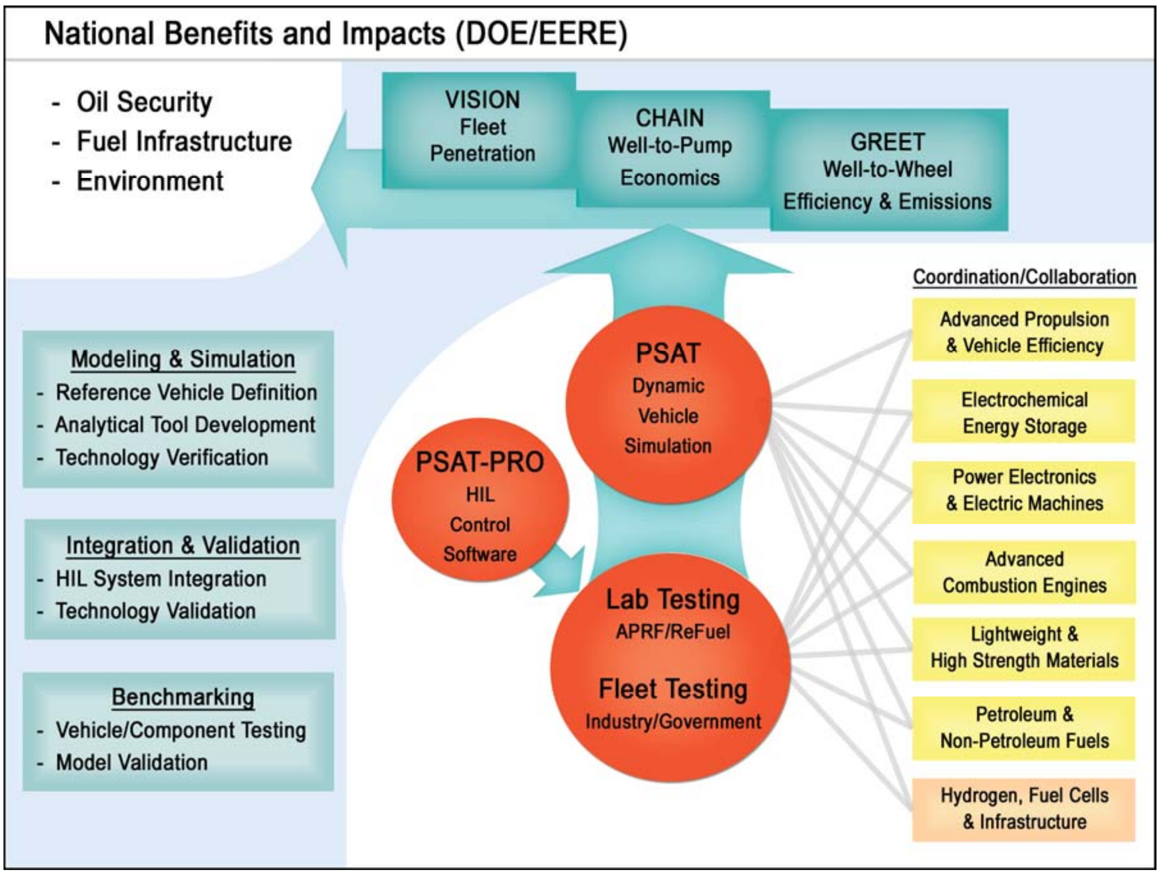
The integration of computer modeling and simulation, hardware-in-the-loop testing, vehicle benchmarking, and fleet evaluations is critical to the success of the AVTAE team. Each respective area feeds important information back into the other, strengthening each aspect of the team. A graphical representation of this is shown in the figure below.



Integration of AVTAE computer modeling and testing activities

FY 2007 AVTAE Activities

AVTAE provides an overarching vehicle systems perspective in support of the technology R&D activities of DOE's VT and Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Programs. AVTAE uses analytical and empirical tools to model and simulate potential vehicle systems, validate component performance in a systems context, verify and benchmark emerging technology, 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 VT 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 VT and HFCIT Programs 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.



AVTAE activities providing estimates of National benefits and impacts of advanced technologies

AVTAE is comprised of the following four (4) main focus areas, each of which are described in detail in this report:

1. ***Modeling and Simulation***

   A unique set of tools has been developed and is maintained to support VT research. VISION, CHAIN, and GREET are used to forecast national-level energy and environmental parameters including oil use, infrastructure economics, and greenhouse gas contributions of new technologies, based on VT vehicle-level simulations that predict fuel economy and emissions using the Powertrain Systems Analysis Toolkit (PSAT) modeling tool. Dynamic simulation models (i.e., PSAT) are combined with DOE's specialized equipment and facilities to validate DOE-sponsored technologies in a vehicle context (i.e., PSAT-PRO control code and actual hardware components in a virtual vehicle test environment). Modeling and testing tasks are closely coordinated to enhance and validate models as well as ensure laboratory and field test procedures and protocols comprehend the needs of coming technologies.

   PSAT (Powertrain Systems Analysis Toolkit) allows dynamic analysis of vehicle performance and efficiency to support detailed design, hardware development, and validation. A driver model attempts to follow a driving cycle, sending a torque demand to the vehicle controller which, in turn, sends a demand to the propulsion components (commonly referred to as "forward-facing" simulation). Dynamic component models react to the demand (using transient equation-based models) and feed back their status to the controller. The process iterates on a sub-second basis to achieve the desired result (similar to the operation of a vehicle). The forward architecture is suitable for detailed analysis of vehicles/propulsion systems and the realistic command-control-feedback capability is directly translatable to PSAT-PRO control software for testing in the laboratory. Capabilities include transient performance, efficiency and emissions (conventional, hybrid, plug-in hybrid and fuel cell vehicles), development and optimization of energy management strategies, and identification of transient control requirements.

   PSAT-PRO (PSAT rapid control PROtotyping software) allows dynamic control of components and subsystems in Rapid Control Prototyping (RCP) or hardware-in-the-loop (HIL) testing. Hardware components are controlled in an emulated vehicle environment (i.e., a controlled dynamometer and driveline components) according to the control strategy, control signals, and feedback of the components and vehicle as determined using PSAT. The combination of PSAT-PRO and RCP/HIL is suitable for propulsion system integration and control system development, as well as rigorous validation of control strategies, components, or subsystems in a vehicle context (without building a vehicle). Capabilities include transient component, subsystem and dynamometer control with hardware operational safeguards compatible with standard control systems.

2. ***Integration and Validation***

   Hardware-in-the-loop (HIL) simulation provides a novel and cost effective approach to evaluating advanced automotive component and subsystem technologies. HIL allows actual hardware components to be tested in the laboratory at a full vehicle level without the extensive cost and lead time for building a complete prototype vehicle. This task integrates modeling and simulation with hardware in the laboratory to develop/evaluate propulsion subsystems in a full vehicle level context.

   In this initiative, a versatile Mobile Automotive Technology Testbed (MATT) has been developed. 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 has been developed to assist DOE in validating advanced technology. As the VT Program matures, 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 system 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 PHEV research, ANL has developed and implemented a battery hardware-in-the-loop simulator to test potential battery packs in vehicle level operating conditions. In FY07, the battery HIL has been used to evaluate a JCS 41 amp*hr lithium ion battery. H2-ICE technology potential evaluation within hybrid vehicle architectures was performed using MATT starting in FY06. In preparation, ANL expanded its hydrogen engine testing and calibration capabilities by building a hydrogen engine test cell. Work is underway to adapt and optimize the engine control to the hybrid vehicle environment, providing a sound integration and enabling this technology to be validated in a suitable hybrid vehicle context.

3. Laboratory Testing and Benchmarking

This section describes the activities related to laboratory validation of advanced propulsion subsystem technologies for advanced vehicles. In benchmarking, the objective is to extensively test production vehicle and component technology to ensure that VT-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 VT programs and facilitates the setting of performance targets.

Validation and benchmarking require the use of internationally accepted test procedures and measurement methods. However, many new technologies require adaptations and more careful attention to specific procedures. ANL engineers have developed many new standards and protocols, which have been presented to a wide audience such as FreedomCAR partners, other government laboratories, and the European Commission.

To date, over 100 PHEVs, HEVs, fuel cell vehicles, and propulsion subsystem components have been benchmarked or validated by ANL staff. The propulsion system hardware components: batteries, inverters, electric motors and controllers are further validated in simulated vehicle environments to ensure that they will meet the vehicle performance targets established by the government-industry technical teams.

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. A multi-dynamometer facility for testing components (such as engines and electric motors) and a 4-wheel vehicle dynamometer that allows accurate testing of all types of powertrain topologies. During 2004, the quality of lab data was validated by correlating results with Ford's Allen Park vehicle test facility using one of their Ford Explorer correlation vehicles. ANL now has its own correlation vehicle for test repeatability.

4. Operational and Fleet Testing

The Advanced Vehicle Testing Activity (AVTA), working with industry partners, accurately measures the 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. The testing results are also used by fleet managers and the public for advanced technology vehicle acquisition decisions. Light-duty vehicle testing activities are conducted by Idaho National Laboratory (INL) in partnership with an industry group led by Electric Transportation Applications (ETA). 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.

The AVTA performs three types of tests depending on the vehicle technology, end-use application, and the needs of the testing partner; the tests are described below.

Baseline Performance Testing

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 "apple-to-apple" comparisons within respective vehicle technology classes. The APRF at ANL is utilized for the dynamometer testing of the vehicles.

Fleet Testing

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 available 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.

Under fleet testing, idle reduction demonstration and evaluation focuses on data collection, cost reduction, and education and outreach activities to overcome barriers to the implementation of idle reduction technologies in heavy-duty trucks. Data collection and demonstration activities include evaluation of fuel consumption, cost, reliability and durability, engine and accessory wear, and driver impressions. Cost reduction activities are focusing on development and evaluation of advanced idle reduction technologies for on-line, factory installation.

Accelerated Reliability Testing

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. The testing goal for HEVs is to accumulate 160,000 miles per vehicle within three years. 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 than two 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.

Major projects conducted by the national laboratories in support of these areas in FY 2007 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 AVTAE

Near term solutions for reducing the nation's dependence on imported oil, such as plug-in hybrid electric vehicles (PHEV), will require the development 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 2008, the AVTAE will expand activities in the area of PHEV simulation and evaluation including further baseline performance testing of conversion and OEM PHEVs, and validation of simulation models for PHEVs tested in the APRF. Field and laboratory testing will continue to be integrated with modeling/ simulation tools. Fleet evaluation of PHEV conversion vehicles will continue; however, emphasis will be place on establishing evaluation fleets of OEM production PHEVs. Deviation of test procedures for PHEVs will be completed. Work will focus on validation of these procedures. ANL and INL will continue working together to complete construction of a Plug-In Hybrid Test Bed (PHTB) that will be used for evaluations of motors, batteries, and control algorithms. Significant work will continue on the development of a heavy vehicle dynamic simulation tool, similar in nature to PSAT. This tool will complement work being done in other VT R&D programs, most notably Heavy Vehicle Systems Optimization. Work on a revised vehicle cost model incorporated into PSAT will also be undertaken in FY 2008. Although the development of light vehicle simulation models will be essentially completed, the vehicle and component models, as well as their respective control strategies, will continually be updated and enhanced to reflect the progress of technology in the transportation sector. Validation of VT technologies for advanced power electronics, energy storage, and combustion engines will be ongoing as each technology progresses towards the targeted performance.

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

Lee Slezak
Technology Manager
Advanced Vehicle Technology Analysis and Evaluation
Vehicle Technologies Program

II. MODELING AND SIMULATION

A. PSAT Model Validation

Aymeric Rousseau (Project Leader), Vincent Freyermuth, Jason Kwon
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261, e-mail: arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Use test data to develop a controller for the Lexus RX400h and Civic Hybrid models in PSAT that replicates the observed vehicle behavior.

Approach

- Gather component test data.
- Determine validation criteria.
- Tune each component model using vehicle test data.
- Use test data and various curve fitting, clustering, and optimization methods to force the simulated controller to replicate the behavior of the vehicle.
- Understand the limitations on the accuracy of the modeling technique.

Accomplishments

- Component models were integrated into PSAT.
- Control strategy was developed based on vehicle test data.
- Vehicle model was validated using several driving cycles.

Future Directions

- Continue to validate PSAT using test data from ANL's Advanced Powertrain Research Facility (APRF.

Introduction

Test data from ANL's Advanced Powertrain Research Facility (APRF) were used to validate the models of two advanced hybrid vehicles, the Lexus RX400h and the Civic Hybrid.

Lexus RX400h

The Lexus RX400h configuration is based on the Toyota THS2 powertrain system connected to the front axle, along with an additional electric machine connected to the rear axle. The vehicle is, hence, a 4×4, even though at times power is transferred to only one axle.

The architecture, composed of a planetary gear set, an engine, and three electric machines, was implemented in PSAT. In order to duplicate the vehicle in PSAT, several initialization files and models were created and/or modified.

Because the powertrain on the front axle is similar to the Prius system, the strategy developed for the Prius was used and modified to suit this application. In addition, a control strategy for the rear electric was developed.

For simplification, we will refer to the electric machine installed on the rear axle as motor 3. Motor 1 is the front motor link to the ring gear. Motor 2 is the electrical machine connected to the sun, also called generator.

Propelling logic

Based on the ring torque demand, a motor power demand is determined and divided between motors 1 and 3:

- If the engine is on and the vehicle is not in WOT (wide open throttle), motor 3 provides one-third of the power requested and motor 1 provides the remaining two-thirds.
- If the engine is off, motor 3 does not provide power.
- Under WOT conditions, both motors are providing their maximum power.

Braking logic

During braking, the regenerative power is divided between motor 3 and motor 1.

- Motor 3 regenerates 10% of the regenerative power demand.
- Motor 1 regenerates 90% of the regenerative power demand.

Figures 1 through 3 demonstrate the validation of the vehicle model in PSAT using the urban dynamometer driving schedule (UDDS) cycle.

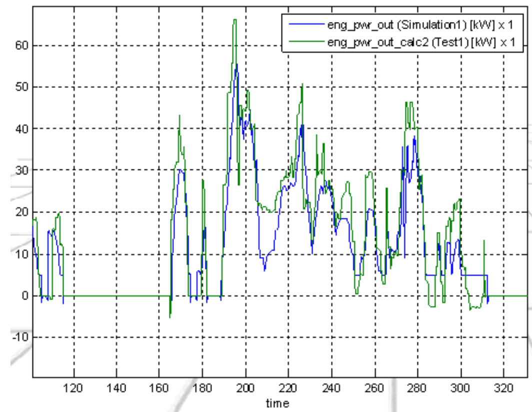


Figure 1. Engine Power on UDDS

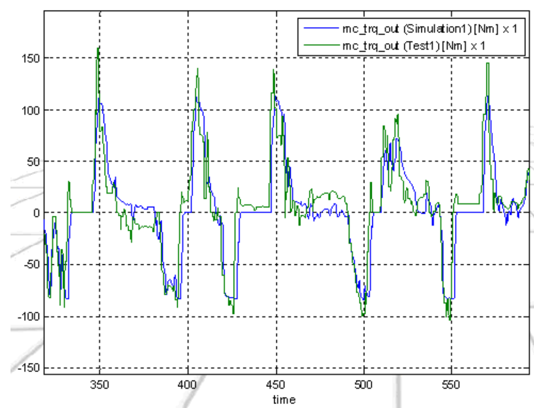


Figure 2. Motor Power on UDDS

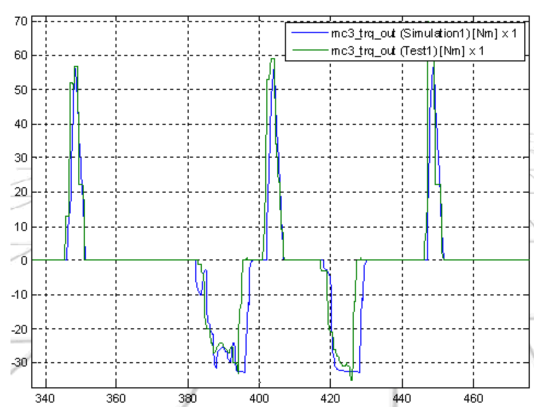


Figure 3. Rear Motor Power on UDDS

The simulated adjusted fuel economies compare well with the EPA values. The PSAT value is 29.6 mpg (vs. 31 mpg for EPA) for the city and 25.2 mpg (vs. 27 mpg for EPA) for highway.

Civic Hybrid

The Civic Hybrid model was validated on several drive cycles. The validation was performed in collaboration with Hyundai Motor Company. Indeed, several component models and vehicle test data were provided by Hyundai. The main focus of the control strategy, in addition to engine ON/OFF logic, was the continuously variable transmission (CVT) logic.

Figure 4 shows the vehicle-level control of the Civic Hybrid.

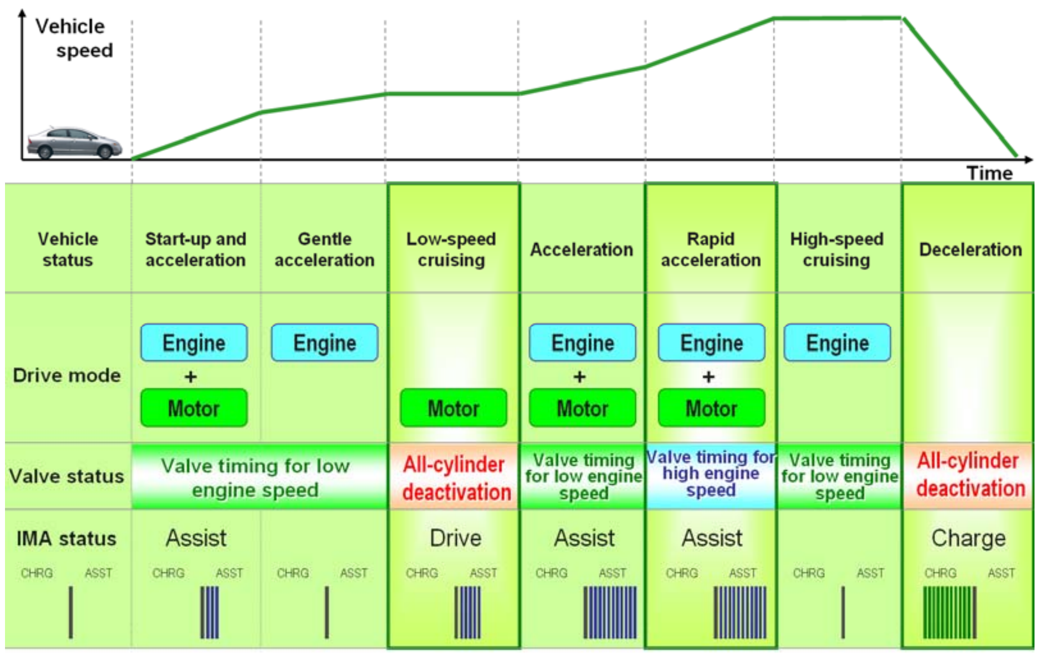


Figure 4. Civic HEV Vehicle Level Control (source: Honda)

Several new technologies were introduced in the Civic Hybrid to increase its fuel economy, including:

- Pumping losses reduction and increase of engine output at high speed.
- Increased regenerative power as a result of cylinder deactivation and cooperative regeneration brake control.
- Modified electric machine, CVT, and battery.
- Idle stop range expanded due to the adoption of a hybrid air conditioner.

Figures 5 through 7 show some examples of comparisons between simulated and test parameters.

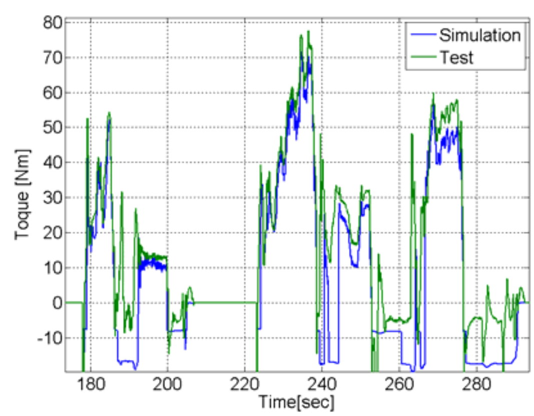


Figure 5. Engine Torque on Japan1015

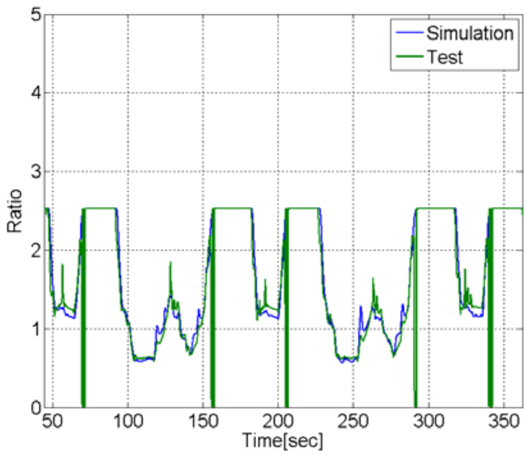


Figure 6. CVT Ratio on Japan1015

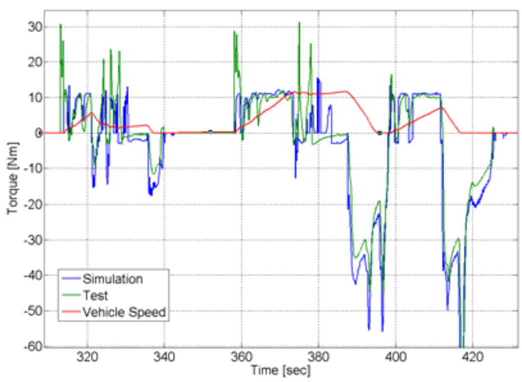


Figure 7. Motor Torque on Japan1015

Conclusions

Several vehicles were validated in PSAT to ensure the validity of the component models and control strategies used for all the simulations.

B. Simulation Runs to Support GPRA

Sylvain Pagerit (Project Leader), Vincent Freyermuth, Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261, e-mail: arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- The goal is to simulate multiple vehicle platforms, configurations, and timeframes to provide fuel economy data for analysis in support of GPRA.

Approach

- Validate component and vehicle assumptions with the different National Laboratories and FreedomCAR Tech Teams.
- Use automatic component sizing to run the study.

Accomplishments

- More than 700 vehicles were sized and simulated.
- New vehicles were simulated 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 2008.

Introduction

DOE management is interested in a side-by-side review of alternative pathways to reducing U.S. oil use and greenhouse gas (GHG) emissions from the light-duty vehicle fleet, and the National Research Council has called for a similar review, in the context of exploring alternatives to the hydrogen/fuel cell pathway. This study is Phase I of this review and will examine some of the key alternatives using a limited set of evaluation criteria — oil use reductions, GHG emission reductions, refueling infrastructure challenges, environmental impacts (aside from GHG emissions), and risk. Phase II will explore more pathways (and more scenarios, such as combinations of pathways) with more evaluation criteria (including cost).

Assumptions

The following assumptions have been defined for three vehicle classes: midsize car, crossover SUV, and midsize SUV. Six configurations are proposed for the study:

- Conventional gasoline
- Conventional diesel
- Full hybrid gasoline (no all-electric range [AER]; 20 and 40 miles)
- Full hybrid diesel (no AER; 20 and 40 miles)
- Fuel cell hybrid
- Electric vehicle

Two driving cycles were used: urban dynamometer driving schedule (UDDS) and highway fuel economy test (HWFET).

Additional assumptions:

- AER will be defined on UDDS.
- Hydrogen storage tanks will be sized for 320-mile range (UDDS and HWFET combined).
- For fuel cell hybrid electric vehicle (HEV) configurations, only batteries will be considered. However, it has been shown that ultracapacitors would achieve similar fuel economy than lithium-ion batteries for lower-hybridization-degree configurations.

The vehicle and component assumptions were reviewed by the FreedomCAR Technical Teams.

Results

The results herein were obtained after several modifications to the assumptions and sizing of the vehicles in response to feedback from the original runs.

Figure 1 shows the fuel economy ratios for the timeframes considered (2015, 2030, and 2045) for the midsize car compared with the conventional gasoline car of the same year. As one notices, the ratio between each powertrain configuration is fairly constant across the timeframes. The conventional gasoline vehicle becomes better with time because an increase in engine efficiency will have a greater impact than a similar increase in fuel cell efficiency. This is a consequence of the assumptions used in the study.

Figure 2 shows the fuel economy ratios for the timeframes considered (2015, 2030 and 2045) for midsize cars compared with the 2007 conventional gasoline car. Similar trends and values are noticed than for the other vehicles.

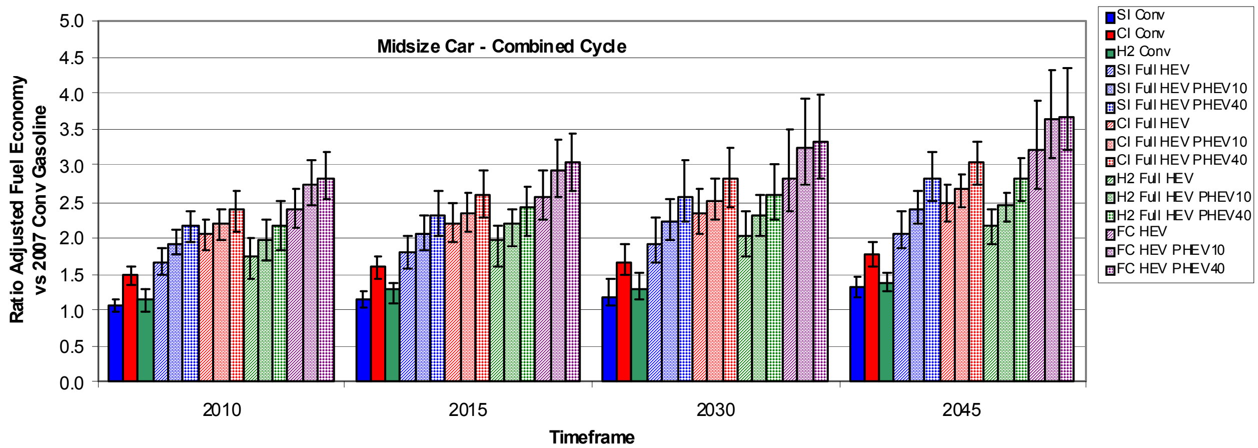


Figure 1. Fuel Economy Ratios vs. 2007 Conventional Gasoline Midsize Car — Combined Driving Cycle

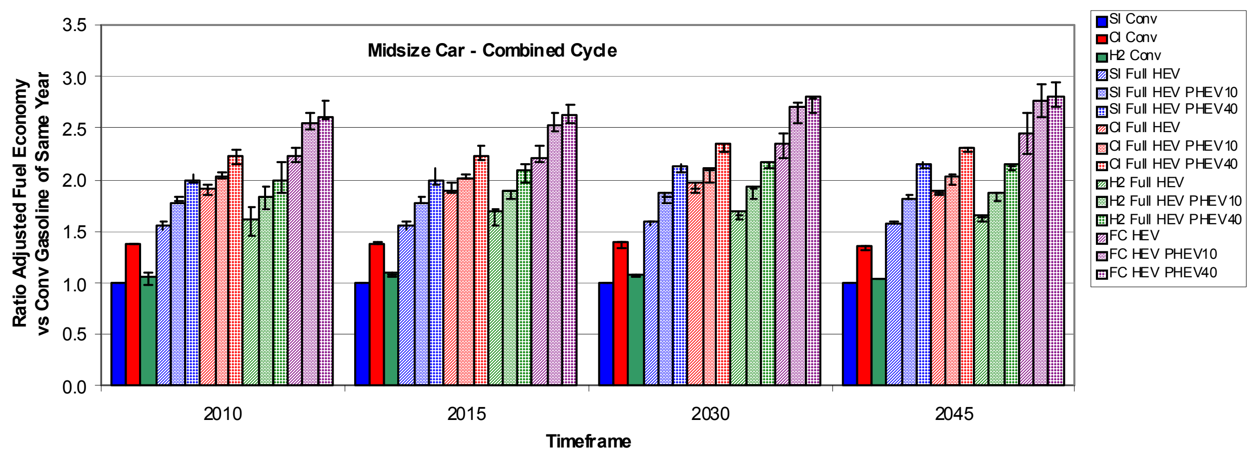


Figure 2. Fuel Economy Ratios vs. Conventional Gasoline of Same-Year Midsize Car — Combined Driving Cycle

Conclusions

All the simulations to support GPRA were performed. The use of automatic sizing allowed for a faster response time. The results will also be used as inputs to the cost model and GREET to perform further analysis to support the FreedomCAR Fuels Technical Team.

C. Comparison of Hydrogen Engine and Fuel Cell System Fuel Economies for Advanced Powertrain Configurations

Aymeric Rousseau (Project Leader)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261, e-mail: arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Evaluate the fuel economy potential of the hydrogen internal combustion engine compared with that of a fuel cell system for several advanced powertrain configurations.

Approach

- Define current and future technology characteristics for hydrogen engines and fuel cell systems.
- Select configurations with highest potential.
- Size the components for each option considered.
- Compare results.

Accomplishments

- Fuel economy results were compared for nonhybrid, charge-sustaining hybrid, and plug-in hybrid vehicles.
- Uncertainty was assessed for each system.

Future Directions

- Refine fuel economy comparison when updated component data are available.

Introduction

This study compares the fuel economy potential of hydrogen internal combustion engines (ICEs) with that of fuel cell vehicles for both nonhybridized and hybridized systems. To take uncertainties into account, port-injected and direct-injected hydrogen ICE technologies were considered. Whereas the complete port-injected data were obtained from engine testing, the direct-injected map was developed from single-cylinder data. The fuel cell system data represent current technology status as well as FreedomCAR goals. Several powertrain configurations were considered for each component technology, including series and power-split hybrid electric vehicle (HEVs).

Vehicle Descriptions

Two hybrid families were considered in the study. For each option, several hundreds of combinations are possible, including the number of electric machines, their locations, and the type of transmission. The following configurations were selected for this study:

- Series configuration with a single gear ratio
- Power-split configuration

For each configuration, both charge-sustaining and charge-depleting options were considered. The fuel cell system and hydrogen engine technologies were compared for each powertrain configuration and component size considered.

For comparison purposes, the vehicle class used for all four configurations is the same: a midsize sedan. The main characteristics are defined in Table 1.

Table 1. Main Vehicle Characteristics

Glider mass	990 kg
Frontal area	2.1 m^2
Coefficient of drag	0.29
Wheel radius	0.317 m
Tire rolling resistance	0.008

Because the primary goal of the study is to compare the fuel economies of fuel cell systems to those of hydrogen engines, the uncertainties and potentials of the technologies were considered.

Figure 1 shows the fuel cell system efficiencies used in PSAT. The current system is characterized by a peak efficiency of 55% with a specific power of 500 W/kg, while the future technology achieves 60% efficiency with 650 W/kg. Several systems currently achieve 60% peak efficiency using a compressor expander module (CEM); however, CEM are not used in vehicles because of cost, leading to lower system efficiencies.

In addition, the fuel cell system efficiency curves are developed at steady-state. One needs to keep in mind that the parasitic load is much higher on real-world driving because of transients and nonoptimum control. This would make both curves even more aggressive.

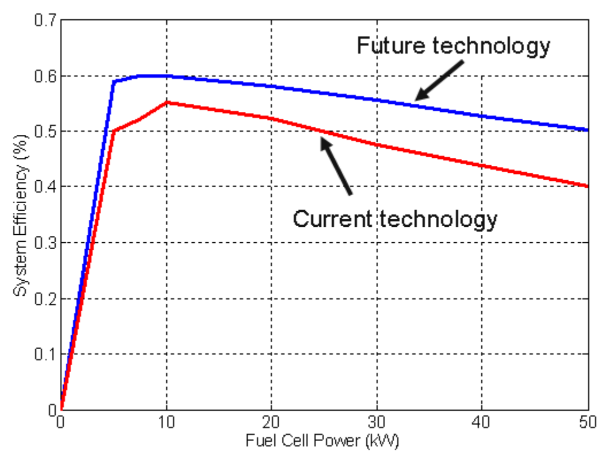


Figure 1. Fuel Cell System Efficiencies

Figure 2 shows the current hydrogen engine technology used in the simulation, based on port-injected data. The map was generated at ANL's test facility based on several air/fuel ratio data points.

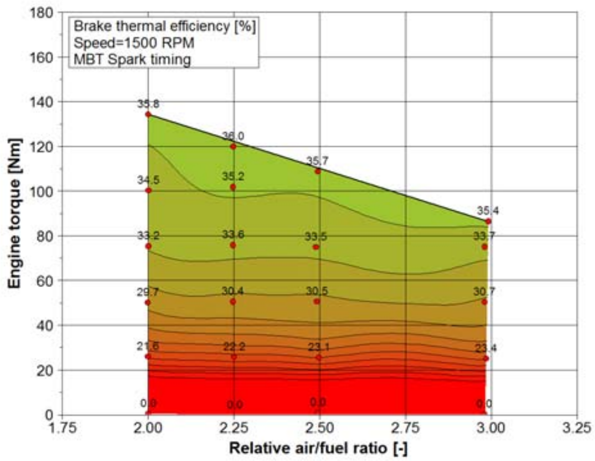


Figure 2. Port-Injected Hydrogen Engine Map

The direct-injection hydrogen engine map was developed based on single cylinder data, taking into account the following factors:

- Hydrogen direct injection will increase the peak torque curve.
- Increased compression ratio will result in higher engine efficiency.
- Turbocharging will increase the engine efficiency more than supercharging will.
- Lean part-load operation will result in higher part-load efficiency than throttled operation.

The peak efficiency is based on the FreedomCAR goal of 45%.

Fuel Economy Results

As discussed previously, uncertainties were taken into account for each technology considered. The graphs in Figures 3 through 6 highlight the fuel economy ratios of the different vehicles. The uncertainties are calculated as the lowest and the highest ratios. For example, the lowest ratio comparing the hydrogen engine conventional vehicle with the fuel cell conventional on Figure 3 is obtained by comparing the current fuel cell technology with the future engine technology. The ratios are based on unadjusted fuel economy values from hot start. The fuel cell system configurations are used as the reference.

Conventional Configurations

As expected, the fuel economy of the nonhybridized configuration largely favors the fuel cell vehicle, as shown in Figure 3. Even when comparing current fuel cell with future engine, the ratio is only 0.58.

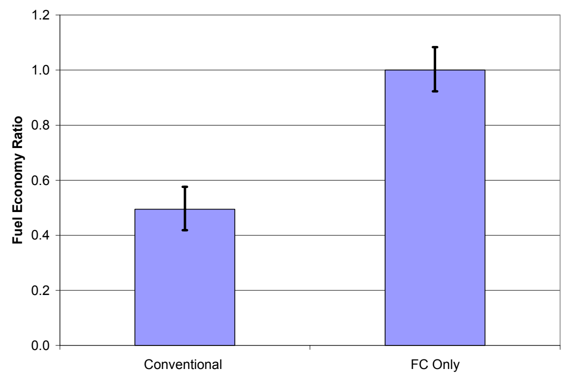


Figure 3. Fuel Economy Ratios for non-HEVs, Combined Drive Cycle

Hybrid Configurations

The hybrid configurations shown in Figure 4 show fewer discrepancies among the technologies because the engine configurations benefit more from hybridization than do their fuel cell counterparts. The series engine shows the lowest fuel economy results due to higher vehicle mass and additional component inefficiencies when the engine is turned on. The highest ratio achieved in that case is 0.65.

The power split allows decoupling of the engine speed from the vehicle speed, similarly to the series engine. However, it also allows a direct path to the wheels, resulting in higher vehicle fuel economy. When comparing direct injection hydrogen ICE with current fuel cell technologies, the ratio is 0.91.

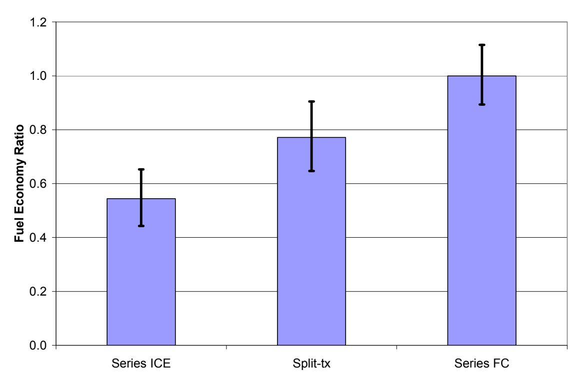


Figure 4. Fuel Economy Ratios for HEVs, Combined Drive Cycle

PHEV 10 AER Configurations

Plug-in hybrid electric vehicles (PHEV) use a larger amount of electrical energy to propel the vehicle. As a consequence, the configurations with the most efficient path from the battery to the wheel will benefit more. As shown in Figure 5, the series configuration remains the least efficient (highest ratio of 0.63) compared with the other options. The power-split configuration shows a ratio of 0.83 when compared with current fuel cell technology and 0.76 when considering advanced fuel cell systems.

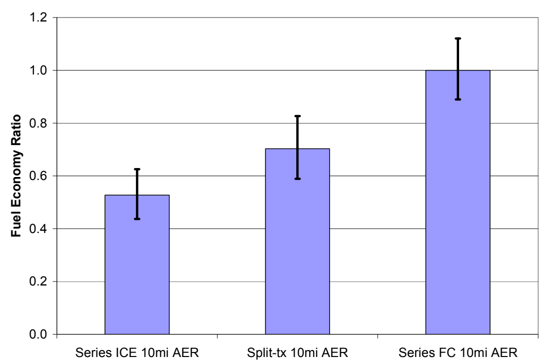


Figure 5. Fuel Economy Ratio, for PHEVs with 10 miles AER, Combined Drive Cycle

PHEV 40 AER Configurations

With a 40-mile PHEV vehicle, the electrical path becomes the critical factor in comparing technologies. As shown in Figure 6, the trends highlighted for the PHEV 10 configurations remain valid, with the series engine showing the least potential (highest ratio of 0.59) and the power split the highest (highest ratio of 0.84).

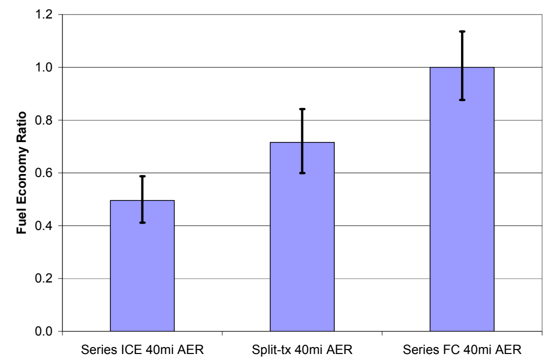


Figure 6. Fuel Economy Ratio for PHEVs with 40 miles AER, Combined Drive Cycle

Fuel Economy Summary

Figure 7 shows the fuel economy ratios of all the configurations considered in the study. The conventional hydrogen engine is use as a reference.

One interesting point of the graph is that the same or higher fuel economy could be achieved with a parallel configuration using a hydrogen engine with 10 miles AER as is achieved with a fuel cell hybrid. The main question would then be which component is the cheapest and most reliable.

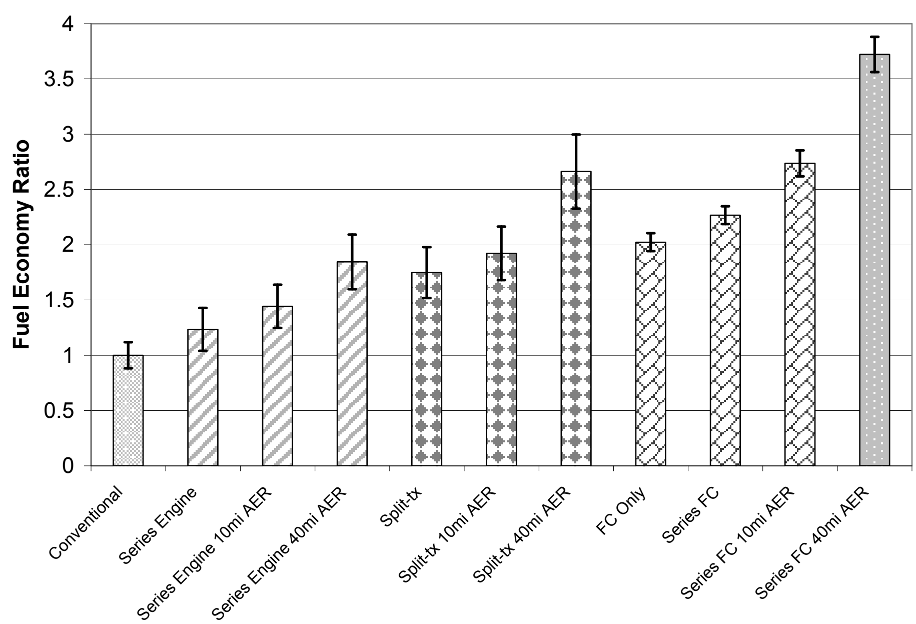


Figure 7. Fuel Economy Ratio for All Vehicles – Reference Conventional H2 Engine, Combined Drive Cycle

Conclusions

The fuel economy potentials of two promising technologies using hydrogen fuel have been compared. The uncertainties of each technology were taken into account as part of the evaluation. The necessary developments to achieve the respective efficiency and cost goals are significant.

The results show that hydrogen engine technology can only be competitive with fuel cell systems if it is hybridized.

If one considers that the current fuel cell system efficiencies will remain constant in the future because most research is focused on cost and durability, the direct-injection hydrogen engine could be a valid short-term option. Depending on the configuration considered, such an engine could achieve values close to those of the fuel cell, from 1.02 (PHEV40) to 1.06 (HEV).

When known future technologies are compared, the hydrogen engine still achieves acceptable fuel economy compared with the fuel cell system, with ratios close to 1.2.

Considering the uncertainties of research and the potential of each technology, pursuing both options in parallel offers the greatest chance to quickly achieve a hydrogen economy.

Publications / Presentations

1. C. Haliburton, H. Luque, A. Rousseau, T. Wallner, and H. Lohse-Busch, "Comparison between Hydrogen Engine and Fuel Cell Vehicle Fuel Economies for Advanced Powertrain Configurations," SAE World Congress, Detroit (April 2007).

D. PSAT Maintenance and Enhancements

Aymeric Rousseau (Project Leader), Shane Halbach, Sylvain Pagerit, Phil Sharer, Dominik Karbowski, Vincent Freyermuth, Jason Kwon
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261, e-mail: arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- The goal is to enhance and maintain PSAT and PSAT-PRO as needed to support DOE, the user community, and HIL projects. This effort includes development of updates for the latest Matlab/Simulink version(s) and an annual release of the software with the latest models and data.

Approach

- Use the feedback from PSAT users to implement new features.
- Enhance PSAT capabilities to support DOE studies.

Accomplishments

- Development of PSAT V6.1, to be released in November 2007.
- Improvement of the Graphical User Interface.
- Addition of new powertrain configurations, including GM 2 mode.
- Redesign of all vehicle-level control strategies.
- Implementation of heuristic optimization routines.

Future Directions

- Continue to enhance PSAT based on DOE needs and user feedback.

Introduction

To better support the U.S. Department of Energy (DOE) and its users, several new features have been implemented in the Powertrain System Analysis Toolkit (PSAT). Some of the most significant accomplishments are described below.

Results

The Vehicle Systems Analysis Team at Argonne National laboratory (ANL) will release the newest version of its vehicle simulation modeling software in November 2007. The latest version, PSAT V6.2, includes many new features and improvements. These changes were based on feedback from users in industry and at universities, as well as the needs expressed by staff at DOE and ANL. The PSAT V6.2 runs with Matlab R2007b.

Graphical User Interface

Numerous new features have been implemented on the basis of user feedback and in support of DOE activities.

Transient Models Selection

Transient blocks are used in PSAT to determine how the vehicle changes from one state to another (e.g., gear shifting, engine start, etc.). In previous releases of PSAT, users did not have the ability to change any of the default controls. The addition of the Tab in the Graphical User Interface allows the users to implement their own transients (Figure 1).

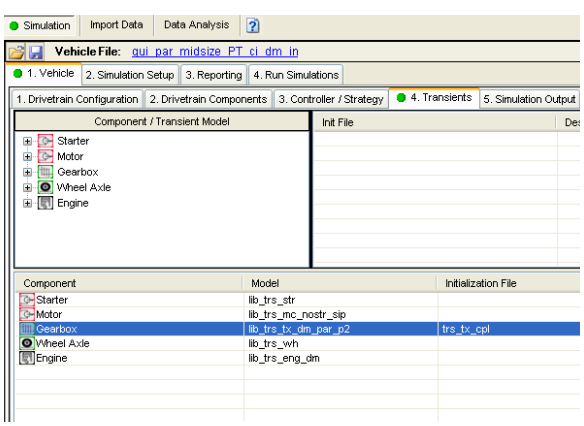


Figure 1. Transient Model Selection

Building the Drive Cycles

With the increasing importance of PHEVs, the vehicle must be evaluated on longer distances than for charge-sustaining hybrids. The need to combine cycles to create different trips led to the development of a new interface. Users can now create any trip based on combinations of existing drive cycles by using drag and drop (Figure 2).

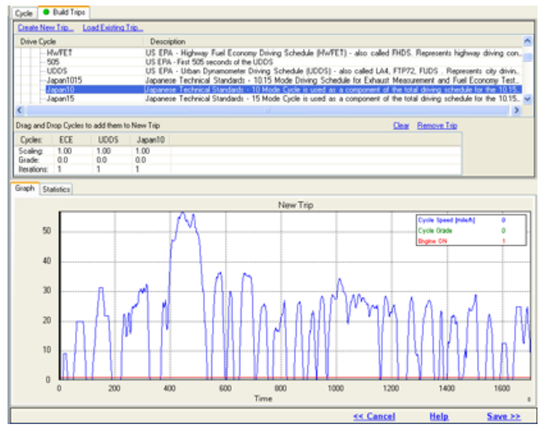


Figure 2. Interface to Build Trips

Enhanced Energy Balance

The visualization of the energy balance has been improved to allow users to simultaneously view the different energy paths (e.g., acceleration and deceleration). This modification solves the issue of having efficiencies that differ from the energy values if only a single value is used (Figure 3).

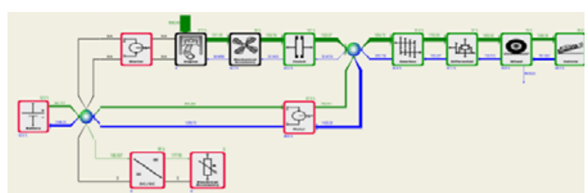


Figure 3. Enhanced Energy Balance

Additional Test Procedure

Two test procedures have been implemented in PSAT:

- EPA 5 Cycle Procedure
- PHEV J1711 Procedure

Each test procedure is still based on hot start simulations. Correction factors are being developed to adjust for cold start penalties.

Additional Powertrain Configurations

Numerous powertrain configurations have been added in PSAT. The notable configurations include:

- GM2 mode,
- Power split with read motor (similar to Lexus RX400h), and
- Pre-transmission parallel configuration with two clutches (before and after electric machine).

The vehicle-level control strategies for each of these configurations also have been developed.

Figure 4 shows the RX400h configuration.

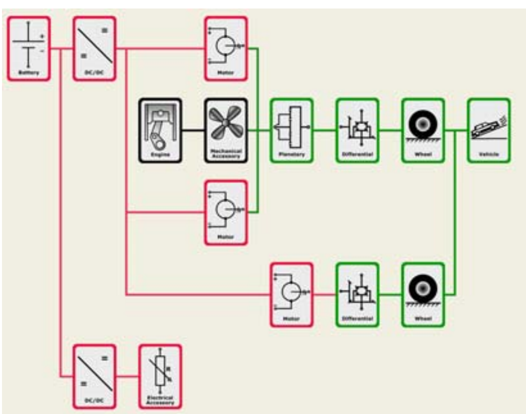


Figure 4. RX400h Configuration

New Control Strategies

The vehicle-level control strategies for all the powertrain configurations have been rewritten to ensure greater stability of the vehicle behavior and consistency between the different controls. All the models are based on the same organization, with the calculations developed in Simulink and the logic in StateFlow. The Stateflow controllers, in addition to the torque/power split, also include drive quality metrics with, for example, limitations of engine ON/OFF (Figure 5).

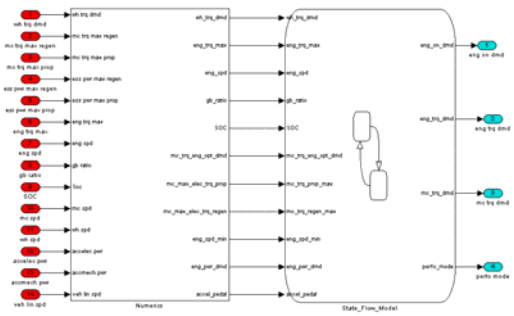


Figure 5. New Control Organization

Implementation of Heuristic Control Strategies

Divided rectangle (DIRECT) and genetic algorithms have been integrated in PSAT. This new capability allows ANL to automatically tune parameters to minimize any cost function (Figure 6).

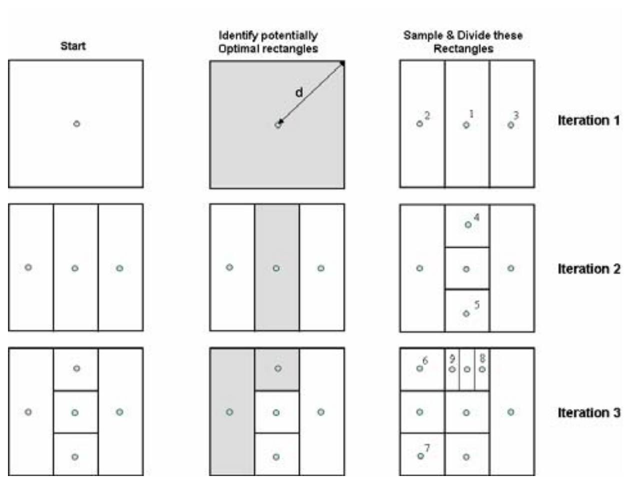


Figure 6. First Three Iterations of the DIRECT Algorithm

Conclusions

The PSAT V6.2 will be released with numerous new features based on feedback from DOE and the user community.

E. Validation of the Hymotion Prius PHEV

Aymeric Rousseau (Project Leader)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261, e-mail: arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Use test data to develop a controller for the Hymotion Prius plug-in hybrid electric vehicle (PHEV) that replicates the observed vehicle behavior.

Approach

- Gather component test data.
- Determine validation criteria.
- Tune each component model by using vehicle test data.
- Use test data and various curve fitting, clustering, and optimization methods to force the simulated controller to replicate the behavior of the vehicle.
- Understand the limitations on the accuracy of the modeling technique.

Accomplishments

- Generic data-quality analysis process developed and implemented for the Hymotion Prius.
- Component models integrated into the Powertrain System Analysis Tool (PSAT).
- Control strategy developed based on vehicle test data.
- Vehicle model validated on several driving cycles, including the urban dynamometer driving schedule (UDDS).

Future Directions

- Evaluate the change in control strategy between different versions of the Hymotion Prius and compare with other after-market power split PHEVs.

Introduction

The plug-in hybrid electric vehicle (PHEV) is a promising alternative to conventional gas-powered vehicles. As the energy storage system can be recharged by using an outside plug, the battery charge can be depleted, allowing significant fuel displacement.

Because the set of conceivable hybrid electric vehicle (HEV) powertrains is so large, it is impractical to perform an exhaustive search that uses fabrication and testing of prototypes to provide information on the ideal powertrain for a given application. Instead, a simulation tool should be used to provide guidance of similar quality, assuming that the models used in this tool accurately predict the behavior of the powertrains under investigation.

The Advanced Powertrain Research Facility (APRF) at Argonne handles U.S. Department of Energy (DOE) validation and benchmark testing of advanced vehicle technologies. Argonne tests new HEVs and PHEVs to provide data that are used to update the PSAT. The data are also used to provide DOE and auto industry engineers with benchmark specifications that aid in forecasting future technology developments.

To verify the accuracy of a PSAT model, the outputs predicted by the component and powertrain models need to be compared to test data, a process referred to here as "validation." This paper describes the steps used to validate the Hymotion L5 PHEV model by using test data measured at Argonne's APRF.

Vehicle Testing

The vehicle testing results are presented in another section of this report. Beginning from a cold start, the PHEV Prius was tested on consecutive UDDS cycles. The battery energy was depleted through the second hill of the fourth consecutive UDDS. In total, 25 miles were driven in the charge-depleting (CD) mode. During those cycles, the powertrain was primarily operated by using the battery energy, except above 40 mph or when the electric-vehicle mode power threshold was exceeded. After the repeated UDDS cycles were completed, 4.3 kWh of AC energy was measured to fully recharge the battery pack. This charging event took approximately 6 hours.

Figure 1 shows the consecutive UDDS cycles. The red dots on the graph indicate when the engine is operating and consuming fuel. Note the accumulated fuel consumed is much lower for the Hymotion CD PHEV Prius than the stock charge-sustaining (CS) Prius. After the vehicle fully depletes the usable battery energy, it operates in the standard CS mode, just as a production Prius operates.

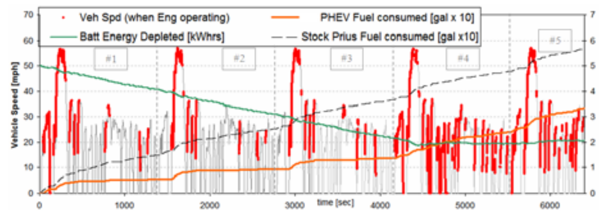


Figure 1. Hymotion Prius Driven on Repeated UDDS Cycles (cold start from 100% SOC to charge-sustaining operation)

Model Validation

The first step in the validation process consists of matching the component operating conditions, such as engine ON/OFF, torque, and speed. Once each component operates according to the tests, the values for fuel economy and electrical consumption should match the test data, pending component data accuracy. The 2004 Prius HEV model was validated on the basis of component data provided by Oak Ridge National Laboratory (electric machine and boost converter), Idaho National Laboratory (battery), and Argonne (engine and vehicle). The performance characteristics of the additional components of the Hymotion PHEV Prius (battery and power electronics) were estimated on the basis of input from component experts. The battery model was developed by Argonne's battery group to represent similar Li-ion technology.

The validation was performed on both the UDDS and highway fuel economy test (HWFET) drive cycles. However, only the UDDS cycle data are presented in this paper because they showed the most differences when compared with the HEV Prius. Figure 2 shows a comparison between the test and simulated engine torque. Because the Hymotion vehicle controller is unknown, as is the impact of the driver, it is difficult to exactly reproduce every engine ON/OFF event. Except for the first and last events, all engine ON/OFF events are reproduced in the simulation.

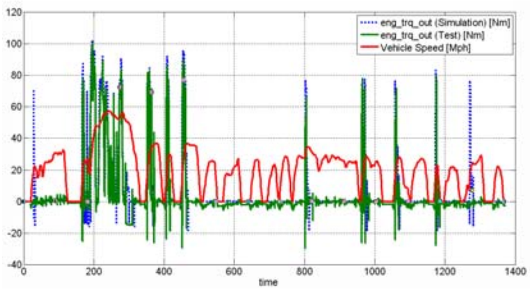


Figure 2. Engine Torque Comparison (UDDS during CD mode)

Figure 3 shows the engine torque comparison on the second hill of the UDDS, indicating good correlation with the test data.

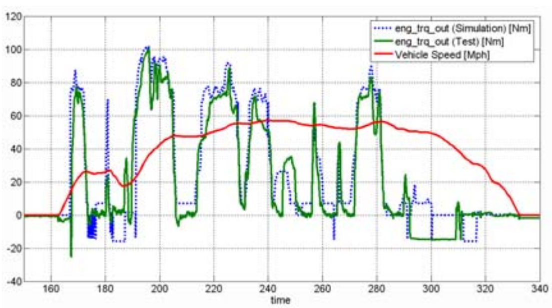


Figure 3. Engine Torque Comparison (UDDS during CD mode) – ZOOM

Figure 4 shows the power of the high-capacity battery during a portion of the UDDS. Note that the battery does not take part in the regenerative braking events.

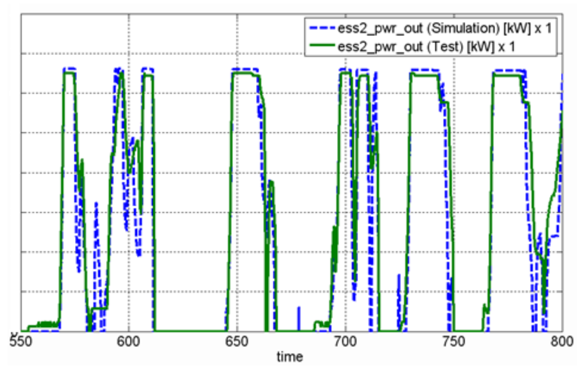


Figure 4. High-Capacity Battery Power Comparison (UDDS during CD mode)

Tables 1 and 2 summarize the main results of the test and simulation for the CD and CS modes. The fuel and electrical consumption and state of charge (SOC) demonstrate good correlation with the test data.

Table 1. Validation Results – UDDS during CD Mode (Test # 60610104)

Parameter	Units	Test	Simulation	Absolute Difference	Relative Difference
Fuel Consumption	l/100 km	1.33	1.22	0.11	8.8%
Elec. Consumption	Wh/km	86.3	83.8	2.5	2.8%
SOC Initial	%	62	62	0	0
SOC Final	%	62	62.8	0.8	1.3%

Table 2. Validation Results – UDDS during CS Mode (Test # 60610106)

Parameter	Units	Test	Simulation	Absolute Difference	Relative Difference
Fuel Consumption	l/100 km	3.64	3.58	0.06	1.7%
SOC Initial	%	62	62	0	0
SOC Final	%	62	61.8	0.2	0.3%

<u>Control Strategy Improvements</u>

When analyzing the Hymotion control strategy, one notices that the engine average efficiency is lower in the CD mode than in the CS mode, 30.1% to 33.5%, respectively. This significant difference is due to the large amount of fuel that is consumed at low power, as shown in Figure 5.

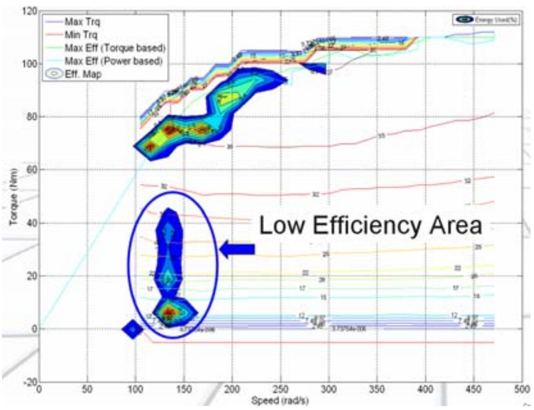


Figure 5. Engine Operating Conditions:
Density = f(Energy) – (UDDS during CD) – Simulation

Two control strategy changes were considered to improve the average engine efficiency during the cycle.

Engine ON/OFF Reduction

As shown in Figure 6, several engine ON events occur at times of low vehicle-power demand during the UDDS cycle. By changing some control parameters, such as the minimum power required at the wheel to start the engine and the constraints of the power supply of the high-capacity battery, these engine ON events can be deleted.

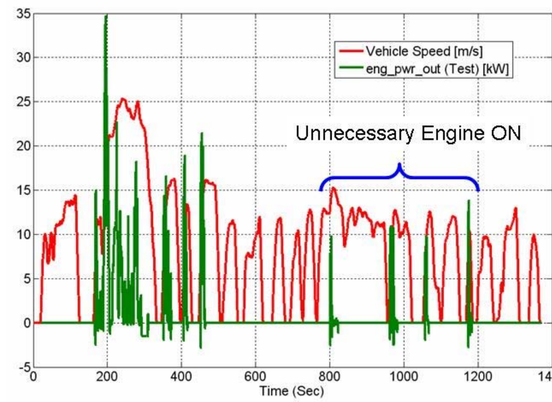


Figure 6. Engine ON/OFF Modification (UDDS during CD mode)

Figure 7 shows the electrical consumption as a function of fuel economy for the reference control (from both the test and simulation) as well as the modified control. Note that the relationship between both energies remains unchanged.

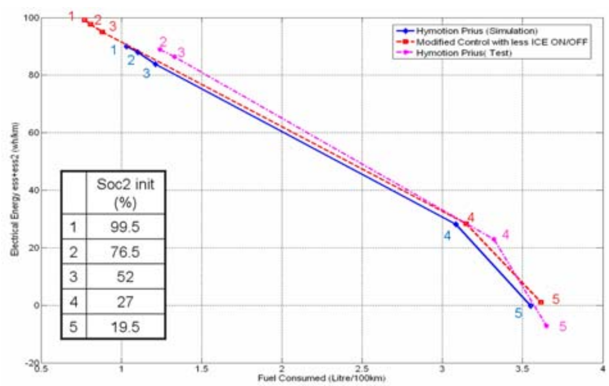


Figure 7. Energy Consumption Change Due to Fewer Engine ON/OFF Events (UDDS)

Engine Operating Conditions Improvement

In addition to the logic modifications in the engine ON/OFF events, we changed the engine operating conditions during CD. As can be seen in Figure 8, the Hymotion Prius engine operates at lower power during the second hill of the UDDS than does the Prius HEV. As a result, engine efficiency drops.

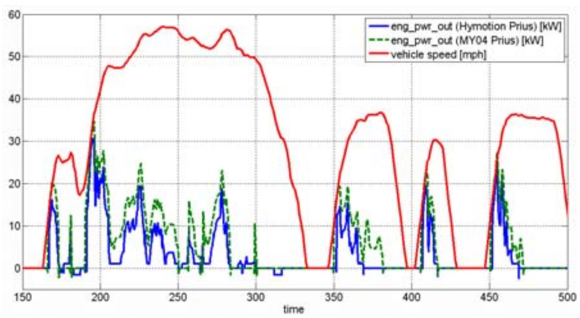


Figure 8. Engine Power Comparison between Hymotion and Reference Prius (UDDS)

Figure 9 shows the engine power for both the HEV and the Hymotion Prius after control modification, indicating a good correlation. The control logic algorithm has been modified.

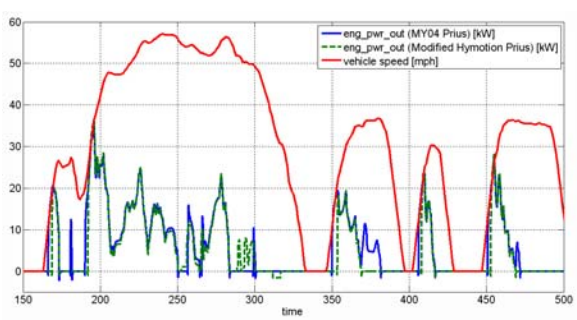


Figure 9. Engine Power Comparison after PHEV Control Modification (UDDS)

The amount of fuel consumed in the area of low efficiency has now almost disappeared, as shown in Figure 10.

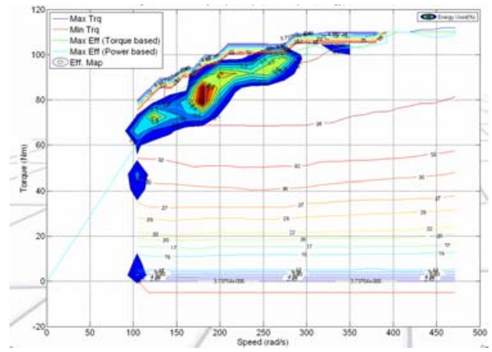


Figure 10. Engine Operating Conditions after Engine ON/OFF and Power Modifications:
Density = f(Energy) – (UDDS during CD Mode)

Figure 11 shows electrical consumption as a function of fuel economy for the reference control (from both the test and simulation) as well as both modified controls. Note that the relationship between both energies changes when the engine operates at higher power. The slope of the control based on the higher engine power is not as stiff as the other slope. This finding is due to the engine being used to recharge the battery. This approach is consistent with the one used in previous studies based on global optimization, which demonstrated that the engine, when ON, should operate close to its best efficiency curve.

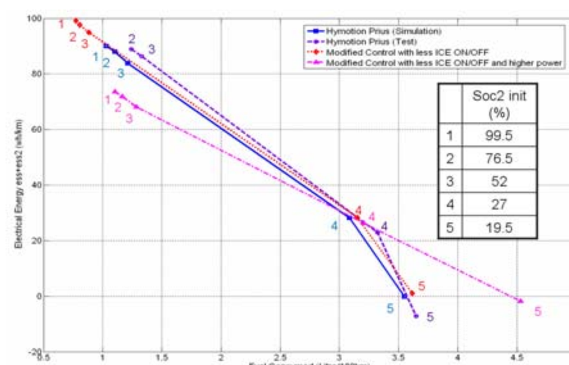


Figure 11. Energy Consumption Change due to Control (UDDS)

Control Strategy Comparison

Figure 12 shows the amount of fuel consumed after driving six UDDS cycles in a row as a function of distance for the reference HEV Prius and the PHEV Hymotion with original and modified control. As expected, the PHEV results in a significant reduction in fuel consumption compared to that of the Prius HEV. Once the PHEV reaches the CS mode (i.e., 35 km for the modified control strategy with minimum engine ON), the slope of the fuel consumed becomes identical to that of the reference HEV vehicle.

As shown in previous studies, the optimum control for PHEVs depends highly on the distance traveled. When someone is driving a short distance, he or she should use the battery as much as possible to minimize the amount of fuel consumed. When driving a long distance, that person should instead retain some battery energy to allow more flexibility in the control strategy. Around 48 km, the modified control strategy options cross each other. This shift indicates that, for a short distance, the engine should not be used to recharge the battery, while for longer distances, the engine should be operated at higher power.

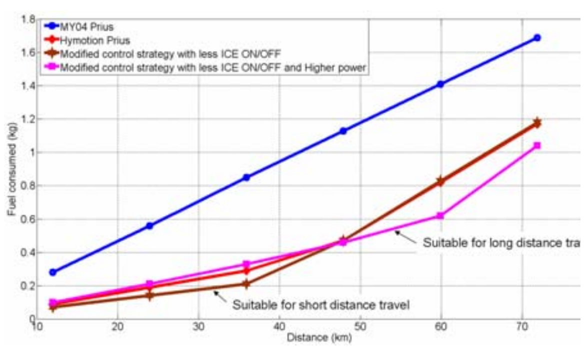


Figure 12. Fuel Consumed for Each Control Option as a Function of Distance (UDDS)

Conclusions

On the basis of vehicle test data collected in Argonne's four-wheel-drive dynamometer, the model of the 5-kWh Hymotion Prius was validated in the PSAT. The engine ON logic and its operating points were correlated with test data.

On the basis of the analysis of the control strategy, several changes were proposed to minimize the number of engine ON/OFF events and maximize the engine's efficiency throughout the drive cycle. Each control option demonstrated its benefits for specific applications. The study demonstrated that it is preferable to operate the engine at low power during short trips and higher power during longer trips to maximize the efficiency of the entire system.

Publications / Presentations

1. Ciao, Q., Pagerit, S., Carlson, B., and Rousseau, A., "PHEV Hymotion Prius Model Validation and Control Improvements," EVS23, Anaheim (December 2007).

2. Rousseau, A., "PHEV Hymotion Prius Model Validation and Control Improvements," Presentation to FreedomCAR Vehicle System Technical Team, September 2007.

F. PHEV Fuel Economy Potential of Existing Powertrains

Phil Sharer (Project Leader), Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261,e-mail: arousseau@anl.gov

DOE Program Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Evaluate the fuel economy potential of existing powertrains.

Approach

- Use validated model for the plug-in hybrid electric vehicle (PHEV) based on the power split configuration.
- Develop several options for control strategies.
- Tune each control strategy parameter.
- Compare the electrical and fuel consumptions on several drive cycles, including the urban dynamometer driving schedule (UDDS).

Accomplishments

- Several control options were integrated in the Powertrain System Analysis Tool (PSAT).
- Advantages and drawbacks of each option were defined.

Future Directions

- Compare the results from the rule-based controls with ones from global optimization.
- Examine the robustness of this study on different trips.

Introduction

To satisfy the California Air Resource Board requirement to be qualified for a zero emission credit, a PHEV can drive all-electrically over repetitions of the UDDS cycle. The constraint to drive all-electrically imposes certain size limitations on the battery and the electric motor, which also imply certain vehicle cost constraints. To minimize the cost of the electric powertrain in these hybrids, a charge-depleting (CD) control strategy can be used to turn the engine on during high power demand. Besides a lowering of the power requirements for the battery and electric machines, there has been some interest in use of CD strategies to also reduce fuel consumption when the vehicle all-electric range (AER) is exceeded. If the control strategy assumes a priori that the AER will be exceeded, the strategy can start planning from the beginning of the trip to conserve battery energy at the beginning of the cycle for later use near the end of the cycle.

Three possible CD PHEV control strategies were simulated for a power-split hybrid by means of the PSAT: Differential Engine Power, Full Engine Power, and Optimal Engine Power. The results were examined to determine if any of the three strategies could reduce the power split configuration's fuel consumption beyond what a simple all-electrical (EV) strategy followed by a charge-sustaining (CS) strategy could afford.

Control Strategy Description

Philosophy behind Selection of CD Control

PHEVs would benefit from knowledge of their routes because their control strategy can schedule the blending of power from the engine and the battery. Knowing the route, the PHEV control strategy can conserve battery energy during high load and use it to propel the vehicle during low load, thereby moving the average operating point of the engine to a higher average efficiency. This concept is illustrated in the following figure.

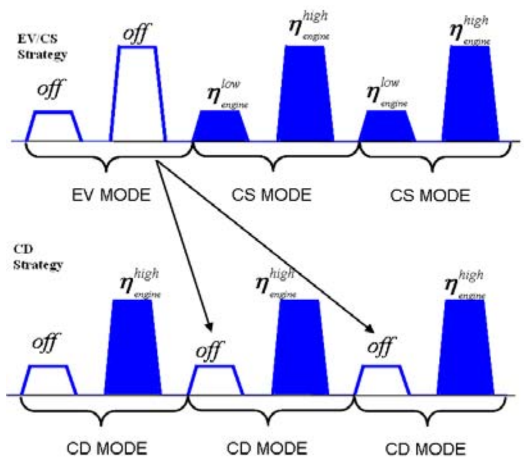


Figure 1. How a CD Strategy Lowers Fuel Consumption When Compared to an EV/CS Strategy

EV/CS Strategy

The EV/CS control strategy was included as a baseline for comparison. Given a UDDS trip distance of 32 km, the controller drove the first 16 km using energy from the battery, which depleted the battery state of charge (SOC) from 90% to 30%. The engine only turned on if the road load exceeded the power capability of either the battery or the electric machine. As both components were sized for the UDDS cycle, the engine never turned on during these simulations. The remaining 16 km was then driven by drawing upon a combination of the engine and battery with the SOC being maintained. This is the CS operation of the strategy. Figure 2 gives an example SOC trajectory for the EV/CS strategy.

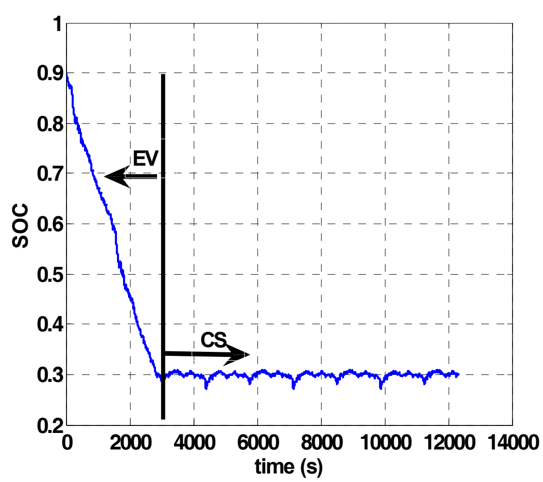


Figure 2. Illustration of SOC Trajectory for EV/CS Operation

Differential Engine Power Strategy

The Differential Engine Power strategy was identical to the EV/CS strategy, except that the power threshold at which the engine turned on was set lower than the maximum power of the electrical system.

Table 1 summarizes the different values for the engine start threshold that were used as trip distance increased for the Differential Engine Power strategy.

Table 1. Engine Start Threshold Values for Differential Engine Power Strategy

Nominal Distance (km)	Engine Threshold (W)
16	38000
32	11500
48	7500

Full Engine Power Strategy

The Full Engine Power strategy calculated the engine power differently. When the engine is turned on, it supplies the entire road load demand, while the electric machine is not used. The goal is to force the engine to operate at high power and consequently at high efficiency. If the marginal gain in efficiency is large enough, it will compensate for the increased operating power of the engine.

Table 2 shows the control strategy values of the engine start threshold as trip distance was increased from 16 km to 96 km.

Table 2. Engine Start Threshold Values for Full Engine Power Strategy

Nominal Distance (km)	Engine Threshold (W)
16	38000
32	17438
48	13379
64	11447
96	8800

Optimal Engine Power Strategy

The last strategy is the Optimal Engine strategy. This strategy borrowed the idea of the previous strategy, Engine Full Power, of operating the engine at high power, except that this strategy attempts to maintain the engine operating region close to the peak efficiency of the engine.

Table 3. Engine Start Threshold Values for Optimal Engine Power Strategy

Nominal Distance (km)	Engine Threshold (W)
16	38000
32	15593
48	13039
64	11216
96	8910

Simulation Setup

For this study, the three strategies were simulated for fixed distances on trips composed of UDDS cycles. The PHEV was designed to operate all electrically for a range of 16 km, but most of the trip lengths simulated exceed this distance. Thus, to drive the longer trip distances in the CD mode, the strategies had to be changed. The threshold that controls the engine start event was adjusted by using the Matlab fzero routine until the PHEV met the longer trip distance by supplementing battery energy with energy from the engine. The objective function optimized was the PSAT PHEV model with the engine start threshold as the input variable. The simulation depleted the battery SOC from 90% to 30%. The distance predicted by the simulation was then compared to the desired distance to compute the error. The Matlab fzero function was run until this error was minimized. This convergence to the desired trip distance is also demonstrated in Figure 2.

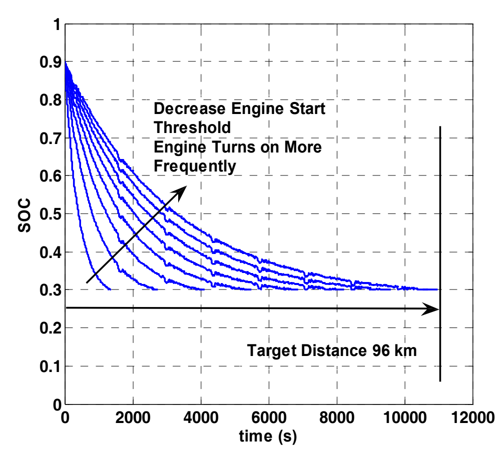


Figure 2. Computed Engine Start Thresholds

Simulation Results

Figure 3 shows the total energy consumption for each control strategy and set of control parameters. Energy consumption is fuel energy combined with battery energy, as defined in the equation below.

$$EC_{total} = \frac{m_{fuel} \times LHV + \int Voc \times I_{ess} dt}{d}$$

In this equation the efficiency of the wall charger was not taken into account.

Figure 3 indicates no appreciable difference between the EV/CS strategy and the Differential Engine Power strategy. The latter strategy used the engine earlier than the EV/CS strategy; however, it ran the engine at lower power, which resulted in a lower average efficiency for the engine.

The Full Engine Power strategy showed the greatest decrease in energy consumption, as large as 6% for the 32-km trip distance. As trip distance increased, the energy savings dropped to 2%, well within the error margin of the simulation.

The Optimal Engine Strategy performed worse than the Full Engine Power strategy. This result was unexpected, because the reduction in energy consumption of a CD strategy over EV/CS is theorized to come from an increase in engine efficiency. Figure 4 clearly shows that the Optimal Engine Strategy had the highest engine efficiency, but this gain came at the cost of operating the engine at a power much higher than the required cycle power. This excess power unnecessarily charged the battery. The unnecessary charging brought down the overall efficiency of the vehicle.

Figure 3 also shows that as trip distance increases the energy consumption asymptotically approaches the vehicle energy consumption in the CS mode. The following equation expresses this relationship.

$$EC_{Total} = \frac{E_{fuel}(d) + E_{ess}}{d}$$

Taking the limit as the trip distance goes to infinity gives

$$\lim_{d \to \infty} EC_{Total} = \lim_{d \to \infty} \frac{E_{fuel}(d) + E_{ess}}{d} = \frac{E_{fuel}(d)}{d} + 0$$

As the electric consumption, $\frac{E_{ess}}{d}$, approaches 0, the fuel consumption approaches the CS value, and the total energy consumption also approaches the CS value.

$$\lim_{d \to \infty} EC_{Total} = \lim_{d \to \infty} EC_{cs}$$

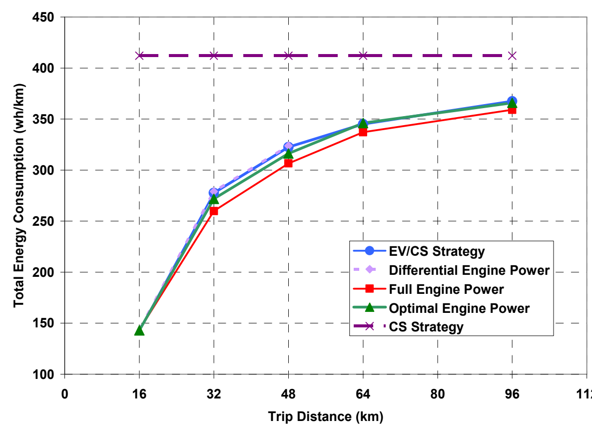


Figure 3. Vehicle Energy Consumption versus Trip Distance for Each Control Strategy

In Figure 4, the percent decrease in energy consumption when compared to the EV/CS strategy is plotted versus the CD options.

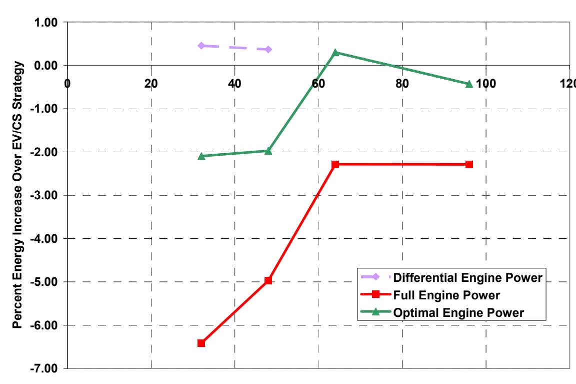


Figure 4. Percent Increase in Fuel Consumption When Compared to the EV/CS Strategy for Different Trip Distances

Conclusions

This study demonstrated that the rather simple knowledge of trip distance combined with a simple control scheme can decrease the fuel consumption of a PHEV when the vehicle is driving beyond its all-electric-capable range. A CD control strategy has the advantage over an EV/CS control strategy because it has the flexibility to ration a vehicle's battery energy throughout an entire trip, assuming the trip distance is known either through user input or through algorithmic prediction.

This result relies on a significant simplification that a trip is composed of repetitions of the same driving cycle, in this case, UDDS. If the statistics at the beginning of a trip significantly differ from the statistics at the end of a trip, a fixed power threshold, as used in this study to trigger the engine ON event, would not be a judicious choice. Instead of a fixed power threshold, a real-time optimization routine could continuously update the engine start threshold. Thus, these results demonstrate that a rudimentary CD control strategy with limited cycle information can provide better results than an EV/CS control strategy.

Of the three CD control strategies simulated for this study, two of them gave improvements over the baseline EV/CS control strategy. Both of these strategies, the Engine Optimal Power and Engine Full Power, operated the engine at higher power than the third strategy, Engine Differential Power. Operating the engine at high power also resulted in these first two strategies operating the engine at higher efficiency.

Future studies can examine the robustness of this result by using a stochastic trip generated by a Markov process. That is where the total trip length is held constant but the driving statistics change randomly. An adaptive controller can then be compared to the three CD strategies simulated in this study, along with the baseline EV/CS strategy. Knowing the trip distance alone may not be sufficient to allow the CD strategies to have a significant benefit over the EV/CS strategies when the driving style fluctuates. One may conjecture that the basic EV/CS strategy may turn out to be the best compromise when handling uncertainty in trip speed and acceleration.

Simple heuristics such as delaying engine starts to higher road load demand and choosing an engine operating power that maximizes engine efficiency are not sufficient for the split configuration to yield a significant reduction in energy consumption over the EV/CS strategy, rather more intelligent heuristic algorithms are needed to realize a greater fuel consumption reduction, and even then, this reduction is limited by the improvement in engine efficiency that can be obtained over a CS strategy.

Publications / Presentations

1. Sharer, P., Rousseau, A., Karbowski, D., and Pagerit, S., "Plug-in Hybrid Electric Vehicle Control Strategy: Comparison between EV and Charge Depleting Options," SAE World Congress, Detroit (April 2008).

G. Comparison of Powertrain Configuration for Plug-in HEVs from a Component Requirement and a Fuel Economy Perspective

Vincent Freyermuth (Project Leader), Aymeric Rousseau, Sylvain Pagerit
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261, e-mail: arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Compare different powertrain configuration options for plug-in hybrid electric vehicles (PHEVs) based on component sizes and fuel economies.

Approach

- Select most promising powertrain configurations.
- Develop control strategies using similar philosophy to allow fair comparison.
- Size the component to match the same vehicle level requirements.
- Compare the electrical and fuel consumptions on several drive cycles.

Accomplishments

- Compared component sizes for each configuration.
- Compared fuel economy for each configuration.

Future Directions

- Evaluate additional drivetrain configurations.
- Refine the component sizing process.

Introduction

Similar to hybrid electric vehicles (HEV), PHEVs offer two power sources that are able to independently propel the vehicle. However, they also offer additional electrical energy on-board. One can think of a PHEV as an electric vehicle with an extra safety feature to avoid getting stranded on the side of the road. This feature is usually referred to as a "range extender." A PHEV can also be thought of a hybrid vehicle whose battery state of charge (SOC) is allowed to drift down. Along with those considerations come configuration choices or powertrain architectures. In this paper we analyze three potential configurations for PHEV with 10 and 40 AER (all electric range), and define the components and their respective sizes needed in order to meet a set of requirements.

Vehicle Configurations

Three powertrain configurations exist for advanced vehicles:

- Series
- Parallel
- Power Split

For each configuration, several hundred combinations are possible, including the number of electric machines, their location, type of transmission, etc.. In this study, one combination for each configuration was selected.

The series engine configuration, shown in Figure 1, is often seen as being closer to a pure electric vehicle compared to a parallel configuration. In this case, the vehicle is propelled solely from the electrical energy. The engine speed is completely decoupled from the wheel axles, and the engine operation is independent of vehicle operations. As a result, the engine can be operated consistently at a very high efficiency. The configuration selected includes a single gear ratio before the transmission, similar to the GM Volt.

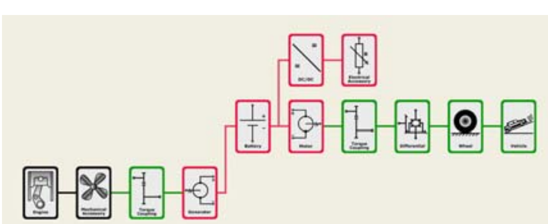


Figure 1. Series Engine Architecture

In a parallel configuration, both the electric machine and the engine can be used to directly propel the vehicle. As shown in Figure 2, the configuration selected is a pre-transmission parallel hybrid similar to the one used by DaimlerChrysler for the PHEV Sprinter. The electric machine is located in between the clutch and the multi-gear transmission.

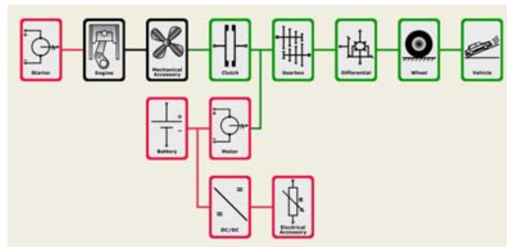


Figure 2. Pre-transmission Parallel Architecture

The power split configuration, shown in Figure 3, uses a planetary gear set to transmit power from the engine to the wheel axles, similar to the Toyota Prius. The power split system is the most commonly used system in current hybrid vehicles. The split system allows, to some extent, decoupling the engine speed from vehicle speed. On one hand, the power from the engine can flow mechanically to the wheel axle via the ring of the planetary system. On the other hand, the engine power can also flow through the generator, producing electricity that will feed the motor to propel the wheels. Hence, the power split system combines both "parallel like" and "series engine like" operations.

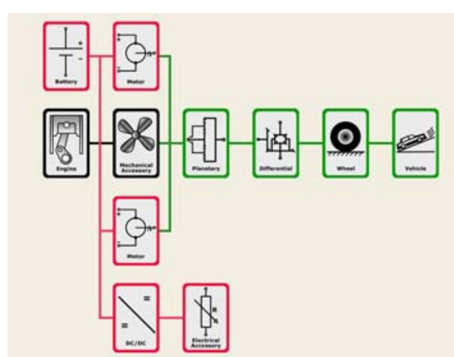


Figure 3. Power Split Architecture

Vehicle Description and Component Sizes

For comparison purposes, the vehicle class used for all three configurations is the same, a midsize sedan. The main characteristics are defined in Table 1.

Table 1. Main Vehicle Characteristics

Glider Mass	990 kg
Frontal Area	2.1 m^2
Coefficient of Drag	0.29
Wheel Radius	0.317 m
Tire Rolling Resistance	0.008

The components of the different vehicles were sized to meet the same vehicle performance:

- 0-60 mph < 7 sec
- Gradeability of 6% at 65 mph
- Maximum speed > 100 mph

To quickly size the components of the powertrain, an automated sizing process was developed. While the engine power is the only variable for conventional vehicles, PHEVs have two variables: engine power and electric power. In our case, the engine is sized to meet the gradeability requirements while the battery is sized to meet the target performance as well as the AER requirements. We also ensure that the vehicle can capture the entire energy from regenerative braking during deceleration on the urban dynamometer driving schedule (UDDS). The vehicle mass is calculated by adding each component mass to the glider mass. Each component mass is defined based on its specific power density.

The main characteristics of the sized vehicles are described in Tables 2 and 3 for the 10 and 40 AER cases, respectively. As evident from the tables, the engine power is similar for the parallel and power split configurations and significantly larger for the series. This difference is explained by the additional efficiencies for the components (both generator and electric machine) included in the series configuration.

Because the propulsion motor is the only component used in the series, its power is also significantly higher than that for the other configurations. However, because no multi-gear transmission is considered, and the component specific powers represent 2015 technology, the overall vehicle mass difference among all the configurations is minimal.

Note that, while the series configuration is heavier for the 10 AER case, the power split configuration has the largest mass for the 40 AER case.

The PHEV will operate in the electric vehicle (EV) mode at higher vehicle speed compared to regular hybrids. Hence, the engine needs to be able to start at high vehicle speed. In the series configuration, where the engine is completely decoupled from the vehicle speed, and in the parallel case, where the engine can be decoupled via the clutch, starting the engine is not an issue. In the power split configuration, however, the generator is used to start the engine. Since all those elements are linked to the wheels via the planetary gear system, one needs to make sure that the generator, for which speed increases linearly with vehicle speed when the engine is off, still has enough available torque even at high speed to start the engine in a timely fashion.

Table 2. Component Size – 10 AER Case

	Pre-trans Parallel	Split	Series
Engine Power (kW)	76	74	109
Max Engine Torque (N·m)	150	146	214
Propulsion Motor Power (kW)	48	62	90
Generator Power (kW)	--	63	106
Battery Power (kW)	58	52	55
Battery Capacity (Ah)	18	21	18
Total Vehicle Mass (kg)	1675	1667	1700

Table 3. Component Size – 40 AER Case

	Pre-trans Parallel	Split	Series
Engine Power (kW)	79	77	114
Max Engine Torque (N·m)	156	151	223
Propulsion Motor Power (kW)	50	71	95
Generator Power (kW)	--	65	111
Battery Power (kW)	61	64	58
Battery Capacity (Ah)	71	69	71
Total Vehicle Mass (kg)	1764	1800	1794

Vehicle Control Strategy Algorithms

PHEV vehicle operations can be divided into two modes, as shown in Figure 4:

- Charge depleting (CD): When the battery SOC is high, the vehicle operates under a so-called blended strategy. Both battery and engine can be used. However, whenever possible, preference is given to the battery, whose charge depletes. Engine usage increases as SOC goes down. The engine tends to be used in rapid acceleration as well, even though the SOC is high. For fuel economy purposes, this blended strategy is defined for a battery going from full charge to a self-sustained SOC, typically from 90% to 30% SOC.
- Charge sustaining (CS): Once the battery SOC is down to 30%, the vehicle operates in the charge-sustaining mode, similar to a regular hybrid vehicle.

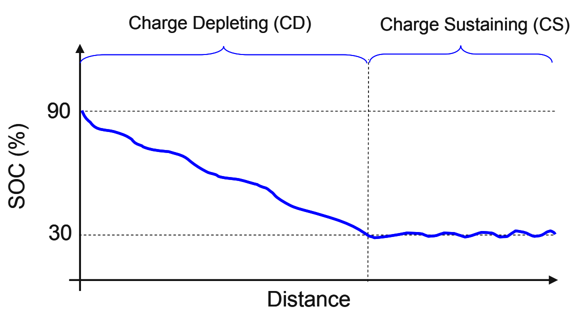


Figure 4. Control Strategy SOC Behavior

Series Configuration

Since the engine is completely decoupled from the vehicle operation in the series configuration, numerous control strategy choices can be used. In this study, the engine "on" logic is based on the SOC. As shown in Figure 5, the engine turns on when a lower SOC limit is reached (e.g., 0.25) and will stay on until the battery gets recharged to its high limit (e.g., 0.3) if the power request remains positive. If a braking event occurs, the engine is allowed to shut down and will restart when the lower SOC limit is reached again. When the engine is on, it operates at its best efficiency point unless a component saturates (for instance, the battery could reach its maximum charging capability).

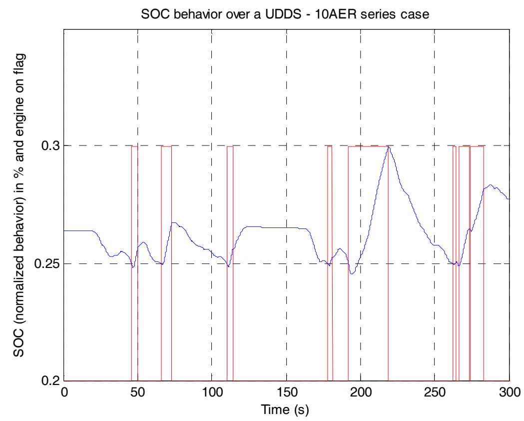


Figure 5. Series Engine SOC Behavior

Parallel and Power Split Configurations

Both of these configurations have similar means of vehicle control. The first critical part of the control strategy is related to the engine ON/OFF logic. As Figure 6 shows, the engine ON logic has three main conditions:

- The requested power is above a threshold.
- The battery SOC is lower than a threshold.
- The electric motor cannot provide the requested wheel torque.

In addition to these parameters, further logic is included to ensure proper drive quality by maintaining the engine ON or OFF for a certain duration. To avoid unintended engine ON events resulting from spikes in power demand, the requested power has to be above the threshold for a pre-defined duration. The engine OFF logic condition is similar to that of the engine ON. Both power thresholds used to start or turn off the engine as well as determine the minimum duration of each event have been selected as input parameters of the optimization problem.

To regulate the battery SOC, especially during the charge-depleting mode, the power demand that is used to determine the engine ON/OFF logic is the sum of the requested power at the wheel plus an additional power that depends on battery SOC. This power can be positive or negative depending on the value of the current SOC compared to the target.

¶

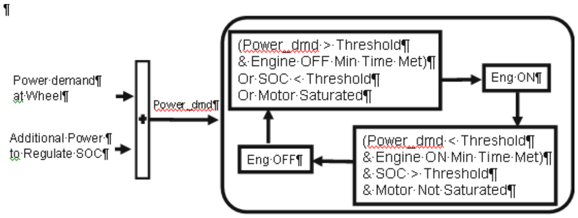


Figure 6. Simplified Engine ON/OFF Logic

Figure 7 shows the different parameters used to define the additional power to regulate the SOC in greater detail. The SOC target was set at the value where the vehicle is considered entering the charge-sustaining mode (30% SOC).

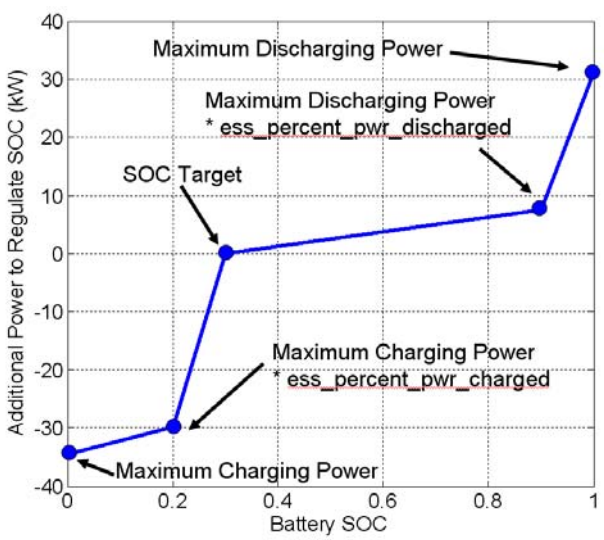


Figure 7. Example of Additional Power to Regulate SOC

Control Comparison

Even if the control strategy is similar for different powertrain configurations, their implementation differs to take advantage of the vehicle properties. Figure 8 shows the evolution of the battery SOC on the UDDS, starting from a charged battery at 90% for the PHEV 10 miles AER vehicles.

As evident in the figure, the series configuration discharges the battery the fastest, followed by the parallel and the power split ones. The differences have several possible sources, including component operating conditions, vehicle mass, and control parameters.

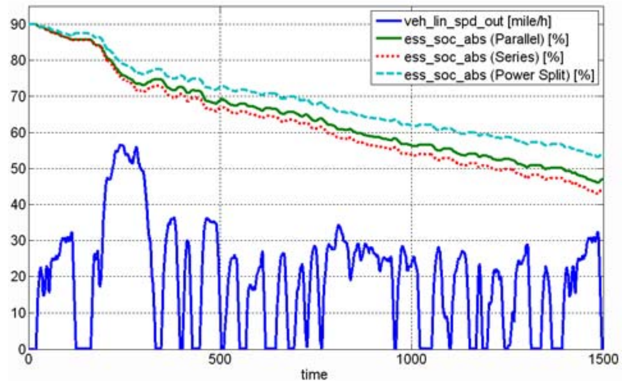


Figure 8. SOC Comparison between Each Configuration on UDDS – PHEV 10 Case

To compare the different powertrain configurations as fairly as possible, we tried to maintain the controls consistent as much as possible. However, one needs to keep in mind that the results obtained depend upon the control choices made.

Fuel Economy Results

Table 4 shows the fuel economy results for each powertrain configuration and AER considered for the UDDS and the highway fuel economy test (HWFET).

Table 4. PHEV Fuel Economy Results

J1711 Fuel Economy	UDDS	HWFET
	mpg	mpg
Pre-trans Parallel – 10 AER	54	55
Series – 10 AER	50	48
Split – 10 AER	65	56
Pre-trans Parallel – 40 AER	73	75
Series 40 AER	72	66
Split 40 AER	85	74

Urban Driving

The split configuration provides the best fuel economy in urban driving. In the 10 AER case, the parallel configuration outperforms the series one. The weight given to the charge-depleting phase is 25%, and the remaining part of the fuel economy relies on the charge-sustaining number. The higher efficiency of the power transfer from engine to wheels benefits the parallel case. However, this difference in the parallel and series configurations reduces in the 40 AER case because the PHEV number weighs more heavily on the charge-depleting phase. Hence, the parallel case advantage due to the higher efficiency in power transfer from engine to wheel is less pronounced.

Highway Driving

The split and parallel configurations provide similar fuel economy in highway driving, and both outperform the series configuration. The series configuration suffers from dual power conversion, from mechanical (engine) to electrical (generator) and back to mechanical (motor). Compared to urban driving, the parallel configuration performs better since highway driving depends less on battery usage. The engine efficiency in the parallel case is lower than in the split case. However, the parallel case does not incur losses due to the power recirculation that occurs in the split case and tends to be higher as vehicle speed increases.

Table 5. Engine Efficiency

Engine Efficiency	UDDS	HWFET
	%	%
Pre-trans Parallel – 10 AER	27.7	29.2
Series – 10 AER	34.1	34.6
Split- 10 AER	32.6	32.9
Pre-trans Parallel – 40 AER	27.5	29
Series 40 AER	34.2	34.3
Split 40 AER	32.5	32.8

As shown in Table 5, engine efficiency is highest for the series configuration. In this case, the engine is completely decoupled from the wheel and, hence, can be operated at its best efficiency point. In the split case, the extra degree of freedom provided by the gearbox allows decoupling the engine and vehicle speeds as to a certain extent. Engine efficiency remains high in this case as well. The parallel configuration exhibits the lowest engine efficiency. The engine speed is directly linked to the wheel via the fixed ratio gearbox, and hence, this engine is more difficult to operate around the best efficiency area.

The data in Table 5 also indicate that the engine efficiency depends on the driving conditions for the parallel case and not for the two other cases. The data also show that the parallel configuration tends to perform better in highway driving than in city conditions.

Table 6. Electrical versus Fuel Path

Electrical Path vs. Fuel Path	Electrical Path UDDS	Fuel Path - CS UDDS	Fuel Path - CS HWFET
	Wh/km	mpg	mpg
Pre-trans Parallel – 10 AER	134	45.7	46.9
Series – 10 AER	133	42.2	40.6
Split - 10 AER	131	43.3	46.9
Pre-trans Parallel - 40AER	140	42.9	45.3
Series 40 AER	138	41.3	39.3
Split 40 AER	137	51.0	45.1

Table 6 presents data for the charge-sustaining fuel economy, referred to as the "fuel path," and the electrical consumption during the EV mode, referred to as the "electrical path." Figure 9 is a graphical representation of the 10 AER data presented in Table 6.

This figure allows taking a closer look at the PHEV fuel economy number by breaking it down into its fuel and electrical paths.

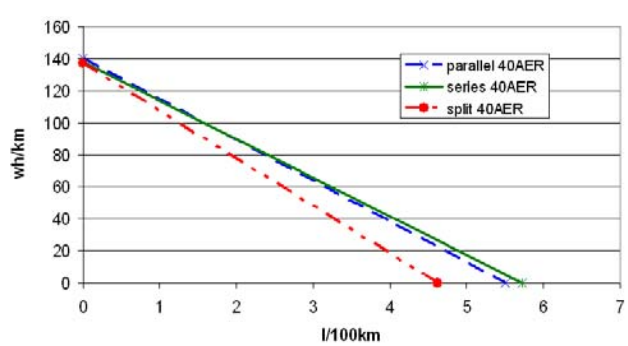


Figure 9. Electrical versus Fuel Path – 40 AER Case

Electrical Path

The electrical-path efficiency is practically identical for all three configurations. Table 7 shows an overview of the overall efficiency of the main components for the 40 AER case. The 10 AER case was not reported here as results and trends are identical to the 40 AER case.

Table 7. Component Average Efficiency on UDDS (%)

	Pre-trans Parallel 40 AER	Series 40 AER	Split 40 AER
Motor Efficiency	85.8	83.4	83.6
Trans Efficiency	94.1	--	96.6
Final Drive Efficiency	97.5	97.5	97.5
Single Ratio Efficiency	--	97.5	--
Battery Efficiency	95	95	95

The split and series cases are similar configurations when operated in the EV mode. The motor is directly linked to the wheels in both cases through a fixed gear and a final drive. Minor spin losses occur in the planetary system but not enough to put the split system at a disadvantage when compared to the series configuration.

The parallel configuration, even though the overall efficiency is identical to the other cases, shows a different partition of the losses. The transmission efficiency is approximately 2% lower than that of the power split. However, because of the presence of the transmission between the motor and the final drive, the motor can be operated in a more efficient manner than the series or power split configurations, as shown in Figures 10 and 11. The motor efficiency in this case is approximately 2% higher than the split case, canceling out the extra losses occurring in the transmission.

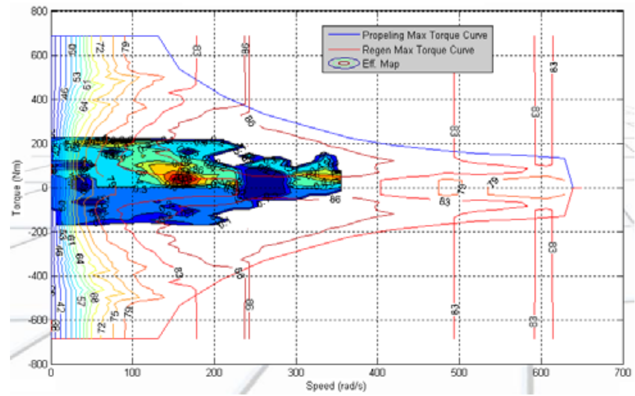


Figure 10. Electric Machine Operating Conditions on Series Engine 10 AER – UDDS Cycle

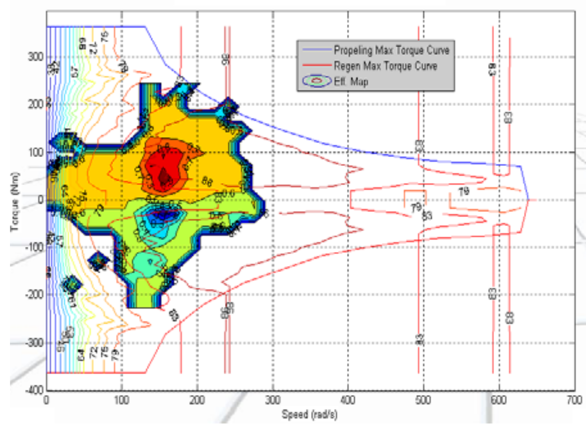


Figure 11. Electric Machine Operating Conditions on Parallel 10 AER – UDDS Cycle

Fuel Path

The CS fuel economy ranks from best to worse as follows: split, parallel, and series. Engine fuel consumption maps are proportional to maximum engine power. Split and parallel configurations have similar engine sizes. The series configuration requires a significantly bigger engine to meet the performance requirement. The series is hence at a disadvantage from the start. Also, the power goes through two electric machines, which increase the amount of losses and hence the power required by the engine. This affects the series configuration even more in highway driving.

The parallel configuration suffers from the losses in the transmission and its inability to operate the engine at its best operating point, as shown in Figure 12. This configuration is also not capable of regenerating all the braking energy from the wheels during down-shifting events.

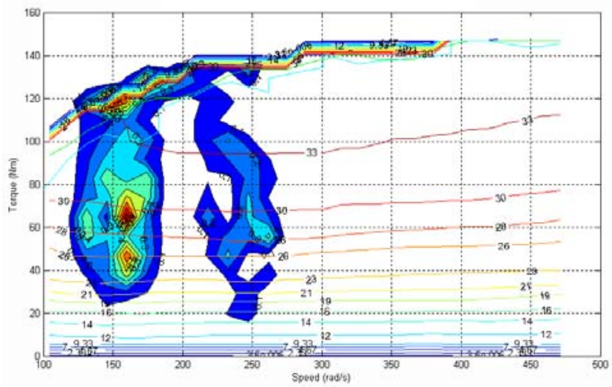


Figure 12. Engine Operating Conditions on Parallel 10 AER – UDDS Cycle

The split configuration allows operating the engine close to its best efficient point without having to send all of its power through both electric machines, as shown in Figure 13. The high engine efficiency along with the ability to send mechanical power directly to the wheel, allows this configuration to provide the best charge-sustaining fuel economy.

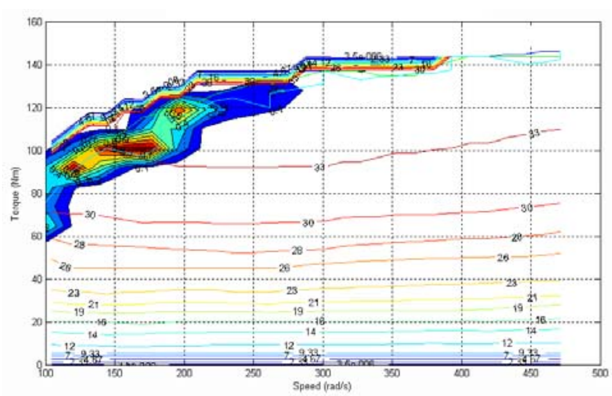


Figure 13. Engine Operating Conditions on Power Split 10 AER – UDDS Cycle

Conclusions

Hybrid vehicles offer a compromise between conventional and purely electric vehicles. Depending on the degree of hybridization, they become more or less close to one of the two extremes. In this study, several powertrain configurations, including series, pre-transmission parallel, and power split, were compared on the basis of component sizes and fuel economy for PHEV applications.

While both the power split and series configurations require two electric machines and an engine, the series configuration, as expected, requires significantly higher component power due to the many component efficiencies between the engine and the wheel.

From an efficiency point of view, all the configurations achieve similar characteristics when operated in the electric mode. Both series and power split configurations do not use a multi-gear transmission, but the parallel configuration makes up from the losses by operating the electric machine at higher efficiency points. In the charge-depleting mode, the power split provides the best fuel economy due to its dual path of power from the engine to the wheel.

Based on the analysis, the series configuration appears to be an appropriate choice for vehicles designed to provide long AER due to the simplicity of its control, while the power split configuration appears to be a valid choice for vehicles based on the charge-depleting approach.

Several other configurations, such as post-transmission hybrids, should also be considered as part of a larger study.

Publications / Presentations

1. Freyermuth, V., Fallas, E., and Rousseau, A., "Comparison of Powertrain Configuration for Plug-in HEVs from a Fuel Economy Perspective," SAE World Congress, Detroit (April 2008).

H. Impact of Component Technology on PHEV Fuel Economy

Aymeric Rousseau (Project Leader), Paul Nelson
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261; arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Evaluate the potential of advanced Li-ion chemistry on fuel economy.

Approach

- Develop component models representing the technologies.
- Create complete models for several battery packs based on vehicle requirements.
- Define the vehicle and the control strategies.
- Analyze the electrical and fuel consumptions on several drive cycles.

Accomplishments

- Specific Li-ion battery materials were evaluated for PHEV applications for several all-electric range options.
- Fuel economy potential was assessed for each configuration.

Future Directions

- Evaluate the technology potential on additional powertrain configurations.
- Evaluate additional battery technologies.

Introduction

In this study, electric-drive vehicles with series powertrains were configured to utilize a lithium-ion battery with very high power and achieve sport-sedan performance and excellent fuel economy. The battery electrode materials are $LiMn_2O_4$ and $Li_4Ti_5O_{12}$, which provide a cell area-specific impedance of about 40% of that of the commonly available lithium-ion batteries. Data provided by EnerDel Corporation for this system demonstrate this low impedance and also a long cycle life at 55°C. All the batteries for these vehicles were designed to deliver 100 kW of power at 90% open-circuit voltage to provide high battery efficiency (97–98%) during vehicle operation. This heats the battery by only 1.8°C per hour of travel on the urban dynamometer driving schedule (UDDS) cycle, which essentially eliminates the need for battery cooling. Three vehicles were designed, each with series powertrains and simulation test weights between 1,575 and 1,633 kg: a hybrid electric vehicle (HEV) with a 45-kg battery, a plug-in HEV (PHEV)10 with a 60-kg battery, and a PHEV20 with a 100-kg battery. The Powertrain System Analysis Toolkit (PSAT) simulations showed that these vehicles could accelerate to 60 miles per hour in 6.2 to 6.3 seconds and achieve fuel economies of 50 to 54 miles per gallon on the UDDS and highway fuel economy test (HWFET) cycles. If this type of vehicle is mass produced, it shows promise of having a moderate cost because it has no transmission, the engine and generator may be less expensive because they are designed to operate at only one speed, and the battery electrode materials are inexpensive.

Spinel-Titanate Battery Performance Modeling

Experimental Data

Tests with a 1.8-A·h MS-TiO cell demonstrated outstanding power; 97% of the capacity measured at the 1C discharge rate was delivered at the 50C rate (Figure 1). These results were correlated to obtain the impedance equations required for the vehicle simulation tests.

The capacity stability was demonstrated in tests in which the entire cell capacity was discharged and charged at the 5C rate at an elevated temperature of 55C, to accelerate degradation, for 2,300 cycles with little indication of capacity loss (Figure 2). Pulse power characterization tests were carried out at 30C after 1,000 and 2,000 cycles and demonstrated little loss of power with cycling.

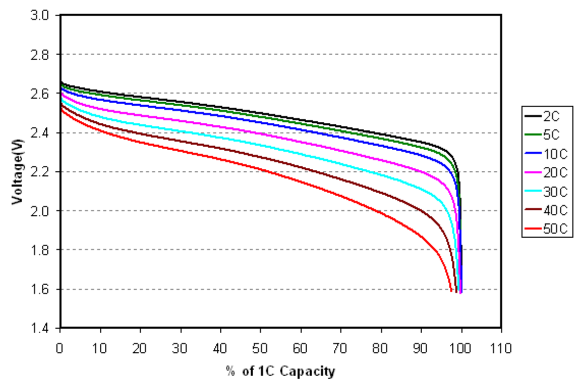


Figure 1. Lithium-Manganese Spinel/Lithium-Titanate 1.8-A·h Cell Charged at 1C Rate and Discharged at Varying Rates at 30°C

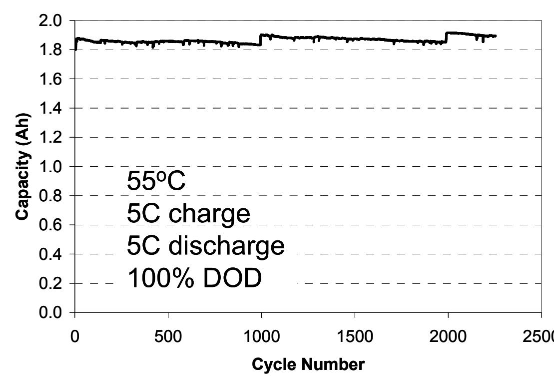


Figure 2. Deep Discharging of Lithium-Manganese Spinel/Lithium-Titanate Cell to Demonstrate Long Cycle Life

Battery Design Modeling

We have developed a method for designing cells and batteries that has been applied to several battery systems. In recent years, the method has been used primarily for designing lithium-ion batteries for HEVs and PHEVs. One form of input for this method is test results from measurements of capacity and ASI on small cells with areas of only a few square centimeters. It also is possible to accept data from larger cells by accounting for the resistance of the current collection system in the tested cell. By this method, three batteries were defined from the data in Table 1 for the MS-TiO system and from other proprietary input.

Table 1. Cell Parameters for Lithium-Manganese Spinel/Lithium-Titanate Batteries for HEVs and PHEVs

Cell Parameter	HEV	10-Mile* PHEV	20-Mile* PHEV
Cell capacity (1/C rate), A·h	10.0	16.6	33.3
Positive first charge loading density, m A·h /cm^2	0.54	0.88	1.79
Negative-to-positive 1st charge capacity ratio	1.0	1.0	1.0
Maximum voltage on charging, V	2.7	2.7	2.7
Average voltage on discharge, V	2.51	2.51	2.51
Positive electrode			
Active material	$Li_{1.06}Mn_{1.94}O_4$	$Li_{1.06}Mn_{1.94}O_4$	$Li_{1.06}Mn_{1.94}O_4$
Thickness of coating (each side), µm	25	40	82
Negative electrode material			
Active material	$Li_4Ti_5O_{12}$	$Li_4Ti_5O_{12}$	$Li_4Ti_5O_{12}$
Thickness of coating (each side), µm	21	34	70
Total cell area, cm^2	20,500	20,500	20,500
Cell dimensions, mm			
Height	189	219	219
Width	104	116	187
Thickness	12.2	12.4	12.5
Cell weight, g	471	648	1,102
Power, W	1,251	1,251	1,251
Cell-specific power, kW/kg	2.66	1.93	1.14
Cell-specific energy (1/C rate), Wh/kg	53	64	76

*Based upon energy usage of 300 Wh/mi.

Vehicle Simulation for High-Power Batteries

Vehicle Characteristics

Several vehicles were sized for different specifications on the basis of the same vehicle attributes: HEV, PHEV with a 10-mi all-electric range (AER), and PHEV with a 20-mi AER. The main component masses are shown in Table 2.

Table 2. Mass of Vehicle Components (kg)

Component	HEV	PHEV10	PHEV20
Engine	120	120	120
Generator	86	86	87
Motor	144	144	146
Battery	45	60	100
Vehicle	1,575	1,590	1,633

Table 3 lists the main characteristics of the simulated midsize car.

Table 3. Vehicle Main Specifications

Component	Specifications
Engine	2004 U.S. Prius
Electric machine	Ballard IPT - Induction
Single gear ratio	2
Final drive ratio	3.8
Frontal area	2.1 m^2
Drag coefficient	0.25
Rolling resist.	0.007 (plus speed-related term)
Wheel radius	0.317 m

As shown in Figure 3, the configuration selected is a series engine hybrid, very similar to the one used in the GM Volt.

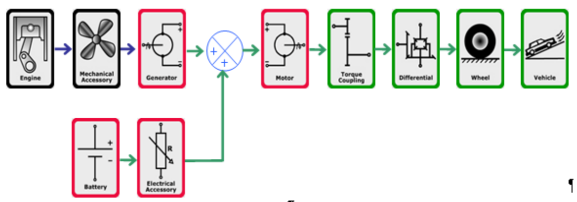


Figure 3. Series Engine Configuration

The components of the different vehicles were sized to meet the same vehicle performance values: 0 to 60 mph in less than 7 seconds and gradeability of 6% at 65 mph. The main component characteristics resulting from the sizing algorithm are described in Table 4.

Table 4. Component Sizing Results

Parameter	Unit	HEV	PHEV10	PHEV20
Engine power	kW	100	100	102
Generator power	kW	95	95	96
Motor power	kW	130	130	132
Battery power	kW	100	100	100
Vehicle mass	kg	1,575	1,590	1,633
Accel. time 0–60 mph	s	6.2	6.2	6.3

Control Strategy

The control strategy of the PHEVs can be separated into two distinct modes, as shown in Figure 4:

- Charge-depleting (CD) mode: Vehicle operation on the electric drive, engine subsystem, or both, with a net decrease in battery state-of-charge (SOC).
- Charge-sustaining (CS) mode: Vehicle operation on the electric drive, engine subsystem, or both, with a "constant" battery SOC (i.e., within a narrow range), which is similar to that in current production HEVs.

During a simulation, the engine is turned on when the battery SOC is low or the power requested at the wheel cannot be provided by the battery alone. Turning on the engine expends fuel but conserves battery energy, so that more miles can be traveled before the battery reaches its discharged state. When the engine is ON, it is operated close to its best efficiency curve. As a result, the battery is being charged by the engine during low power requests, leading to lower electrical consumption.

The initial SOC of the battery, which is also the battery's maximum charge, is 100%, and the final SOC of the battery, which is also the battery's minimum charge, is 10%. For the CD mode, the engine logic was written in StateFlow and used several conditions, such as battery SOC, motor power limits, and vehicle speed, to determine when the engine should turn on and the output torque of the engine. The logic of the CS mode was similar to that of current HEVs.

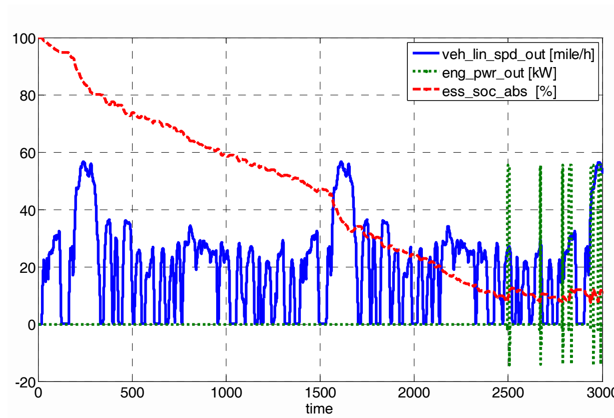


Figure 4. Control Strategy SOC Behavior on the UDDS

Fuel Economy Results

As previously mentioned, several driving cycles have been considered to evaluate the benefits of the advanced lithium-ion batteries on PHEVs. Table 5 summarizes the electrical consumption on each PHEV on the first cycle of each drive cycle. These results highlight the differences in aggressiveness in the different drive cycles. As expected, the standardized drive cycles (UDDS, HWFET, and NEDC) require a lower electrical consumption than the cycles that are more "real-world." The ATDS is the most aggressive drive cycle.

Table 5. PHEV Electrical Information

AER	PHEV	UDDS	HWFET	NEDC	LA92	ATDS
10-mi	Elec. cons. first cycle (Wh/mi)	224.6	204.3	234.1	282.6	190.4(1)
	AER (mi)	13.8	14.3	12.8	10.3	9.5
20 mi	Elec. cons. first cycle (Wh/mi)	257.9	209.9	241.6	297.9	300.8
	AER (mi)	26.6	28.6	26.5	20.4	19.9

(1) Engine started during the first cycle.

Because the primary goal of PHEVs is to maximize fuel displacement, the following analysis focuses on fuel consumption.

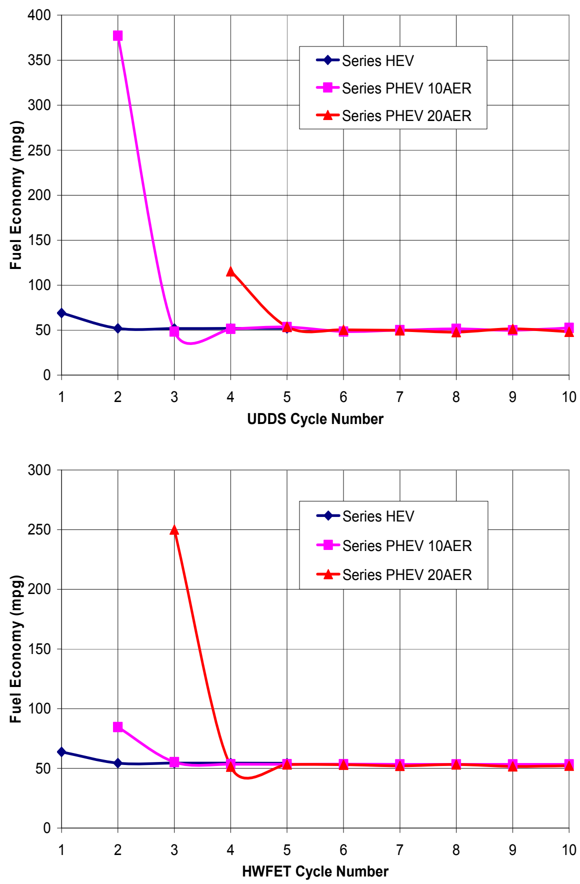


Figure 5. Fuel Economy Evolution on UDDS and HWFET

The benefit of high-power batteries is noticeable in the more aggressive driving cycles (Figure 5). When an engine start would have been necessary for low-power batteries, the initial distance can be achieved in EV mode without any help from the engine. Note, however, that previous studies have demonstrated the need to know the trip distance to properly minimize fuel consumption. However, higher battery power allows additional flexibility in deciding when to start the engine.

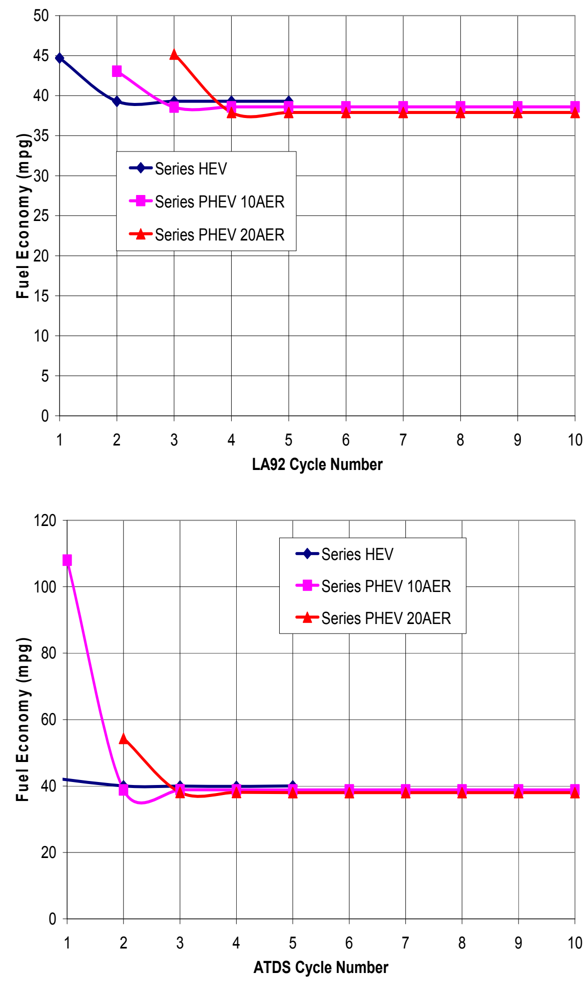


Figure 6. Fuel Economy Evolution on LA92 and ATDS

Figure 6 shows the evolution of the fuel economy when each cycle is repeated 10 times.

Table 6 shows the CS fuel economies of the different vehicles. Because of increased vehicle mass, the fuel economy decreases slightly with an increase in AER.

Table 6. CS Fuel Economy (mpg)

Vehicle	UDDS	HWFET	NEDC	LA92	ATDS
HEV	51.9	54.4	52.3	39.3	40.0
PHEV 10	51	53.3	51.5	38.6	38.8
PHEV 20	49.6	52	50.5	37.9	38

Figure 7 shows the evolution of the electrical consumption for the UDDS and ATDS drive cycles. The impact of the cycle aggressiveness can be seen by slope of the electrical consumption. In the case of the ATDS, the slope is much stiffer than for the UDDS.

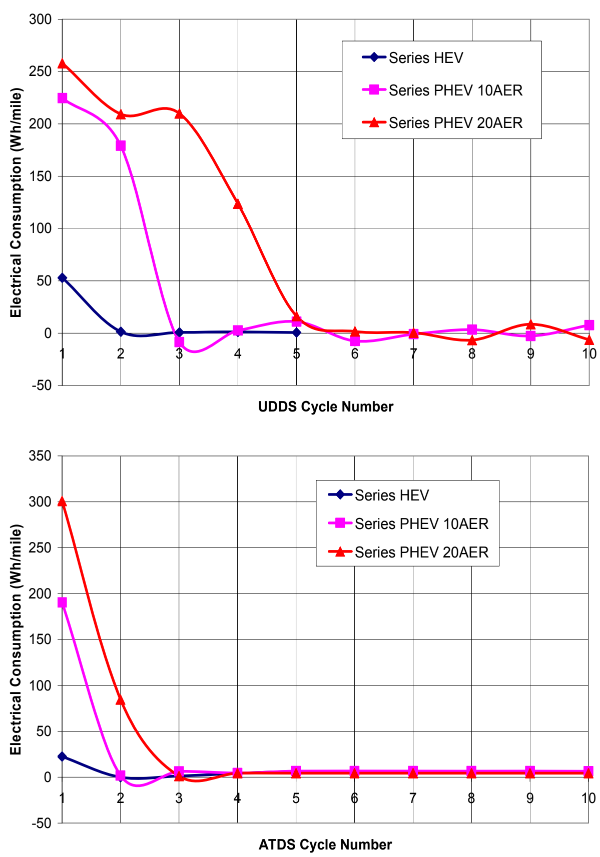


Figure 7. Electrical Consumption Evolution on UDDS and ATDS

The efficiencies of the vehicle components are very high, as illustrated in Table 7 for the UDDS cycle. Improvement in the fuel economy for these vehicles could be achieved by increasing the motor efficiency. An additional low-power (30–50 kW) motor could be provided for use with light loads, when it could operate at a higher efficiency than the high-power motor (130 kW) in the evaluated designs.

The high battery efficiency results in very little battery heating. One hour of travel on the UDDS cycle would heat up the PHEV10 battery by 1.6°C under adiabatic conditions.

Table 7. Component Average Efficiencies on UDDS

Component	HEV	PHEV10	PHEV20
Engine	36.9	37.2	37.2
Generator	91.9	91.9	91.9
Motor	80.4	80.4	80.4
Battery	98.4	97.5	97.4
Gear	97.5	97.5	97.5

Conclusions

High vehicle performance, of the type expected from sport-sedans, and high fuel economy can be achieved at the same time by a vehicle having a series powertrain and a high-power manganese spinel/lithium titanate battery. Further improvement in fuel economy might result from improving the motor efficiency. This battery can provide high power at such high battery efficiency that battery cooling is virtually unnecessary. If this type of vehicle is mass produced, it shows promise of having a moderate cost because it has no transmission, the engine and generator may be less expensive because they are designed to operate in a narrow range, and the battery electrode materials are inexpensive.

Publications/Presentations

1. Nelson, P., Amine, K., Rousseau, A., Yomoto, H., "Advanced Lithium-Ion Batteries for Plug-in Hybrid-Electric Vehicles," EVS23, Anaheim (December 2007).

I. Impact of Drive Cycles on PHEV Component Requirements

Jason Kwon (Project Leader), Aymeric Rousseau, Sylvain Pagerit
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261, e-mail: arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Evaluate the impact of several drive cycles on component requirements.

Approach

- Develop component models representing the technologies.
- Create complete models for several battery packs based on vehicle requirements.
- Define the vehicle and the control strategies.
- Analyze the electrical and fuel consumptions on several drive cycles.

Accomplishments

- Evaluated specific Li-ion battery materials for PHEV applications for several all-electric range options.
- Assessed fuel economy potential for each configuration.

Future Directions

- Evaluate the technology potential on additional powertrain configurations.
- Evaluate additional battery technologies.

Introduction

Due to the early stage of plug-in hybrid electric vehicle (PHEV) technology development, most studies have focused on fundamental engineering questions, such as component requirements and optimization of PHEV design. As a part of these studies, for example, the impact of vehicle characteristics (i.e., vehicle class, mass, or electrical accessories) on battery requirements has been conducted. However, outstanding questions still remain regarding the impact of drive cycles and powertrain configurations.

A discussion of component requirements would be incomplete without considering the large variety of drive cycles in addition to the Urban Dynamometer Driving Schedule (UDDS). Drive cycles vary with respect to issues such as aggressiveness and distance. An electric-vehicle- (EV-) based PHEV driven more aggressively than the cycle for which it was originally designed must utilize its engine during charge-depleting operation or else fail to meet the higher-power road load demand. For instance, CARB awards zero emission range credit based on the distance a PHEV can drive all-electrically over repetitions of the U.S. Environmental Protection Agency's (EPA's) standard UDDS. However, an EV-based PHEV designed to just satisfy the mild UDDS cycle may fail to achieve its all-electric range (AER) rating when driven more aggressively in the "real world."

To help avoid this problem, the vehicle design could instead consider AER operation on more aggressive drive cycles, such as the EPA US06 cycle, or a "real-world" drive cycle, such as the LA92 cycle. Such a consideration, however, would lead to even larger or costlier electric motor and energy storage system (ESS) requirements. The alternative would be to allow engine assistance when the vehicle is driven more aggressively than the original AER-designed cycle.

In this study, we will describe the methodology used to size the midsize PHEV based on CARB requirements over the UDDS cycle. We will also assess the impact of various drive cycles on the power and energy requirements.

Vehicle Description

A pre-transmission parallel hybrid configuration was selected as a reference configuration for this study, as shown in Figure 1. This configuration is very similar to the one used by DiamlerChrysler for the PHEV Sprinter. The electric machine is located between the clutch and the multi-gear transmission.

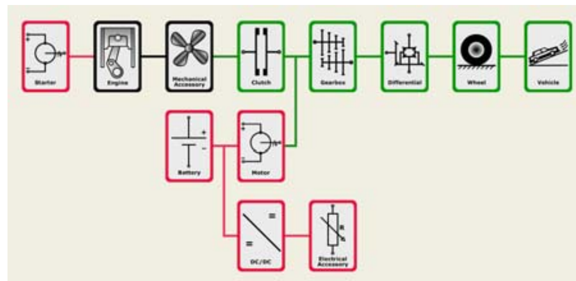


Figure 1. Pre-transmission Parallel Architecture

The main characteristics are defined in Table 1.

Table 1. Main Vehicle Characteristics

Glider mass	990 kg
Frontal area	2.1 m^2
Coefficient of drag	0.31
Wheel radius	0.317 m
Tire rolling resistance	0.008
Gear ratio	3.42,2.14,1.45,1.03,0.77
Final drive ratio	3.75

Vehicle Sizing

The components were sized to meet the same vehicle performances over different cycles:

- 0–60 < 9 s
- Gradeability of 6% at 65 mph
- Maximum speed > 100 mph
- Range of 10, 20, and 40 miles

To quickly size the component models of the powertrain, an automated sizing process was developed.

The main characteristics of the sized vehicles on the UDDS for different all-electric driving ranges are described in Table 2.

Table 2. Component Sizes over UDDS

Parameter	10 AER	20 AER	40 AER
Engine power (kW)	79.5	79.6	82.4
Motor power (kW)	44.2	45.8	47.2
ESS power (kW)	64.7	65.7	68.2
ESS capacity (A·h)	19.4	38.4	67.4
Number of cells for ESS	57	57	66
Total vehicle mass (kg)	1,546	1,583	1,659

As shown in Figure 2, the component power requirements are not significantly influenced by the AER as a result of the high specific power of the Li-Ion battery used in the model. Consequently, a PHEV with a 40-mile range requires a battery with rated energy capacity of 16 kWh, which is four times higher than the 10-mile range, as shown in Figure 3. However, the peak power of the battery is increased only by 3.5 kW, from 64.7 kW to 68.2 kW.

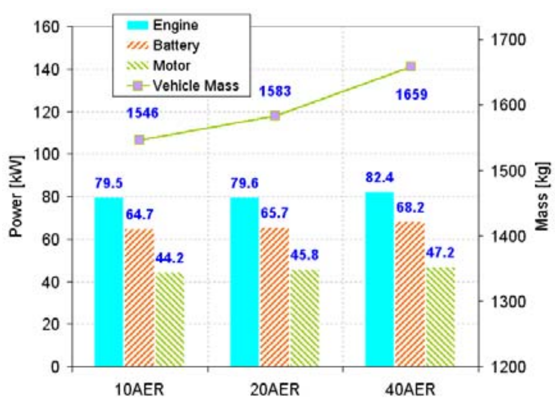


Figure 2. Component Sizes over UDDS

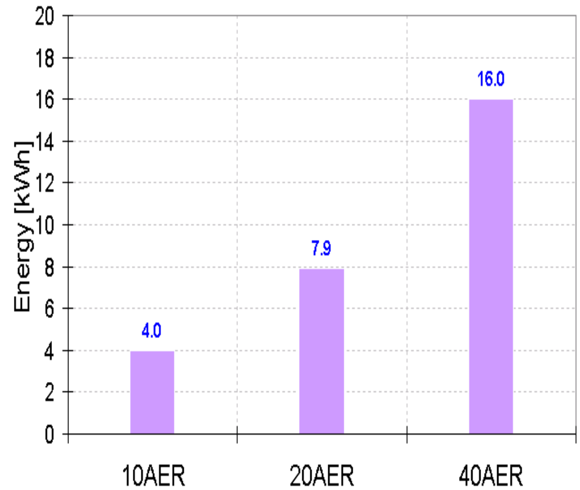


Figure 3. Battery Energy over UDDS

Control Strategy

The PHEV vehicle operations can be divided into two modes, as shown in Figure 4. These modes are described below:

- Charge-depleting (CD) mode: When the battery state-of-charge (SOC) is high, the vehicle operates under a so-called blended strategy. Both the battery and engine can be used. However, whenever possible, preference is given to the battery with the depleted charge. Engine usage increases as the SOC goes down. The engine tends to be used in heavy acceleration as well, even though the SOC is high. For fuel economy purposes, this blended strategy is defined for a battery going from full charge to a self-sustained SOC, typically when the SOC drops from 90% to 30%.
- Charge-sustaining (CS) mode: Once the battery is down to 30%, the vehicle operates in charge-sustaining mode, similar to a regular hybrid vehicle.

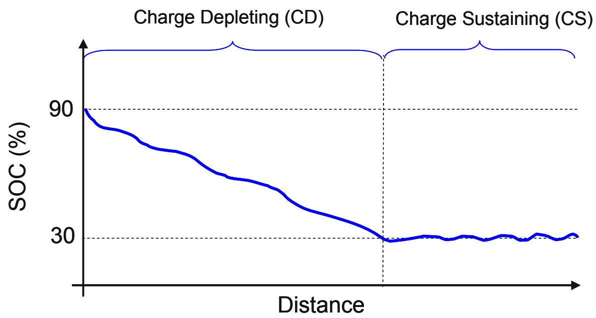


Figure 4. Illustration of Charge-Depleting (CD) vs. Charge-Sustaining (CS) Modes

However, only the CD strategy is considered in this study, since the purpose is to meet the required AER during CD operation.

Depending on how the engine is used, the control strategy can be divided by two modes. The first mode is called Engine Minimum Assistance. The vehicle operates all-electrically until the driving demand exceeds the power capability of the electric machine. As shown in Figure 5, the engine is turned on only when the power capability of the motor reaches its maximum power curve. The engine provides the delta power between required power at the gearbox input and maximum motor power. This strategy is used to define the maximum share of the drive cycle that can be driven in EV mode.

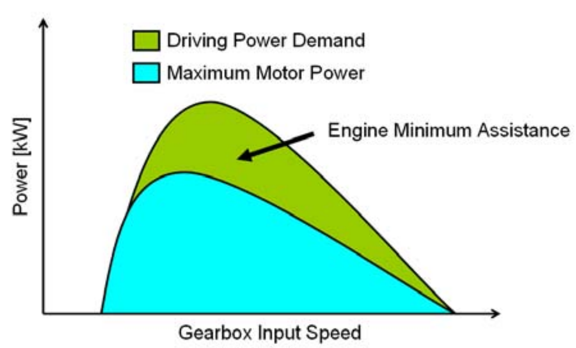


Figure 5. Engine Minimum Assistance Logic

The second control option, Engine Assistance at Best Efficiency, operates similarly to Engine Minimum Assistance. As shown in Figure 6, the engine also is turned on when the electric motor power reaches its maximum power curve, but the engine is now operating close to its best efficiency curve. The surplus power from the engine is used to charge the battery.

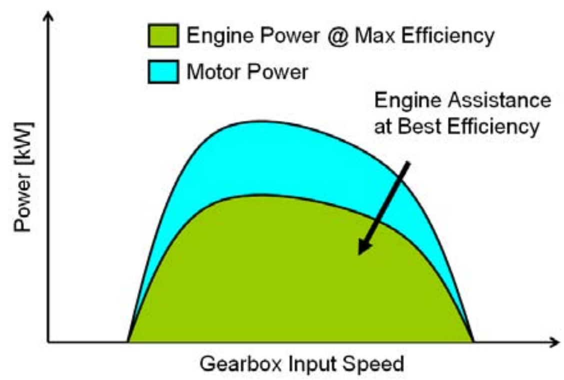


Figure 6. Engine Assistance at Best Efficiency Logic

Drive Cycle Characteristics

To assess the impact of additional drive cycles on the vehicle operating conditions, six additional drive cycles are selected: *Japan1015, Highway EPA Cycle (HWFET), New European Drive Cycle (NEDC), SC03, LA92, and US06*. This selection of drive cycles provides a wide aggressiveness and driving range spectrum.

The main characteristics of these drive cycles are shown in Figures 7 and 8, from the least aggressive drive cycle (Japan1015) to the most aggressive (US06). Japan1015, NEDC, and UDDS represent city driving patterns, including softer accelerations, lower speeds, and shorter driving distances. The LA92 and US06 have been selected to represent harder accelerations, higher speeds, and longer driving distances.

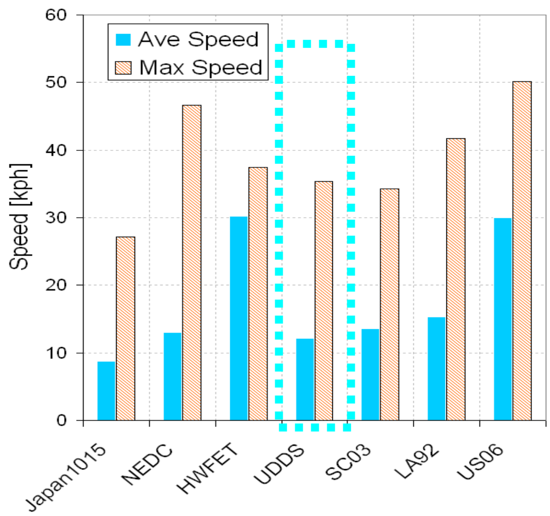


Figure 7. Average Speed and Maximum Speed of Selected Drive Cycles

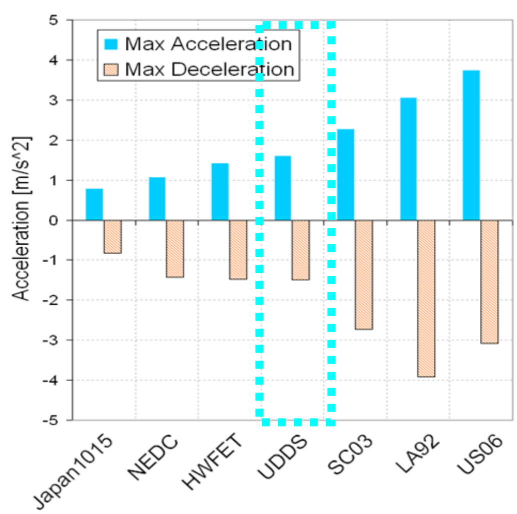


Figure 8. Maximum Acceleration and Deceleration of Selected Drive Cycles

Drive Cycle Impact on Vehicles Sized on UDDS

To assess the behavior of an AER-based PHEV designed on UDDS over other cycles, three vehicles (10, 20, and 40 miles AER) were simulated on the drive cycles.

Engine Minimum Assistance

As discussed previously, the goal of the engine minimum assistance control strategy is to determine the maximum capabilities of the battery on several drive cycles when the engine is used only to provide the difference of the torque requested to follow the drive cycle.

Figure 9 shows the distances driven by an AER-based PHEV for ranges of 10, 20, and 40 miles until the battery SOC reaches 30%, where the operating mode changes from CD to CS. The AER is maintained for the Japan1015, NEDC, HWFET, and UDDS, but drops for the most aggressive cycles —as much as 30% on the SC03 and LA92 and 35% on the US06.

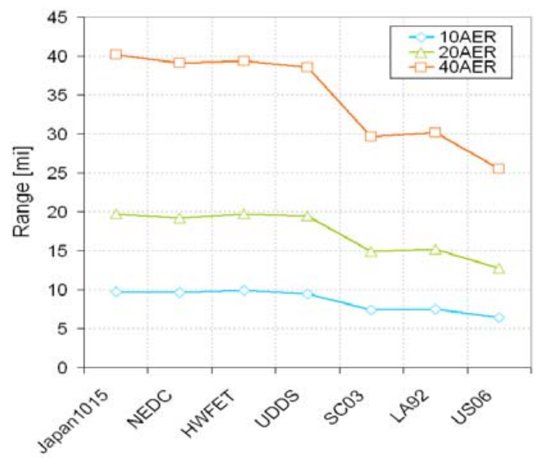


Figure 9. Distance Driven by a PHEV Designed Based on UDDS over Various Drive Cycles (10 AER)

Figure 10 illustrates utilization of the engine during CD mode for the 10 AER vehicle. The engine is used only when the vehicle power demands are higher than the electric machine. During the moderate drive cycles, such as Japan1015, NEDC, HWFET, and UDDS, the engine never turns on because the electric machine is capable of satisfying the full vehicle power demand. However, during higher power demand cycles, such as SC03, LA92, and US06, the engine is used to provide additional assistance when the power demands of the given drive cycles exceed the maximum power that the electric motor can provide.

Figure 10 also shows that the energy consumption required by an AER-based PHEV driven on UDDS is 241 Wh/mi. In addition to higher power, the aggressive drive cycles also require larger electrical consumptions, which explains the drop in AER, as shown previously.

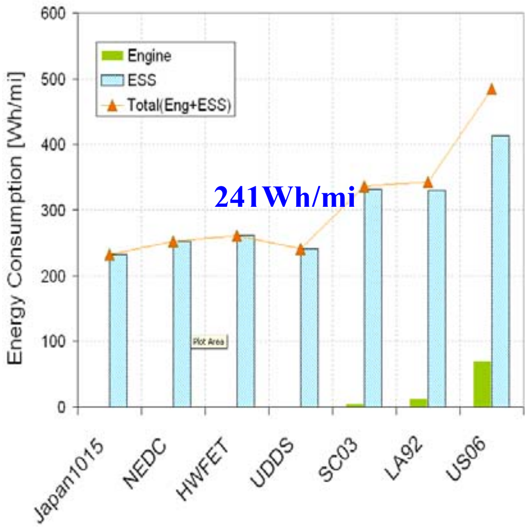


Figure 10. Energy Consumptions of a PHEV Designed Based on UDDS, Driven over Various Cycles (10 AER)

Figure 11 shows the distribution of the electric machine power on the UDDS and the US06 drive cycles. The average electric machine power is much higher for the US06 than for the UDDS.

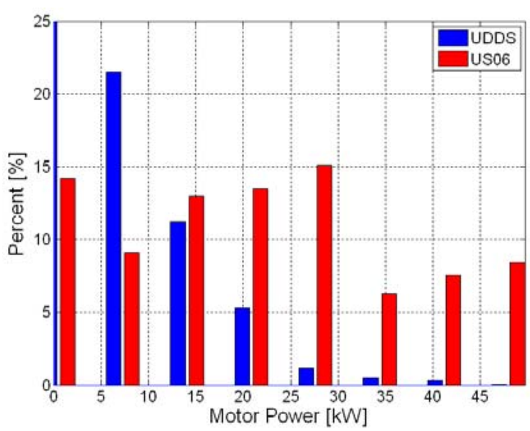


Figure 11. Comparison of Motor Power Distributions between Driving on UDDS and US06 (10 AER)

While the UDDS requires only ~45 kW to follow the trace, the US06 needs approximately 65 kW during hard accelerations at the input of the gearbox. Consequently, the engine must be started to follow the trace. Figure 12 shows the minimum engine power distribution.

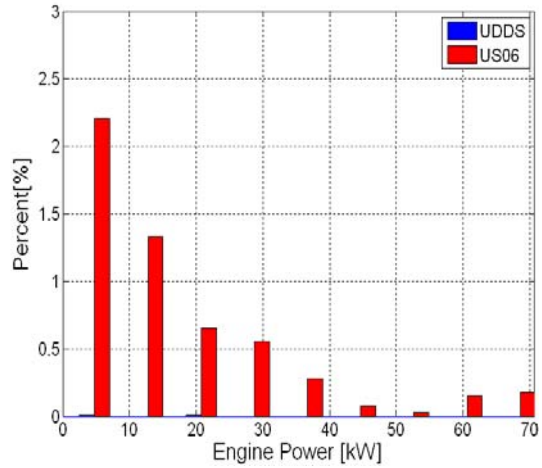


Figure 12. Comparison of Engine Power Distributions between Driving on UDDS and US06 (10 AER)

This control strategy, while maximizing the electrical consumption, leads to poor average engine efficiencies, as shown in Figure 13. As a result, it will not be implemented in vehicles.

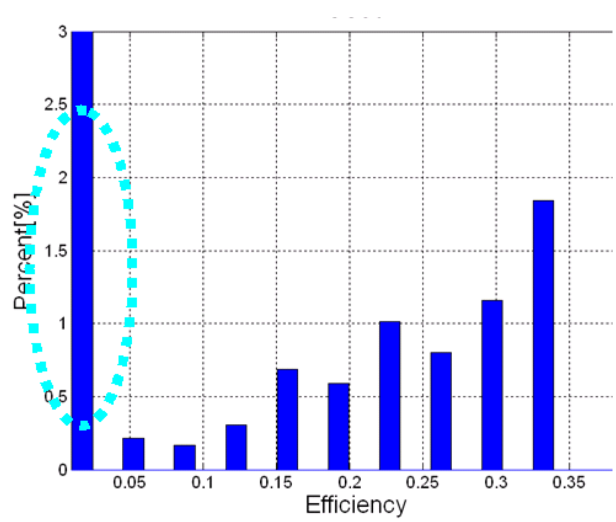


Figure 13. Efficiency of Engine Distribution (10 AER)

In order to overcome the poor engine operating efficiency from engine minimum assistance strategy, the alternative is to use the engine close to its best efficiency curve to maximize the system efficiency.

Engine Assistance at Best Efficiency

Figure 14 illustrates the impact of engine operation close to the best efficiency during CD mode with respect to the drive cycle's intensity and distance for

10 AER. As the engine is now used to charge the battery, the range is increased for the aggressive drive cycles. The largest improvement occurs for the US06, which represents the most aggressive driving pattern with longer driving distance.

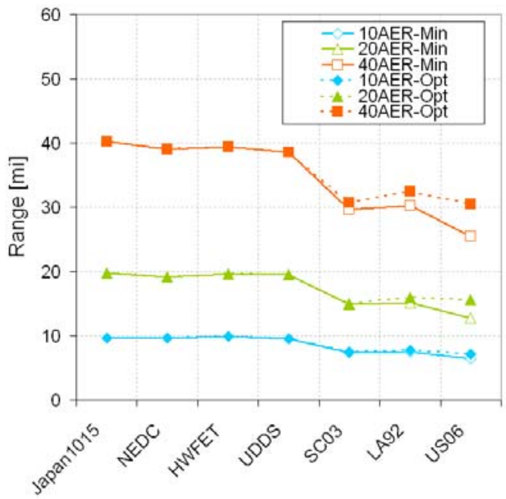


Figure 14. Distance Driven by a PHEV Designed Based on UDDS with Engine Assistance at Best Efficiency Strategy over Various Drive Cycles (10 AER)

The significant improvement in the driving range on the US06 occurs due to spreading out the engine's utilization with higher efficiency to reduce the use of the electric motor and battery. The more aggressive the drive cycle, the more the range is improved. As seen in Figure 15, total energy consumption on the US06 was improved by approximately 18%. The energy consumption of the engine on the US06 was increased from 80.2 Wh/mi to 104.6 Wh/mi, while the energy consumption of the electric motor was decreased from 410 Wh/mi to 380 Wh/mi. Overall, the fuel consumption of the system is improved from 480 Wh/mi to 450 Wh/mi. Even though the engine consumes more energy per unit mile, the net energy produced by the engine (output energy of the electric machine) is significantly improved because of the higher engine efficiency. The average engine efficiency with the engine assistance at best efficiency strategy over US06 is improved up to approximately 31%.

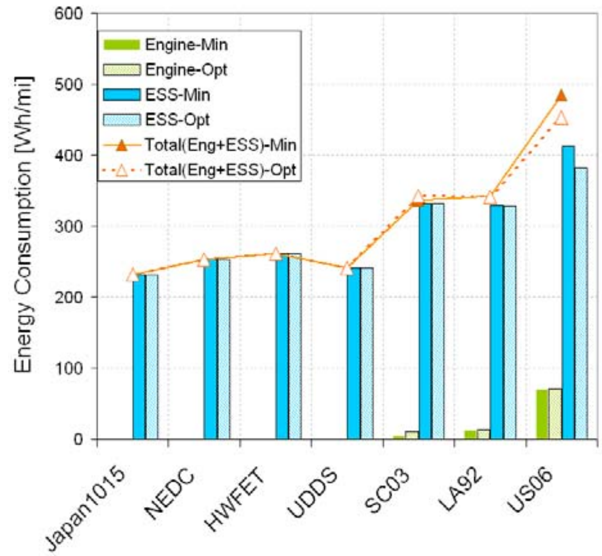


Figure 15. Energy Consumptions of a PHEV Designed Based on UDDS, Driven with Engine Assistance at Best Efficiency Strategy over Various Cycles (10 AER)

Drive Cycle Impact on Component Sizing

To help meet the AER requirements on more aggressive cycles when the vehicle is designed on UDDS, the vehicle could instead be designed considering the AER operation on various drive cycles.

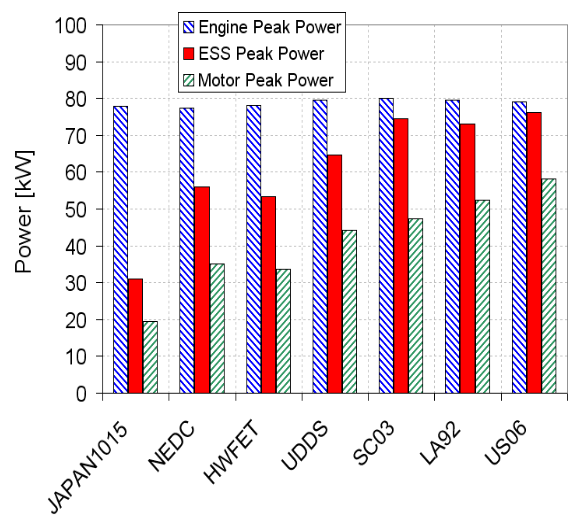


Figure 16. Component Sizes over Various Drive Cycles (10 AER)

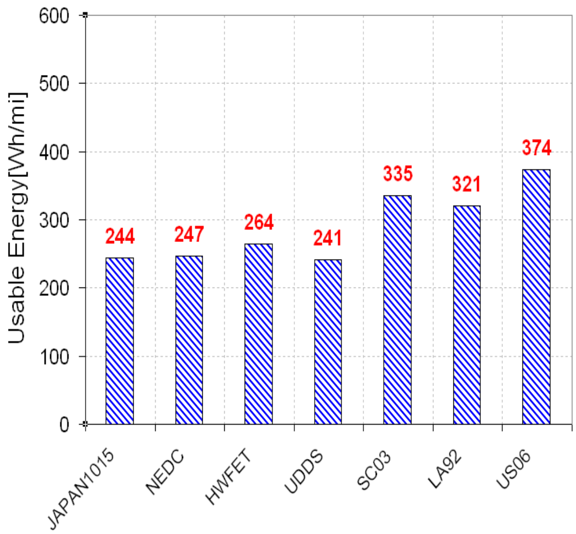


Figure 17. Usable Energy of the Battery Based on Various Drive Cycles (10 AER)

Figure 16 shows the components power sized on various drive cycles for 10 AER. The drive cycle has little to no impact on the engine power, since the engine is sized to meet only the gradeability requirement (6% grade at 65 mph). However, the electric machine and battery powers are impacted by the drive cycle characteristics (Figure 17). The electric machine peak power is increased by 24% from UDDS to US06, and decreased by more than 50% as it changes from UDDS to Japan1015.

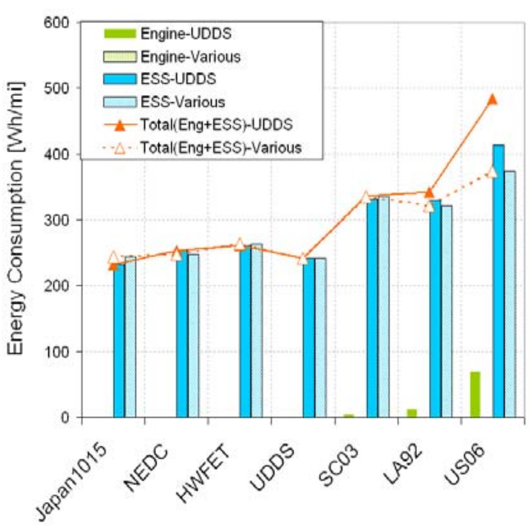


Figure 18. Energy Consumptions of a PHEV Designed Based on Various Cycles (10 AER)

Figure 18 illustrates the impact on energy consumption that results from sizing a PHEV based on various drive cycles. The impact of the drive cycle on energy is minimal compared with the influence on power. The greater impacts are shown on the more aggressive cycles, such as SC03, LA92, and US06.

A trade-off must be performed between power and energy. Indeed, although a PHEV sized on the US06 improves its total energy consumption from 410 Wh/mi to 380 Wh/mi without turning on the engine, it brings the increment of size of the electric motor from 42 kW to 58 kW, which leads to a larger and costlier electric drive.

Conclusions

In this study, the sensitivity of driving distance and energy consumption of a midsize pre-transmission parallel PHEV to increased cycle aggressiveness was studied.

The simulation results demonstrated the following:

- The choice of drive cycle directly influences PHEV design decisions. It is sensitive to increased cycle aggressiveness and driving range, since the vehicle will be unable to satisfy significant power demands all electrically during CD mode, as designed.
- In cases where it is necessary to use the assistance of the engine, the *engine assistance at best efficiency* strategy has the advantage of improving driving range as well as energy consumptions for the designed PHEV.
- A PHEV sized on the basis of aggressive drive cycles, such as LA92 and US06, requires larger and more expensive electric components, but offers the potential to operate in AER operations.

Many trade-offs occur among costs, emissions, energy consumptions, and customer appeal during the PHEV design decision-making process. For instance, although cost remains a major challenge in PHEV development, the additional cost increment for the additional power could be worthwhile, especially since the increased electric power would improve the vehicle's acceleration capability and drive quality.

Overall, this study has demonstrated that the PHEV designed to satisfy UDDS will fail to achieve AER for real-world driving. Consequently, what customers will be told will differ from what they truly experience. To overcome this failure, the alternative could be to employ the CD vehicle strategy with the engine operating at best efficiency. This alternative would deliver effective utilization of engine energy during CD operation and could result in a relatively small fuel efficiency opportunity loss for longer driving distances.

Publications / Presentations

1. Kwon, J., Kim, J., Fallas, E., Pagerit, S., Rousseau, A., "Impact of Drive Cycles on PHEV Component Requirements," SAE World Congress, Detroit (April 2008).

J. Plug-in Hybrid Electric Vehicle Control Strategy Parameter Optimization

Aymeric Rousseau (Project Leader), Sylvain Pagerit
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261, e-mail: arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Tune the parameters of a pre-defined control strategy for several distances and drive cycles.

Approach

- Use the heuristic optimization algorithm (DIRECT) to tune the parameters on different distances and drive cycles.
- Evaluate the possibility of selecting a single set of parameters for all the situations.

Accomplishments

- A non-derivative based algorithm, DIRECT, was used to optimize the main parameters of a pre-defined control strategy algorithm.
- Different sets of parameters were generated for several drive cycles and distances.
- The results demonstrated the need to have different control parameters, depending on distance and drive cycle.
- If only one parameter was used, the best compromise for fuel economy average and variance was achieved with the parameters defined for medium distances.

Future Directions

- Define parameters for additional drive cycles.
- Develop algorithms to recognize trip characteristics and distance.
- Revisit initial control strategy logic based on the global optimization results.

Introduction

One of the primary outcomes of the vehicle analysis is to define the component performance goals and requirements for R&D/solicitations. The Powertrain System Analysis Toolkit (PSAT) has been used to set the battery technical target, which was used to develop the United States Advanced Battery Consortium (USABC) PHEV Request for Proposal. In addition to parameters that influence the control strategy (such as battery state-of-charge [SOC] or drive cycle) of hybrid electric vehicles (HEVs), several studies have demonstrated the impact of driving distance on fuel displacement for plug-in hybrid electric vehicles (PHEVs). This additional parameter makes it even more difficult to tune the parameters that minimize fuel consumption manually.

Numerous optimization algorithms are available, and these can be categorized in different ways. Examples of this include the local optimization algorithm versus the global optimization algorithm, the deterministic optimization algorithm versus the stochastic optimization algorithm, or the gradient-based algorithm versus the derivative-free algorithm. Making the proper selection of an optimization algorithm for the application of hybrid powertrain design is not obvious. In this paper, the DIRECT (for DIvided RECTangles) algorithm has been selected on the basis of previous work performed by the University of Michigan.

This paper will focus on the optimization of the parameters of a pre-transmission parallel PHEV with a 10-mile all-electric range (AER). After describing the vehicle and its control strategy logic, we will evaluate the impact of the drive cycle and distance of several key parameters of the control.

Vehicle Description

The vehicle class used for the simulation is a midsize SUV, since this platform was used to define the USABC short-term battery requirements. The components selected, shown in Table 1, are those that have been implemented in Argonne's Mobile Advanced Automotive Testbed (MATT). The MATT is a rolling chassis used to evaluate component technology in a vehicle system context. The control strategy, developed on the basis of the optimization results, will ultimately be implemented and tested on hardware.

Table 1. Main Specifications of the Vehicle

Component	Specifications
Engine	2.2 L, 100 kW Ford Duratec
Electric machine	60 kW PM electric machine
Battery	Li-ion, 75kW, 23A·h
Transmission	5-speed automatic transmission
	Ratio: [3.22, 2.41, 1.55, 1, 0.75]
Frontal area	2.76 m^2
Final drive ratio	3.58
Drag coefficient	0.395
Rolling resist.	0.008 (plus speed related term)
Wheel radius	0.33 m
Vehicle mass	1,823 kg

As shown in Figure 1, the configuration selected is a pre-transmission parallel hybrid, which is very similar to the one used in the DaimlerChrysler Sprinter Van.

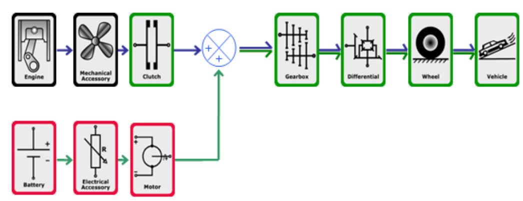


Figure 1. Configuration Selected: Pre-Transmission Parallel HEV

Control Strategy Algorithm

The control strategy can be separated into two distinct modes, as shown in Figure 2:

- Charge-depleting (CD) mode: Vehicle operation on the electric drive, engine subsystem, or both, with a net decrease in battery SOC.
- Charge-sustaining (CS) mode: Vehicle operation on the electric drive, engine subsystem, or both, with a "constant" battery SOC (i.e., within a narrow range), which is similar to those in HEVs that are in current production.

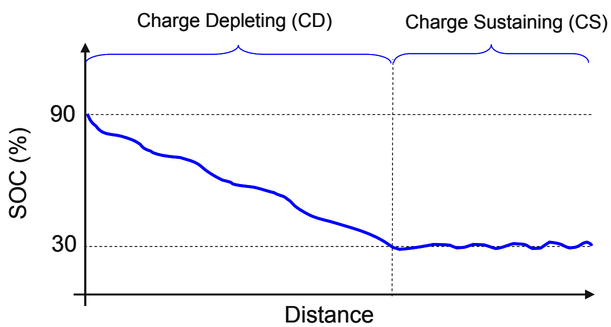


Figure 2. Control Strategy SOC Behavior

The first critical part of the control strategy logic is related to the engine ON/OFF logic. As Figure 3 shows, the engine ON logic is based on three main conditions:

- The requested power is above a threshold,
- The battery SOC is lower than a threshold, and
- The electric motor cannot provide the requested wheel torque.

In addition to these parameters, additional logic is included to ensure proper drive quality by maintaining the engine ON or OFF during a certain duration. Also, to avoid unintended engine ON events resulting from spikes in power demand, the requested power must be above the threshold for a pre-defined duration. The engine OFF logic condition is similar to that of the engine ON. Both power thresholds used to start or turn off the engine, as well as to determine the minimum duration of each event, have been selected as input parameters of the optimization problem.

To regulate the battery SOC, especially during the charge depleting mode, the power demand that is used to determine the engine ON/OFF logic is the sum of the requested power at the wheel plus an additional power that depends on battery SOC. This power can be positive or negative, depending on the value of the current SOC compared with the target.

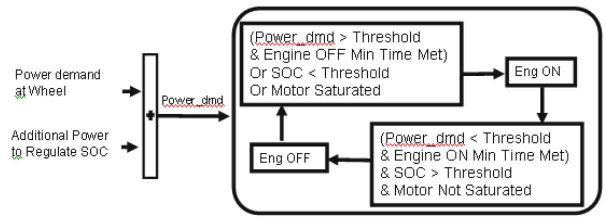


Figure 3. Simplified Engine ON/OFF Logic

Figure 4 shows the different parameters used to define the additional power to regulate the SOC in greater detail. The SOC target has been set when the vehicle is considered entering the charge-sustaining mode (30% SOC). Both e*ss_percent_pwr_discharged* and *ess_percent_pwr_charged* have been selected as input parameters to the optimization problem.

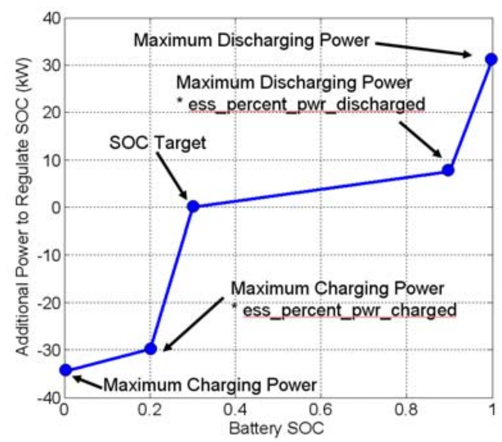


Figure 4. Example of Additional Power to Regulate SOC

In electric only mode, the vehicle is propelled by the electric machine. When the engine is ON, it is operated close to its best efficiency curve, depending on the vehicle power request and the battery SOC status. Table 2 summarizes the selected control parameters used as part of the optimization process.

Table 2. Control Parameter List

Parameter	Unit	Min	Max	Description
eng_pwr_wh_above_turn_on	W	5,000	30,000	Power above which the engine is turned ON
eng_pwr_wh_below_turn_off	W	500	25,000	Power below which the engine is turned OFF
eng_time_min_stay_on	sec	1	10	Minimum time the engine stays ON
eng_time_min_stay_off	sec	1	10	Minimum time the engine stays OFF
ess_percent_pwr_discharged	%	20	100	Percentage of maximum battery discharging power at high SOC
ess_percent_pwr_charged	%	20	100	Percentage of maximum battery charging power at low SOC

Optimization Results

Parameter Control Values

Some of the parameters have a higher impact than other on the outcome of the results. Based on the correlation coefficients between the inputs and the fuel economy values, the parameters with the highest impact are the power threshold to turn the engine ON (*eng_pwr_wh_above_turn_on*) and the time the engine is maintained ON (*eng_time_min_stay_on*). Conversely, those with the lowest impact are the power threshold to turn the engine OFF (*eng_pwr_wh_above_turn_on*) and the percentage of maximum battery charging power at low SOC (*ess_percent_pwr_charged*).

To simplify the analysis, only the UDDS drive cycle will be considered in the following paragraphs. Table 3 shows the optimization results of the UDDS standard drive cycle. As the table shows, both power thresholds related to the engine tend to decrease with increasing distance. This result can be explained by the fact that the engine should be turned ON more often for longer distances than for shorter ones. Figure 5 demonstrates that point, comparing the engine power on the UDDS when the cycle is repeated 2 and 8 times. Even if the engine is used at similar operating conditions (i.e., efficiency is fairly constant around 32%, independently of the distance), it turns ON less often during a short distance cycle (2.2% on the UDDS*2 vs. 11.6% on the UDDS*8 during the first cycle).

Table 3. Optimized Parameters for UDDS Drive Cycle

Parameter	Unit	2 UDDS	4 UDDS	6 UDDS	8 UDDS
eng_pwr_wh_above_turn_on	W	17,500	16,265	15,820	15,340
eng_pwr_wh_below_turn_off	W	12,750	8,515	8,313	7,608
eng_time_min_stay_on	s	1.5	1.05	1.018	1.018
eng_time_min_stay_off	s	1.5	1.16	2.129	1.055
ess_pwr_chg_at_target	%	0.244	0.79	0.926	0.863
ess_pwr_dis_at_target	%	0.6	0.215	0.2	0.205

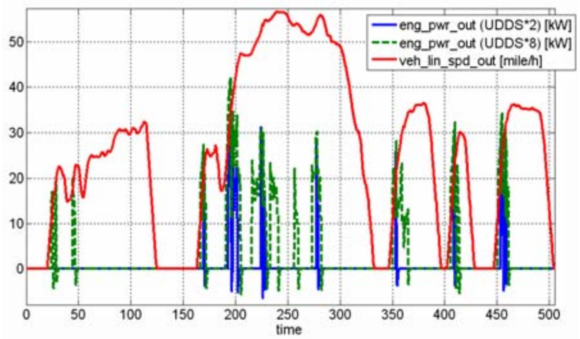


Figure 5. Engine Power for 2 and 8 UDDS

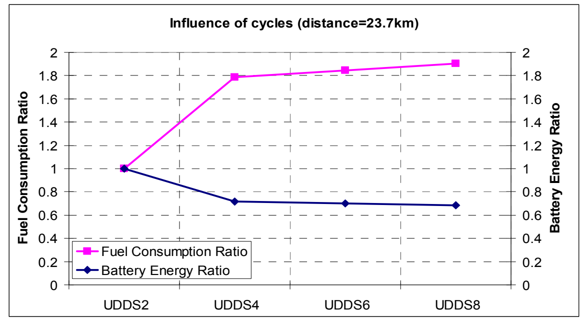


Figure 6. Fuel Consumption and Battery Energy Ratios on 2*UDDS

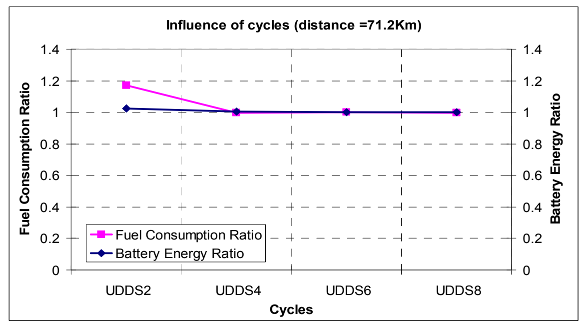


Figure 7. Fuel Consumption and Battery Energy Ratios on 6*UDDS

To assess the impact of the parameters, we will consider different options:

- Same distance, different parameters,
- Same parameter, different distances, and
- Same parameter, different cycles.

Influence of Different Parameters on Distance

To evaluate the impact of parameters on the fuel economy, the same trip was run with the optimized parameters of the different drive cycle distances. For instance, Figure 6 shows the vehicle simulated on 2 UDDS (total distance of 23.7 km), with the parameter values optimized for 2, 4, 6, and 8 UDDS drive cycles. The ratios are in respect to the 2xUDDS results.

Figure 6 shows that, for a short distance (23.7km), a significant difference in fuel consumption occurs between the set of parameters obtained for 2 UDDS and the others. The longer the distance to optimize, the less difference there is in fuel consumption. Figure 7 reinforces this point by showing the same information for 6 successive UDDS drive cycles. In addition, the difference between the parameter values generated for 2 UDDS is not as stringent. The results generated for 4 and 8 UDDS are similar to the results for 6 UDDS.

On the basis of the information above, at least two sets of parameters should be used to properly control the vehicle: one set for short distances and one for long distances. However, this approach is valid only when one knows the trip distance in advance.

Influence of Different Distances on Parameters

To evaluate the impact of drive cycle distance on the fuel economy, different trips were run with each set of optimum parameters. Figure 8 shows the vehicle simulated on 2, 4, 6, and 8 UDDS using the parameter values optimized for 2 UDDS.

Figure 8 shows the fuel consumption and battery energy ratios for several distances (2, 4, 6, and 8 UDDS) based on optimum parameters defined for 2 UDDS. The increased distances reflect a ratio of almost 4. This value is much higher than the one generated with optimum parameters defined for 6 UDDS, as shown in Figure 9. This behavior is similar when considering 4 and 8 UDDS.

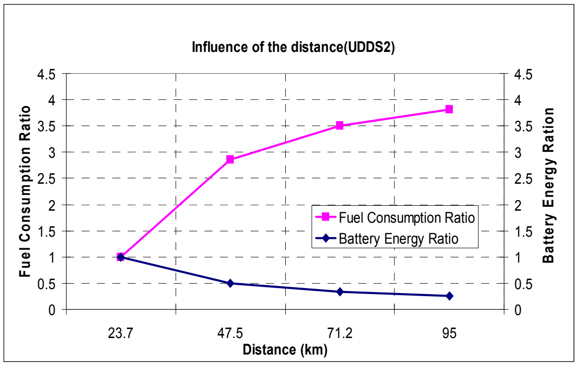


Figure 8. Fuel Consumption and Battery Energy Ratios on Different Distances Based on Optimized Parameters from 2*UDDS

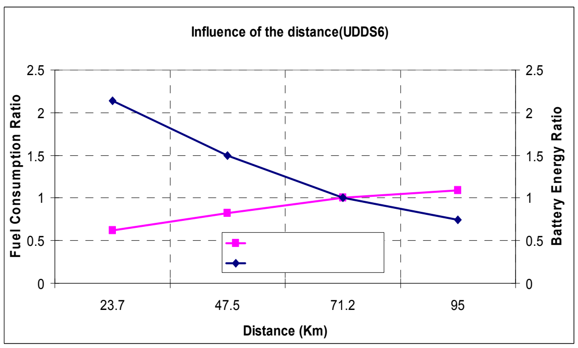


Figure 9. Fuel Consumption and Battery Energy Ratios on Different Distances Based on Optimized Parameters from 6*UDDS

Figures 8 and 9 demonstrate that optimizing for a short distance but driving a longer one leads to higher losses in fuel economy than optimizing for a longer distance and driving a shorter one.

Selection of the Best Single Set of Parameters

To select a single set of parameters, we considered the average as well as the spread of the fuel economy from two different points of view:

- Same distance with parameters optimized for different ones (2, 4, 6, and 8 UDDS).
- Different distances with parameters optimized on only one (2, 4, 6 or 8 UDDS).

In our case, the lower the spread, the better the parameter selection.

Figure 10 shows the average and spread of each set of runs and optimum parameters for UDDS. Independent of the distance on which the parameters were optimized, driving a short distance will always bring the best fuel economy. In addition, driving an equal number of short and long distances will lead to similar average fuel economy. The longer the driving distance, the less important which distance was used to optimize the parameters (red spread smaller for 4, 6, and 8 UDDS than for 2). Finally, if the parameters are optimized on a short distance but longer distances are driven, the fuel economy will fluctuate more and can get higher than optimizing on a long distance and driving a short one.

As a result, selecting a single set of parameters will depend on the average driving distance and will consequently differ from one drive to another. Considering the high sensitivity to distance of the parameters based on 2 UDDS, the parameters from the 4 UDDS appear to be the best compromise if only one set can be selected. Knowing the trip distance is critical for maximizing fuel displacement through GPS or additional algorithms.

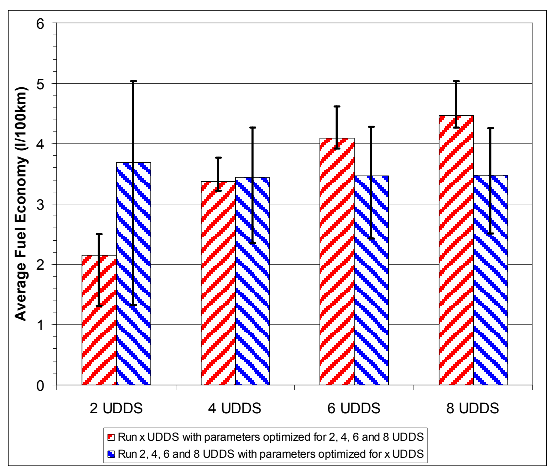


Figure 10. Average and Spread of Each Set of Runs and Optimum Parameters for UDDS

Conclusions

A non-derivative based algorithm, DIRECT, was used to optimize the main parameters of a pre-defined control strategy algorithm. Different sets of parameters were generated for several drive cycles and distances. Their impact on the drive cycles and distances was analyzed.

The results demonstrate the need to have different control parameters, depending on the distance and drive cycle. Since none of the trip characteristics might be known at the outset, if only one parameter is used, the best compromise for fuel economy average and variance is achieved with the parameters defined for medium distances.

Future work will focus on defining the parameters for additional drive cycles, as well as developing algorithms to recognize trip characteristics and distance. The initial control strategy logic will also be revisited based on outputs from the global optimization algorithm.

Publications/Presentations

1. Rousseau, A., Pagerit, S., Gao, D., "Plug-in Hybrid Electric Vehicle Control Strategy Parameter Optimization," EVS, Anaheim (December 2007).

K. Impact of Component Size on Plug-In Hybrid Vehicle Energy Consumption Using Global Optimization

Dominik Karbowski (Project Leader), Aymeric Rousseau
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7261, e-mail: arousseau@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Evaluate the impact of several drive component sizes on fuel economy for PHEVs.

Approach

- Use global optimization algorithm to allow fair comparison by taking into account the uncertainties of control strategies
- Analyze the control patterns for different battery usable energy, including engine operating conditions, engine ON/OFF.

Accomplishments

- Charge-depleting mode is always preferred to an EV-mode followed by charge-sustaining mode
- The relation between the wheel power demand threshold used to start the engine and the available electric consumption has been defined
- The engine desired operated conditions (high efficiency, high power) have been defined
- Based on the 2010 American energy mix, which heavily relies on coal, greenhouse gases emissions are not reduced by an increased use of grid electricity

Future Directions

- Add additional drive cycles, use combination of cycles to create trips
- Include charge sustaining as part of the global optimization
- Generate a rule-based control based on the global optimization results

---

Introduction

Plug-in Hybrid Electric Vehicles (PHEVs) are a promising alternative to conventional gas-powered vehicles. They can indeed be driven in an all-electric mode (EV mode) for a relatively short distance, although long enough for most daily trips. Thanks to an internal combustion engine (ICE), a PHEV can still take advantage of the high energy density of gasoline and provide the customer with an acceptable driving range.

The electric power system, composed of the battery and the electric machine, is critical in a PHEV. Its mass has to be low enough not to increase significantly the energy consumption at the wheels. To be marketable, the cost of the electric power system has to remain within limits defined by the market. Energy and power are the two main physical characteristics impacting cost and weight. It is therefore of paramount importance to adequately size the battery and the electric machine.

This study focuses on the impact of electric power system energy and power on the overall energy consumption, by comparing parallel pre-transmission PHEV with various power and energy sizing. When comparing different vehicles, a bias may, however, be introduced if the control is optimized for some vehicles, but not for others. Running a global optimization algorithm on the torque split between the engine and the electric machine, as well as the gear, ensures that each sizing is used at its maximum potential. As the control is an output and no longer an input of the simulations, this allows a fair comparison.

Vehicle Characteristics

The configuration selected for this study is a parallel pre-transmission, as shown in Figure 1. It is very similar to the one used in the DaimlerChrysler Sprinter van. Only one electric machine is used for both propelling and regenerative braking. This configuration is also used in the Argonne's Mobile Advanced Automotive Testbed (MATT). MATT is a rolling chassis used to evaluate component technology in a vehicle system context, and it can be used for the practical applications of this study.

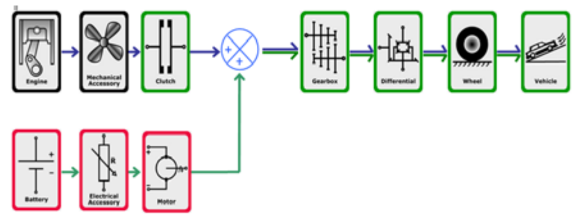


Figure 1. Component configuration of the parallel pre-transmission PHEV

The base vehicle size corresponds to a small SUV similar to Chevrolet Equinox or Toyota Rav4. The electric machine and battery size are variable. The main components characteristics are summarized in Table 1.

Table 1. Specifications of components

Component	Specifications
Engine	2.2 L, 100 kW Ford Duratec
Electric machine	Various power Based on Toyota Prius MY04 motor
Battery	Various capacity and power Based on Li-ion – Saft VL41M
Transmission	5-speed automatic transmission
	Ratio: [3.22, 2.41, 1.55, 1, 0.75]
Frontal area	2.76 m^2
Final drive ratio	3.58
Drag Coefficient	0.395
Rolling resist.	0.008 (plus speed related term)
Wheel radius	0.33 m
Vehicle mass	1710 kg + motor mass + battery mass
Electric accessories	240 kW

Control Analysis

The global optimization algorithm outputs the optimal solution for given initial and final state (i.e., SOC). Because of the structure of the algorithm, getting a solution for the same final SOC and a different initial SOC does not require additional computations. For one run of the algorithm, it is possible to have the optimal control and minimal fuel consumption for various variations of SOC (ΔSOC). A ΔSOC of zero means the final and initial SOC are equal to 0.3: it is a charge-sustaining (CS) mode, as no electric energy from the grid is consumed. On the other hand, ΔSOC of 0.6 means the battery is fully depleted from 0.9 to 0.3 of SOC.

A given ΔSOC can be associated with a "plug-to-wheel" electric energy: the amount of electric energy the grid has to provide to enable battery SOC to return to its initial value. To compute this electric energy, the charging current is assumed to be 15 A, while the charger efficiency is 0.9. Divided by the driven distance, it gives the electric consumption, in Wh/km.

In the following subsections, the analysis of the output of global optimization for a vehicle sized to run 20 miles in EV mode on the UDDS (called hereafter 20AER) highlights the patterns behind the optimal control.

Engine ON Events

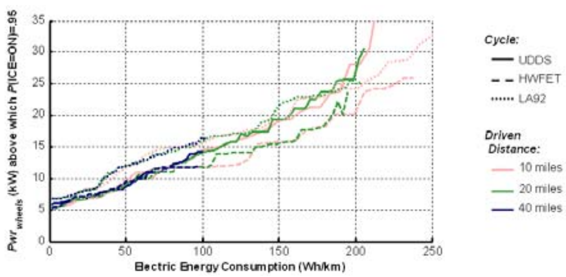


Figure 2. Power demand at the wheels above which ICE is on 95% of time 20AER, various cycles (differentiated by colors/shade), various distances driven (differentiated by line style). For example, lighter shade/pink dotted line corresponds to 10 miles on LA92

In real-world powertrain controllers, the decision to turn the engine on is often linked to the power demand at the wheels. When the power demand is above a given threshold, the engine turns on. The power demand at the wheels, above which the probability of the engine being on is higher than 0.95, is a good indication. It is hereafter called wheel power threshold. It is shown on Figure 2 for various cycles (differentiated by line style) and various distances (differentiated by line colors/shade). The wheel power threshold increases linearly as a function of electric consumption: the more electric energy is used, the less the engine operates, and the "later" (in terms of power) it starts. The influence of cycle type appears to be minimal.

Longer driven distance results in lower maximum electric consumption, since the total energy available from the battery is the same while distance increases. Even though the battery is fully depleted, the engine is still needed to power the vehicle.

Engine Operating Points

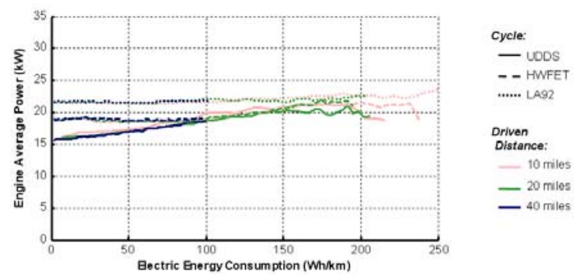


Figure 3. Engine average power – 20AER, various cycles, various distances driven

Once the engine is on, it is necessary to know how it operates. As shown in Figure 3, the average engine power increases linearly with the available battery energy. While it is started less often, it is used at higher power values and consequently at higher efficiencies, as shown in Figure 4.

Figure 3 also shows that the average engine power also depends on the cycle. On more aggressive cycles, such as LA92, it is almost constant and higher than less-aggressive ones, which means that the engine operates at similar power levels in CS or CD mode. It is also interesting to observe that for high electric energy consumption, the difference in average power disappears; around 175 Wh/km, the engine power does not depend any longer on the cycle.

The destination of the engine output also varies in function of the cycle. On the more aggressive LA92, the engine has more opportunities to propel the vehicle while working efficiently; a lower share of its output goes to the battery, as shown in Figure 4. HWFET is the cycle with the highest share of engine output charging the battery. As there are less power peaks during this cycle, the engine has to operate more often above the power required to propel the vehicle in order to maintain a good efficiency. The extra energy is taken by the electric machine to charge the battery.

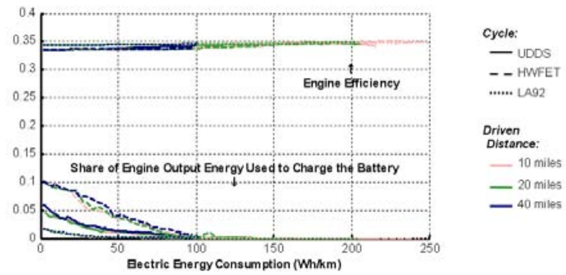


Figure 4. Engine efficiency and destination of its output – 20AER, various cycles, various distances driven

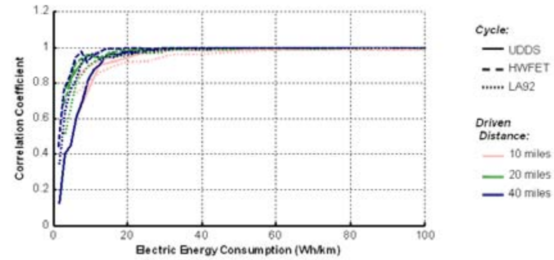


Figure 5. Correlation between SOC from actual and linear depletion – 20AER, various cycles, various distances driven

Battery SOC Management

Figure 5 compares the actual SOC depletion with a linear depletion. Linear battery depletion results in a SOC curve (as a function of time) that is a straight line. For ΔSOC = 0, a linear battery depletion means a constant SOC of 0.3, whereas for ΔSOC = 0.6, SOC decreases linearly from 0.9 to 0.3. A correlation of 1 means that the actual SOC curve (as a function of time) is very close to a straight line.

For low ΔSOC, or low electric consumption, the correlation is very low because there is an important SOC swing around 0.3, which is typical of a CS mode. The correlation is, however, very high for higher ΔSOC, which suggests charge-depleting mode is the optimal way to discharge the battery. The latter conclusion is valid with the driving schedules used in this study. Each of them is the result of the multiple repetition of the same cycle.

Influence on Energy Sizing

Influence on Control

The parameters used to describe the control are not much affected by the battery energy/AER. For a given electric energy, the behavior, in its macroscopic view, of the vehicle does not depend on its AER; the engine is on above similar wheel power demand, while outputting slightly higher power for longer-range vehicles, because of vehicle mass.

The main influence of battery energy is that for a given driven distance and vehicle, electric consumption is limited. Figures 6 (a) and (b) illustrate this fact. The same parameter is plotted (wheel power threshold), but with different abscissa. Figure 6 (a) uses the ΔSOC, while figure 6 (b) uses the electric consumption. The maximum depletion on the 10-AER vehicle is 0.6 (from 0.9 to 0.3 SOC) and results in a maximum electric consumption of 110 Wh/km. The 20-AER vehicle has the same depletion, but the maximum electric consumption is about 200 Wh/km, because the vehicle runs closer to an EV mode as the higher energy battery allows it. While the 20-AER, 30-AER and 40-AER vehicles have similar maximum electric consumption, their maximum depletion is all the lower as the AER is high; all of them run in EV-mode, but the depletion level will be lower for higher AER.

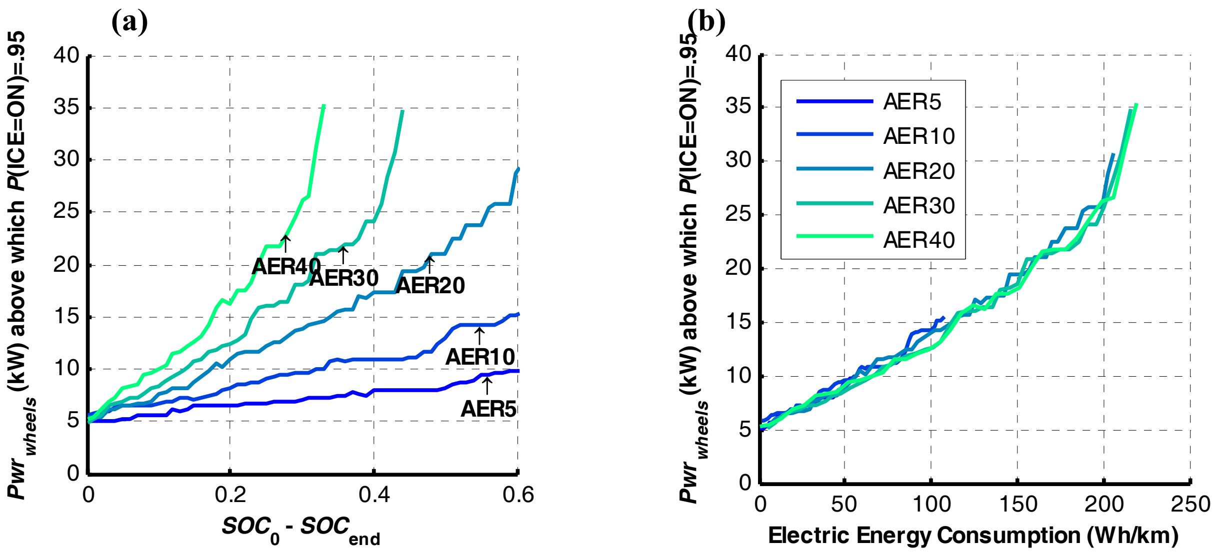


Figure 6 (a) and (b). Power demand at the wheels above which ICE is on 95% of time – various AER, UDDS, 20 miles

Influence on Fuel Economy

The influence of energy sizing on the fuel economy is similar. Even though longer-range vehicles tend to use more energy because of their weight, the difference is small enough to conclude that, for a given electric consumption, the influence on fuel consumption is minimal. This is shown on Figure 7.

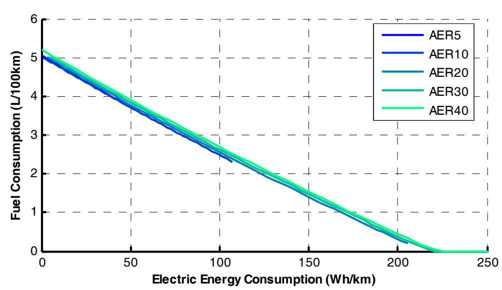


Figure 7. Fuel consumption – various AER, UDDS, 20 miles

When the focus is not on electric consumption, battery energy has an obvious impact. The minimum fuel consumption a vehicle can achieve on a given cycle and distance is all the lower as the battery energy is high, because it uses more electricity than fuel to propel itself, as shown on Figure 8.

Higher battery energy means higher fuel displacement (i.e., more fuel is saved in comparison to a car whose input energy comes from fuel only). However, when the driven distance is below the range, as for the 20-AER and 30-AER vehicles on 10 miles on UDDS, longer-range vehicles tend to be slightly penalized because of their higher mass.

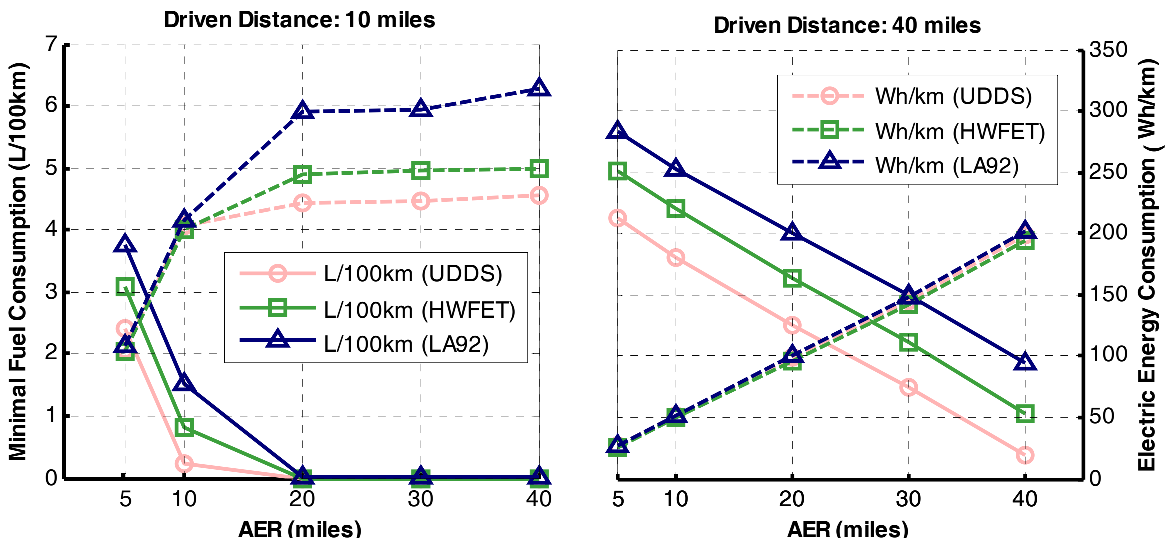


Figure 8. Minimal fuel consumption and associated electrical consumption

Influence on Power Sizing

Influence on Control

Power directly affects regenerative braking, since a more powerful electric system can recuperate more energy from strong decelerations. This is all the more true as the cycle is aggressive, as shows Figure 9. With 60% of original power, the vehicle captures 60% of the available energy, while this rate rises to 72% with 140% of original power. On the other hand, power scaling ratio has no influence on the regenerative braking energy recuperation on the UDDS and HWFET cycles.

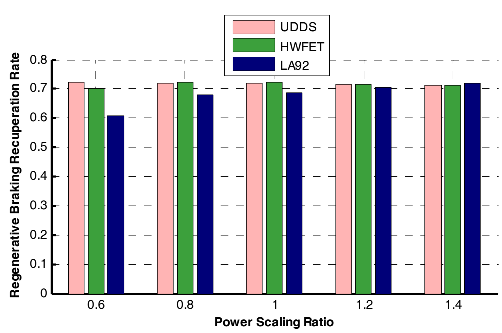


Figure 9. Regenerative braking recuperation rate – driven distance: 20 miles

Among all the control parameters previously mentioned, the power demand at the wheels above which the probability of the engine being on is higher than 0.95 is the only parameter significantly affected by the power-scaling ratio. As can be observed on Figure 10, this threshold is lower for less-powerful vehicles. A lower-power electric system has less ability to propel the vehicle on its own, which results in longer engine running time.

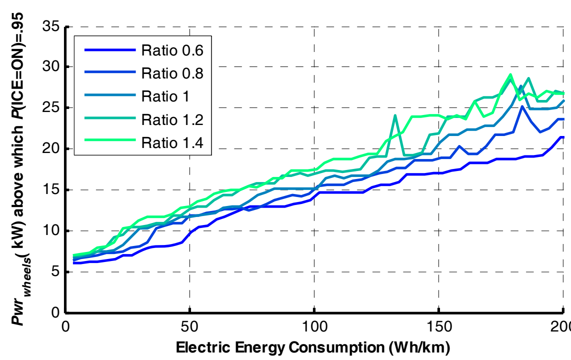


Figure 10. Power demand at the wheels above which ICE is on 95% of time – various ratios, UDDS: 20 miles

Influence on Fuel Economy

Figure 11 shows the minimal fuel consumption on several cycles, for the same driven distance of 10 miles, as well as the electric consumption at which this minimum is reached. The less powerful electric system, the less ability the vehicle has to run in EV mode, which results in an increased use of the engine, and increased fuel consumption. That increase is all the more significant as the cycle is aggressive, due to the reduced regenerative braking energy recuperation rate. The upsizing of the electric components improves the fuel consumption in a lower rate than the downsizing worsens it.

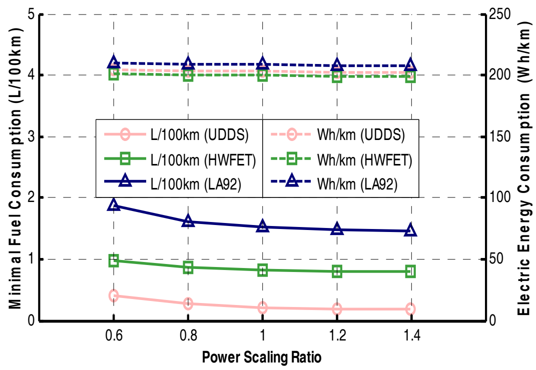


Figure 11. Minimal fuel consumption and associated electric consumption – driven distance: 10 miles

Conclusions

Global optimization allows a fair comparison of various vehicles because each of them is controlled optimally. The analysis of the control patterns showed common points. In particular, the wheel power demand threshold that depends on the available electric consumption has been identified, and the engine operates at high efficiency when it is on. This gives a valuable indication for the design of actual rule-based controllers, since it is very common to link the decision to start the engine to the power demand at the wheels. The global optimization also showed that a charge-depleting mode is always preferred to an EV-mode followed by charge-sustaining mode.

Energy sizing unsurprisingly impacts the amount of fuel that can be displaced, since a vehicle with higher battery energy can rely longer on electricity before turning the engine on. On the other hand, power sizing, especially downsizing, impacts fuel displacement as lower electric power limits the recuperation of regenerative braking energy, as well as the ability to run in EV mode.

Future work will be focused on extending the global optimization study, such as adding additional trips or including charge-sustaining optimal control, to generate a rule-based control that would maximize the fuel displacement for various driving conditions.

Publications / Presentations

1. Karbowski, D., Rousseau, A., " Impact of Component Size on Plug-In Hybrid Vehicle Energy Consumption Using Global Optimization", EVS, Anaheim (December 2007)

L. Automotive System Cost Modeling

Sujit Das
Oak Ridge National Laboratory
National Transportation Research Center
2360 Cherahala Boulevard, Room I-05
Knoxville, TN 37932-6472
(865) 946-1222, e-mail: dass@ornl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Develop a stand-alone, system-level cost model for generic production-cost estimation of advanced class vehicles and systems to facilitate progress toward FreedomCAR affordability objectives;
- Enable relative vehicle life cycle cost estimation via a uniform estimation methodology, allowing a comparison of alternative technologies under consideration by the FreedomCAR community to facilitate component technical target setting and research focus; and
- Develop a repository of cost data about various component-level technologies being developed today for new generation vehicles.

Approach

- Use a bottom-up approach, to define the vehicle as five major subsystems consisting of a total of 30+ components;
- Consider performance and system interrelationships to estimate system and subsystem costs for calculating total vehicle production cost; and
- Use a spreadsheet-based modular structure to provide “open” design and allow for future expansion.

Accomplishments

- Automotive system cost model (ASCM) for light-duty vehicles was integrated into the performance model PSAT including the model documentation; and
- Several long-term advanced technology vehicle cost scenarios were considered using the integrated modeling framework.

Future Directions

- Continue the validation of cost data assumptions and approach by coordinating and providing the cost assessment of advanced technology vehicles using the integrated cost modeling framework to various DOE program offices
- Collect and update the advanced technology component cost data.

Introduction

An early understanding of the key issues influencing the cost of advanced vehicle designs is vital for overcoming cost problems and selecting alternative designs. The affordability issue remains a concern with the recent FreedomCAR Partnership, where the focus is on a longer timeframe, hydrogen-powered fuel cell vehicles, and technology development applicable across a wide range of vehicle platforms. The collaboration among the previous vehicle engineering technical team (VETT), Argonne National Laboratory, ORNL, and support from IBIS Associates, Inc. over the past several years has resulted in a modular automotive system cost model (ASCM) for the life cycle cost estimation of 13 EPA light-duty vehicle classes for different types of advanced vehicle designs including hybrid and fuel cell vehicles. The focus of this year's work has been to integrate the original standalone spreadsheet based ASCM into the performance model PSAT to facilitate both the performance and cost estimation capability for advanced technology vehicles at the same time.

Approach

Cost assessment of advanced vehicle designs needs to be performed at the vehicle system/subsystem level, with the capability that implications on the complete vehicle due to any changes occurring in any vehicle component can be assessed. Total production cost of advanced vehicle designs is estimated based on cost estimates of five major subsystems consisting of a total of 30+ components, where each component represents a specific design and/or manufacturing technology. A representative vehicle is selected for each vehicle class to reflect major technical differences in 35+ vehicle components considered in ASCM. Cost estimates can then be made for any vehicle configuration and time period by making appropriate changes to reflect likely technology and cost improvements in various vehicle components.

Results

ASCM Integrated Design Framework

The basic design of the ASCM integrated design framework, as shown in Figure 1, is based on three primary elements: (a) a Matlab file containing mass and cost calculation procedures besides PSAT vehicle and vehicle cost input files necessary for cost calculations; (b) the XML database consisting of mass and cost relationships of various technology options for vehicle components, and (c) a graphical user interface framework using the calculation procedures and the XML database interacts with the user for the vehicle life cycle cost estimation. The framework consists of a collection of separate screens for six different vehicle subsystems, and the remaining two screens for overhead/operation and results. Each user-interface screen contains types of inputs necessary for mass and cost calculations for all vehicle components within a specific vehicle subsystem including available vehicle component technology options. Estimated mass and cost values both at the levels of components and vehicle subsystems are also displayed instantaneously on these screens as changes are made to the input parameters.

As mentioned before, vehicle component-level descriptions are provided under six major vehicle subsystems in which all 35+ vehicle components are grouped – the level of ASCM cost estimation capability it has been originally designed for. These six vehicle subsystems are: powertrain, body, chassis, interior, electrical, and assembly each of which are represented under six different screens. Overhead/operation is the additional screen besides the "Results" screen containing all the cost elements beyond the vehicle manufacturing cost necessary for the vehicle life cycle cost estimation. All screens are designed in a similar fashion to facilitate consistent user-friendly presentation. Each screen is generally divided into three broad areas where given estimates and parameter values can be overridden by the user. The three broad screen areas in the top to bottom order are: listing of components within a vehicle subsystem and available vehicle component technology options to select from which are directly read from the XML database; mass and cost equations and their estimates and description for each vehicle component which all are read from the cost input file; and finally the list of input parameters whose values affect the mass and cost of vehicle components also read from the cost input file. Finally, at the bottom screen outline area vehicle weight vs. PSAT

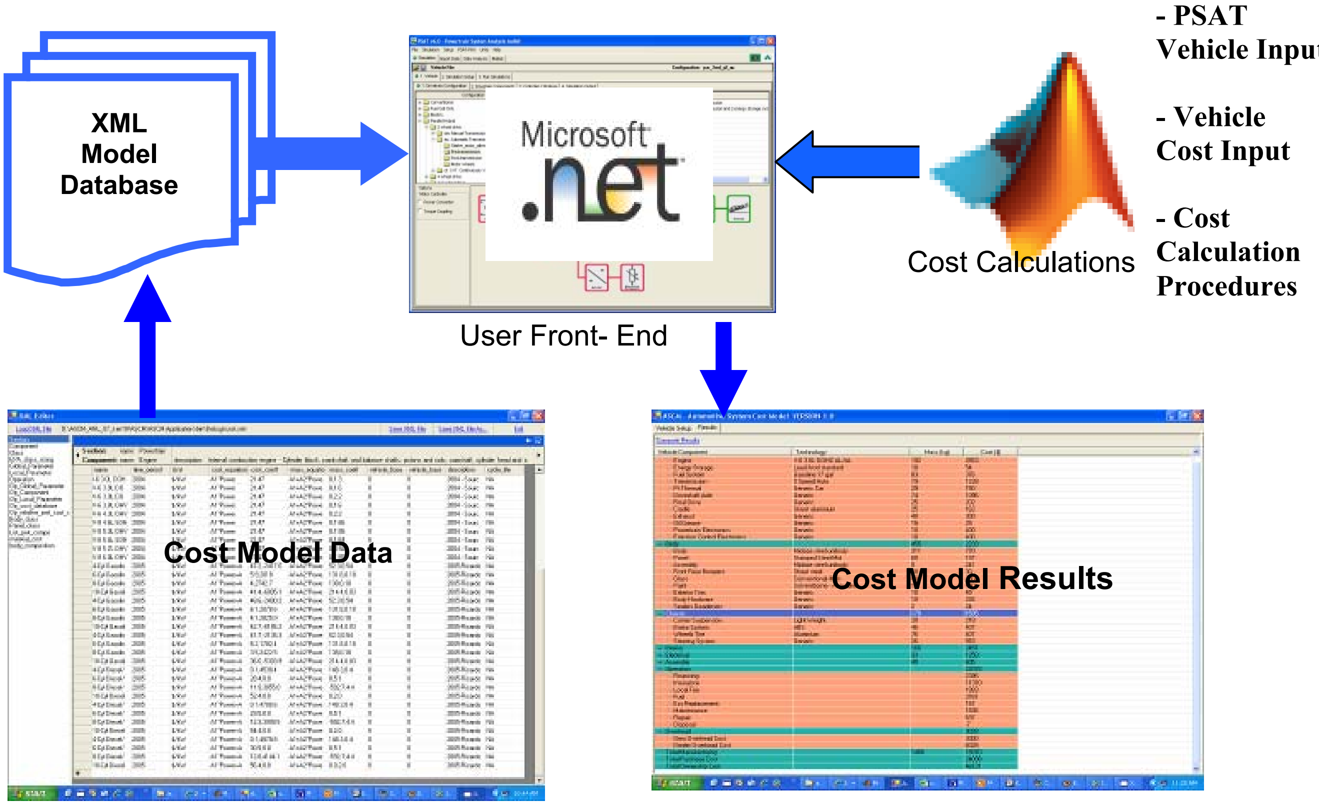


Figure 1. ASCM design framework layout

vehicle weight, and total estimated mass and cost of the given vehicle subsystem are displayed.

Several user-friendly features exist in this framework which facilitates in developing advanced technology vehicle life cycle cost scenarios. Some of these features are as follows:

- Drag and drop method for component technology selection
- Allows to override either or both component mass and cost estimates with known values
- "Secondary Savings" option allows to reflect change in component cost due to change from original baseline component mass
- "Use EPA Ref" option allows consideration of changes in chassis component masses when total vehicle weight and power changes – mass compounding effect
- "Use PSAT" options allows to maintain powertrain component sizing information for cost estimation
- Mass and cost scaling factors can be used for some vehicle components to reflect other vehicle models within the same vehicle class
- Vehicle mass used in PSAT simulation shown on every vehicle subsystem screen for its calibration

The Overhead/Operation screen considers the cost input parameters to estimate vehicle life cycle cost beyond the direct vehicle manufacturing cost. Overhead cost includes OEM overhead and dealer cost, whereas operation cost includes financing, insurance, local fees, fuel, battery replacement, maintenance, repair, and disposal. The "Results" screen provides in detail both mass and cost estimates for 35+ vehicle components, including the component technology option selected. The framework also allows to export the results in a spreadsheet format for future customized use. Cost input data files exist for 13 EPA vehicle classes, which can be used as the starting point for any class of advanced technology vehicle cost estimation. New cost input data created can also be saved for future use. New component technology cost information as becomes available can easily be input by using the user-friendly XML database framework.

Plug-In Hybrids Life Cycle Cost Analysis

Long-term life cycle cost projections of mass produced plug-in hybrids (PHEVs) were made using the integrated PSAT/ASCM modeling framework. Spark ignition plug-in hybrids with 10 and 40 miles all-electric range were considered for four forecast periods, i.e., 2010, 2015, 2030, and 2045. In addition, for each forecast year, three scenarios were considered to capture the uncertainty in meeting desired vehicle performance and cost targets. Battery cost of PHEVs is an important parameter and was projected based on the assumption that USABC target of $150/kWh will not be achieved until 2030. Specific battery cost of PHEVs is assumed to be higher than for pure electric vehicles as in the former case production rate (in terms of MWh) for the same number of vehicles would be lower, thereby lower economies of scale and increasing the contribution of inactive cell materials and manufacturing to total cell costs. PSAT powertrain component sizing information is used and fuel cost is based on Energy Information Agency projections, projected to be about $4/gal for gasoline by 2045. In addition, lower maintenance and repair costs were assumed for PHEVs due to low maintenance of electrical components. It is projected that vehicle mass will be lighter in future and lightweight materials such as carbon fiber polymer composites will be necessary to achieve vehicle mass goal.

Figure 2 shows the estimated life cycle cost of PHEVs compared to 2010 conventional baseline vehicle. Life cycle vehicle cost is estimated to be between 10-15% higher in the near-term, and only in 2030 and beyond they become cost-effective with conventional vehicles. On the other hand, purchase cost of PHEVs is estimated to be significantly higher, about 30% higher than the conventional vehicle in the near-term. PHEVs become cost-effective on the basis of purchase cost only under the most optimistic scenario in 2045.

These findings are consistent with the earlier estimates in the literature that it would be difficult to achieve the competitiveness of PHEVs on the basis of purchase cost alone even when the battery cost decreases from current $1500/kWh to around $350/kWh. Estimated PHEV life cycle cost savings lie within the reported values in the literature; however, reported increment purchase cost estimates vary over a wide range of $3,000-$11,500/vehicle. We estimate a significantly lower incremental purchase cost of around $1,000 under the most optimistic scenario in 2030.

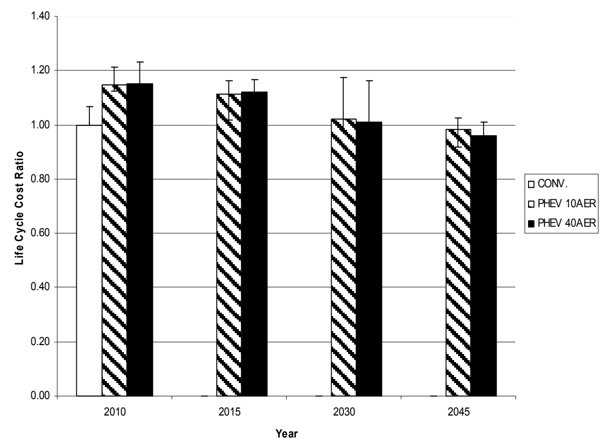


Figure 2. Life Cycle Cost of PHEVs

Future Directions

With the completion of cost model integration into the performance model PSAT including model documentation, the model should be distributed to a wide range of users and validation activity be initiated. Model database should be updated, as well as data on advanced technologies should be collected for various vehicle powertrain subsystems which have been considered in the PSAT as they become available. In addition, cost estimates of advanced technology vehicles (as per requests by several DOE Program offices) will be made by coordinating with other national laboratories and industries for the consistent use of cost data assumptions, validation, and approach.

M. Development of Models for Advanced Engines and Emission Control Components

Stuart Daw (Principal Investigator)
Oak Ridge National Laboratory
National Transportation Research Center
2360 Cherahala Boulevard, Room L-04
Knoxville, TN 37932-6472
(865) 946-1341, e-mail: dawcs@ornl.gov

DOE Program Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Ensure that computer simulations using the Powertrain System Analysis Toolkit (PSAT) have the necessary components to accurately reflect the performance, cost, fuel savings, and environmental benefits of advanced combustion engines and aftertreatment components as functions of combustion mode, system configuration, and emerging fuel type.

Approach

- Develop and validate low-order, physically consistent computational models for emissions control devices including oxidation catalysts (OCs), lean NOx traps (LNTs), diesel particulate filters (DPFs), and selective catalytic reduction reactors (SCRs) that accurately simulate performance under realistic steady-state and transient vehicle operation.
- Develop 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, aftertreatment, and exhaust heat recovery components in order to accurately account for their integrated system performance in both conventional and hybrid electric vehicle (HEV) powertrains.
- Translate the above models and strategies into a form compatible with direct utilization in the PSAT framework.
- Leverage the above activities as much as possible through inclusion of experimental engine and aftertreatment data and models generated by other Department of Energy (DOE) activities.

Accomplishments

- An updated map for the Mercedes 1.7-liter light-duty diesel engine has been generated, validated against experimental data, and installed in PSAT.
- The previously developed LNT model has been included in PSAT and validated against experimental data.
- Simulations of HEV performance with LNT NOx control have been demonstrated with PSAT.
- Engine maps have been generated for gasoline and ethanol fueling of the 2.0-liter port-injected, turbo-charged flex-fuel engine used in the Saab 9-5 BioPower sedan.
- The previously developed 0-D DPF model is now coded in Simulink format and ready for inclusion in PSAT.
- Two heat exchanger models have been developed and implemented in Matlab and Simulink format to evaluate the potential for exhaust energy recovery with thermoelectric regeneration.

Future Directions

- Continue development and demonstration of HEV and Plug-In HEV (PHEV) PSAT simulation capabilities in combination with NOx and particulate matter (PM) emissions controls.
- Expand multi-mode diesel engine map database to include the 1.9-L GM standard platform.
- Expand Mercedes and GM engine maps to include alternative fuels such as ethanol and biodiesel.
- Improve LNT model to account for sulfur poisoning and desulfation.
- Improve OC model to account for PM effects and NO oxidation as they impact downstream DPF performance.
- Complete integration and testing of DPF model in PSAT under federal test procedure cycling conditions.
- Construct and test Simulink urea-SCR model using current kinetics model and experimental data from the literature and the Crosscut Lean Exhaust Emissions Reduction Simulation (CLEERS) activity.

Introduction

Accurate systems simulations 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) maintained by Argonne National Laboratory (ANL). A distinctive feature of PSAT is its 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 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 NOx controls, the availability of appropriate component models or the data to construct them is very limited.

Oak Ridge National Laboratory (ORNL) is a collaborator with ANL on the vehicle systems analysis technical team (VSATT) and is specifically tasked with providing data and models that augment PSAT's capabilities. Specifically, ORNL's role has focused on the experimental measurement of performance data from advanced diesel engines and emissions controls components and the incorporation of that data in the form of maps or low-order transient models into PSAT. In FY2007, the ORNL team concentrated their efforts in the following areas:

- Refinement and validation of a performance map for the 1.7-liter light-duty Mercedes engine;
- Implementation and validation of a previously developed LNT NOx control model;
- Simulation of an HEV with LNT NOx control;
- Development of a map for a 2.0-liter ethanol-capable spark-ignition engine;
- Continued development of a DPF PM control model; and
- Development of the capability to simulate thermoelectric exhaust energy recuperation.

Approach

Today's advanced combustion 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 aftertreatment 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. The demands on the engine operation are further heightened by the need to periodically denitrate and desulfate LNTs and oxidize the carbonaceous particulate matter in DPFs. 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 basing the aftertreatment component models developed for PSAT on conventional approaches used for simulating transient chemical 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 PSAT users. 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 for PSAT to determine both instantaneous and cumulative 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 aftertreatment 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 needs to operate (e.g., make transient shifts in combustion regime) in order to accommodate the needs of aftertreatment devices downstream. Typically, this also involves development of sensor models that indicate the state of the aftertreatment 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 WAVE, 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

Engine Mapping

Using the updated Mercedes 1.7-liter engine map described in the previous annual report [1], we have been able to validate the exhaust composition and temperature variations predicted by the map against experimental chassis dynamometer measurements made at ORNL. Example results are illustrated in Fig. 1. As far as we are aware, this is the first experimental validation of engine map predictions of exhaust composition and temperature coming from PSAT.

During the validation process, it was determined that the engine speed and load controller output in the current version of PSAT contains a large high-frequency noise component that propagates through the engine into the exhaust and downstream aftertreatment devices. Evaluations of the simulation results in the presence of this noise indicated that it produces unacceptable errors in the simulated performance parameters. Further studies have demonstrated that this noise can be adequately removed by applying moving average or low-pass filters to either the main controller output or the output of the engine map. After discussions between the ORNL and ANL teams, the ANL coordinators have decided to apply the filter directly to the main controller output in future versions of PSAT.

A new PSAT engine map has been generated from chassis dynamometer measurements made with a Saab 9-5 Bio-Power sedan at ORNL. The Saab 9-5 engine is a 2.0-liter, port-fuel-injected, spark-ignition engine configured for flex-fuel operation with either gasoline or ethanol (but optimized for ethanol). Following the standard procedure used for other PSAT engine maps, the experimental measurements of fuel consumption and exhaust composition over the full speed and load ranges of the engine were converted into interpolated surfaces in Matlab. Figure 2 illustrates the CO emissions surface for E85 fuel (85% ethanol, 15% gasoline). Draft E85 and gasoline maps for this engine have been transmitted to ANL for testing in PSAT, but additional checks of the measurements are still underway. One particular concern is a larger than expected difference in apparent engine efficiency between ethanol and gasoline.

Aftertreatment Modeling

The lean NOx trap (LNT) NOx control model described in last year's report has now been fully integrated into PSAT. Comparisons of the PSAT predictions against experimental chassis dynamometer measurements indicate good agreement, as shown in Fig. 2. This agreement is especially encouraging because the experimental LNT regeneration was actually accomplished with post-engine syngas injection rather than by modulating the engine fueling. In spite of these differences in reductant injection details, the relatively good agreement between predictions and experiment suggest that the PSAT LNT model is suitable for simulating either injection strategy. As with the Mercedes map validation, this is apparently the first direct confirmation of PSAT predictions with experimental measurements.

The simplified diesel particulate filter (DPF) model that was upgraded and tested last year in Matlab has been translated to Simulink and verified to function as intended (see the example output in Fig. 3). Unfortunately, the current unavailability of DPF performance measurements for engines operating under realistic drive cycle conditions makes direct experimental validation of the model at device scales impossible at the present time. The most likely option for near-term validation will be to compare model predictions with experimental measurements of bench-scale DPF cores. Such studies are now planned for biofuels projects at ORNL. As it stands, the DPF Simulink model is now ready for inclusion and verification in PSAT, which is planned for early 2008.

Due to shifting priorities, the planned work on completing the urea-SCR device model and improving the existing oxidation catalyst model to include PM occlusion/oxidation and NO to NO_2 oxidation were again postponed. These features are still recognized as playing very important roles in the efficiency performance of lean exhaust emissions controls, so they have been explicitly included in the list of proposed tasks for FY08.

Hybrid Electric Vehicle Simulation

PSAT simulations of hybrid electric vehicle (HEV) operation were also demonstrated this year with LNT NOx control. As shown in the example in Fig. 4, the inclusion of an LNT has significant impact on both NOx emissions and fuel consumption. This is true for both series and parallel HEV system configurations. These studies also made it clear that the presence of an LNT further complicates the issue of making consistent fuel economy estimates for HEV systems. Such analyses are already difficult because of changes in the battery state-of-charge (SOC) for operation over a small number of cycles. To accurately determine fuel requirements, it is important to account for the fuel savings or losses associated with bringing the battery SOC back to its initial value. This accumulation effect is also true for LNTs, because changes between the initial and final stored NOx inventory represent similar fuel savings or losses that should be accounted for.

- **Modeling Exhaust Energy Recuperation**

  Because of the widespread interest in maximizing fuel efficiency through exhaust energy recuperation, we developed and tested (based on consultation with the DOE project manager) a simple thermo-electric generator model for potential inclusion in PSAT. The basic approach adopted was to adapt an existing ORNL heat exchanger model to include a commercially available Bi-Te thermo-element separating hot exhaust from one of two possible heat sinks; ambient air (counter-flow) or glycol engine coolant (cross-flow). PSAT simulations of the power output from these two different versions of the thermoelectric recuperator were then made assuming a 1.7-L Mercedes engine installed in a Honda Civic vehicle operating at steady-state at maximum power and also in the transient US06 cycle. Of the two different designs, the glycol-cooled cross-flow exchanger appeared to give better results. Key observations concerning the latter were that the thermoelectric power output was only 355 watt at maximum engine power and the accumulated thermoelectric power out over the US06 cycle was less than 20% of what would be available from the alternator (see Figure 6).

Conclusions

- The emissions predictions of the Mercedes 1.7-L diesel engine map in PSAT agree well with experimental chassis dynamometer measurements for conventional combustion in urban and highway driving cycles.
- A preliminary engine map for the 2.0-liter port-injected, turbo-charged flex-fuel engine used in the Saab 9-5 BioPower sedan indicates significant differences in emissions and fuel efficiency for gasoline and E85.
- The simulated NOx emissions control and fuel penalty for the PSAT LNT model coupled to the Mercedes 1.7-L diesel engine agree well with experimental chassis dynamometer measurements for conventional combustion with an LNT in urban and highway driving cycles.
- The simplified DPF model implemented in Simulink format is functioning as intended.
- Hybrid electric vehicle operation with LNT NOx control has been successfully simulated using PSAT with the new LNT module.
- Studies with a thermoelectric generator model implemented in PSAT reveal that optimization of such generators is a complex issue. However, it appears that the maximum power output available from such a generator installed on the Mercedes 1.7-L engine would be less than 20% of the alternator output for a typical urban driving cycle.

FY 2007 Publications/Presentations

1. "Integration of a Lean NOx Trap Model and an Engine map into PSAT," A. Rousseau and K. Chakravarthy, 10th CLEERS Workshop, May 1-3, 2007, http://www.cleers.org.

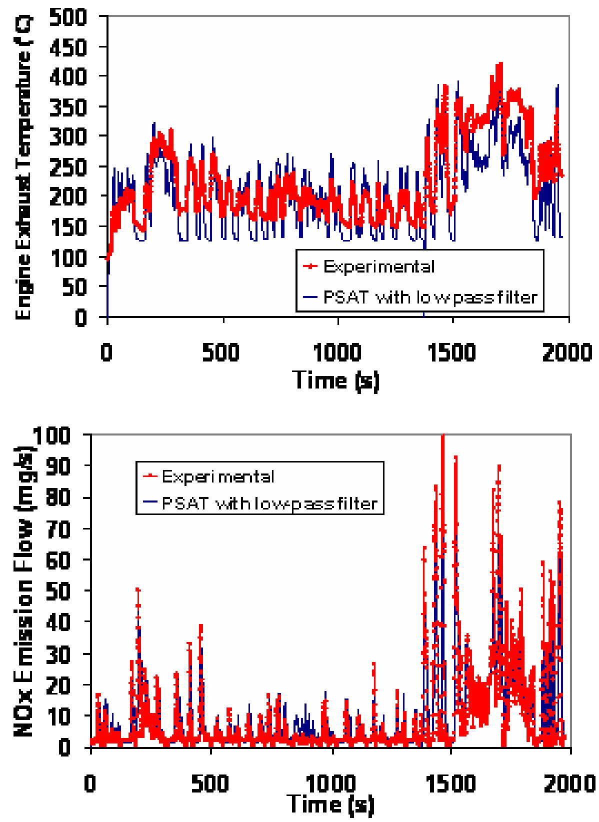


Figure 1. Experimental validation of PSAT predictions for engine exhaust temperature and composition. The engine is a Mercedes 1.7-L diesel operating in a Honda Civic vehicle configuration. The driving profile is based on the LA4 and US06 cycles. A low-pass filter has been applied to the engine speed and torque signals in PSAT to remove spurious controller noise. The predicted overall engine out NOx is 1.223 g/mile compared to the experimentally measured value of 1.148 g/mile.

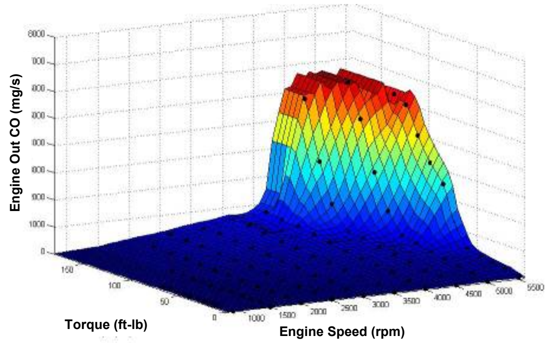


Figure 2. Example CO engine emissions map for E85 fueling of the 2.0-liter, port-fuel-injected spark-ignition engine installed in the Saab 9-5 Bio-Power flex-fuel sedan. This and similar maps were constructed for PSAT from quasi-steady chassis dynamometer measurements made at ORNL.

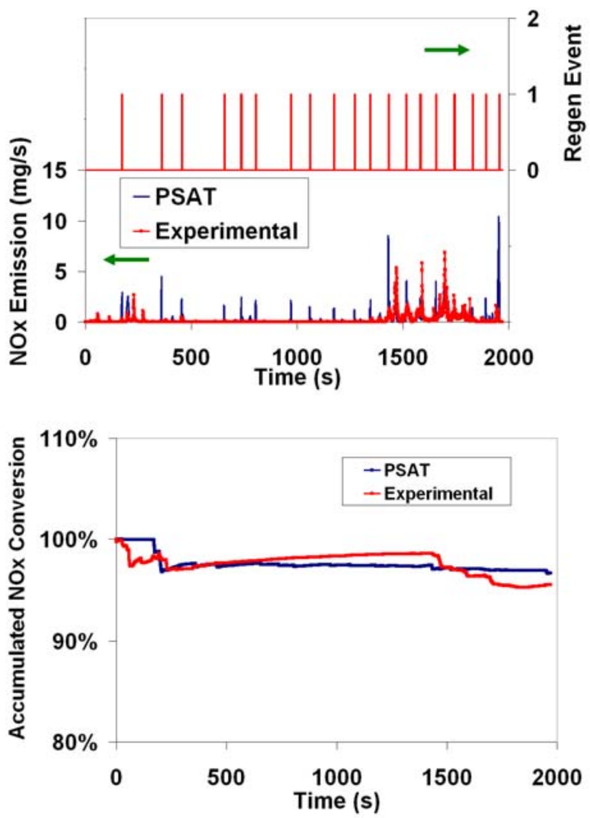


Figure 3. Experimental validation of PSAT LNT model predictions. The engine is a Mercedes 1.7-L diesel operating in a Honda Civic vehicle configuration driven over the LA4 and US06 cycles. A low-pass filter has again been applied to the engine speed and torque signals in PSAT to remove spurious controller noise. The predicted tailpipe NOx emissions are 0.032 g/mile compared to the experimentally measured 0.024 g/mile.

The predicted and observed fuel penalties for NOx control are 2.4% and 2.7%, respectively.

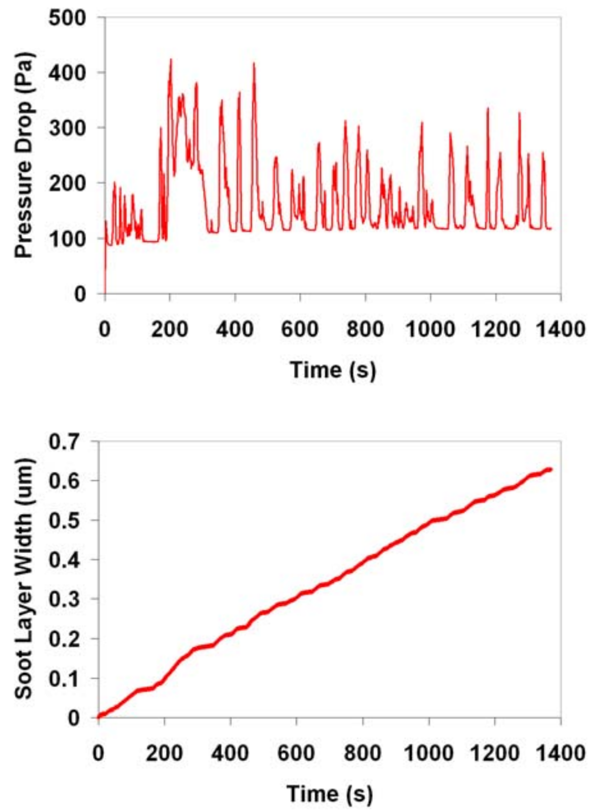


Figure 4. Example output from the ORNL DPF model now coded in Simulink. The plotted device pressure drop and filter cake thickness are for a DPF operating in the exhaust of a Mercedes 1.7-L diesel installed in a Civic vehicle driven through the Urban Dynamometer Driving Schedule (UDDS). No DPF regenerations are included in this simulation.

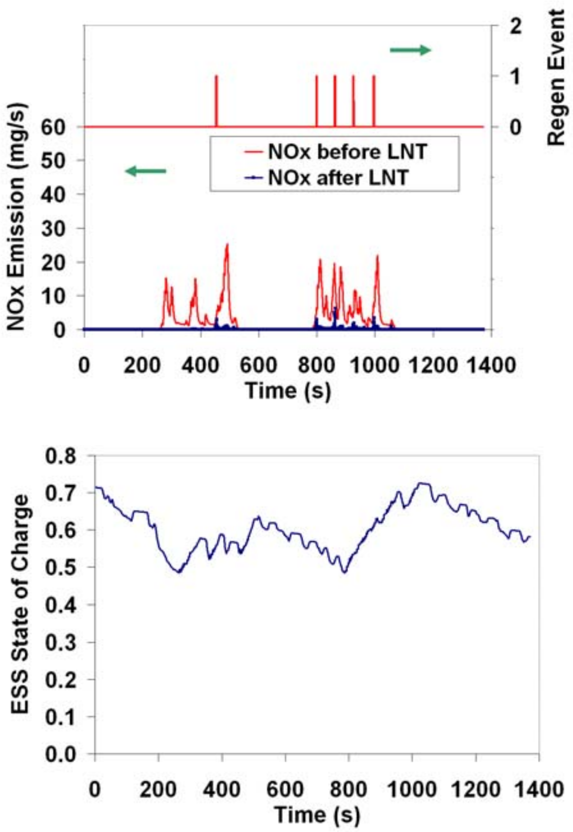


Figure 5. Example verification of PSAT capability to combine both a multi-mode diesel engine and LNT NOx control in hybrid vehicle simulations. The engine is a Mercedes 1.7-L diesel installed in a Honda Civic vehicle with a series hybrid configuration (engine, generator, and Toyota Prius battery connected in series to the drive train). The simulation condition is for a UDDS cycle. The predicted tailpipe NOx emissions are 0.011 g/mile, corresponding to a 97.5% reduction from engine out with a resulting fuel penalty of 3.1%.

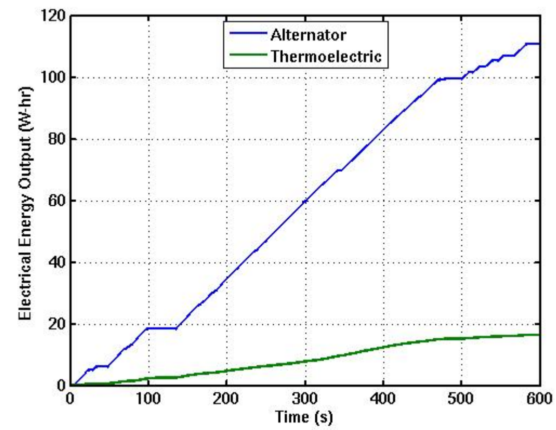


Figure 6. Example simulation results for thermo-electric recuperation of exhaust energy in PSAT. The engine is a Mercedes 1.7-L diesel installed in a Honda Civic vehicle with a cross-flow, glycol-cooled Bi-Te thermo-electric recuperator. The simulation condition is a US06 cycle. The overall estimated power generation from the recuperator amounts to less than 20% of the alternator output.

N. Plug-In Hybrid Vehicle Systems Analysis

Tony Markel (Principal Investigator), Jeffery Gonder, Aaron Brooker, Kevin Bennion, Matthew Thornton
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393
(303) 275-4478, e-mail: tony_markel@nrel.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Objectively assess PHEV technology, support the larger DOE PHEV assessment effort, and complement activities at other national laboratories.

Approach

- Collect and assemble information and conduct analysis to enhance our understanding of the benefits and barriers of plug-in hybrid electric vehicle technology.

Accomplishments

- Initiated analysis of the integration benefits of PHEV and renewable fuel technology.
- Expanded spectrum of real-world duty cycle database for use in simulations with data from Los Angeles, Kansas City, and several Texas cities.
- Used simulation results to highlight PHEV operational impacts on Power Electronics, Energy Storage, and Emissions Control systems.
- Expanded PHEV economic analysis including attribute-based market study suggest per vehicle economics will be challenging.
- Recommendations for test procedure revisions for PHEVs published in World Electric Vehicle Association Journal.

Future Directions

- Collaborate with others to expand to refine PHEV fuel economy and emissions test procedures and reporting methods.
- Use database of real-world driving profiles to improve understanding of travel behavior.
- Explore the vehicle emissions impacts of PHEV technology using real-world driving profiles.
- Refine PHEV economic analysis and develop alternative scenarios that lead to market adoption.

Introduction

NREL's plug-in hybrid electric vehicle (PHEV) analysis activities made great strides in FY07 to objectively assess PHEV technology, support the larger DOE PHEV assessment effort and complement activities at other national laboratories, while sharing technical knowledge with the vehicle research community and vehicle manufacturers through the FreedomCAR Vehicle Systems Technical Team and the Electrochemical Energy Storage Technical Team.

The NREL research team has participated in many key industry meetings and NREL research has been documented in several presentations and technical papers. This report highlights important insights that emerged from NREL's PHEV systems analysis efforts.

Real-World Duty Cycle Database

PHEVs differ significantly from existing vehicles in that they consume two fuels (petroleum and electricity) at rates depending on the distance driven and the aggressiveness of the cycle. NREL contributes to the DOE mission by developing a database of real-world personal vehicle duty cycles that form the key input for vehicle systems simulation efforts. In FY06, a database of full day driving profiles for 227 vehicles from the St. Louis metropolitan area was created. Simulation results in FY07 using this data showed the potential fuel consumption benefits of HEV and PHEV technology in real-world applications.

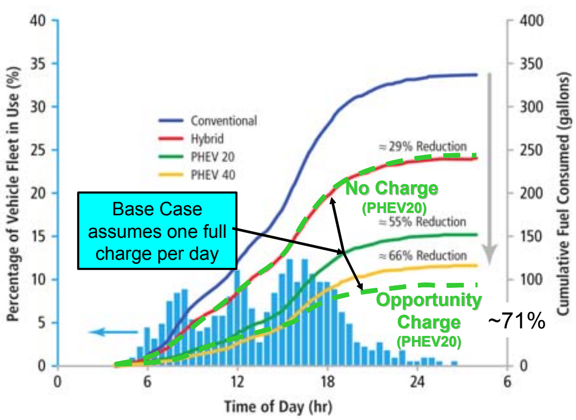


Figure 1. Simulation of PHEVs on Real-World duty cycles from St. Louis, MO

In Figure 1, the solid lines represent the cumulative consumption of all 227 vehicles as 4 architectures. The PHEV cases assume a single recharge per day and ability to operate entirely on electricity for the EPA urban cycle. The PHEV scenarios displace 55-66% of the conventional vehicle fleet consumption.

The dashed lines then show an opportunity charge scenario (outlets are available everywhere for recharging) and a no charge scenario (consumer never plugs in). The opportunity recharge scenario more fully utilizes the potential displacement benefits of on-board grid electricity to displace petroleum, using substantially less fuel than a PHEV40 recharged once per day.

Component Impacts of PHEV Operation

The Vehicle Technologies Program is focused on addressing component technology barriers and supporting industry in advanced component development. NREL is using systems analysis to highlight potential component impacts of PHEV operation. In FY07, effort focused on three specific areas, the energy storage system, the power electronics, and the emissions control system.

PHEV impacts on energy storage system

The energy storage system is a key component in the PHEV. Its stored energy will provide the petroleum displacement potential. From Figure 1, the petroleum displacement potentially is dependent on both the PHEV design and usage profile.

Given the desire to operate on electricity as much as possible, it is likely that the PHEV battery must provide both short duration peak power and long duration moderate power output. The FreedomCAR energy storage team has incorporated this knowledge into the PHEV battery requirements set during FY07.

Life of the PHEV battery will likely be a challenge due to the desire to recharge at least on a daily basis to obtain significant benefits. Time and cycling at a specific State of Charge (SOC) level can influence the life of the battery.

Figure 2 shows the percent of total time spent at a specific SOC level from simulations for the entire group of 227 vehicles from St. Louis. Four vehicle/recharge combinations are shown. Both the PHEV20-no charge with a lot of time at low SOC and the PHEV20-opportunity charge with a lot of time at high SOC could each be detrimental on the battery pack life in different ways.

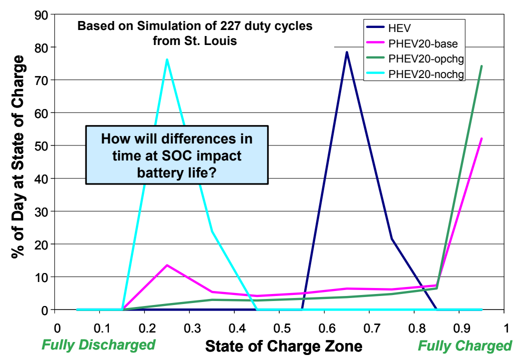


Figure 2. PHEV Recharge Scenario Impacts Time at SOC

PHEV impacts on power electronics system

Thermal management of the power electronics system is a key challenge for advancing electric drive technology. Given that a PHEV intends to operate on the electric drive system as much as possible, we expect that that power electronics may face even greater thermal management challenges than we see with HEVs.

Analysis of the simulation results of PHEVs on real-world travel profiles suggest that there are significant differences in usage of the electric drive motor and power electronics systems as compared to an HEV. The HEV drive system is typically used for short duration high to moderate power events to allow engine operation to shift to more efficient load points. In contrast, the PHEV motor is used for more long duration moderate power events. The operation is similar to that of an electric vehicle except that it does not need to meet the short duration, very high power demands of a full performance electric vehicle.

Simulation results also suggest that the operating voltage range of the PHEV components will need to be larger than that of an HEV. This would suggest a need to develop more efficient DC/DC converter technology. Data from test vehicles suggests that the voltage window for the electronic components is smaller than an HEV. The PHEV power electronics usage pattern requires additional analysis and testing.

PHEV impacts on emissions control system

Both simulation and test results continue to suggest petroleum consumption benefits from PHEV technology. However, testing of the emissions performance of the current conversion vehicles suggests that the vehicle emissions may increase from that of the HEV. Although the PHEV emissions are still well below the national standards, it is important to work towards achieving fuel displacement and acceptable emissions in parallel.

The simulations completed this year assumed that the PHEV would have all electric range on the EPA urban drive cycle. No available PHEV vehicle yet has this capability. All must use the engine above ~25-35mph.

Given the aggressiveness of real-world driving, even the simulated vehicles designed with urban all electric capability had to use the engine in 82% of the 227 driving profiles.

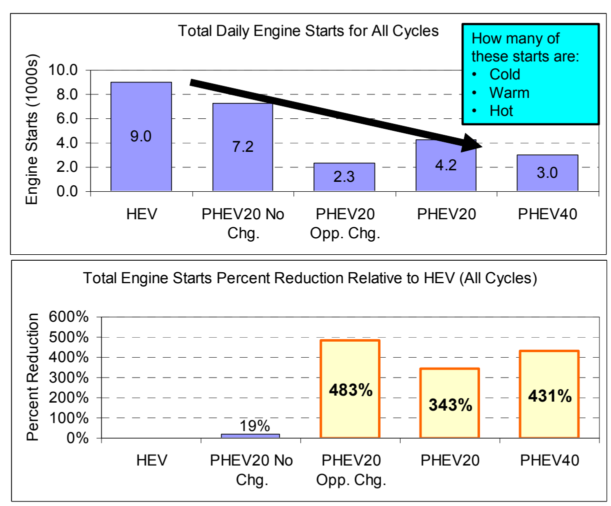


Figure 3. Simulations Suggest PHEV Technology will Reduce Total Number of Engine Starts

In Figure 3, it is clear that the total number of engine starts for the entire group of 227 vehicles simulate decreased substantially from the HEV to the PHEV cases. This is a significant result because every engine start, whether hot or cold, seems to produce substantial emissions. Reducing the total number of engine starts maybe a significant benefit of PHEVs designed with urban all electric range capability.

It is still unclear what the actual emissions benefits of PHEV technology maybe although research efforts in the coming year will attempt to more fully define the technology necessary to achieve both petroleum displacement and emissions benefits.

PHEV Biofuels/Integration Analysis

PHEV technology provides petroleum displacement using electricity instead. What if the little gasoline that a PHEV used was an ethanol blend?

Well to wheels analysis of using ethanol in a PHEV suggests a potential petroleum consumption reduction of 80-90%. With today's national average electricity grid as the electricity source, the ethanol-fueled HEV is likely the lowest CO_2 producer; however, with a future grid with more renewable electricity, the PHEV easily surpasses that CO_2 reduction of the HEV scenario. Use of biofuels in a PHEV will likely have a spectrum of environmental values that will be dependent on the specific regional conditions.

Conclusions

NREL's assessment of PHEV technology continues to add value to the DOE Vehicle Technologies Program. The efforts support the President's Advanced Energy Initiative in the goal of developing a plug-in hybrid vehicle with 40 miles of electric range as a means of changing the way we fuel our vehicles. The PHEV research completed in FY07 explored the potential benefits of PHEV design scenarios on real-world travel profiles. The results not only summarize the consumption benefits, but also identify how components will be used differently in a PHEV. The component operating insights feed the DOE effort to develop components for PHEVs.

In FY08, NREL's vehicle systems analysis will expand the scope of PHEV analysis to also include medium duty vehicle applications. Other key items will include contributing to the development of test procedures for PHEVs and further analysis of PHEV economics that incorporates the value attributes of a PHEV beyond its petroleum consumption benefit.

Publications

1. J. Gonder and A. Simpson. "Measuring and Reporting Fuel Economy of Plug-In Hybrid Vehicles." 22nd Electric Vehicle Symposium. October, 2006. NREL CP-540-40377 and JA-540-41341.
2. J. Gonder and T. Markel. "Energy Management Strategies for Plug-In Hybrid Electric Vehicles." SAE 2007-01-0290. NREL CP-540-40970.
3. Parks, K.; Denholm, P.; Markel, T. "Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory." NREL TP-640-41410. 2007.
4. Markel, T. (2007). "Platform Engineering Applied to Plug-In Hybrid Electric Vehicles." SAE 2007-01-0292. NREL Report No. CP-540-41034.
5. A. Simpson. "Cost-Benefit Analysis of Plug-In Hybrid Electric Vehicle Technology." 22nd Electric Vehicle Symposium. October, 2006. NREL CP-540-40485 and JA-540-40969.
6. J. Gonder, T. Markel, A. Simpson, M. Thornton "Using GPS Travel Data to Assess the Real World Driving Energy Use of Plug-In Hybrid Electric Vehicles (PHEVs)." *TRB 86th Annual Meeting*. January 2007. NREL CP-540-40858.
7. T. Markel and A. Peseran. "PHEV Energy Storage and Drive Cycle Impacts." *Advanced Automotive Battery Conference*. May, 2007. NREL PR-540-42026.
8. M. P. O'Keefe and T. Markel. "Dynamic Programming Applied to Investigate Energy Management Strategies for a Plug-In HEV." 22nd Electric Vehicle Symposium. October, 2006. NREL CP-540-40376.
9. T. Markel, K. Bennion, A. Brooker, Paul Denholm, J. Gonder, and M. Thornton. "NREL PHEV Analysis Activities Summary." FY07 Milestone Report. September, 2007.
10. Markel, T., Pesaran, A., Kelly, K., Thornton, M., Nortman, P. "Research Experience with a Plug-in Hybrid Electric Vehicle – EnergyCS Conversion of a Toyota Prius." To be presented at EVS-23. October 2007. NREL CP-540-42365.

O. Evaluating Route-Based Control of Hybrid Electric Vehicles (HEVs)

Jeffery Gonder (Principal Investigator)
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393
(303) 275-4462, e-mail: jeff_gonder@nrel.gov

DOE Vehicle Systems Analysis Activity Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Evaluate use of upcoming driving route predictions to increase the fuel efficiency of hybrid electric vehicles (HEVs).

Approach

- Build on the work from FY06 identifying the source of potential route-based control efficiency improvements and categorizing the range of related work conducted by others.
- Select the hybrid platform for simulation, and rigorously optimize the control parameters to provide a good general baseline tuning.
- Using the methodology identified last year, implement and refine the example route-based control approach on the simulation platform; quantify the fuel savings.

Accomplishments

- Implemented route-based control approach in a modeling environment by building off an existing HEV control architecture.
- Demonstrated fuel savings (relative to results from a rigorously optimized baseline strategy) on the order of 2-4% over various cycles.

Potential Future Directions

- Collaborate on hardware demonstration of route-based control fuel savings in a partner's HEV platform.
- Explore the logistics of translating GPS map routes into representative driving cycle predictions, and further investigate the results' sensitivity to cycle variations.
- Use approach to enhance fuel savings on a plug-in hybrid electric vehicle (PHEV) platform, and/or to achieve other benefits such as extending battery life or reducing vehicle emissions.

Introduction

Hybrid electric vehicles (HEVs) hold promise to help reduce vehicle fuel use, and thus the nation's large level of oil imports. However, general HEV control settings do not necessarily provide optimal performance over all drive cycles. This is because in addition to the primary optimization goals (minimizing fuel use and emissions while maintaining good driveability), the hybrid controller must also respect battery state-of-charge (SOC) limits. Operating conditions that drive a vehicle to reach a 'hard' SOC limit can result in sub-optimal performance (e.g., preventing the vehicle from either capturing regenerative braking energy or providing electric assist). The resulting tendency to maintain SOC near the middle of the acceptable operating window can also lead to sub-optimal performance by distracting from the primary control goals. A controller using information about the upcoming route could potentially minimize these SOC control related opportunity losses while still respecting the defined battery operating limits. This advancement could be accomplished solely through software modifications, delivering improved efficiency at relatively little incremental cost.

Approach

Research conducted in FY06 identified a "look-ahead" route-based control approach (using GPS route predictions) as the area providing the best tradeoff between improved fuel efficiency and reduced sensitivity to a particular driving cycle. The work also highlighted the importance of establishing a sound baseline strategy against which to compare and make valid claims about the route-based strategy's fuel savings. Vehicle simulations for this analysis used a forward-facing modeling tool with an existing rule-based control construct. A midsize car platform, pre-transmission parallel hybrid configuration was investigated. The proposed route-based control implementation relied on computationally-intensive off-line simulations to determine the best control options for different driving types. A route predictor would then divide the anticipated future driving cycle into segments based on driving type, and schedule the control sequence for each segment to minimize fuel use over the cycle.

Results

Formal baseline control selection was accomplished through optimization on the New European Drive Cycle (NEDC), which has been shown to provide a good general control tuning [1]. Optimization involved conducting a parametric study over repeated cycle simulations using different parameter settings. Two control settings were found to provide equivalent 'optimal' performance on the NEDC cycle and were subsequently tracked as possible baseline control options. Over many driving types, both options provided comparable performance close to that of the fuel-minimized control setting for that specific type of driving. However, the charge-sustaining (CS) performance comparison for some driving types indicated significant improvement from the (fuel minimized) route-based control option. For instance, Figure 1 shows as much as an 11% improvement for the route-based control relative to one of the potential baseline options. For this driving type, the other considered baseline setting performs significantly better, but still leaves 3% improvement possible from the optimized solution – a significant achievement for control adjustments alone. The figure also reemphasizes the importance of rigorous baseline tuning. As suggested by these further results, the lower fuel consuming of the two NEDC-tuned options in the figure was selected as the more robust baseline setting against which to compare additional route-based control results.

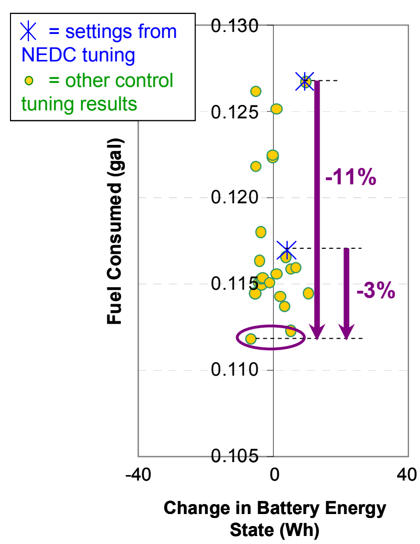


Figure 1. Example charge-sustaining parametric control tuning results over a low-speed, stop-and-go driving segment.

Applying route-based control optimization over cycles consisting of multiple driving types necessitated expanding beyond solely CS results comparisons. This is because a control combination providing charge-gaining operation over one driving segment type, followed by charge-depleting operation over a subsequent segment type, could potentially use less fuel than a pair of CS control options over the two segments. Figure 2 illustrates the process for optimizing control options with charge-varying results over a particular driving segment. While CS results, such as from Figure 1, suggest a single optimal (minimum fuel consumption) tuning, optimization based on charge-varying results indicates the series of options along the lower right of the scatter in Figure 2. These options provide the best combinations of low fuel and battery energy use for this driving condition. Considering these together with similar results for other driving types enables selection of the route-based control sequence providing a fuel-minimized and net CS result over a multi-segment cycle. Example application of this approach over a three-segment cycle indicated 2% fuel savings from route-based control optimization.

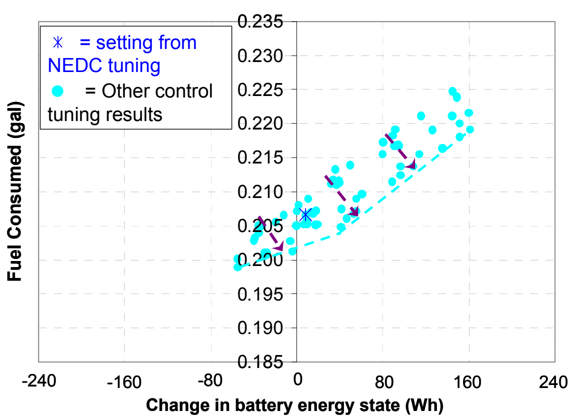


Figure 2. Example control optimization with charge-varying results over an aggressive, high-speed driving segment.

Conclusions

Route-based HEV control has the potential to reduce vehicle fuel consumption with low incremental cost by doing so solely through software innovations. However, avoiding overstating the savings potential of the approach requires rigor in establishing a sound baseline control strategy for comparison. For the route-based control approach discussed in this study, comparison with results from optimized baseline control indicates fuel savings on the order of 2-4%. The savings is limited by factors such as working with a fixed control rules format, but can nonetheless be considerable in aggregate when applied across the entire HEV fleet.

A logical next step for this work is to collaborate on hardware demonstration of route-based control fuel savings in a partner's HEV platform. Other possible areas include exploring the logistics of translating GPS map routes into representative driving cycle predictions, and further investigating the results' sensitivity to variations within the representative cycle. The approach may also be applied next to fuel savings on a plug-in hybrid electric vehicle (PHEV) platform, and/or to achieve other benefits such as extending battery life or reducing vehicle emissions.

References

1. K. Wipke, T. Markel and D. Nelson. "Optimizing Energy Management Strategy & Degree of Hybridization for a Hydrogen Fuel Cell SUV." *EVS-18*. October, 2001.

2. J. Gonder, J. Hsu, A. Simpson and T. Markel. "Adaptive HEV Control Strategy Report." *FY06 Milestone Report*. July, 2006.

3. J. Gonder. "Route-Based Hybrid Electric Vehicle (HEV) Control Strategy Report." *FY07 Milestone Report*. July, 2007.

4. J. Gonder. "Route-Based Control of Hybrid Electric Vehicles (HEVs)." To be published at *SAE Congress*. April, 2008.

P. Feasibility of Onboard Thermoelectric Generation for Improved Vehicle Fuel Economy

Kandler Smith (Principal Investigator), Matthew Thornton
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393
(303) 275-4423; e-mail: kandler_smith@nrel.gov

DOE Vehicle Systems Analysis Activity Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Quantify the amount of waste heat in the engine exhaust stream and evaluate the fuel savings potential of using thermoelectric (TE) devices to convert a portion of that waste heat to electricity.

Approach

- A vehicle road-load and engine model quantifies potential fuel savings under scenarios where some or all of the engine-driven accessories are replaced with electrically-driven ones powered by a TE system.
- An engine waste heat model quantifies the how much electricity can be generated for various vehicle speeds and driving cycles, given expected near-term and future TE system efficiencies.
- Four classes of vehicles (passenger car, SUV, Class 4 truck, Class 8 truck) are compared to determine the most attractive platform.

Accomplishments

- Model results show that, provided sufficient waste heat is available and the system is not too heavy, replacing the engine-driven alternator with a TE generation system could reduce fuel consumption by 1-3%. Replacing all engine-driven accessories with electrically-driven accessories could reduce fuel consumption by 3-15%.
- An engine waste heat model (quantifying the amount of waste heat available in the engine exhaust stream under different driving scenarios) shows the Class 8 truck to be the most attractive platform due to the high levels of engine power needed to propel the heavy, aerodynamically inefficient vehicle down the road. The Class 8 truck was also the most attractive due to its low sensitivity of mass on fuel economy and high number of miles-traveled per year, shortening the payback period to recover TE device costs.
- Capturing the most power for a given driving cycle requires a large and expensive TE system to recover peak acceleration/speed events and may require a battery to store the peak power. Low power TE systems, insensitive to vehicle speed and duty cycle, can be expected to generate relatively constant power near their power rating.
- With present TE system efficiencies of 5 to 10%, sufficient exhaust power is available to replace the Class 8 truck's alternator in suburban and interstate driving conditions. Low speed city driving and cold temperatures present challenges, however.

Future Directions

- Use transient simulations to quantify mass compounding effects on fuel economy and sensitivity to cold start conditions.
- Develop modeling tools to predict the impact of heat exchanger location/sizing, pumps and other thermoelectric ancillary devices on TE system efficiency.
- Establish technical targets for TE systems.

Introduction

In a typical engine, approximately two-thirds of the fuel combustion energy is wasted as heat. Thermoelectric (TE) generators offer the potential to increase vehicle fuel economy by converting a portion of that waste heat to electricity [1,2] and using the extra electrical power to reduce alternator loads and/or electrically drive accessories such as power steering [3]. The application is challenging, however, as present-day thermoelectric systems are costly, have low efficiency, and require large heat exchangers to carry heat to the thermoelectric module. Objectives of the present work are to quantify the amount of waste heat available for different driving profiles, quantify possible fuel savings and identify the most attractive vehicle platforms and applications for onboard TE generation systems.

Approach

Fuel savings are estimated for four classes of vehicles (passenger car, SUV, Class 4 truck, Class 8 truck) under scenarios where some or all of the engine-driven accessories are eliminated and the vehicle's engine is downsized commensurate with the lower average power requirement. To establish whether it is feasible to meet these increased electrical loads using a TE generation system, an engine waste heat model was created to quantify the amount of waste heat available in each vehicle's exhaust stream at various speeds and for various driving cycles. The analysis provides a determination of what TE system efficiency and power ratings are necessary to meet the power requirements of various electrically-driven accessories.

Results

Figure 1 compares fuel savings potential for various vehicle platforms under two scenarios:

1) The engine-driven alternator is eliminated.

2) All engine-driven accessories are replaced by electrically-driven accessories.

Both scenarios assume the TE system generates sufficient power to meet the increased electrical loads and that the TE system adds no weight to the vehicle. In this sense, the predictions present a best-case fuel savings. Scenarios 1 and 2 provide fuel savings on the order of 1-3% and 3-15%, respectively.

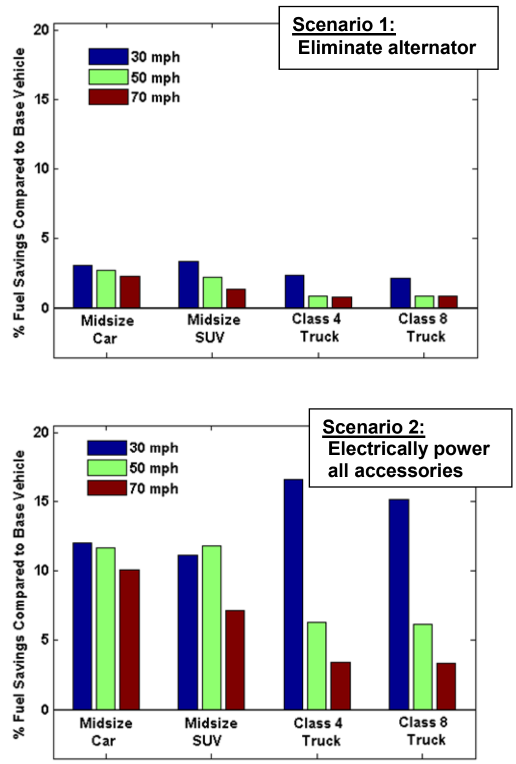


Figure 1. Fuel savings for two scenarios, compared to a base vehicle with alternator and engine-driven accessories.

To assess whether sufficient waste heat is available for a TE system to achieve these scenarios, an engine waste heat model was created and validated using data taken by NREL for a Caterpillar C12 engine. Combined with a vehicle road load model estimating the engine power required to propel the vehicle under different driving scenarios, the models predict that plenty of waste heat is available at high speeds, however little is available at low speeds. The Class 8 truck is somewhat of an exception in that, due to its large mass and poor aerodynamics, a moderate amount of waste heat is available at low speeds as well.

Based on the predicted amount of waste heat, the percentage of that heat which a TE system must recover to achieve the scenarios of alternator elimination and complete accessory electrification can be calculated. Only a small fraction of waste heat must be recovered to eliminate the alternator of the Class 8 truck. For smaller, more efficient vehicles, however, progressively higher system efficiencies would be required to achieve the alternator elimination scenario. With present TE device efficiencies only in the range of 5-10% (and, when combined with necessary heat exchangers and pumps, complete system efficiencies perhaps half of that), it is apparent that complete accessory electrification is infeasible for all vehicle platforms.

In addition to the large amounts of waste heat available, Class 8 trucks are also attractive platforms as their (i) fuel economy is relatively unaffected by the additional weight of a TE system and (ii) the higher number of miles-traveled per year means that any fuel savings realized by a TE system will more quickly pay for that system. Additional duty cycle analysis was performed for the Class 8 truck to determine the influence of different types of driving profiles on TE system power generation.

Table 1 shows the electrical power output expected from Class 8 truck TE systems of various efficiencies for city, suburban, and interstate driving. The average alternator output (0.7 kW) can be met by a TE system provided the driving is at highway speeds and/or the TE system efficiency is 10% or more. Given that TE system efficiencies are presently only on the order of 5%, it is presently not possible to eliminate the alternator altogether. With a near-term system efficiency of 10%, sufficient power is available to replace the alternator for suburban and interstate driving. Low speed city driving and cold start conditions would still present challenges, however. If system efficiencies can reach 15% in the future, a TE system could provide power for up to half of the engine accessories for a Class 8 truck.

Conclusions

This initial analysis on the feasibility of onboard thermoelectric (TE) generation systems shows Class 8 trucks to be the most attractive platform for initial adoption of the devices. Efficient, small-engine vehicles are less attractive as little waste heat is available except at high speeds. With near-term TE system efficiencies, it may be possible for the

Table 1. Average electrical power output of Class 8 truck TE system for various types of driving. Red text indicates it will not be possible to eliminate the 0.7 kW alternator. Green text indicates it will be possible to electrically power up to half of the truck's 7.1 kW mechanical accessories.

TE system efficiency:	5%	10%	15%
Interstate Driving	1-2 kW	2-4 kW	3-5 kW
Suburban Driving	0.5-0.8 kW	1-1.5 kW	1.5-2.5 kW
City Driving	0.3-0.4 kW	0.5-0.8 kW	0.8-1.4 kW

Class 8 truck to achieve 1-3% fuel savings by eliminating the alternator. With future TE system efficiencies, it may be possible to achieve 2-9% fuel savings by shifting up to half of the accessories (such as air conditioning and power steering) from engine-driven to electrically-driven.

Future work should address the sensitivity of cold starts on TE power generation and develop more detailed TE system models accounting for losses arising from heat exchangers, pumps and electrical power conversion devices. The work would establish technical targets for TE systems to be successfully adopted into vehicle waste heat recovery applications.

References

1. John LaGrandeur. *Automotive Waste Heat Conversion to Electric Power using Skutterudites, TAGS, PbTe and Bi2Te3*. IEEE 25th International Conference on Thermoelectrics, Vienna, Austria 2006.

2. K. Smith, M. Thornton "Feasibility of Thermoelectrics for Waste Heat Recovery in Hybrid Vehicles." *EVS-23*. December, 2007.

3. K. Smith, M. Thornton. *Feasibility of Onboard Thermoelectric Generation for Improved Vehicle Fuel Economy*. Diesel Engine-Efficiency and Emissions Research Conference, Detroit, Michigan 2007.

III. INTEGRATION AND VALIDATION

A. Mobile Advanced Technology Testbed (MATT)

Henning Lohse-Busch (Project Leader)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-9615, e-mail: HLB@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Design and develop the Mobile Advanced Technology Testbed (MATT) from concept to deployment to serve as a uniquely flexible powertrain platform that can accommodate quick "plug-n-play" evaluation of various hybrid vehicle components.
- Evaluate different component technologies and control strategies for advanced hybrid vehicle systems by using the MATT Hardware-in-the-Loop (HIL) concept.
- Validate and correlate observed results with PSAT simulations and the new Battery HIL setup.
- Emulate different types of plug-in hybrid vehicles to assist in the test procedure development by analyzing the energy consumption and emissions data.

Approach

- Focus early efforts on solving the engine control issues and the computer controlled clutch actuation problems to enable fully functional vehicle hardware and operation.
- Develop the lower-level control for each major component.
- Follow an evolutionary development path by starting with a display of conventional vehicle operation and all-electric vehicle operation, and, finally, a simulation of several different hybrid control variants.
- Validate test results with baseline vehicles and simulations.

Accomplishments

- Extensive engineering skill and effort were devoted to ensuring that the MATT hardware is fully operational.
- The conventional vehicle test results correlate well to the baseline vehicle. The launch with the dry clutch is reliable, the computer controlled shifting is optimized, and the mechanical braking is accurately applied.
- The electric vehicle test results yield all-electric range indications for plug-in hybrid vehicles. The results are correlated to those of the Battery HIL testing.
- Different hybrid operations have been explored, ranging from full hybrid to electric assistant hybrid.
- Different plug-in hybrids have been emulated to generate preliminary energy consumption and emissions data to support the hybrid test procedure development project at Argonne National Laboratory.

Future Directions

- Continue to use MATT experimentation for further support for the hybrid test procedure development.

- Utilize MATT to verify the optimized sizing of the energy storage and electric motor system for plug-in-hybrid studies.
- Validate the global control optimization methodology, which was developed to determine its value when studied on actual powertrain hardware.

Introduction

The Mobile Advanced Technology Testbed (MATT) is built to quickly evaluate a variety of component technologies in a pseudo-vehicle system environment. The concept is to clamp component modules on a frame and interconnect them with shafts to the drive wheels. The PSAT-Pro control software provides the interface that enables a real-time simulation to react to the physical hardware on the testbed. MATT is best described as a hardware-intensive approach to hardware-in-the-loop testing.

The MATT's concept and layout is illustrated in Figure 1. This pre-transmission parallel hybrid configuration is tested in the Advanced Powertrain Research Facility (APRF). The hard-to-model losses of the physical components, such as tire losses that are temperature dependent, are measured with extensive instrumentation.

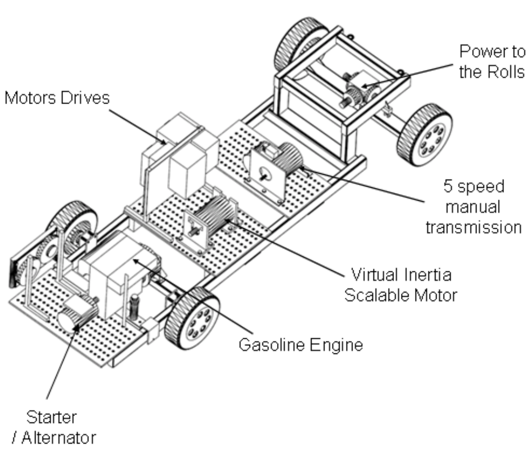


Figure 1. The Concept of MATT

This report starts with a section about our progress in developing the testbed hardware and operation. Next, the conventional vehicle calibration and test results are discussed, followed by a synopsis of the all-electric vehicle work. A quick vehicle sizing study is also presented, followed by the planned hybrid development exercise.

Hardware Summary

Current hardware setup

MATT currently uses a 2.3-liter 4-cylinder gasoline engine. The engine provides measured fuel consumption and emissions data. The automotive cooling system enables cold start work.

The electric motor is the "virtual scalable inertia" electric motor, which is powered from the grid. This motor is used to emulate the physical torque to the driveline that the electric motor and battery combination contribute in the real-time simulation. This flexible concept is the enabler for any plug-in hybrid study, since the motor can be instantly rescaled and the energy storage system can be changed in any manner, from capacity to technology.

An automated 5-speed transmission is coupled to the wheels. The energy flow and losses are monitored by the torque and speed sensors on each component. The hardware setup is depicted in Figure 2.

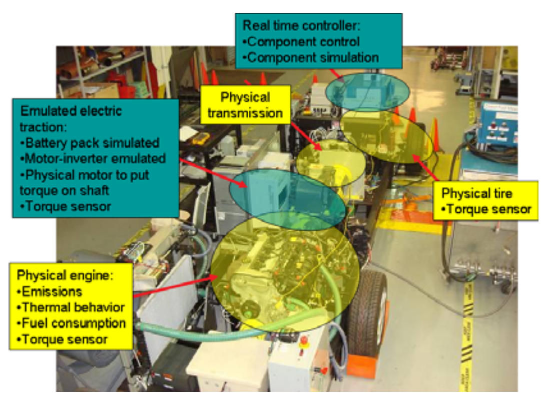


Figure 2. The Current Hardware Setup on MATT

Hardware breakthroughs

The major hardware challenge in developing MATT was to ensure that the engine operates on a stock calibration, as it would in a vehicle. Initially, the engine was operating in a "safe" mode. Mahle Powertrain recalibrated the ECU to operate on the stock calibrations on MATT. A new camshaft was required to improve the sync time between the crankshaft and the camshaft. This is particularly important to reduce start-up emissions, a critical step in the hybrid engine start/stop operation. Figure 3 shows the work performed on the engine. Now MATT has a gasoline internal combustion engine that runs on stock calibration with an electronic throttle that is controlled via PSAT-PRO.

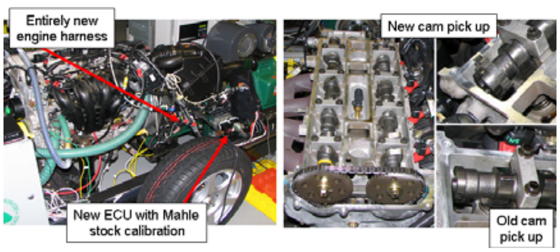


Figure 3. Engine Improvements

The second hardware hurdle was the clutch actuator. The clutch actuator fulfills two functions: first, the precision position control for the launch of the vehicle, and second, the fast speed control for quick shift times. These functions are conflicting for a single actuator, since speed is the enemy of precision. The actuator also needs to push over 300 lbs of resistive force. After partnering with an industrial motion company, the system shown in Figure 4 was developed as a solution to that problem.

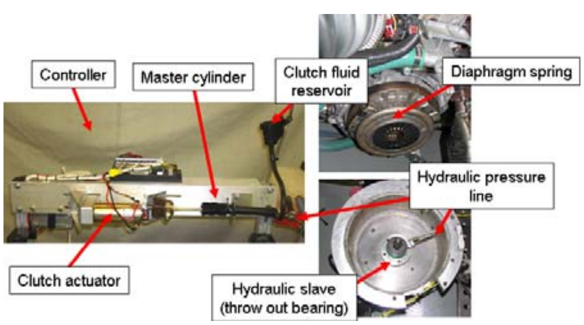


Figure 4. Clutch Actuation Improvements

These two hardware upgrades were the pieces that enabled MATT to operate as a conventional vehicle.

MATT vehicle operating modes

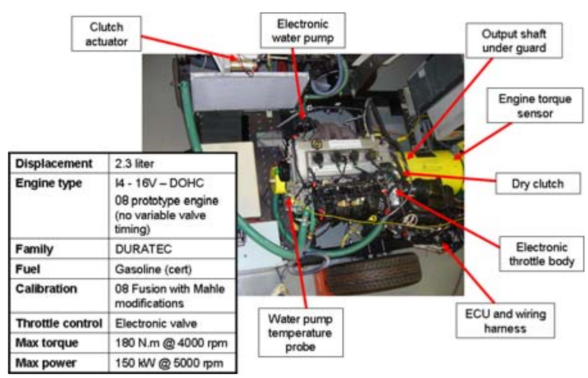
In this pre-transmission parallel configuration, MATT can operate as three different types of powertrain platforms to enable specific testing and analysis:

- *Electric vehicle:* by decoupling the engine with the clutch.
- *Conventional vehicle:* by canceling the motor inertia and driving the platform with only the engine, clutch, transmission, and mechanical brakes.
- *Hybrid vehicle:* by using any combination of engine, motor, and mechanical brakes to control MATT.

Conventional Vehicle Work

Gasoline engine

The gasoline engine, its characteristics, and the support system packaging are shown in Figure 5.



Displacement	2.3 liter
Engine type	I4 - 16V – DOHC 08 prototype engine (no variable valve timing)
Family	DURATEC
Fuel	Gasoline (cert)
Calibration	08 Fusion with Mahle modifications
Throttle control	Electronic valve
Max torque	180 N.m @ 4000 rpm
Max power	150 kW @ 5000 rpm

Figure 5. Engine Characteristics and Support System Integration

The components are mapped out by using the instrumentation on MATT. Figure 6 and Figure 7 show examples for the engine data that were produced from maximum performance to efficiency data, respectively.

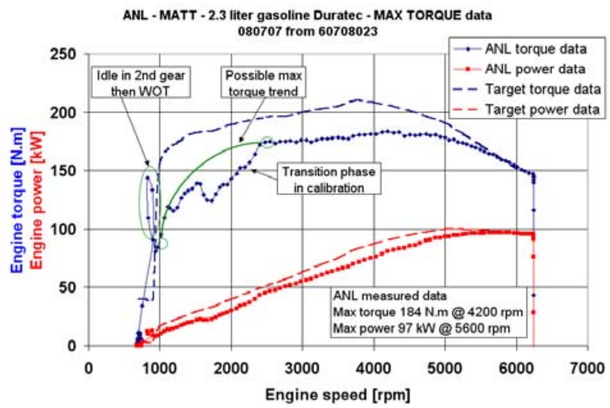


Figure 6. Maximum Engine Torque and Power Curve Data

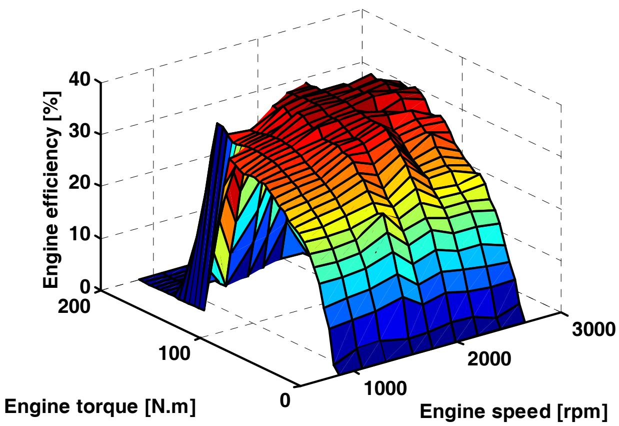


Figure 7. Engine Efficiency Data

Since the engine operates differently in a hybrid operation than in a conventional vehicle operation, the cooling system required particular attention. MATT was outfitted with an automotive-type cooling system with a radiator fan combination and thermostat housing. The coolant pump is an electric variable flow pump (Figure 8). The pump attempts to maintain a coolant target temperature and adjust the cooling flow accordingly.

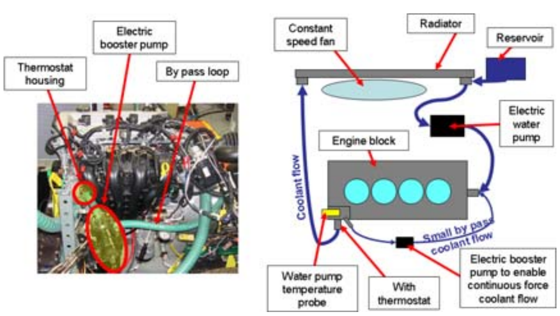


Figure 8. Description of the Engine Cooling System

Extensive work went into the calibration and validation of this cooling system. Figure 9 shows some sample data from a cold start test compared with results from other conventional vehicle tests. In hybrid operation, the engine cooling is still ensured even if the vehicle rolls at low speed and the engine is under high load.

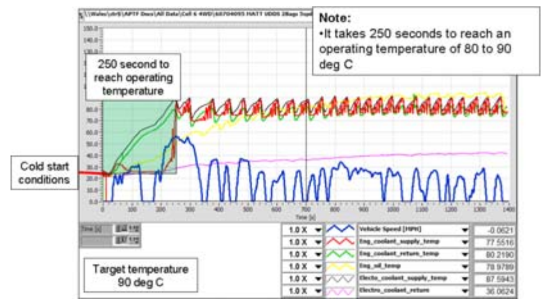


Figure 9. Example Cooling Data on a Cold Start UDDS Cycle Performed in Conventional Mode

Launch

The start of any cycle in conventional mode is the launch with the engine and the clutch. The PSAT-PRO replicates human behavior by detecting the clutch engagement point and feathering the throttle based on engine reaction and vehicle launch speed. Figure 10 illustrates this algorithm.

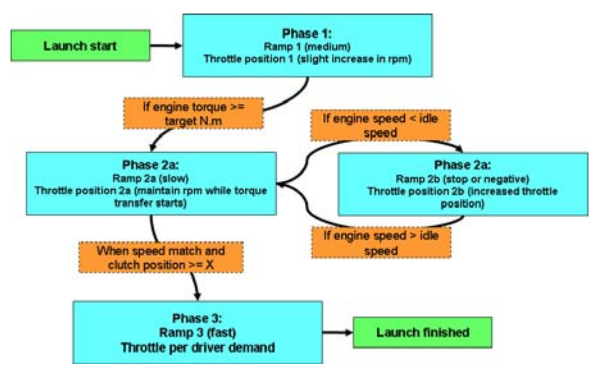


Figure 10. Launch Algorithm for the Conventional Mode

A large amount of calibration and clutch system behavior characterization yields a reliable and robust vehicle launch. Some software is added to account for special cases, such as engine stalling and miss-shifting. Figure 11 shows data from a vehicle launch in conventional mode.

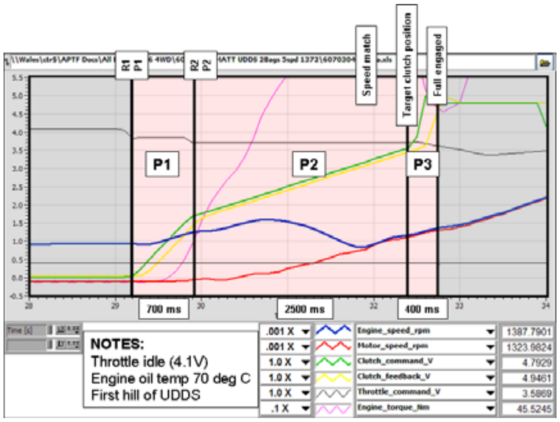


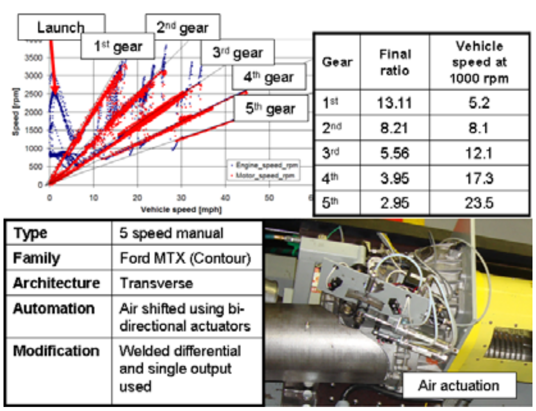
Figure 11. Sample of Launch Data

Drive

Once the vehicle is in motion and the clutch is completely closed, a PID loop called "the driver" modulates the engine throttle position to achieve the desired vehicle speed dictated by the drive cycle. "The driver" uses a correlation between engine speed and requested torque to establish a throttle position. That correlation was established during the engine mapping and characterization.

Shifting

The shifting is performed by a 5-speed manual transmission. This transmission is retrofitted with actuators to enable PSAT-PRO to change the gears. Figure 12 presents a summary of the transmission characteristics.



Gear	Final ratio	Vehicle speed at 1000 rpm
1st	13.11	5.2
2nd	8.21	8.1
3rd	5.56	12.1
4th	3.95	17.3
5th	2.95	23.5

Type	5 speed manual
Family	Ford MTX (Contour)
Architecture	Transverse
Automation	Air shifted using bi-directional actuators
Modification	Welded differential and single output used

Figure 12. Transmission Characteristics

In the conventional mode, PSAT-PRO follows an established shift schedule. If needed, the software modifies the shift schedule based on successful launch, time between shifts, and engine speed ranges.

Since there is no clutch between the electric motor and the transmission, the motor must be matched to the transmission input speed in the next gear to complete the shift. Figure 13 presents the lower-level control logic followed for the shifting process.

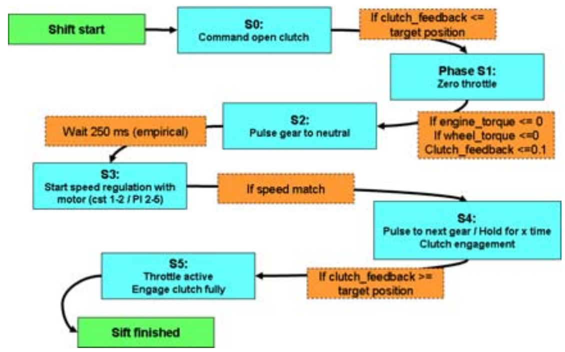


Figure 13. Shifting Algorithm for the Conventional Mode

Figure 14 shows a sample of shift data. A fair amount of time was spent on optimizing the shift time. Shift time is calculated from the end of power transfer to the start of power transfer. The shift time ranges from 1 to 1.5 seconds, depending on the selected gears.

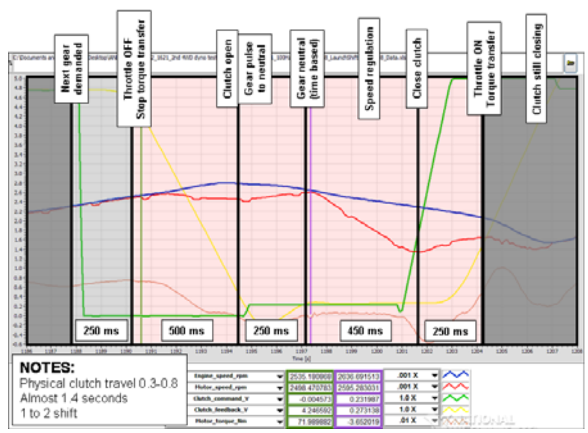


Figure 14. Sample of Shift Data

This longer shift time causes a more pronounced loss of the drive trace. Once the gear is engaged, MATT must provide extra power to catch up to the trace, which causes some anomalies in the emissions results. Our next iteration plans to replace the manual-shift transmission with an automatic transmission to minimize some of the issues encountered.

Mechanical braking

The braking system is built from automotive components. The brake pads are pressed against the rotor by the hydraulic calipers. The computer controls the force in the hydraulic line through an air actuator. Figure 15 depicts the components used.

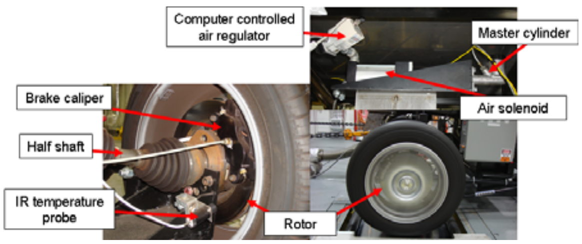


Figure 15. Mechanical Brake System on MATT

The PSAT-PRO PID control loop (the driver) still dictates the brake torque needed to meet the drive-cycle trace. This torque request is transformed into braking pressure. The control system also receives temperature feedback from the brake rotor. Figure 16 presents some data depicting braking events.

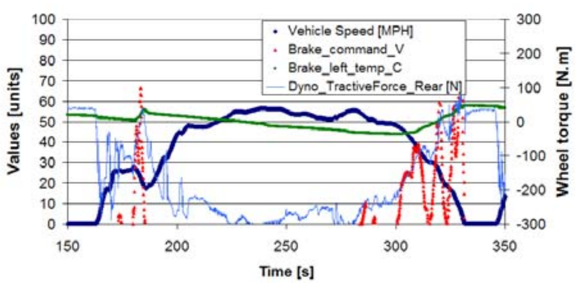


Figure 16. Data Sample from Some Braking Events from MATT in a Conventional Mode

Baseline conventional gasoline vehicle

The baseline vehicle for results comparison is the APRF correlation vehicle: a 2004 Ford Focus. The Focus uses a 2-liter (4-cyl) engine coupled with a 4-speed automatic transmission that is only slightly different from MATT. Figure17 presents the average fuel economy on different drive cycles.

Fuel economy in mpg	MATT conventional	Correlation Focus
UDDS Cold start	24.8	26.6
UDDS Hot start	25.7	27.5
HWY	39.8	38.0
US06	27.7	26.0

Figure 17. Fuel Economy Comparison

This effort to validate MATT's performance indicates a close correlation with real vehicles and reliable operation as a conventional vehicle.

Electric Vehicle Work

Virtual inertia scalable motor

The physical electric motor on MATT is an AC induction NEMA machine electrically coupled to an industrial drive. The power is provided by a 408-V AC feed. Thus, this motor is not powered by an energy storage system. Figure 18 shows the physical hardware. This setup can provide high continuous power compared to an automotive motor and battery pack combination.

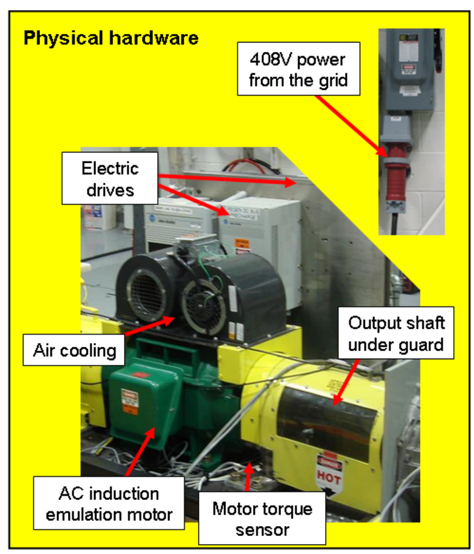


Figure 18. Physical Motor Setup

The fast response time of the motor enables an interesting feature. The motor can compensate for its own inertia. Thus, a virtual inertia can be set, and the motor eliminates its own inertia with torque and then adds the request torque from PSAT-PRO. The PSAT-PRO runs a real-time model of a selected motor and battery combination. In the current MATT setup, the motor is a UQM 75, and therefore PSAT-PRO uses the torque speed curves of the UQM 75 to limit the physical motor torque output. The battery pack is the SAFT VL41M, which also is used in the Battery HIL setup. The available current and resulting voltage on the virtual high-voltage power bus is computed in real time. Figure 19 shows the hardware emulated on MATT. Eventually, this hardware will be used to validate the models.

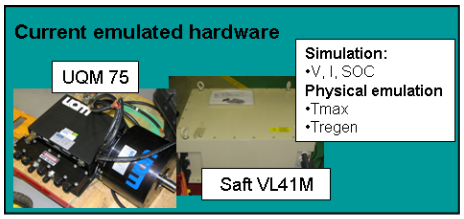


Figure 19. Pictures of the Emulated Hardware

This motor setup is an enabler for plug-in hybrid testing. The key component technology associated with plug-in hybrid operation is the battery. Since that is emulated in the MATT setup, diverse technologies, including small and larger capacity battery packs, can be emulated. MATT can accommodate virtually any size pack. Also, SOC is calculated in the real-time model.

Electric vehicle operation

In general, the electric vehicle operations are simpler than the conventional vehicle operations. The faster response and zero idle speed simplify the launch and drive portion of the test cycles. Due to the zero speed idle speed of electric motors (compared with ~700-rpm idle speeds of internal combustion engines) the launch is performed on torque control and no launch device (such as a clutch) is needed. The normal drive situations are also simplified, since no throttle position calculation is required and no thermodynamic torque delivery delays occur.

Since the engine is already declutched, the shifting consists of simply shifting to neutral, followed by the speed match of the motor to the next gear, and engaging the new gear.

The braking is a bit more complicated compared with a conventional vehicle, since regenerative braking and mechanical brakes can, and sometimes must, be used together. If the battery pack and motor can absorb the regenerative power, 100% of the brake torque is from the electric motor. In cases where the SOC for the battery pack is high enough that only a little electrical power can be absorbed, the electric motor absorbs that limited amount, and the mechanical brakes provide the rest of the braking power. The blending of regenerative and mechanical braking must be smooth to protect the drive component and fast to meet the drive trace. The calibration of that process is critical, both from an emulated vehicle perspective and from a safety perspective.

Figure 20 shows some data from the first hill on the UDDS: one at high SOC, where the mechanical brakes supplement the regenerative braking, and the other at low SOC, where braking is performed by the electric motor and battery pack.

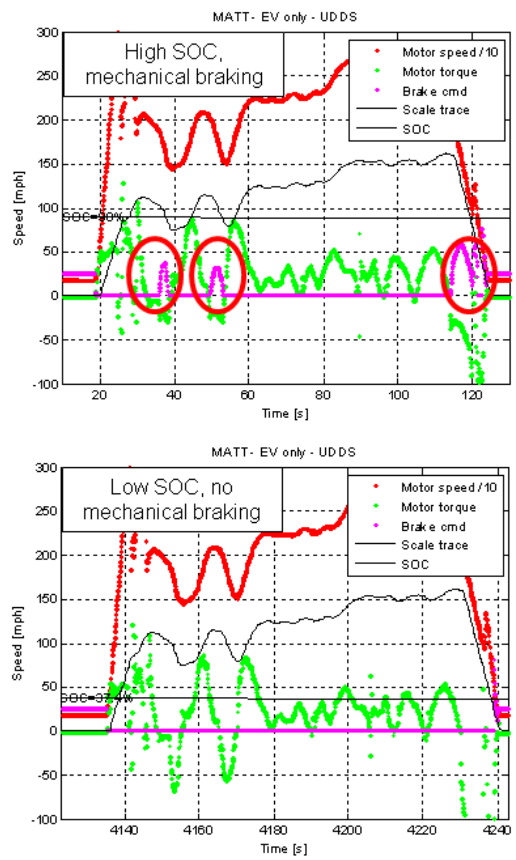


Figure 20. Regenerative and Mechanical Braking Sample Data at Different SOCs

Once the lower-level algorithms are completed and calibrated, MATT is ready to operate as an electric vehicle.

All-electric range operation

The first task was to test the all-electric range (AER) capability for the SAFT VL41M in the baseline vehicle configuration. In that configuration the AER is 26.7 miles, assuming a start SOC of 90% and a final SOC of 30%. Table 1 presents some results from the energy storage system, broken down by urban cycles. The results show that the first cycle used more electric energy due to the limited regenerative braking at the high SOC and the higher losses from the cold components.

Table 1. All-Electric Range Results for the Midsize Sedan

UDDS	1	2	3	4
Electric consumption (Wh/mi)	237	233	233	231
Battery energy used (kWh)	1.76	1.73	1.73	1.72
Battery capacity used (Ah)	6.65	6.79	6.99	7.16

The benefits of the physical hardware are that the losses due to temperature effects can be quantified – values that are usually complicated to model. Figure 21 shows the test data, including the temperature of the transmission and the tires. Two urban cycles were run in back-to-back, thus the slight cool down after the second urban cycle.

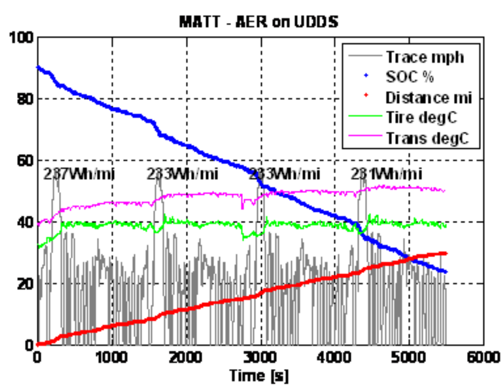


Figure 21. Time Data of the AER Test, Including Temperature Indications

MATT is a valuable tool to gain greater insight into the electric vehicle operations for plug-in hybrids. It measures a variety of performance figures, from the component losses to the energy storage sizing and performance.

Different Size Vehicle Study

Purpose

One of the first studies emulated different size vehicles in order to test the hardware's flexibility with a wide range of vehicle sizes. Each vehicle has a test mass and vehicle losses (defined by the A B C coefficients from coast downs). The larger the vehicle, the higher the power and energy demand on the driveline components.

Vehicle sizes

Considering the fixed engine size, three types of vehicles were selected:

- Small efficient coupe
- Small/midsize sedan
- Crossover SUV

Figure 22 shows the emulated vehicles. All of these vehicles have been tested in the APRF. Therefore, plenty of test data, especially fuel economy figures, are available for comparison.

Figure 22. Different Types of Vehicles Emulated

Test procedure and results

For each emulated vehicle, a coast down test was performed on MATT after a double highway test for warm up. After the coast downs, MATT completed an urban cycle as a conventional gasoline vehicle and an urban cycle as an electric vehicle. The electric vehicle tests were completed in third gear from start to finish, eliminating the shift schedule variations. Table 2 presents the test results.

Table 2. Energy Economy and Consumption Test Results for the Different Emulated Vehicles

	Honda Insight	Ford Focus	Ford Escape
Coast down	yes	yes	yes
HWY Conventional (mpg)	45	39.8	36
UDDS Conventional (mpg)	30	25.7	23.5
2x UDSS Electric only (Wh/mi)	210	308	375

In all of the tests the engine and the motor were powerful enough to completely meet the trace without difficulty. For the crossover SUV, the engine was loaded significantly higher then it was for the small sedan. The results showed that the lighter the vehicle, the higher the fuel economy and the less efficient the engine's cycle efficiency. For the Insight emulation, the drive calibration was tuned to be more sensitive, since the lower inertia rendered the vehicle more responsive to throttle changes. For the crossover SUV, the higher vehicle inertia simplified the calibration.

Detailed torque speed look

Figure 23 shows the torque speed curves of the electric machine on the UDDS for each emulated vehicle. The data are collected from the torque speed sensor on MATT.

The crossover SUV required about twice the average propulsion power. In this study, the hardware was tested on drive cycles over a large range of power requirements, and it was demonstrated that MATT can successfully emulate different size vehicles.

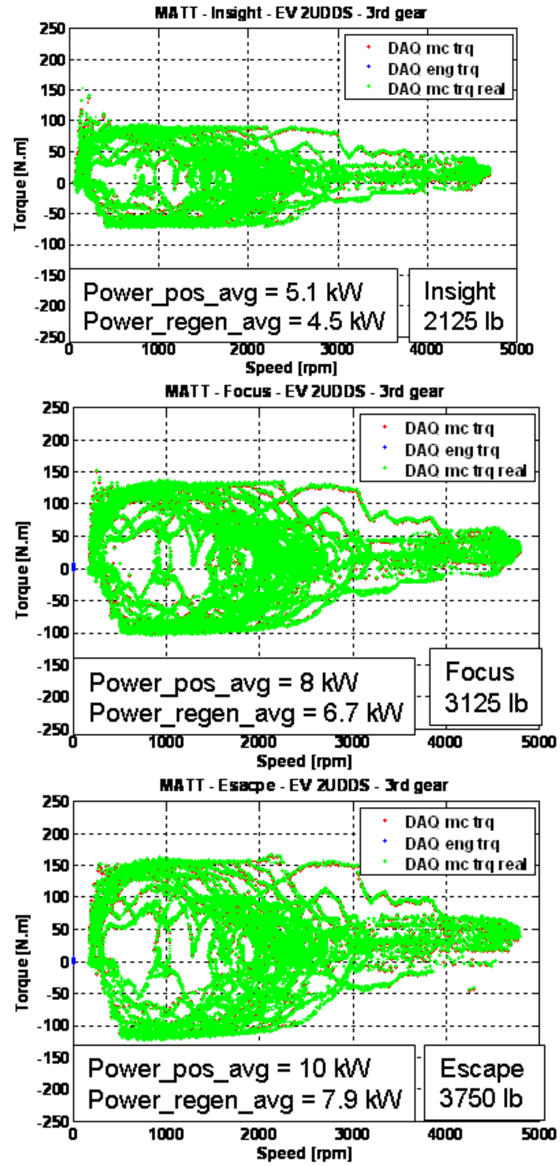


Figure 23. Torque Speed Curves for Each Vehicle Emulation on the UDDS

Hybrid Vehicle Progress

Process

The hybrid development was based on hardware interactions. The first goal was to keep the transitions between different modes smooth and protective of the components. Two approaches were taken:

- ***Full hybrid:*** Start with an electric vehicle and add different engine operations based on factors such as wheel power level and SOC. This hybrid has full electric capability.
- ***Mild hybrid:*** Start with a conventional vehicle and add an engine start/stop feature and smaller assist and generator functionality.

Figure 24 illustrates the road map followed in the development of the different hybrid features.

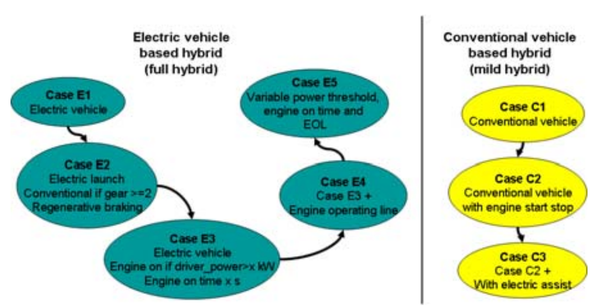


Figure 24. Development Map for the Different Hybrid Operation Modes

The electric vehicle (Case E1) and the conventional vehicle (Case C1) have already been presented. The following paragraphs give an overview of the hybrid work performed.

Case E2: Electric launch + conventional + regenerative braking

In this case, MATT is launched as an electric vehicle. When the shift to second gear (and higher gears) occurs, the engine is started and used as the primary mover. During deceleration the electric motor brakes and the regenerated energy is stored in the virtual battery pack.

Case E3: Electric propulsion + engine constant power for set time

In this case, the main propulsion is as an electric vehicle with launch, tractive torque, and regenerative braking. When a set wheel power demand for the driver is reached, the engine is started and loaded at a constant power level to charge the battery pack for a set amount of time. The net charge of the battery pack over a cycle is defined by the power threshold level, the engine power level, and the "engine on" time.

Case E4: Engine operating line (EOL)

The additional feature for this case is the engine operation line (EOL) that is followed during the "engine on" time. A preset engine torque speed curve dictates the loading of the engine based on engine speed. Ideally, this EOL is the best efficiency line to ensure optimal average engine efficiency over a cycle.

Case E5: Target SOC full hybrid

Finally, a target SOC is added. In this case the engine power threshold level, the EOL correction, and the "engine on" time are a function of the actual SOC and a target SOC. The final hybrid configuration is a charge-sustaining full hybrid. Figure 25 presents engine and motor data on a charge-sustaining UDDS cycle.

The engine is used only on higher speed – thus higher power – portions of the cycle. When the engine is operating, it is loaded to 110 N·m between 1,500 to 2,000 rpm. At rarely occurring lower engine speed, the torque is slowly ramped up.

The baseline conventional fuel economy is around 25–26 mpg, and the full hybrid charge-sustaining fuel economy is 43 mpg. That is well over a 60% improvement.

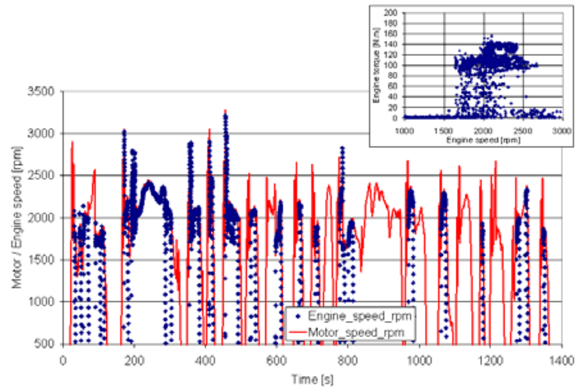


Figure 25. MATT Full-Hybrid Data on a Charge-Sustaining UDDS Cycle

The transitions between the different phases, such as engine start/stop and engine loading, were calibrated to prevent large torque spikes from occurring in the driveline.

Case C2: Conventional vehicle with engine start/stop feature

The first feature added to the conventional vehicle is an engine start/stop feature. As the vehicle comes to a stop, the engine is turned off; when the driver is about to launch the vehicle, the engine is started again. This saves the idle fuel flow. On the UDDS, the vehicle is stopped for over 17% of the time. Figure 26 compares the engine start/stop feature (red) to the conventional engine idle (blue).

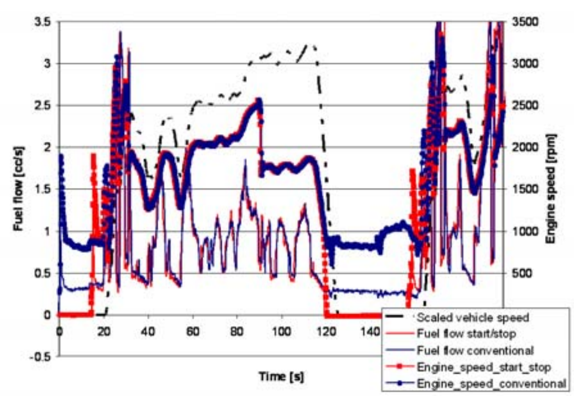


Figure 26. Comparison of Engine Start/Stop Feature with the Conventional Vehicle Operation

The average fuel economy improvement on the UDDS cycle is 3%.

Case C3

The next engine-dominant (mild) hybrid is emulated by adding electric assist to the engine start/stop feature. Since the main goal is to prove the hardware transition on this particular hybrid, it was not tuned or calibrated to be charge-sustaining. The assist was used to help in the launch and capture some regenerative braking. During times of large power requirements for the engine (such as accelerations), the electric motor assists the engine. During cruise, the motor loaded the engine to recharge the battery pack. This operation mode was the smoothest of all the hybrid cases explored.

Conclusion

The hardware transitions for all hybrid cases were able to be demonstrated in the hybrid work performed on MATT. Every possible hybrid operation, from a very mild engine start/stop hybrid to a rough charge-sustaining full hybrid was successfully and safely demonstrated.

Plug-in Hybrid Work

Process

Using the full hybrid mode as a starting point, a plug-in hybrid can easily be derived by starting with a fully charged large battery pack and adding an initial charge-depleting strategy. With the full hybrid, a pure EV charge-depleting strategy or a blended charge-depleting strategy can be used.

Preliminary results

Figure 27 shows the fuel economy and SOC results for an all-EV charge-depleting plug-in hybrid, followed by the charge-sustaining operation.

Figure 28 presents 10-Hz data from the same testing and summary information for each urban cycle. This testing also yielded emissions data that have been used to prove the proposed SAE J1711 hybrid test procedure. From Figure 28, MATT operated as an EV until hill 2 in the third urban cycle, after which point fuel start to be consumed by the engine.

Figure 29 shows the temperature information collected during the plug-in testing. As the engine starts for the first time in the third urban cycle, the coolant temperature rises. In the conventional vehicle the engine reaches operating temperatures in less then 5 minutes, whereas in the plug-in hybrid vehicle the engine reaches operating temperatures after well over 10 minutes due to the engine's intermittent operation.

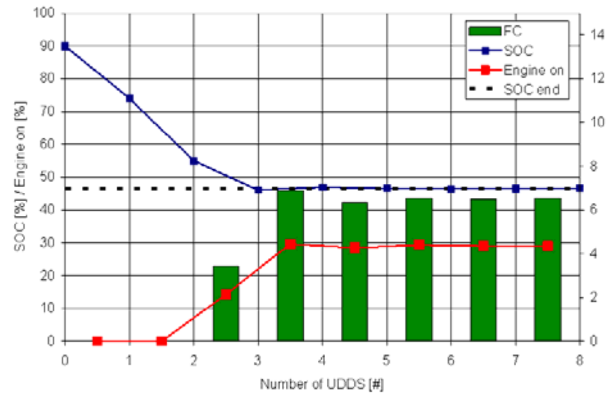


Figure 27. EV Charge-Depleting Plug-in Hybrid Followed by Charge-Sustaining Operation

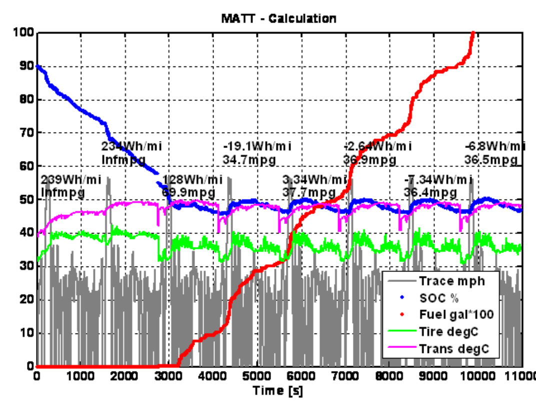


Figure 28. Time Data from the Plug-in Testing

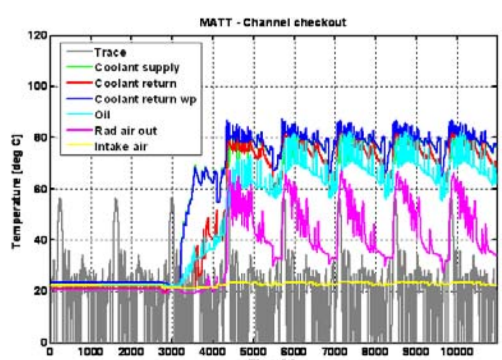


Figure 29. Temperature Information on the Plug-in Testing

Fuel consumption versus electric energy consumption for each UDDS cycle is plotted in Figure 30. From an in-tank and in-battery-pack perspective, the electric vehicle operation is over three times as efficient compared with the conventional vehicle operation.

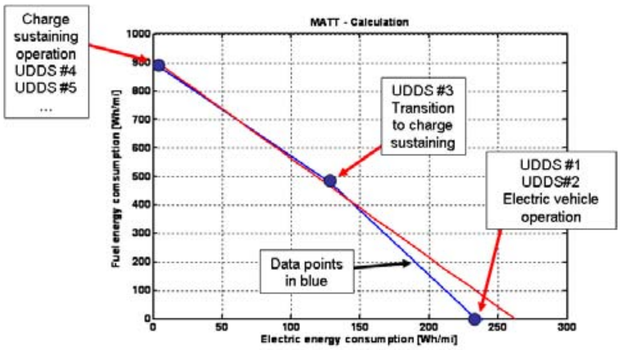


Figure 30. Fuel Energy Consumption versus Electric Energy Consumption Data for the Urban Cycle

Hybrid test procedure support

MATT has been used to generate fuel economy data and emissions numbers to test the revised version of the proposed J1711 hybrid test procedures. MATT has completed the blended charge-depleting long test, the EV-depleting long test, and a shortcut procedure.

Conclusions

MATT is a valuable tool to gain greater insight into the electric vehicle operations for plug-in hybrids. It measures a variety of performance figures, from the component losses to the energy storage sizing and performance. The hardware transitions for all hybrid cases were able to be demonstrated in the hybrid work performed on MATT. Every possible hybrid operation, from a very mild engine start/stop hybrid to a rough charge-sustaining full hybrid was successfully and safely demonstrated. MATT has been used to generate fuel economy data and emissions numbers to test the revised version of the proposed J1711 hybrid test procedures.

Publications/Presentations

1. Henning Lohse-Busch, Thomas Wallner, and Neeraj Shidore, 2007-01-2046, “Efficiency-Optimized Operating Strategy of a Supercharged Hydrogen-Powered, Four-Cylinder Engine for Hybrid Environments,” peer-reviewed paper at the SAE Powertrain and Fluid Systems Conference, Kyoto, Japan, 2007.

2. Neeraj Shidore, Henning Lohse-Busch, Ryan W. Smith, Ted Bohn, and Philip B. Sharer, “Component and Subsystem Evaluation in a Systems Context Using Hardware-in the-Loop,” presented at the VPPC 2007 Conference, Arlington, TX, USA, August 2007.

3. Henning Lohse-Busch, Neeraj Shidore, and Ryan Smith, “MATT Results Conventional, Electric and Hybrid Operation,” presented at VSATT in INL, September 2007.

4. Henning Lohse-Busch and Neeraj Shidore, “Progress Update on MATT as a Conventional Vehicle,” presented at DOE, Washington DC, April 2007.

B. Battery Hardware-in-the-Loop Testing

Neeraj Shidore (project in charge)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-7416, e-mail: nshidore@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Evaluate advanced prototype batteries for plug-in hybrid applications by using the concept of hardware-in-the-loop (HIL)/software-in-the-loop.

Approach

- Build a battery test stand in which the battery is connected to a bi-directional power supply that acts as a power source/sink.
- Control the bi-directional power supply to source/sink power to/from the battery, so that the instantaneous battery power is equivalent to the instantaneous battery power in a plug-in hybrid vehicle running a drive cycle.
- Use PSAT-PRO computer simulation software to emulate a plug-in hybrid vehicle and control the DC power supply, so the battery can be evaluated in a closed loop, real battery-virtual vehicle scenario (concept of HIL).

Accomplishments

- Completed construction of a permanent Battery HIL test stand.
- Validated the PSAT VL41M battery model (data provided by Argonne National Laboratory, CMT Division) by using Battery HIL for an all-electric-range test.
- Collected all-electric-range results for the VL41M battery in three different classes of virtual vehicles at a temperature of 20ºC.
- Completed a round-trip efficiency calculation of the VL41M battery based on dynamometer cycles and three charger ratings.
- Completed determination of the sensitivity of vehicle fuel economy to battery state-of-charge (SOC) in charge-sustaining mode at 20ºC ambient conditions.
- Initiated a combination ultra-capacitors and battery-active power sharing experiment with hardware support from Maxwell Ultra-Capacitors.
- Began work on the new Energy Storage Systems HIL Lab (Battery HIL v2).

Future Directions

- Perform all-electric range and charge-depleting range tests on the VL41M battery at hot, cold, and normal ambient conditions.
- Determine the impact of vehicle control strategy on fuel economy and battery temperature rise at cold battery (ambient) temperatures.
- Determine the impact of vehicle control strategy on fuel economy and regulating battery temperature for hot battery (ambient) conditions.

- Benchmark the performance of other battery packs (e.g., A123, the JCS air-cooled 10-mile AER) for component and vehicle systems level evaluation at hot, cold, and normal ambient conditions hardware.

Introduction

Plug-in hybrid electric vehicles (PHEVs) have been identified as an effective technology to displace petroleum because they draw significant off-board energy from the electrical grid with regular charging. The rechargeable energy storage systems (e.g., batteries) have a much larger energy capacity as compared to current production charge-sustaining hybrids. This larger energy storage system can be utilized by powering a significant all-electric range (AER) or by selectively powering low-load portions of the driving demand. The battery's response to variations in control choices will have a significant impact on the vehicle-level performance. The needs of the battery under these control scenarios are of critical interest to battery developers. As such, emulation, modeling, and hardware-in-the-loop (HIL) testing techniques for a plug-in battery system have been developed to support the acceleration in the development of PHEVs for a mass market.

The most significant technical barrier to commercially viable PHEVs occurs in the energy storage system. The challenge resides in developing batteries that are able to perform the requirements imposed by a PHEV system while achieving market expectations in terms of cost and life. In this context, a vehicle systems approach becomes necessary to investigate the operational requirements specific to PHEV technology. Vehicle-level investigations determine the relationship between component technical targets and vehicle system performance and the potential of the entire system design to displace petroleum use. Battery HIL is an important tool in this vehicle-level investigation of the PHEV battery.

Approach

In Battery HIL, the battery is connected to a DC power source, which is controlled by a real-time simulation model that emulates the rest of the power train, for a PHEV operation. The vehicle model is derived from a simulation model developed by using the Powertrain Systems Analysis Toolkit (PSAT).

Concept of Battery HIL

The concept of Battery HIL, as it applies to the present experiment, can be explained by using the classic control theory-block diagram (plant, controller, feedback) closed loop system. Figure 1 shows Battery HIL in a plant-controller-feedback scenario. The plant consists of a real battery connected to a virtual vehicle through a DC power supply, and the controller is the vehicle system controller. Feedback from the battery to the vehicle controller is by CAN. The vehicle and the vehicle controller are simulated in real time in PSAT-PRO. Feedback from the simulated vehicle to the vehicle controller is internal.

The hardware implementation of the plant-controller-feedback diagram is shown in Figure 2.

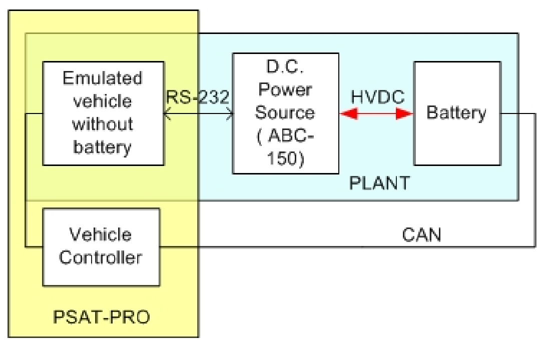


Figure 1. Battery HIL Represented as a Closed Loop Plant-Controller-Feedback System

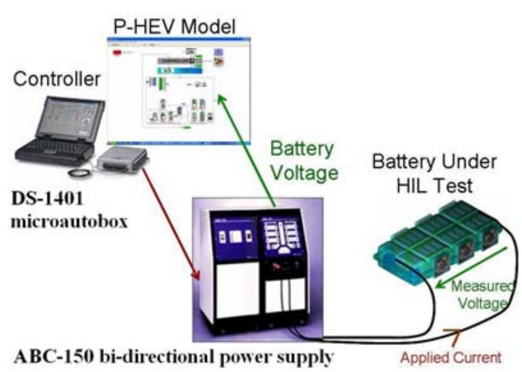


Figure 2. Implementation of Battery HIL in Hardware

Figure 2 shows the causal effort-flow relationship between the battery and the virtual vehicle, which is central to the HIL concept. The current demanded by the traction electric motor in the virtual vehicle is sinked or sourced from the battery. The resultant battery voltage is then fed-back to the vehicle via CAN and used by the virtual electric motor as an effort variable. Factors such as state-of-charge (SOC) and temperature affect the battery current capability and can be sensed by the virtual vehicle indirectly in the form of battery voltage/power available to the traction motor. For example, at high SOC, the battery limits regenerative capability by recommending lower current limits to the virtual vehicle. The vehicle control system receives this feedback from the CAN bus and limits motor regenerative braking.

Various vehicle-level parameters, such as drive cycle, vehicle configuration, vehicle class, vehicle control strategy, and vehicle components can be changed in the virtual vehicle. The battery can be evaluated for all the above scenarios. Similarly, changes in battery performance with temperature and SOC also impact vehicle performance and can be studied in this manner.

As seen in Figure 2, the vehicle controller and the virtual vehicle model developed in PSAT-PRO is compiled and downloaded in the Dspace 1401/1501 MicroAutobox. The Dspace MicroAutobox (DS1401-RTI) is an automotive-grade real-time controller, typically used as a prototyping tool for engine development. The bi-directional power supply is capable of sinking or sourcing power up to a maximum of 125 kW.

Current Battery Used for Plug-in Evaluation

The battery currently being evaluated for plug-in applications is the liquid-cooled, SAFT-Johnson Controls 41-A·h Li-ion battery. An AutoCAD drawing of the battery is shown in Figure 3. An actual picture of the battery is shown in Figure 4.

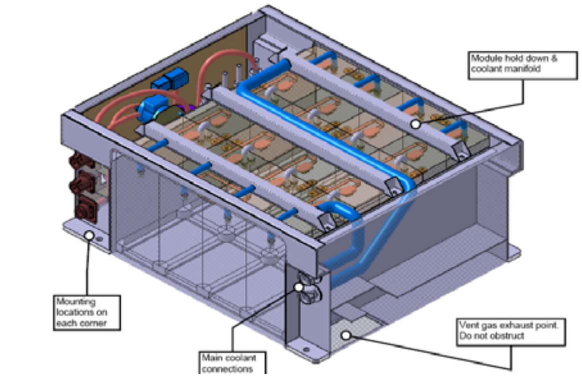


Figure 3. Drawing of the JCS 41-A•h Li-ion Battery

As can be seen from Figure 4, the battery is sealed in a metal box and is for stand-alone purposes only. It cannot be used in a real vehicle because of vibration restrictions.

Figure 4. JCS 41 A·h Li-ion Battery

Some battery level specifications are stated in Table 1.

Table 1. JCS 41A·h Battery Specifications

Cell capacity	41 A·h nominal
Nominal voltage	259.2 V
Voltage range	194.4 V to 288 V
Continuous current	150 A at 30°C
Operating temp.	10º to 40ºC

Accomplishments for FY07

1. Completed Battery HIL test hardware set-up.

Figure 5. Virtual Vehicle, High-Voltage DC Power Supply

Figure 6. External Fuse Box, Contactor Box, Cooling Water Feed to the Battery

The external fuses in the fuse box, between the ABC-150 and the battery, are rated at 200 A to ride through fast current transients but clear during faults (Figure 5). There also is an internal fuse in the battery, rated for 165 A continuous.

The contactor box has 4 contactors (two per channel, two channels). The contactors are powered by a 12-V power supply and are integrated into the E-Stop loop. The battery also has internal contactors, which are controlled by the vehicle controller via CAN.

The Li-Ion battery pack is cooled by a water chiller (Figure 6), which is capable of heating and cooling the pack as needed by the experiment.

2. Completed AER tests for the VL41M for three different vehicle classes at normal ambient conditions.

The battery was subjected to EV mode from an initial state-of-charge (SOC) of ~ 90% to a final SOC of ~ 30%. A pre-transmission parallel vehicle was chosen, with three different vehicle masses, representing a midsize vehicle, a cross-over, and an SUV. The results we measured for All-Electric Range at 20ºC are listed in Table 2.

Table 2. All-Electric Range Results at 20ºC

Vehicle Mass	Battery A·h	AER	Wh/mile	Temp Rise (C)	kWh
Midsize 1,665 kg 3,663 lb	24	21.00	277.01	6	5.3
Crossover 1,845 kg 4,059 lb	24	17.42	325.61	9	5.28
SUV 2,049 kg 4,507.8 lb	24	15.87	359.54	9	5.25

The battery temperature rise for the three vehicle types is shown in Figure 7. The vertical lines depict the first "engine–ON" times for the three vehicles. The controller switches to charge sustaining mode after the first engine–ON.

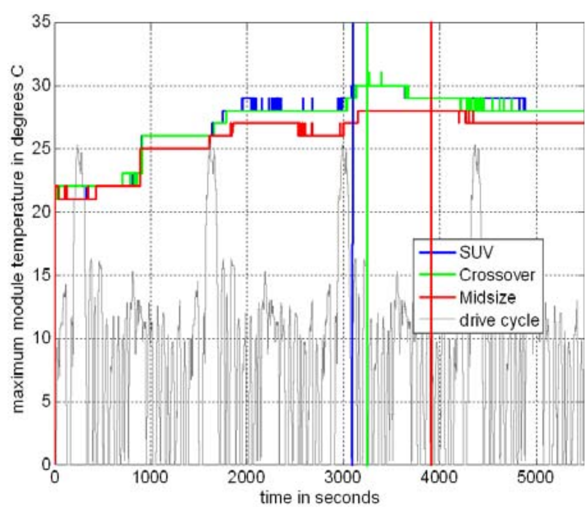


Figure 7. Battery Module Temperature Rise for the Three Vehicle Cases.

3. Validated the PSAT battery model, developed by CMT, for electric-only mode by using Battery HIL.

The VL41M model used in PSAT was developed by using data provided by the CMT group at Argonne National Laboratory. This model was validated in a systems context by comparing it to actual battery behavior in the Battery HIL set-up.

Both PSAT and Battery HIL were subjected to an AER test with the same vehicle and energy management strategy. Vehicle-level results, as well as criteria such as battery voltage and SOC, were compared between the real battery and the battery model in PSAT. The PSAT results for energy management were within 5% of the results obtained by Battery HIL. Figure 8 shows the SOC plot for both Battery HIL and PSAT.

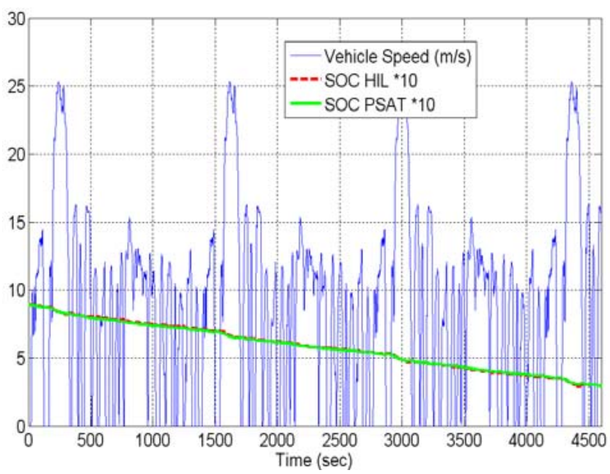


Figure 8. Comparison of the SOC Predicted by the PSAT Battery Model and the SOC Estimated by the VL41M for an AER Test

4. Completed round-trip efficiency calculation of the VL41M based on dynamometer cycles.

Battery HIL was used to determine the round-trip efficiency for the VL41M for an EV and charge-sustaining operation at low SOC for four urban cycles, followed by overnight charging back to the initial battery capacity at the start of the experiment (Figure 9).

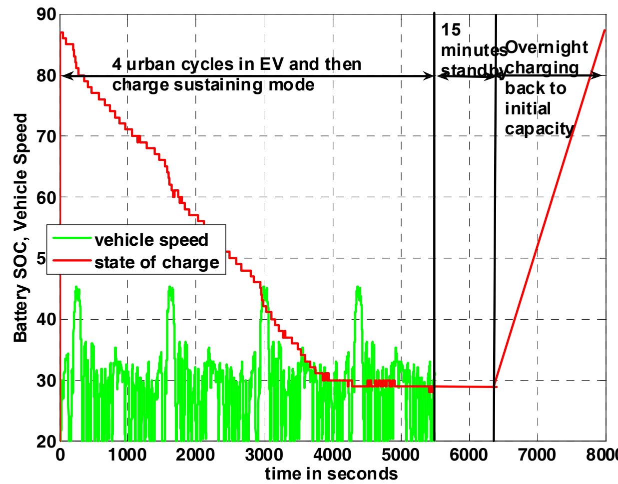


Figure 9. Plot of Vehicle SOC versus Time to Explain Round-Trip Efficiency Calculations

For this particular experiment, battery round-trip efficiency is defined as the ratio of battery energy depleted during the AER and then charge-sustaining mode of operation for the four urban cycles to the energy required to charge the battery back to the original starting capacity by using power from the wall (grid charging). (Refer to the equation below.)

$$\text{Roundtrip battery efficiency} = \frac{\int_0^{drivecycle\,time} Vb * Ib \, dt}{\int_0^{overnight\,charge\,time} Vb * Ib \, dt}$$

The vehicle used for the experiment is the midsize pre-transmission parallel, with the same mass as in the AER test. The experiment was conducted for three ratings of DC power available for the battery, related to three possible ratings of power available from the wall.

Table 3 shows the possible DC power available to charge the battery, based on 3 possible power values available from the wall.

Table 3. DC Power Assumptions, Based on Power Available from the Wall

Plug rating	Assumption on DC power available
120 V AC, 15 Amp	1.4 kW
120 V AC, 20 Amp	2 kW
208/240 V AC, 30 Amp	6 kW

Figure 10 shows the round-trip efficiency for the three different DC powers available to charge the battery (blue curve – Y axis on the left). The pink curve shows the charging current (DC) corresponding to the DC charging power available.

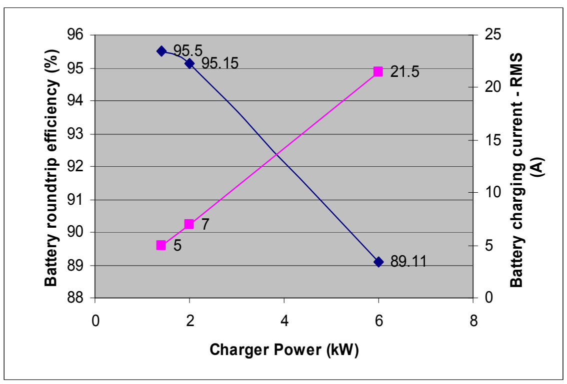


Figure 10. Battery Round-Trip Efficiency as a Function of DC Power Available from the Charger

5. Investigated the sensitivity of vehicle fuel economy to battery SOC in charge- sustaining mode at 20°C ambient conditions.

The battery was subjected to charge- sustaining tests at 20°C for different low (35% to 20%) SOCs. The main focus of this study was to evaluate the change in battery performance with the change in SOC and to assess its potential impact on vehicle fuel economy in charge-sustaining mode. The vehicle was a midsize pre-transmission parallel hybrid, similar to the one used for earlier studies. The virtual vehicle was subjected to consecutive urban cycles in charge-sustaining mode. Figure 11 shows the plot of battery efficiency and estimated fuel economy for different low SOCs.

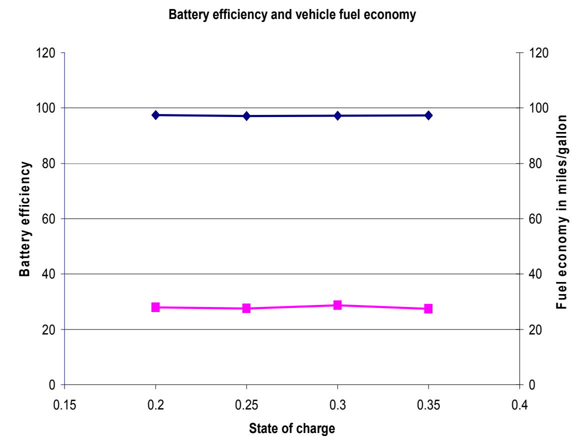


Figure 11. Battery Efficiency and Estimated Vehicle Fuel Economy in Charge-Sustaining Mode for Different States-of-Charge

6. Initiated ultra-capacitors and battery active power sharing experiment.

Ultra-capacitors, when connected to the battery/DC bus through a buck-boost converter (Figure 12), are able to absorb/supply significant amounts of traction power, as compared with direct coupling of ultra-capacitors to the DC bus. This arrangement is of high significance in a plug-in hybrid, where the battery is expected to provide a significant amount of highly transient traction power over a wide SOC window and a wide temperature range. Such battery utilization has a negative impact on battery life. Active power sharing with the ultra-capacitors can greatly reduce this stress on the battery.

Argonne is collaborating with Maxwell Technologies to validate the potential of active power sharing between the ultracaps and the battery.

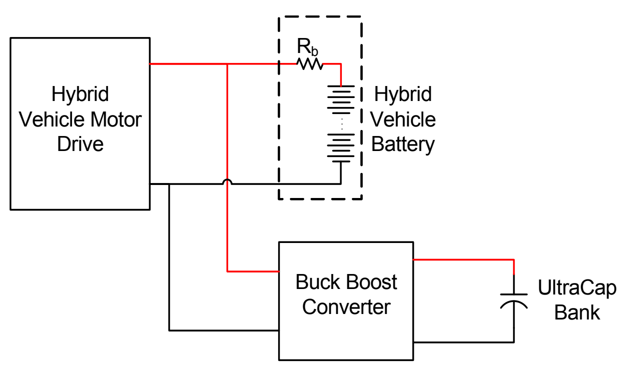


Figure 12. Active Coupling between a Battery and an Ultra-Capacitor — Electrical Block Diagram

Towards this end, ANL has conducted some simulation studies on this concept of active power sharing. Figure 13 (a and b) show the difference between the battery current and the current slew rate, with and without the active power sharing with the ultra-capacitors.

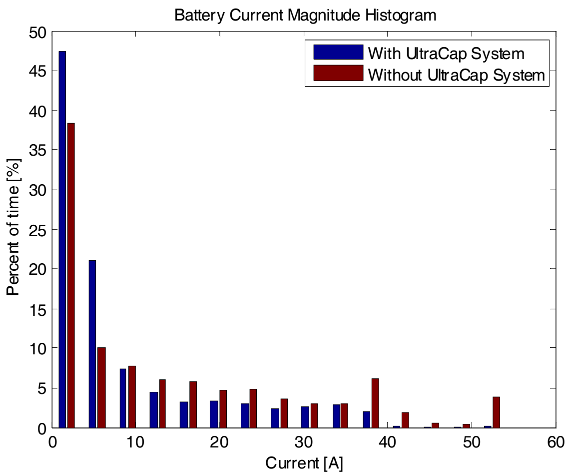


Figure 13 (a). Current Distribution With and Without the Ultra-Capacitors

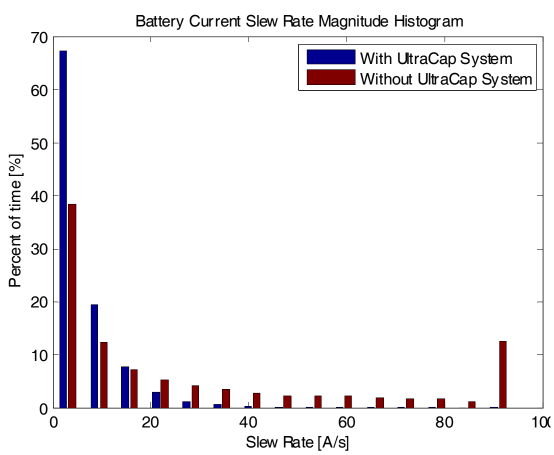


Figure 13 (b). Current Slew Rate Distribution With and Without the Ultra-Capacitors

A proof of concept "miniature HIL" set-up also has been produced for control development (Figure 14).

Figure 14. A Miniature HIL Set-up for Proof of Concept and Control Development

7. Began outfitting of the new permanent Energy Storage Systems HIL lab.

A permanent battery testing facility, called the Energy Storage Systems HIL Lab, is being constructed in building 371. This facility will be dedicated to electric energy storage technology evaluation geared toward investigating solutions for PHEV applications. The new lab will be equipped with a new ABC-170 high-voltage DC power supply and an environmental chamber to simulate hot, cold, and normal ambient conditions for the battery.

Future Work

Testing of the VL41M battery will continue for FY08. The testing will involve battery evaluation under different thermal conditions, as well as vehicle-level control studies to compensate for battery performance at low temperature and to restrict battery usage at high temperature.

Other batteries, as they become available, will be benchmarked by using the HIL technique and will be compared to the VL41M.

Conclusion

Version 1 of the Battery HIL test set-up is complete. Component and system evaluation of JCS-VL41M is under way, with several results being obtained for the battery. Work on the Ultra Capacitor-Battery HIL experiment has been started. A new Energy Storage Systems HIL Lab is being set-up to further enhance Argonne's hardware-in-the-loop capabilities.

Papers/Presentations

1. Neeraj Shidore, Henning Lohse-Busch, Ryan W. Smith, Ted Bohn, and Philip B. Sharer, "Component and Subsystem Evaluation in a Systems Context Using Hardware-in-the-Loop," presented at the VPPC 2007 conference at Arlington, TX, USA, August 2007.

2. Aymeric Rousseau, Neeraj Shidore, Richard Carlson, and Vincent Freyermuth, "Research on PHEV Battery Requirements and Evaluation of Early Vehicle Prototypes," presented at the AABC 2007 Conference, California, USA, May 2007.

3. Ted Bohn, "Plug-in Hybrid Vehicles: Decoupling Battery Load Transients With Ultra-Capacitor Storage," presented at the Advanced Capacitor World Summit, California, USA, July 2007.

C. Design and Construct PHEV to Demonstrate/Validate All-Electric Range Capability

Theodore Bohn (Project Leader)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-9239, e-mail: TBohn@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Develop prototype PHEVs with all-electric range capability to demonstrate and evaluate impact of various component characteristics and control strategies on net petroleum displacement.
- Establish a baseline set of vehicle-level PHEV performance metrics to fill the need generated by the lack of fully capable production plug-in hybrid electric vehicles.
- Provide a platform for blended mode PHEV to aid in development of up-to-date PHEV testing procedures, such as all-electric range capability studies for SAE J1711.
- Evaluate the apples-to-apples comparison of PHEV blended mode operation with different capacity energy storage as well as evaluate impact of control strategies with similar energy storage systems.
- Work with automotive OEMs and other national laboratories to leverage current state-of-the-art PHEV research with ANL PHEV research.
- Use these PHEV prototypes for public outreach events to enlighten media and others about challenges and possible solutions to achieve maximum petroleum displacement for a production/vehicle cost target that may be achievable in the next decade.

Approach

- Evaluate Sizing and Applicability of Component Technologies: The suitability of various production vehicle hardware components for PHEVs needs to be examined. The latest in vehicle powertrain controllers, batteries, power electronics, and electric machine technology were evaluated for a relatively state-of-the-art, feasible ensemble of technologies within the time available.
- Construct multiple prototype PHEV vehicles with various powertrain topologies as component evaluation platforms.
- Develop in-house foundation of vehicle-system level controls in ANL embedded control systems (APECS) lab.
- Leverage PSAT control strategies for vehicle level experiments as a comparison and contrast between vehicle modeling results and hardware level vehicle testing results.
- Leverage ANL-APRF capabilities such as battery hardware-in-the-loop (HIL), MATT-HIL, ChallengeX student competition PHEV vehicle insights and ANL vehicle level benchmarking (PHEV Prius, Escape, Civic, Camry, etc) test data insights.
- Use and quick turn around ANL machine shop for precision components to construct prototype PHEV; modified stock charge sustaining HEV vehicle.
- Outsource hardware fabrication, directly supervised with very specific deliverables
- Collect vehicle (on-road/dynamometer) data using CAN based ARDAQ system.

- Share monthly project status updates with component and vehicle OEMs in the process of implementing off-the-shelf components, such as battery systems, battery controllers, motor-drive systems, and vehicle level interface issues.
- Use press releases about ANL PHEV research to attract the media and political figures to use DOE/ANL PHEV research as an example to make their point about green research (i.e. what is the government doing to help the environment/energy security).

Accomplishments

- Argonne acquired a prototype version of the GM Saturn Vue Green Line Hybrid equipped with GM's Belt-Alternator-Starter system (BAS), which is a mild hybrid that turns off the engine during idle and coasting and provides electric motor/generator assist during acceleration and regenerative braking.
- This Saturn Vue Green Line platform has been converted to a though-the-road (TTR) electric hybrid by installing an electric motor-powered driven axle in the rear of this normally FWD vehicle.
- All of the major hybrid drivetrain components were sized for all-electric range capability. Argonne has acquired a Unique Mobility 75kW permanent magnet motor, as well as an AC Propulsion AC induction motor to be evaluated as candidates for the electric propulsion.

- A Johnson Controls/SAFT VL41M lithium-ion battery (41 Ah) to provide power to the added electric motor propulsion at the rear axle in PHEV mode.
- Evaluated PHEV component requirements for a cross-over sized PHEV as well as a Chevy Volt sized PHEV sedan.
- Evaluated feasibility of available PHEV components that leveraged current ANL PHEV modeling and HIL work. (i.e. components that have existing model information).
- Purchased compatible set of PHEV components for prototype vehicles and developed in-house capability to control these components at the system level.
- Using pre-production Saturn Vue Green Line mild HEV, constructed a CUV sized fully capable PHEV prototype (through-the-road parallel) with 10kWh Li-ion battery, 75kW rear traction drive system that has blended mode as well as all electric range operation.
- Constructed fully capable (series) PHEV hybrid vehicle with Chevy Volt-like capabilities (5 kWh NiCad, 10-16kWh A123 Li-ion battery, 150kW traction motor, flex fuel engine/generator).
- Preliminary vehicle level controls implemented in Simulink, based on existing PSAT models/results.
- Expanded off-the-shelf CAN based data collection module into ruggedized, field tested ARDAQ system, complete with automated quality assurance checking Labview software. Validated data collection capabilities on prototype PHEVs.
- Conducted several PHEV-community related outreach events with Illinois congressman Mark Kirk as well as demo/display at 2007 HybridFest event.
- Vehicle simulation results used to develop SAE J1711 test procedures.

Future Directions

- Develop PHEV Control System Algorithms: Designing the proper hybrid vehicle control system can have a profound impact on vehicle energy consumption and dynamic performance. Several PHEV vehicle control algorithms have been simulated by using PSAT. Many of these variations in controls will be evaluated for their effects and trade-offs on fuel consumption, charge-depletion rate, and all-electric-range, as well as on other novel charge-depleting strategies. The focus, as in all PHEV research, will be to provide the best duty cycle for the chosen battery pack to show the capabilities of the PHEV. In a much longer time-frame project, the powertrain would likely be more optimized to resemble a production-intent design.

- Acquire Weber AG flex fuel MPE750 engine for series hybrid engine/generator, and implement in series PHEV constructed in FY2007.
- Use both PHEV prototypes as component evaluation platform for batteries and motors.
- Design and perform experiments using these two PHEV prototype vehicles to evaluate and refine controls software to investigate impact on fuel economy and performance.
- Report Results: The APRF 4WD chassis dynamometer data, as well as in-use vehicle data, will be provided. These results will be combined with other benchmarking efforts to provide a solid understanding of the current state of the art in PHEV hardware and its vehicle-level performance metrics. These inputs are critical to DOE's multi-year plan in setting targets and performance metrics for the entire PHEV effort.

Introduction

As part of Argonne's multifaceted PHEV research program, Argonne researchers have constructed a PHEV prototype that serves as a rolling test bed to assist in the development of advanced electric vehicle drivetrain components, control systems, and test procedures for competitive evaluation.

The lack of production plug-in hybrid electric vehicles (PHEVs) has generated the need to find a baseline set of vehicle-level PHEV performance metrics. Several charge-depleting (CD) PHEVs will be benchmarked in other annual operating plan tasks. What is missing is a good benchmark that extends the PHEV into a vehicle fully capable of providing an all-electric range (AER). Therefore, Argonne's objective is to build PHEV designs of varying electric capability by using hardware that has OEM support. Using as many off-the-shelf components as possible will shorten the prototype vehicle construction time to fit within necessary program timeframes.

Approach

Purchasing a production-level hybrid electric vehicle as starting point helps to avoid a major vehicle fabrication project that could not be supported in the limited time available. Fortunately, we were able to obtain a pre-production prototype version of the GM Saturn Vue Green Line Hybrid equipped with GM's Belt-Alternator-Starter system (BAS) shown in Figure 1, which is a mild hybrid that turns off the engine during idle and coasting and provides electric motor/generator assist during acceleration and regenerative braking.

In addition to the internal combustion engine/transmission powering the front wheels of the vehicle, Argonne added a second electric drive powertrain to power the rear wheels. This powertrain consists of a 100-HP electric motor drive/transaxle that derives its energy from a liquid-cooled Saft-JCS 10-kW Li-ion battery pack and battery charger. This battery pack has greater energy storage capacity than those used in typical hybrid vehicles on the road today, and it is designed to be "plugged-in" to an electrical outlet to charge the battery overnight. Unlike currently available HEVs, the through-the-road (TTR) vehicle's additional powertrain allows the vehicle to operate on electricity only, up to highway speeds, for commuting to work or local errands — without having to start the conventional gasoline engine.

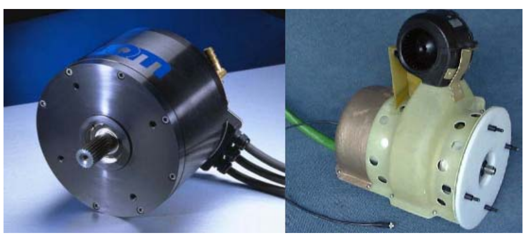
Figure 1. Argonne's Saturn Vue Installed on 4WD Chassis Dynamometer

The purpose of creating a custom-designed PHEV is to use it as a testing mule to investigate the range of electric hybrid vehicle operating modes (including all-electric operation) and various charge-depleting modes to determine optimized fuel-saving operation versus drive cycle. This PHEV test bed can also be used to validate many of the control strategies predicted by PSAT modeling and simulation efforts that have been published recently. Finally, we intend to use this tool to assist in the validation of the SAE J1711 PHEV fuel economy testing procedures, and Argonne has a leading role in helping to develop these procedures for the auto industry.

Accomplishments for FY07

1. Completed Electric Motor Sizing

All of the major hybrid drivetrain components were sized to provide adequate torque for all-electric range capability. Argonne has acquired a UQM permanent magnet motor that provides 75 kW peak power, as well as an AC Propulsion AC induction motor that provides 150 kW peak power, to be tested as candidates for providing electric propulsion (Figures 2 and 3). The different motor technologies and spread of power output will be evaluated for performance comparisons.



Figures 2 and 3. The UQM and AC Propulsion Motors, Respectively

2. Acquired initial choice of battery pack to provide All-Electric Range capability

The battery being evaluated for plug-in applications to provide power to the added electric motor propulsion at the rear axle in PHEV mode is the liquid-cooled, SAFT-Johnson Controls 41-A·h Li-ion battery. Figure 4 shows a picture of the battery.

Figure 4. JCS 41-A·h Li-Ion Battery

Some battery-level specifications are listed in Table 1.

Table 1. JCS 41-A·h Battery Specifications

Cell capacity	41 A·h nominal
Nominal voltage	259.2 V
Voltage range	194.4–288 V
Continuous current	150 A at 30º C
Operating temp.	10–40º C

3. Installed electric motor and differential unit in the GM Saturn Vue Green Line to enable it as a Through-the-Road (TTR) electric hybrid powertrain

Named the TTR, for through-the-road parallel hybrid electric vehicle, our Saturn Vue Green Line platform has been modified by installing an electric-motor-powered driven axle in the rear of this normally FWD vehicle. In other words, the hybrid electric function is connected to the main drivetrain through the tractive efforts of the motor-driven rear axle on the road. This was accomplished by coupling a Honda Civic transaxle to serve as the driven differential in the rear of the Saturn Vue (see Figures 5 and 6).

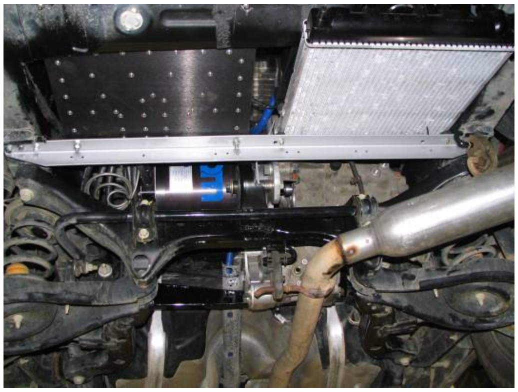


Figure 5. Detail of Honda Civic Transaxle Installation

Figure 6. Installation of the UQM Electric Motor to the Rear Transaxle Assembly

Some modifications were made to the stock Saturn suspension to accommodate the extra weight of the battery pack. A new exhaust system was fabricated to replace the stock system routing that would have interfered with the added rear differential.

4. Integrated the electric machine components in the TTR PHEV vehicle

Whereas most of the major components (including the UQM motor, the JCS VL41M battery pack, and support components) have been packaged and installed in the vehicle (Figure 7), the addition of the battery charger and wiring needs to be completed. All of the low-level operational interface code has been written for the installed components.

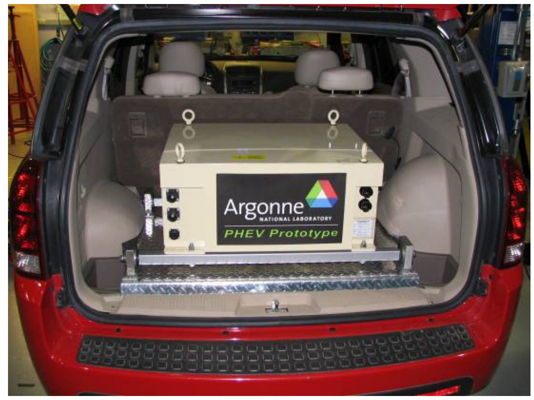


Figure 7. JCS 41 Ahr Li-Ion Battery Installed in Vehicle

5. Developed the PHEV system control strategy

Many hours of chassis dynamometer time were used to investigate the operation of the stock belt-alternator-starting (BAS) system. More specifically, we attempted to determine how the existing system circuits could be tapped into and controlled by the new PHEV control strategy. The objective is to be able to restart the engine at higher speeds and allow it to augment the electric machine system. The hybrid controller, the high-level control strategy to make it all work together like a PHEV, is being developed in FY08 as part of a project goal.

6. Implementation of Series hybrid PHEV with Chevy Volt Sized Components

Using a Chevy Geo Metro lightweight chassis (on hand at ANL), a series PHEV prototype vehicle was created using components sized similar to the Chevy Volt PHEV prototype.

Figure 8. Series PHEV Prototype

6.1. Implementation of Series hybrid PHEV with Chevy Volt Sized Components

A 150kW AC Propulsion traction drive and transaxle installed in place of engine, shown below. This drive system also has 20kW of Vehicle-to-Grid operation capability.

Figure 9. 150kW Traction drive/axle

6.2. PHEV Battery Evaluation platform.

Rear area of series hybrid vehicle opened up as a platform for various batteries. The first battery, shown below, is 3X of the 2007 Camry/Panasonic NiMH pack (5kWh total).

Figure 10. 5kWh NiMh Battery

6.3. Flex Fuel Engine/Generator

Imported 750cc 75kW flex fuel based Weber AG MPE750 engine/generator installed in rear of vehicle.

Figure 11. 75kWh Flexfuel engine/gen.

Conclusions

The design and development of the TTR PHEV evaluation vehicle at Argonne will be extremely useful in learning about the impacts of control strategy on hybrid fuel savings. The TTR parallel PHEV being created will have the ability to run in an all-electric mode, employ various strategies of charge depletion, and function as a charge-sustaining hybrid. This vehicle will serve to fill the R&D gap that exists right now due to the absence of production-level PHEVs.

Publications/Presentations

1. Advanced Capacitor World Summit- July 2007
2. On display at HybridFest, Madison WI, July 2007

IV. LABORATORY TESTING AND BENCHAMARKING

A. Benchmarking and Validation of Hybrid Electric Vehicles

Michael Duoba (Project Leader)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-6398, e-mail: mduoba@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Provide operational data during chassis dynamometer testing by using novel instrumentation for:
  - 2007 Camry HEV (Level 1)
  - 2006 Civic HEV (Level 1)
  - 2006 Saturn Vue Green Line (Level 1)
  - 2005 Ford Escape (Level 2)
  - 2007 Camry HEV (Level 2)
  - 2005 Accord HEV with Indicated Engine Torque Sensor (to be compared with transmission input torque sensor)

Approach

- Vehicle, manufacturers' service manuals, and diagnostic tools are purchased for the vehicles tested.
- In the case of the Level 1 testing, engine speed, battery current and battery voltage are instrumented.
- In the case of the Level 2 testing, axle torque sensors are installed and an experimental custom engine (transmission input) torque sensor is designed and developed with instrumentation suppliers.
- Also for Level 2 testing, vehicles are wired for instrumentation of major components for speed and easily found stock sensors.
- Tests are run for cycle fuel economy, performance testing, and steady-state load testing for all the vehicles.

Accomplishments

- The Advanced Powertrain Research Facility (APRF) data acquisition system was modified and improved for higher productivity and more modular and higher-quality data.
- An indicated engine torque measurement system was used to collect engine torque data on the Accord HEV. This vehicle also has an engine torque sensor at the transmission input. Data that are simultaneously collected from both sensors were compared and correlated as an experiment to demonstrate the viability of using indicated engine torque measurement to avoid the expense and delays associated with using dedicated engine torque sensors mounted on the input shaft.
- Camry HEV Level 2 testing produced insightful data on the latest hybrid technologies and controls systems from Toyota.

Future Directions

- Argonne will further evaluate engine torque measurement instrumentation, which may be a viable and more cost-effective alternative to the time-consuming and expensive addition of an engine flywheel torque sensor.
- Argonne will address hybrid test-to-test variability by incorporating an industry-standard robot driver.

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 data are applicable to virtually every effort in the FreedomCAR partnership, and all of the "Tech Teams" benefit from the data collected in the Advanced Powertrain Research Facility (APRF) at Argonne's Center for Transportation Research.

Approach

Level 1 testing is conducted to acquire the high-level data in a reduced time frame. Level 1 testing uses less component instrumentation and does not require as the vehicle to be extensively broken down, but it delivers less data. Battery current and voltage, engine speed, emissions data, and fuel economy are recorded and analyzed. However, Level 1 testing is a desirable approach for HEVs that do not represent leading-edge technology.

Level 1 — Model Year 2007 Camry HEV

The Camry HEV (Figure 1) was tested by using Level 1 instrumentation. As compared to the Prius, the Camry HEV is larger and more refined but does not achieve comparable fuel economy. Also, the powertrain is very similar to the Prius, but is has a larger engine and several control differences, including engine-on/off operation. This vehicle was tested in cooperation with Idaho National Laboratory (INL) and the Advanced Vehicle Testing Activity (AVTA).

Figure 1. Toyota Camry HEV Level 1

Level 1 — Model Year 2006 Honda Civic HEV

The Honda Civic HEV (Figure 2), with Level 1 instrumentation, was tested for fuel economy and emissions. The Civic HEV is a parallel HEV configuration with a CVT transmission. The fuel economy was rather high, but it lacked performance with a 0–60-mph time of 14 seconds. This vehicle was tested in cooperation with INL and AVTA.

Figure 2. Honda Civic Level 1

Level 1 — Model Year 2007 Saturn Vue Green Line (BAS HEV)

The Saturn Vue Green Line (Figure 3) uses belt alternator starter architecture (BAS) as a low-cost solution to enable engine start/stop and regenerative braking. The vehicle was tested for fuel economy and emissions with Level 1 instrumentation. This vehicle was tested in cooperation with INL as part of the AVTA.

Figure 3. Saturn Vue Green Line Level 1

Level 2 — Model Year 2005 Accord HEV Torque Sensor Comparison

The Accord HEV (Figure 4) was tested last year by using Level 2 instrumentation. The engine torque sensor that Argonne added (Figure 5), which was located on the input to the transmission, provides extremely valuable information for determining engine efficiency and control strategies. However, the torque sensor is expensive and, because of the required custom fabrication, has a very long lead time.

Figure 4. Honda Accord HEV with Indicated Torque

A possible alternative solution is to use in-cylinder pressure sensors to measure indicated torque (Figures 5 and 6). Although custom spark plugs are required for the system to hold the high-precision pressure transducers, the time to implement the system is much shorter than that required for the torque sensor, and the cost may also be less if the system is used with several vehicles.

Figure 5. Indicated Torque System for Measuring In-Cylinder pressure (pressure transducers are placed inside custom spark plugs)

Figure 6. Honda Accord HEV with Indicated Torque Sensor (pressure transducers are inside the spark plug)

The correlation between the indicated torque measurement and the flywheel torque measurement shows frictional losses from the engine bearings, oil windage, and the drive belt accessories that add up to approximately 9 Nm (Figure 7). The small amount of scatter in the data is from transient noise in both measurements.

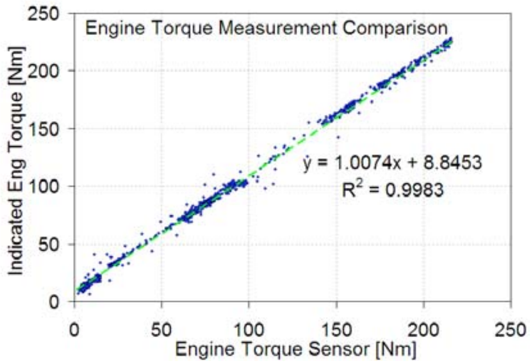


Figure 7. Indicated Torque Sensor in Comparison with Flywheel Torque Sensor

Level 2 — Model Year 2005 Ford Escape HEV

The Escape HEV (Figure 8) tested was an AWD model. It was instrumented with an engine torque sensor, front CV torque sensors, and a rear axle torque sensor. This instrumentation provided efficiency and control logic of the driveline power distribution through all modes of propulsion and regenerative braking.

Figure 8. Ford Escape HEV Level 2

Level 2 — Model Year 2007 Camry HEV

The Camry HEV (Figures 9 and 10) was tested with level 2 instrumentation, but in place of an engine torque sensor, the indicated torque system was used. Other instrumentation included the Hioki power meter for measuring voltage and current, the direct fuel flow scale, and an extensive number of signals recorded from the CAN bus.

Figure 9. Toyota Camry HEV Level 2

Testing revealed control systems strategies for SOC control during normal operation and those for abuse conditions. The typical SOC window was 57–70%, but during repetitive maximum accelerations, the SOC fell to 35%. Also, maximum acceleration tests revealed an interesting difference from the Prius. The power output from the battery during accelerations did not diminish after eight consecutive 0–80-mph events. The Prius reduces battery power as the battery temperature increases after only a few accelerations. Both vehicles did show a decrease in regenerative braking power after several consecutive 0–80-mph events.

Figure 10. Toyota Camry HEV Level 2

Conclusions

The APRF at Argonne has become a powerful tool for gathering data from the most advanced powertrains at a level of detail not available anywhere else in the industry. The OEM partners in FreedomCAR have become close collaborators in terms of sharing time and equipment, and they benefit significantly from the testing programs and studies performed at Argonne's Center for Transportation Research. In addition, Argonne is constantly introducing new instrumentation methods, like the indicated torque measurement equipment to replace the engine output shaft torque sensors, which will improve torque data acquisition reliability and reduce the effort and time delays encountered when no longer removing the engine to insert a custom fabricated torque sensor. Such new testing methodologies will also allow us to collect torque readings from a larger subset of vehicles being tested each month.

Publications/Presentations

1. Duoba, M., et al., Analysis of Power-Split HEV Control Strategies Using Data from Several Vehicles, SAE 2007-01-0291, 2007.

B. Advanced Hydrogen Vehicle Benchmarking

Michael Duoba (Project Leader)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-6398, e-mail: mduoba@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Prepare test facilities and test procedures to take advantage of testing more optimized hydrogen internal combustion engines (H-ICE) and vehicles that will be available for testing in FY07.
- As always, if a fuel cell vehicle is available for test, ANL's Advanced Powertrain Research Facility (APRF) will capitalize on the opportunity to exercise the test lab and current test procedures and will report the findings.
- The challenge is in obtaining accurate and verifiable emission measurements as the test vehicles approach zero emissions capability. Alternatively, our efforts to introduce more refinement and optimization of the existing hydrogen measurement hardware will be validated with hydrogen vehicle testing.

Approach

- Collect vehicle data using Argonne's 4WD chassis dynamometer. For more details of the test facility refer to the efforts described in Section IV.A. Benchmarking and Validation of Hybrid Electric Vehicles.
- Adapt testing methods to measure fuel consumption of non-hydrocarbon-based fuels such as hydrogen.
- Perform mathematical analysis to verify quality control of the data.

Accomplishments

- Performed testing on two H-ICE vehicles.
- Collaborated with BMW engineers to adapt 4WD facility to measure non-hydrocarbon fuel consumption using water content of vehicle exhaust.
- Identified key areas to improve test cell and testing methods for H-ICE vehicles and fuel cell vehicles.

Future Directions

- Test new and unique vehicles that utilize hydrogen as a fuel source.
- Test production-intent liquid hydrogen H-ICE vehicles from BMW.
- Refine fuel consumption methods that are based on water content in the exhaust.

Introduction

Hydrogen as a vehicle fuel is still being researched to continue to resolve the technical and social barriers that exist. Argonne National Laboratory continues to test prototype and proof-of-concept hydrogen vehicles to better understand the fuel consumption, emissions, performance, and testing methods.

This year ANL has integrated a new fuel consumption measurement technique that measures the water content of the exhaust — which is directly proportional to fuel consumed by the vehicle. This method is advantageous because it requires no modification or interruption of the fuel system to measure fuel consumption.

Approach

Hydrogen internal combustion engines (H-ICE) can achieve near-zero regulated tailpipe emissions. However, early concepts of H-ICE demonstrated significant challenges associated with NO_x production and hydrocarbon slip while still maintaining a reasonable specific power of the engine. With additional development over the past 4 years, H-ICE-powered vehicles are now achieving lower NO_x and hydrocarbons and continuing to increase specific power of the engine.

ANL tested two different hydrogen-powered trucks this year to continue to benchmark our Advanced Powertrain Research Facility's (APRF's) capabilities to measure fuel consumption and emissions of hydrogen-powered vehicles, as well as better understand how H-ICE function in a vehicle system.

Figure 1. Hydrogen-Converted Truck Being Tested at APRF

Figure 1 shows one of the two truck-based hydrogen vehicles that we have tested that are part of a demonstration fleet being run by Electric Transportation Engineering Corporation (eTec) under the DOE Advanced Vehicle Testing Activity (AVTA). These vehicles return to ANL twice a year for a durability study that we are also performing.

Our current method of measuring fuel consumption is by the way of an accurate electronic mass flow measurement meter. However, to use this flow measurement equipment with our integrated hydrogen supply system requires us to incorporate these flow meters into the vehicle system. For some vehicles, this is impractical or impossible. Hydrogen fuel delivery system integrity is the key to safety and repeatable operation.

In an effort to improve the quality of the data collected on hydrogen powered vehicles, we have collaborated with BMW engineers to incorporate water-based fuel consumption calculations into our vehicle testing facility. The hydrogen converted trucks have been used to integrate a new hydrogen fuel consumption measurement. Because hydrogen is consumed as a diatomic molecule in its gaseous state, it is not possible to count carbons to determine fuel consumption via our emissions bench. Therefore, if we want to determine fuel consumption via emissions alone, we must measure the water content of the exhaust and ambient air used by the emissions sampling system.

Figure 2 shows the water analyzer that is being used to measure water content of the exhaust. The host system, which choreographs the vehicle tests, had to be modified to use this new measurement technique.

Figure 2. Analyzer to Measure Water Content in Exhaust Stream

For the new water vapor measuring method, all water that is used or generated in the operation of the vehicle or for the dilution requirements of the emissions sampling system must be accounted for. Water enters the vehicle via humidity through the vehicle's intake system, and water is generated in the engine as a by-product of hydrogen combustion and exits the vehicle at the tailpipe.

The water analyzer only has the capability of measuring up to 5% by volume water vapor, while the tailpipe has anywhere from 5–80% water vapor by volume; therefore, we must highly dilute the tailpipe exhaust with dry air. The ratio between tailpipe flow and this dilute air flow is called the dilution ratio. Typically this ratio is calculated by counting carbons in the diluted tailpipe stream; however, this method requires the addition of carbon from the engine combustion, which does not occur in a hydrogen-powered vehicle. The dilution ratio is key to the calculation of fuel consumption and mass of other measured emissions (if any).

Additionally, to make these water fuel consumption measurements, all pipes containing vehicle exhaust emissions must be heated to 20–30 degrees F above the ambient temperature to prevent water from condensing on the surface of the transport system.

Findings

During our cycle testing of the hydrogen ICE trucks, we obtained the fuel consumption results plotted in Figure 3.

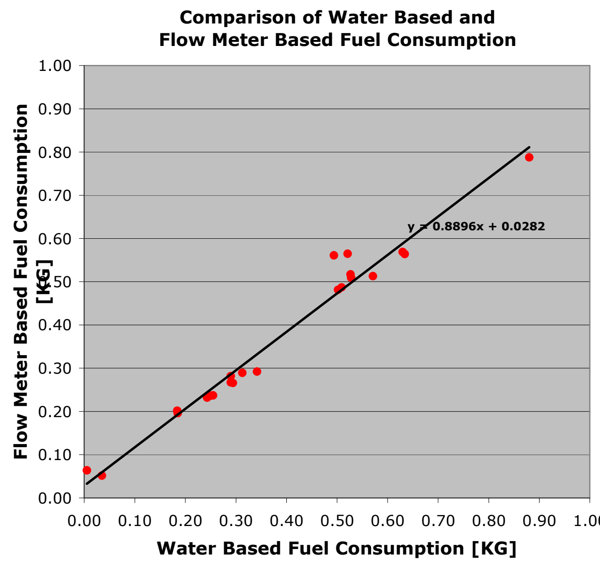


Figure 3. Comparison of Water-Based and Flow-Meter-Based Fuel Consumption

We have shown a linear correlation between fuel consumption via the meter-based measurement and the water-based measurement. However, our water-based measurement is 5–12% higher than our flow-meter-based measurement. After investigating further with our collaborating partners at BMW, we determined that the flow capabilities of our system are making our assumptions for dilution calculations invalid. For example, we have to run the dilution flow rate near the highest limit to achieve the desired dilution of tailpipe emissions.

Future Work

The following upgrades and changes to our system must occur for it to measure fuel consumption more accurately. A higher dilution air flow rate must be achieved to further reduce the water content by volume in the dilute exhaust. Doing so gives increased dynamic range and resolution to the water analyzer, which we were able to determine because results similar to those in Figure 4 were obtained.

Measurements above the red line in Figure 4 represent water levels above the direct measurement range of the meter. These values are being extrapolated by the emissions analyzer, and eventually at high enough levels are saturating the signal and causing loss of data.

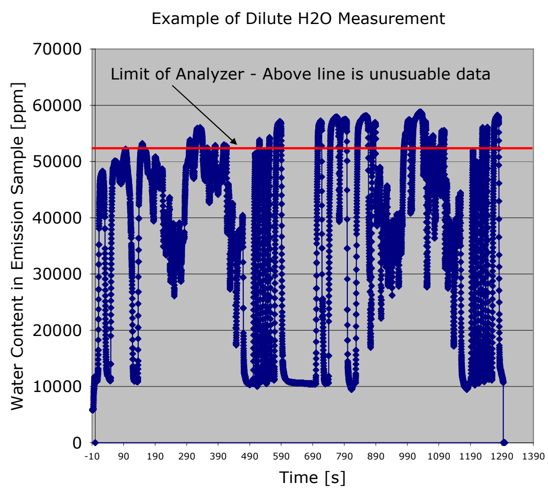


Figure 4. Example of water concentration in the exhaust stream.

However, to accomplish the higher dilution air flow rate, we must also increase the flow capabilities of the dilution mixing tee and the associated piping and plumbing. These are planned upgrades for FY08, when we will continue to validate the new water-emissions-based measurement system. This set of upgrades will make the APRF one of only a few such test facilities in the world that can accurately test emissions from H-ICE-powered vehicles with repeatable accuracy.

Conclusions

As we continue to refine our vehicle test facility we should have the opportunity to test other advanced hydrogen-powered vehicles that we could have not previously tested. Acquiring the water-based fuel consumption measurements, for example, will allow us to test vehicles such as the BMW Hydrogen 7. Additionally, other OEMs are demonstrating new fuel cell vehicles that we can potentially test using our new fuel consumption measurements. The anticipated hardware upgrades of our test cell should allow for better correlation between the flow meter and the tailpipe water measurement. Finally, we have added a unique capability and functionality to our vehicle test cell that very few labs in the world currently possess.

C. PHEV Test Methods and Procedures Development

Michael Duoba (Project Leader)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-6398, e-mail: mduoba@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Develop a viable (manageably short) set of chassis dynamometer test procedures specifically designed for plug-in hybrid electric vehicles (PHEVs) evaluated in the DOE's Advanced Vehicle Test Activities (AVTA) program.
- Work with SAE by chairing the industry subcommittee to rework the existing SAE J1711 standard for HEV test procedures, to accommodate the testing specifically of PHEVs.

Approach

- The AVTA program sends PHEVs converted from the fleet for testing at the Advanced Powertrain Research Facility's chassis dynamometer facility. Various approaches were tried before a workable "5-Day" procedure was sequenced based upon data needs.
- Over the course of the year, Argonne took delivery and installed in the highly instrumented Prius, two PHEV retrofit conversion kits. Results were gathered and shared with the SAE J1711 subcommittee monthly to develop both a long method and a minimum test method.

Accomplishments

- A "5-Day" AVTA test procedure was sequenced and was included in Idaho National Laboratory's (INL's) AVTA procedures.
- A minimum test method was crafted for use with "blended-type-operation" PHEVs and successfully tested using Argonne's HybridsPlus Prius and A123 Systems Hymotion Prius test vehicles.

Future Directions

- There are still major obstacles in setting a standard test procedure for PHEVs that can demonstrate an all-electric range mode of operation. Furthermore, the implications for emissions certification require that this procedure be closely developed with CARB and EPA. To the extent that the SAE J1711 subcommittee votes to approve these test procedures, they will be published worldwide as a recommended practice subject to the final adoption of the major regulatory agencies around the world.

Introduction

The principle characteristic of a plug-in hybrid electric vehicle (PHEV) is the ability to store electricity taken from the electrical grid by charging at home (or elsewhere) to be later used for propulsion power. This energy is depleted in some manner during driving, after which charge-sustaining operation would be required to continue driving longer distances. The depleting range is a result of how quickly the electric energy was used during the driving cycle, and this is affected by the maximum power capability of the PHEV.

When exploring how to apply test procedures, it helps to be specific about the type of electric propulsion power capability of the PHEV. Significant changes in engine operation (or lack thereof) represent the most significant hurdles in adapting test procedures for PHEVs that were originally suited for the operation of conventional vehicles. These definitions are in the context of grouping a wide array of possible PHEV designs into convenient categories useful in test procedure application. Certainly other definitions may be defined that are more applicable to customer operation.

The required wheel power to drive a Prius-sized vehicle was calculated for the urban dynamometer driving schedule (UDDS) cycle and plotted in Figure 1. Shown on the plot is the maximum electric propulsion power of the Toyota Gen 2 Prius of about ~20 kW at the wheel. Notice that there are several peak power requirements in excess of this level, thus the engine is required to meet the power demand. Notice the solid horizontal line of roughly 17 kW that represents the observed engine-on power levels for several retrofitted Gen 2 Prius PHEVs. "Blended-type" is a label for PHEVs that require engine assistance to drive the test cycle in question. This means that a blended-type PHEV will have an engine start sometime during each test cycle.

Approach

One fundamental approach to evaluating a PHEV for a given cycle is to charge the battery up to "full" and run a full charge test (FCT). This is essentially the drive cycle in question repeated in a series of tests run until charge-sustaining behavior is observed. In practice, running successive cycles poses new questions about how to impose initial conditions and how to apply a valid prep cycle. For this paper, the scope was limited to testing the Federal Test Procedure's UDDS and the HWY cycles. Note that EPA has specified a new, more comprehensive procedure to determine the EPA "label" mileage ratings that include results from the SC03, cold CO Federal Test Procedures, and the US06 tests, sometimes referred to as the "EPA 5-Cycle Test."

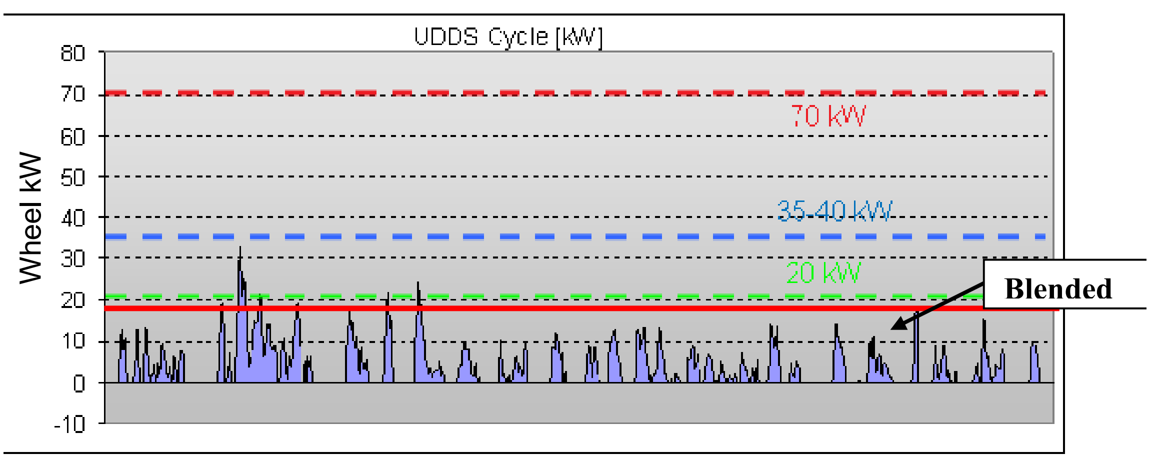


Figure 1. Wheel Power Requirements for UDDS Cycle

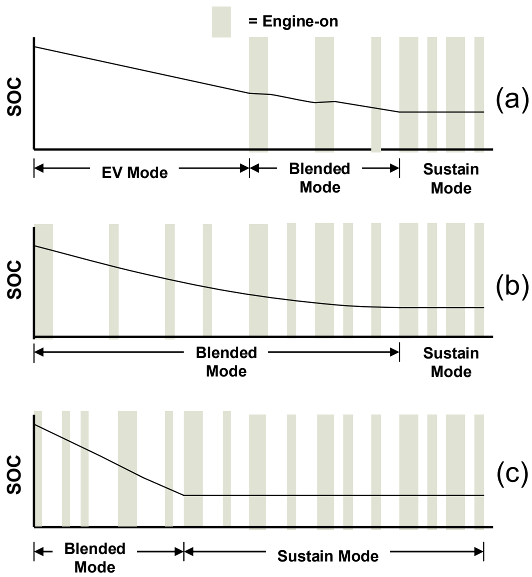


Figure 2. Gen 1 Hymotion Prius UDDS FCT

The objective of the FCT is to capture all possible operation of a specific test cycle from full charge to charge-sustaining. Figure 2 shows possible operational possibilities of a PHEV. Plot (a) represents a PHEV that has all the three basic operational characteristics: EV mode, blended operation, and sustaining operation. Plots (b) and (c) are for blended-type PHEVs. The controls for (b) appear to vary in discharge rate, whereas (c) maintains a constant discharge until the depleting SOC limit is achieved. As will be shown later, the PHEV depicted in (c) may be much easier to test because the depleting mode can be characterized more easily.

Testing the FCT

The first PHEV tested at Argonne National Laboratory was the first-generation Hymotion battery pack installed in ANL's highly instrumented 2004 Prius hybrid. The vehicle was tested according to a UDDS FCT and was found to have roughly 3.0 usable kWh. Figure 3 shows the results of the UDDS FCT.

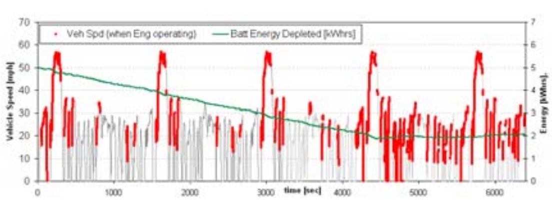


Figure 3. Gen 1 Hymotion Prius UDDS FCT

After the initial benchmarking of the Gen 1 Hymotion Prius, in May of 2006, ANL took delivery of an EnergyCS Prius vehicle to be tested as part of DOE's Advanced Vehicle Testing Activity (AVTA). ANL's role in the program is to dynamometer-benchmark PHEVs before entering (and retiring from) controlled fleet service and testing. The FCT approach was employed.

Figure 4 shows the results of the UDDS FCT for the EnergyCS Prius. Notice here just how many cycles were required to achieve charge-sustaining operation for this FCT. Thirteen UDDS cycles were run without interruption back-to-back with 10- minute soaks in between.

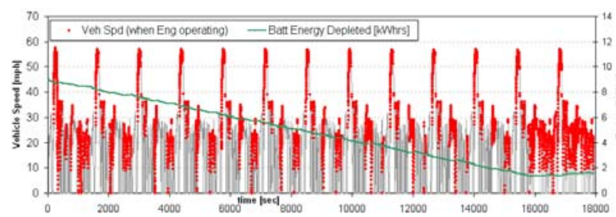


Figure 4. EnergyCS® Prius UDDS FCT

It was evident from these results that this approach may not be a practical solution for a vehicle with a very long charge-depleting range. However, the possibilities for a practical procedure for this PHEV were promising because the results show many of the tests were indeed redundant outputs, revealing similar operational behavior throughout the depleting range. Notice the depleting trend appears almost linear when viewed on a large scale (almost 5 hours of test data are shown).

AVTA "5-Day" Procedure

After these two preliminary PHEV testing projects, the AVTA program needed a standard procedure to follow for all its benchmark PHEVs. ANL developed a "5-Day" PHEV test procedure (included below) in order to satisfy the requirement of the program while keeping the testing time to a manageable one-work-week duration. The 5-Day PHEV test procedure is as follows:

ANL-Developed 5-Day PHEV Test Procedure

Day 1
- Set up vehicle and instrumentation
- HWY×2 w/ coast downs
- US06×2 2bag charge-depleting
- US06×2 2bag charge-sustaining (if time permits)
- Charge overnight

Day 2
- HWY×2 (cold start)
- HWY×2
- HWY×2 until a pair of charge-sustaining tests is completed
- UDDS prep
- Charge overnight

Day 3
- UDDS 2bag (cold start)
- UDDS 2bag
- UDDS 1bag until two charge-sustaining tests completed (max 6 UDDSs)
- DON'T CHARGE OVERNIGHT

Day 4 (Charge-Sustaining Day)
- UDDS charge-sustaining 2bag (cold start)
- UDDS charge-sustaining 2bag
- HWY×2 charge-sustaining
- US06×2 2bag charge-sustaining
- UDDS prep? (is prep needed when charging?)
- Charge overnight

Day 5 (A/C Day) (AVTA Specific testing)
- UDDS w/ A/C 2bag (cold start)
- UDDS w/ A/C 2bag
- HWY×2 w/ A/C
- HWY×2 until charge-sustaining w/ A/C
- UDDS charge-sustaining w/ A/C 2bag
- UDDS charge-sustaining w/ A/C 2bag
- HWY×2 charge-sustaining w/ A/C

HybridsPlus Testing

In July of 2007, ANL took delivery of a PHEV kit from HybridsPlus. This 9-kWh system comes in two packs and is a replacement for the stock NiMH pack. It was also installed in the instrumented Prius. The design has no passive activation of the "EV mode switch" and as a result takes a very long time to deplete charge. This design is an excellent candidate for minimum test methods.

For this vehicle, the critical assumption of constant discharge rate was verified with the control code developer. The vehicle was given a UDDS prep and then left on charge and soak overnight. Two UDDS cycles and two highway cycles were run to make up the data needed for charge-depleting operation. From that point on, all that was needed was some test cycles run until charge-depleting behavior was observed and the capacity recorded. Figure 5 shows the entire test sequence that was run from full charge to charge-sustaining.

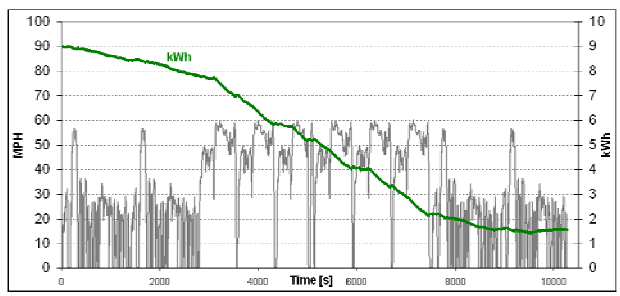


Figure 5. Hybrids Plus® Prius FCT

SAE J1711

For the SAE J1711 test procedure, it was decided that there would be two procedures developed. One would apply to a specific type of blended-type PHEV with predictable and stable depleting behavior, while the other would be a "catch-all" procedure that would apply to any other type of PHEV.

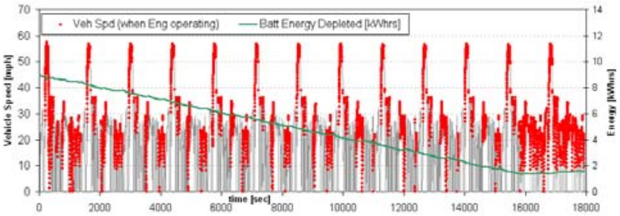


Figure 6. Example of a Linear Energy Depletion Mode

Notice in Figure 6 that on a scale of many cycles, the depletion rate was linear and stable. In this case there were many redundant tests collected. The minimum test method can be applied to these types of PHEVs. In fact, all the PHEVs tested thus far are candidates for the minimum test method. The procedure includes collecting depleting urban and highway results and finding the total usable capacity of the battery pack. Figure 7 shows the generic procedure.

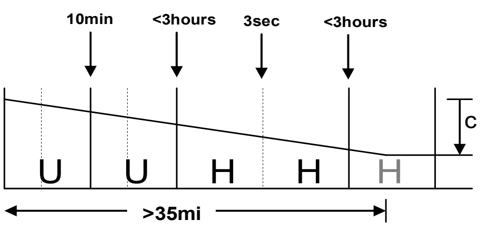


Figure 7. Depiction of Generic Procedure (U = UDDS, H = Highway cycles)

Conclusions

Since 1993, SAE J1711 Committee members have been attempting to tackle the challenge of developing a test procedure true to existing protocols for a radically different vehicle operating mode. Breakthroughs have been made recently because of the access to real working PHEVs and the insights provided from DOE's investment in the APRF state-of-the-art dynamometer facility.

A generic PHEV procedure was developed for the AVTA program and a minimum test method was developed for blended-type PHEVs for the SAE J1711 committee. These successes stress the importance of access to real working hardware to test and validate the continued development of open PHEV platforms also under development at ANL.

Publications / Presentations

1. Duoba et al., "Evaluating PHEV Technology Using Component HIL, Subsystem, and Chassis Dynamometer Testing: Methods and Results," HEV Symposium Presentation, San Diego, CA.

2. Duoba et al., "Test Procedures and Benchmarking Blended-Type and EV-Capable Plug-In Hybrid Electric Vehicles," paper to be published in EVS-23, Anaheim, CA, Dec. 2-5, 2007.

3. Duoba et al., "Test Procedure Development for 'Blended Type,'" paper to be published at SAE Congress, April 2008.

D. Benchmarking of Plug-In Hybrid Electric Vehicles

Michael Duoba (Project Leader)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-6398, e-mail: mduoba@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Provide operational data during chassis dynamometer testing using novel instrumentation for various converted plug-in hybrid electric vehicles (PHEVs):
  - Hymotion Prius with Kokum Li-Ion – Level 2
  - Renault Kangoo – Level 1
  - Hymotion Prius with A123 Li-Ion – Level 1
  - EnergyCS Prius – Level 1
  - HybridsPlus Prius 9 kWh – Level 2

Approach

- Measure energy usage from the vehicle's battery system(s) using the Hioki Power Meter, which includes current and voltage sensors. The Hioki meter also calculates real-time Ah and kWh.
- Measure tail pipe emissions from the vehicle. Calculate fuel economy from this emissions measurement through use of a carbon balance method.
- Collect data from vehicle control signals from the CAN bus.
- Tests fuel economy and emissions over the Federal Testing Procedure and HWY cycles.
- Level 2 instrumentation was utilized for the testing of the Hymotion Prius with the Kokum Li-Ion because it was installed in Argonne's 2004 Prius.

Accomplishments

- Results from preliminary testing and analysis of the Hymotion Prius at Argonne's Advanced Powertrain Research Facility aided calibration changes made by Hymotion, which resulted in their meeting SULEV emission levels.

Future Directions

- Investigate series and parallel PHEVs.
- Utilize indicated torque measurement system to characterize engine operation and efficiency during charge-depletion operation without the need for installing Level 2 instrumentation.

Introduction

Vehicle benchmarking combines testing and data analysis to characterize a vehicle's efficiency, performance, and emissions as a function of duty cycle, as well as to deduce control strategy under a variety of operating conditions. HEV benchmarking is a primary focus of the Advanced Powertrain Research Facility (APRF). Now that PHEVs are emerging, it is important to test, characterize, and benchmark the variety of PHEV designs and control strategies. The PHEV data benchmarking data is applicable to virtually every effort in the FreedomCAR partnership, and all the Tech Teams benefit from the data collected in Argonne's APRF.

Approach

During charge-depletion operation PHEVs use only a fraction of the fuel normally consumed in charge-sustaining operation. For this reason, the accuracy of data collected is of the highest importance. The APRF is able to produce results within repeatability of 1%.

Several vehicles were tested in the APRF over cold- and hot-start urban dynamometer driving schedule (UDDS) and highway (HWY) cycles in both charge-depletion and charge-sustaining operation. Full discharge tests, as well as an abbreviated test, were conducted to investigate the impact of the testing method on the results. Charging events were also collected and analyzed.

Hymotion Prius with Kokum Li-Ion Level 2

The first generation of the Hymotion system was installed in Argonne's 2004 Prius and was tested in the APRF (Figure 1).

Because this vehicle previously was instrumented to Level 2, the engine torque sensor was utilized to calculate engine efficiency. When compared with charge-sustaining operation, the PHEV Hymotion Prius engine efficiency was lower because of reduced load, which was caused by not charging the battery (Figure 2).

Figure 1. Hymotion Prius with Kokum Li-Ion and Level 2 Instrumentation

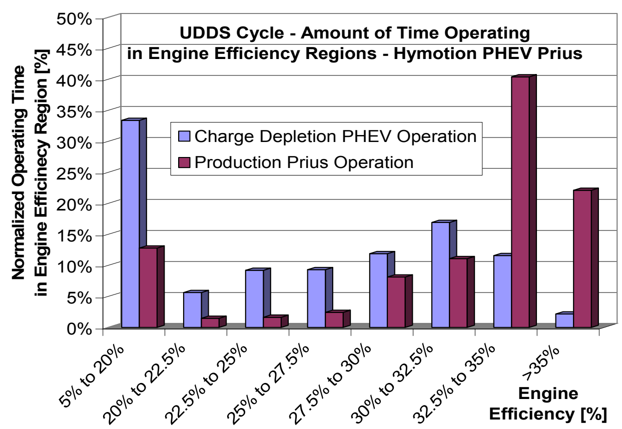


Figure 2. Hymotion Prius Engine Efficiency with Level 2 Instrumentation

EnergyCS Prius

The EnergyCS Prius uses a 9-kWh Li-Ion pack that replaces the production NiMH pack. Nearly all of the PHEVs tested had a nearly constant rate of depletion. The EnergyCS Prius was the exception. The rate of charge depletion decreased as the SOC decreased. This increased the charge-depleting range of the vehicle but the fuel consumption slowly increased with distance as the electrical usage decreased. This vehicle was tested in cooperation with Idaho National Laboratory (INL) and Advanced Vehicle Test Activities (AVTA) and is shown in Figure 3.

Figure 3. EnergyCS Prius Tested in Cooperation with INL and AVTA

Renault Kangoo – Series PHEV

The Renault Kangoo is a series PHEV and so far is the only example of a series PHEV available for testing in the APRF. This vehicle uses older technologies such as flooded NiCd batteries and crude control strategies (driver manual on/off engine switch). Despite these shortcomings, the data from this series PHEV is an important benchmark. This vehicle was tested in cooperation with INL and AVTA and is shown in Figure 4.

Figure 4. Renault Kangoo – Series PHEV Tested in Cooperation with INL and AVTA

Hymotion Prius with A123 Li-Ion

The latest generation of the Hymotion Prius, which utilizes A123 Li-Ion cells, was tested in the APRF (Figure 5). The system is a higher power system than previous generations, which enabled more electrical energy usage and thereby further decreased petroleum consumption. After several calibration revisions, aided from testing and analysis of previous Hymotion systems in the APRF, SULEV emissions levels were obtained for cold-start charge-depletion operation. This is a difficult milestone considering the dramatic change in the on/off engine operation of the engine when compared with the production Prius.

Figure 5. A123 Hymotion Prius Tested in Cooperation with A123 and Hymotion

HybridsPlus Prius 9-kWh pack

The HybridsPlus Prius, shown in Figure 6, utilizes two 4.5-kWh Li-Ion packs. Both packs were used for this testing. The control system has several differences, including not utilizing the "EV Button" of the Prius. This results in a rather low rate of depletion, which also results in reduced petroleum displacement.

Figure 6. HybridsPlus Prius with 9-kWh Pack

Comparison of the PHEVs Tested in APRF

Because PHEVs use gasoline and electrical energy, it is not simple to present the fuel economy of the vehicle as a single number. To aid in understanding the true energy utilization of the vehicle the fuel consumption is plotted versus the electrical energy usage (Figure 7). Electric-only operation would appear on the *x*-axis and charge balanced results would appear on the *y*-axis. Blended charge depletion operation is in between. Table 1 shows the fuel consumption and electrical energy consumption of the four PHEVs on the UDDS. Notice the four cold-start tests consume more fuel than the following hot-start test. Also notice the A123 Hymotion Prius consumes more fuel than the Kokum Hymotion Prius — the new calibration in the A123 Hymotion Prius increases the amount of engine operating time, warming up the catalysts in order to meet SULEV emissions.

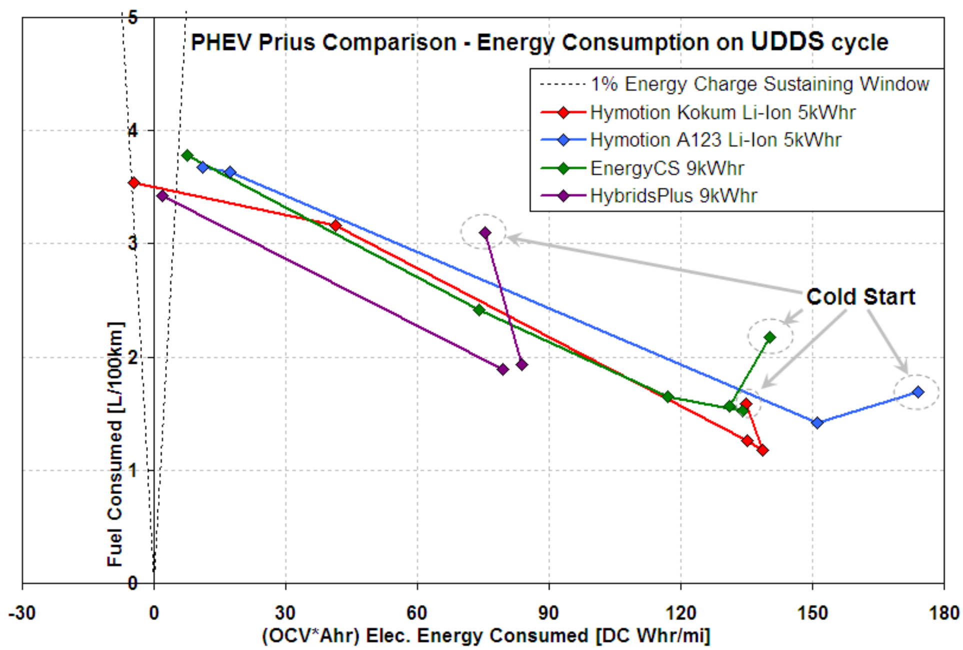


Figure 7. Comparison of Energy Consumption from Four PHEVs Tested on UDDS

Table 1. Comparison of Fuel Consumption and Electrical Energy Usage from PHEVs tested on UDDS in Charge Depletion Operation

	Hymotion Kokum Li-Ion, 5 kWh	Hymotion A123 Li-Ion, 5 kWh	EnergyCS, 9 kWh	HybridsPlus, 9 kWh
All-Electric Range on UDDS (mi)	0	0	0	0
Charge Depletion Range on UDDS (mi)	25	30	34.5	85 est.
Cold-Start UDDS				
(mpg)	147.9	139.4	108.2	75.9
(DC-Wh/mi)	134.9	174.1	140.2	75.5
Hot-Start UDDS				
(mpg)	200.4	165.5	149.9	122.0
(DC-Wh/mi)	138.7	151.1	131.1	83.9

The trade-off between fuel economy and emissions makes calibration a difficult task, but with PHEVs these trade-offs are more dramatic due to the sparse engine operation and higher engine load demands when operating. The production Prius meets the SULEV standard. Only one of the PHEV Priuses, the A123 Hymotion Prius, meets the SULEV standard.

The NOx and NMOG emissions of the four PHEVs are shown in Figure 8. Though the EnergyCS Prius nearly meets SULEV, only the A123 Hymotion Prius clearly falls below the SULEV limits.

The four PHEV Priuses have quite different engine control strategies as shown in Table 2. The Kokum Hymotion Prius control system minimized engine operation. This was changed in the A123 Hymotion Prius in order to meet SULEV emissions. The EnergyCS Prius used catalyst temperature as additional input for its control system to determine when to operate the engine. This caused the engine on/off operation to be irregular from cycle to cycle. The HybridsPlus Prius did not utilize the "EV Mode Button," in an attempt to utilize the production Prius' emissions-control routines, but this was unsuccessful at meeting SULEV emissions.

Table 2. Comparison of Engine Controls from Four PHEVs on the UDDS Cycle

Hot-Start UDDS Cycle	Hymotion Kokum Li-Ion, 5 kWh	Hymotion A123 Li-Ion, 5 kWh	EnergyCS, 9 kWh	HybridsPlus, 9 kWh
Typical Number of Engine Starts	8	12	10–30	12
Engine-On Time During UDDS (%)	17%	25%	16–22%	27%
"Prius EV Mode Button" Utilized?	yes	yes	yes	no

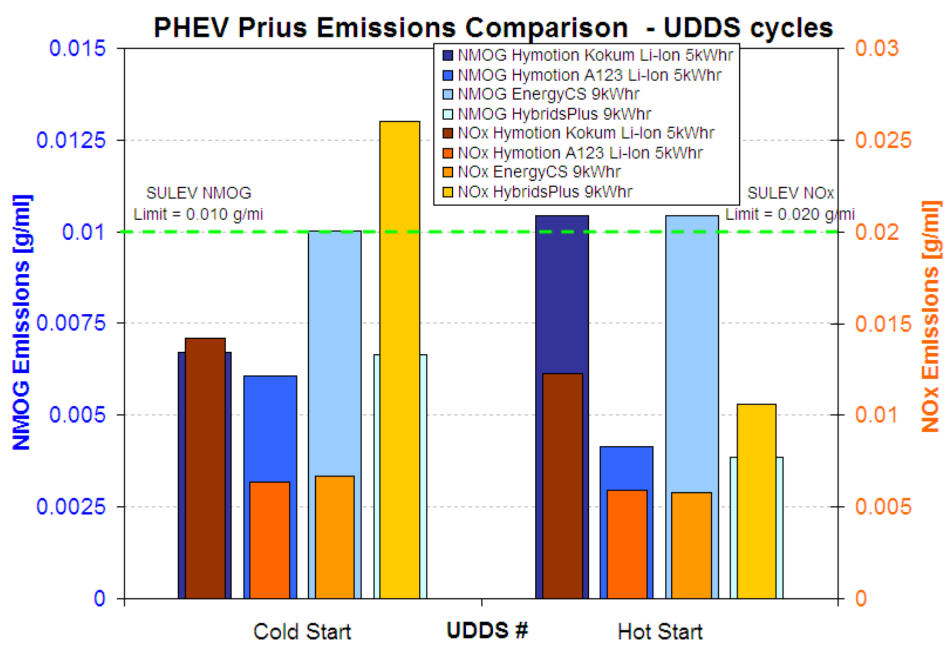


Figure 8. Comparison of Emissions Results From four PHEVs Tested on UDDS in Charge-Depletion Operation

The overall efficiency of the vehicle depends on the charging system. The turn-around efficiency is defined as the net DC battery energy divided by the net AC charger energy. This is the combined efficiency of the charger and battery system. This turn-around efficiency is shown in Table 3. The DC battery energy used over the UDDS cycle is also shown, along with the ratio of battery energy used to the rated battery energy capacity. This reflects how well the battery capacity was utilized.

Table 3. Comparison of Battery and Charger Operation from Four PHEVs

	Hymotion Kokum Li-Ion, 5 kWh	Hymotion A123 Li-Ion, 5 kWh	EnergyCS, 9 kWh	HybridsPlus, 9 kWh
Turnaround Efficiency (DC-kWh OUT / AC-kWh IN)	74%	85%	76%	90%
Battery Energy Used in Charge-Depletion Operation (DC-kWh)	3.1	4.3	4.9	7.3
Battery Energy Used vs. Rated Capacity (%)	62%	86%	54%	81%

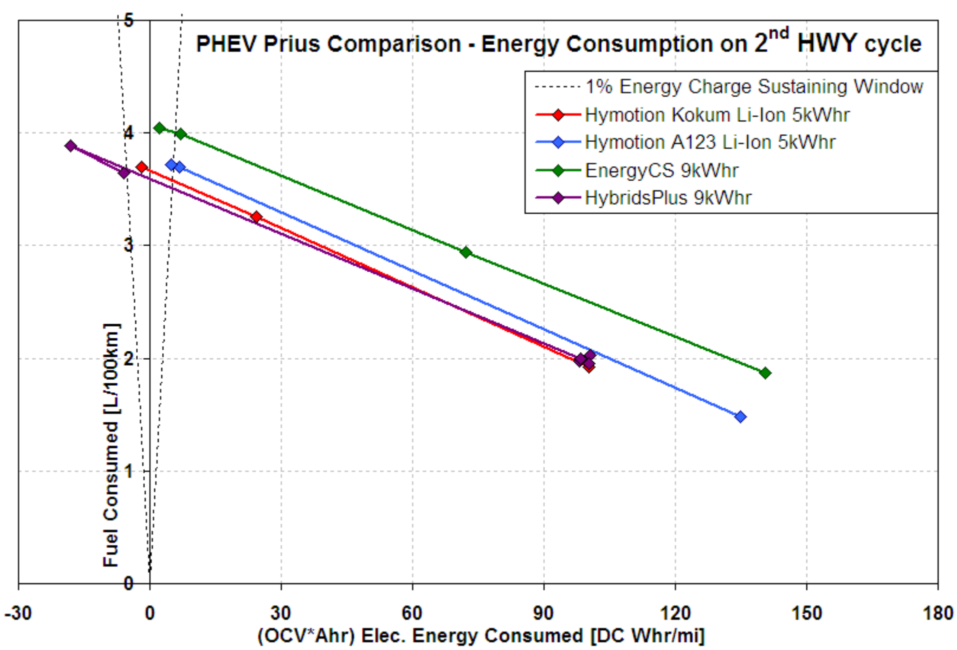


Figure 9. Comparison of Energy Consumption from Four PHEVs Tested on 2nd HWY

Table 4. Comparison of Fuel Consumption and Electrical Energy Usage from PHEVs Tested on UDDS in Charge-Depletion Operation

	Hymotion Kokum Li-Ion, 5 kWh	Hymotion A123 Li-Ion, 5 kWh	EnergyCS, 9 kWh	HybridsPlus, 9 kWh
All-Electric Range on HWY (mi)	0	0	0	0
Charge-Depletion Range on HWY (mi)	33	31	41	88
2nd HWY				
mpg	122.3	155.8	126.1	137.4
DC-Wh/mi	100.3	133.0	140.5	111.8

The fuel consumption and electrical energy usage of the four PHEV Priuses on the 2^{nd} of the pair of HWY cycles are plotted on Figure 9. Table 4 indicates that the EnergyCS Prius shows high fuel consumption and higher electrical energy usage as compared with the other PHEV Priuses. This is most likely due to subtle differences in the controls that determine the load at which the engine is operating.

Conclusions

Many PHEVs are tested and analyzed at the APRF. These data are important as a benchmark for future development of PHEVs, in order to optimize petroleum displacement while maintaining strict emissions standards. The four PHEV Priuses all were handcuffed by having to manipulate inputs to the production Prius control system to achieve the desired charge-depletion results. This made it very difficult to maximize petroleum displacement while striving to reach SULEV emissions levels. The A123 Hymotion Prius produced the least emissions while still significantly displacing petroleum.

Publications / Presentations

1. R. Carlson et al., “Testing and Analysis of Three Plug-in Hybrid Electric Vehicles,” SAE 2007-01-0283, 2007

E. Maintain an On-Line HEV Test Results Database

Steve Gurski (Project Leader)
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439-4815
(630) 252-9359, e-mail: SGurski@anl.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

- Design and construct a web-based database for the repository of hybrid vehicle test data. Enable access from industry and the general public.
- Upload new data from the APRF chassis dynamometer along with the existing APRF data.
- Make some analyses of the data available to DOE and industry partners.
- Add a search and download functionality to the current online repository of data.

Approach

- Collect vehicle data by using Argonne's 4WD chassis dynamometer.
- Perform mathematical analysis to verify quality control of the data and to reduce the data for upload onto the publicly available internet site.
- Upload data to an Argonne web applet server, after which it will be linked into the database to provide search and reference capabilities.

Accomplishments

- An online downloadable database with search capabilities is currently available (https://webapps.anl.gov/vehicle_data/).
- Five hybrid electric and conventional vehicles tested at the APRF currently have data available for download. The 55 data sets for the five vehicles are also available.
- New tools for in-house data quality assurance and reduction have been developed to minimize test-to-upload time.

Future Directions

- Continue to upload data to the website.
- Increase the search functionality and provide high-level data mining rather than delivery of test data.
- Cross-reference applicable and similar work to other DOE national laboratories.

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 has 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/.

Benchmarking data is useful to nearly all aspects of the FreedomCAR partnership, and the Tech Teams also benefit from the data collected in the Advanced Powertrain Research Facility.

Approach

For each of the vehicles tested at the Advanced Powertrain Research Facility at Argonne, a set of data is generated. Depending upon the level and depth of testing, 50 to 200 different pieces of data are collected at the 10-Hz data rate.

At this point, it is necessary to parse through the data and determine if the data is complete, thorough, and representative of the vehicle being tested. We have developed a set of tools that compare and contrast data relative to time and use of the first law of thermodynamics. Since this is a repetitive process, a template to define the time and first law relationships between data is generated. Each new set of data is run against these predefined relationships and setup for visual analysis and comment (Figure 1).

Figure 1. Example of Graph during QC Process for Time Relational Analysis

To perform the first law analysis on the data sets, some mathematical calculations must be performed, since in many cases it is not practical to measure power directly in a vehicle. The QC tool has this functionality and also can be used to make additional repetitive calculations. For our first law analysis, we must directly compare two sets of data together. The QC tool graphs this data and calculates a correlation factor (Figure 2).

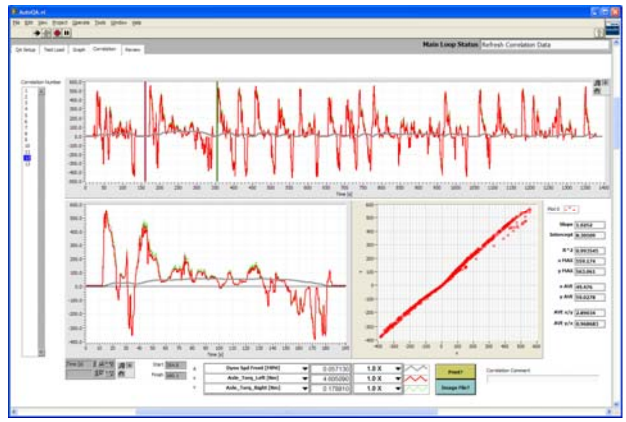


Figure 2. Example of Graph during QC Process for First Law Relational Analysis

Once the data is thoroughly checked, it is 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, emissions (gm/mi), etc.
- Test Information: Summary of testing conditions needed to replicate the work at similar vehicle testing facilities; items include road load, dynamometer setting, test cell environmental conditions, etc.
- 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.

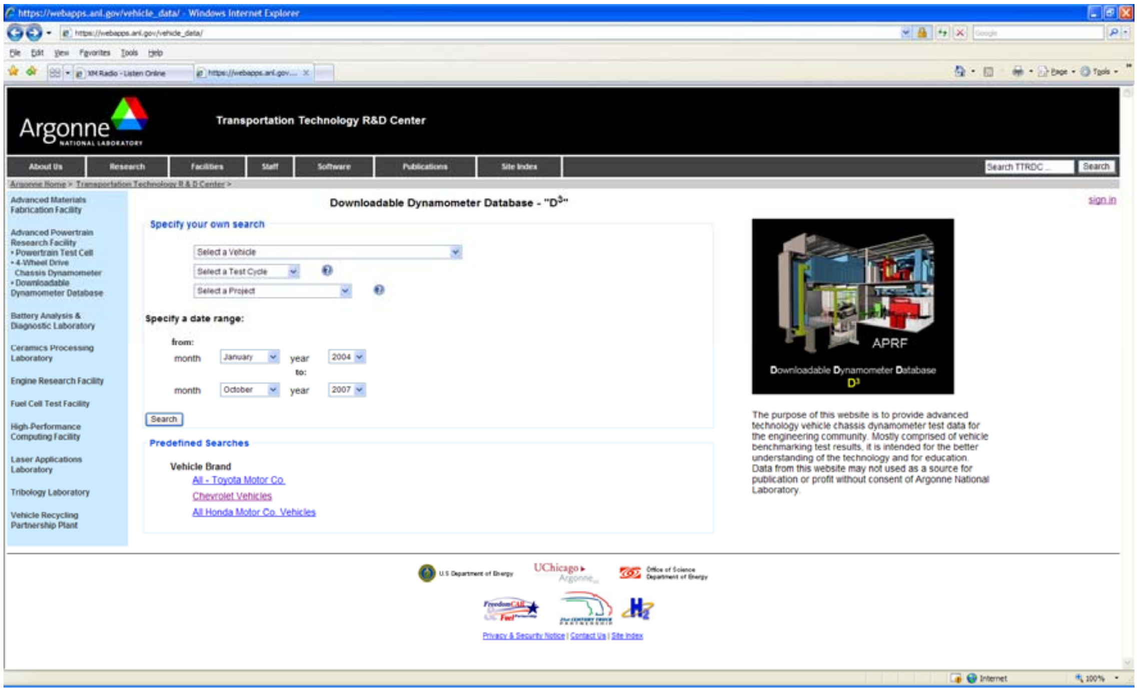


Figure 3. Downloadable Dynamometer Database Homepage

After the data quality control step has been performed, data is uploaded to the D3 website (Figure 3). The term D3 is an acronym for **D**ownloadable **D**ynamometer **D**atabase. It is in this html interface where the relational and searchable database provides functionality. This website is available at: https://webapps.anl.gov/vehicle_data/.

The current interface is designed to enable the user to easily find data, which is organized either by vehicle or by a virtual project binder. Users have the ability to search the entire database by vehicle, project, test cycle, date of collection, or a predefined search. After the user has completed searching for the requested data, all the data is sent via http download in a single compressed data file (zip). As of September 2007, D3 has five vehicles with over 50 sets of test data from a variety of hybrid and conventional vehicles.

As the database size increases, it will be practical to implement other data mining and search algorithms to allow users to collect aggregate data rather than the detailed data. This will allow users to glean high-level results that are already calculated, rather than downloading all the data and mining the data themselves.

Conclusions

The Argonne Downloadable Dynamometer Database, D3, allows our industry, academic, and government partners access to high-quality vehicle chassis testing data. The D3 is a simple and easy-to-use tool that allows for the transfer of useful data for analysis and education.

Publications/Presentations

1. Keller, G. and Gurski, S., et al., "D3 Website," September, VSATT Review, 2007.

V. OPERATIONAL AND FLEET TESTING

A. Hybrid Electric Vehicle Testing

James Francfort (Principal Investigator), Timothy Murphy (Project Leader)
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-3830
(208) 526-6787, e-mail: james.francfort@inl.gov

DOE Program Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Benchmark commercially available hybrid electric vehicles (HEVs)
- Provide HEV testing results to vehicle modelers and technology target setters
- Reduce the uncertainties about HEV battery and vehicle life

Approach

- Perform baseline performance and accelerated reliability tests on 13 HEV models 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

Accomplishments

- Accelerated reliability testing for the HEV fleet, consisting of 37 HEVs, exhibited varying fuel economies: 37.6 mpg for the 4 Generation (Gen) I Honda Civics, 41.0 mpg for the 6 Gen I Toyota Prius, 45.2 mpg for the 6 Honda Insights, 28.1 mpg for the 2 Honda Accords, 44.2 mpg for the 2 Gen II Prius, 17.7 mpg for the 2 Chevrolet Silverado HEVs, 27.1 mpg for the 2 Ford Escapes, 23.7 mpg for the 3 Lexus RX400h, 24.6 mpg for the 2 Toyota Highlanders, 33.3 for the 2 Toyota Camrys, 39.5 for the 2 Gen II Honda Civics, 27.8 for the 2 Saturn Vues, and the 2 Nissan Altimas just started testing with no fueling events as of then end of fiscal year (FY) 2007
- As of September 2006, 3.2 million HEV test miles have been accumulated
- Initiated end of life battery testing on the Gen II Toyota Prius, having previously completed end of life battery testing on the Gen I Toyota Prius, Gen I Honda Civic, and Honda Insight
- Provided HEV testing results to the automotive industry, the U.S. Department of Energy, and other National Laboratories via the Vehicle Technologies Program's Vehicle Simulation and Analysis Technical Team

Future Activities

- Benchmark new HEVs available during FY08, including the new two-mode HEVs from General Motors
- Ascertain HEV battery life by accelerated reliability testing at the end of 160,000 miles
- Continue testing coordination with industry and other DOE entities

---

Introduction

Today's light-duty hybrid electric vehicles (HEVs) use a gasoline internal combustion engine (ICE) and electric traction motor with approximately 1 kWh of onboard energy storage that is never connected to the grid for charging the battery. The HEV batteries are charged by the onboard ICE-powered generator, as well as by a regenerative braking system. Twelve of the thirteen HEV models in testing use nickel metal hydride chemistries as the onboard traction battery. One HEV model uses a lead acid battery. Future HEVs may use lithium battery technologies.

In addition to providing benchmark data to modelers and technology target setters, the Advanced Vehicle Testing Activity (AVTA) benchmarks and tests HEVs to compare the advantages and disadvantages of each technology, and also provides testing results to the public and fleet managers.

Approach

As of the end of fiscal year 2007 (FY07), the AVTA has performed, or is performing, accelerated reliability and fleet testing on 37 HEVs, comprised of 13 HEV models:

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

Baseline performance testing has been completed on 12 of the 13 models, with the Nissan Altima undergoing baseline performance testing as of the end of FY07. Note that the difference between fleet and accelerated reliability 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 accelerated testing, two of each HEV model will each accumulate 160,000 onroad miles in 36 months.

Also during FY07, end-of-life (at 160,000 miles per vehicle) battery testing has been initiated on the two Gen II Prius with the Ford Escape PHEVs to be tested shortly in FY08.

Results

As of the end of FY07, the 37 HEVs have accumulated 3.2 million total accelerated reliability and fleet test miles (Figure 1). Note that the Nissan Altima HEVs are not plotted in any of the graphs as they have only accumulated a combined 137 miles as of the end of F07. The fuel economies ranged from 17.1 to 45.2 mpg in the onroad fleet and accelerated testing (Figure 2). All of the HEVs that have been onroad tested to date exhibit some seasonal variations in fuel economy (Figure 3). The impact from using the air conditioning is evident from the baseline performance testing results (Figures 4 and 5) when average fuel use decreases 9 mpg when the air conditioning is on during dynamometer testing.

In addition to the HEV fuel economy and total test miles data being collected, all maintenance and repair events, including the costs or if under warranty, dates and vehicle miles when an event occurred, is collected to compile life-cycle vehicle costs. This data is presented on the AVTA's Worldwide Web pages as both a maintenance fact sheet and a HEV fact sheet, with includes miles driven, fuel economy, mission, and life-cycle costs on a per-mile basis. The life-cycle costs also include fuel, insurance, registration, and depreciation costs, are averaging about 30 cents per mile for the current group of HEVs being tested (Figure 6). Note that as would be expected, the highest costs per mile are for the HEVs with the lowest mileage accumulations to date.

The Environmental Protection Agency (EPA) has implemented new test methods (http://www.fueleconomy.gov/feg/ratings2008.shtml) for estimating mpg ratings for all light-duty vehicles. Figure 7 shows both the original EPA mpg estimates (light yellow bars) for HEVs the AVTA has tested, and mpg figures the EPA has published if the same vehicles were tested, or calculated to have been tested, to the new test methods (blue bars). The EPA numbers are displayed as the average for both city and highway results. Results for the AVTA fleet testing also are graphed (red bars) to show comparison to the old and new EPA estimates. The HEVs are displayed by all-wheel, two-wheel, and four-wheel drive in order to match EPA test categories. Note that the average AVTA fleet testing mpg is 31.0 mpg, which is close to the new EPA test method average of 31.7 mpg (2.2% higher than results for the AVTA fleet testing). The older EPA test method results averaged 36.6 mpg (18.1% higher than results for the AVTA fleet testing).

Conclusions

The largest single impact on fuel economy is from the use of the air conditioning with these early HEV models during the summer months. The HEV battery packs appear to be robust; as of the end of FY07 and 3.2 million test miles, there were two nickel metal hydride (NiMH) traction battery failures. One NiMH failure was due to a battery controller failure and should not be attributed singularly as a pack failure. The second NiMH pack failed at 147,000 miles. In addition, there was a lead acid HEV traction pack failure at 36,000 miles.

Future HEV onboard energy storage systems may include combinations of multiple battery technologies employing different charge and discharge methods, and ultracapacitors. Future HEVs may operate on alternative fuels such as hydrogen, methane, compressed natural gas (CNG), ethanol, or blends of hydrogen and CNG. If these technologies or combinations of these technologies appear, they will be introduced into the HEV testing activity.

Future Activities

New HEVs available from U.S., Japanese and European manufacturers will be benchmarked during FY08. 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.

Publications

There were approximately 40 HEV baseline performance, fleet, and accelerated reliability testing fact and maintenance sheets presented on the WWW. The HEV baseline performance testing procedures and vehicle specifications were also updated and republished on the WWW. New HEV reports and papers published during FY07 are listed below. In addition to the below testing fact sheets and paper, maintenance requirements and fuel use fact sheets are generated every two 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.

1. 2006 Toyota Camry HEVAmerica baseline performance testing fact sheet. http://avt.inel.gov/pdf/hev/fact7129Camry07.pdf

2. 2006 Honda Civic HEVAmerica baseline performance testing fact sheet. http://avt.inel.gov/pdf/hev/factCivic2006.pdf

3. 2006 Toyota Highlander HEVAmerica baseline performance testing fact sheet. http://avt.inel.gov/pdf/hev/factHighlander2006.pdf

4. 2006 Lexus RX400h HEVAmerica baseline performance testing fact sheet. http://avt.inel.gov/pdf/hev/lexus2006.pdf

5. 2007 Saturn Vue HEVAmerica baseline performance testing fact sheet. http://avt.inel.gov/pdf/hev/factSaturnVue.pdf

6. Karner, D. and J. Francfort. June 2006. *US Department of Energy Hybrid Electric Vehicle Battery and Fuel Economy Testing.* Journal of Power Sources. Elsevier. London, United Kingdom. July 2007

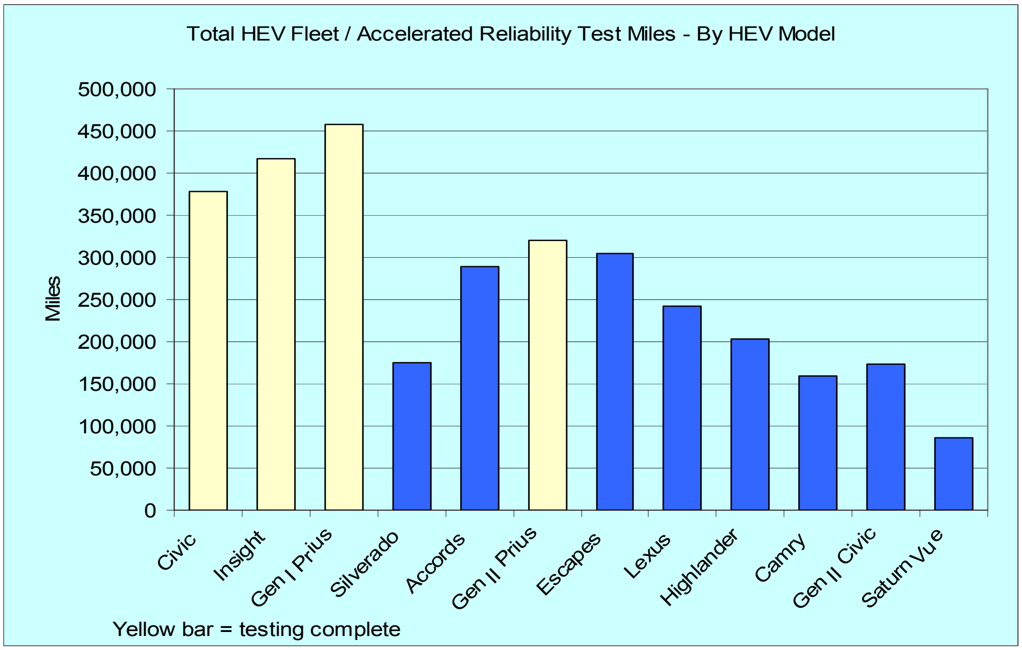


Figure 1. Total HEV test miles by vehicle model.

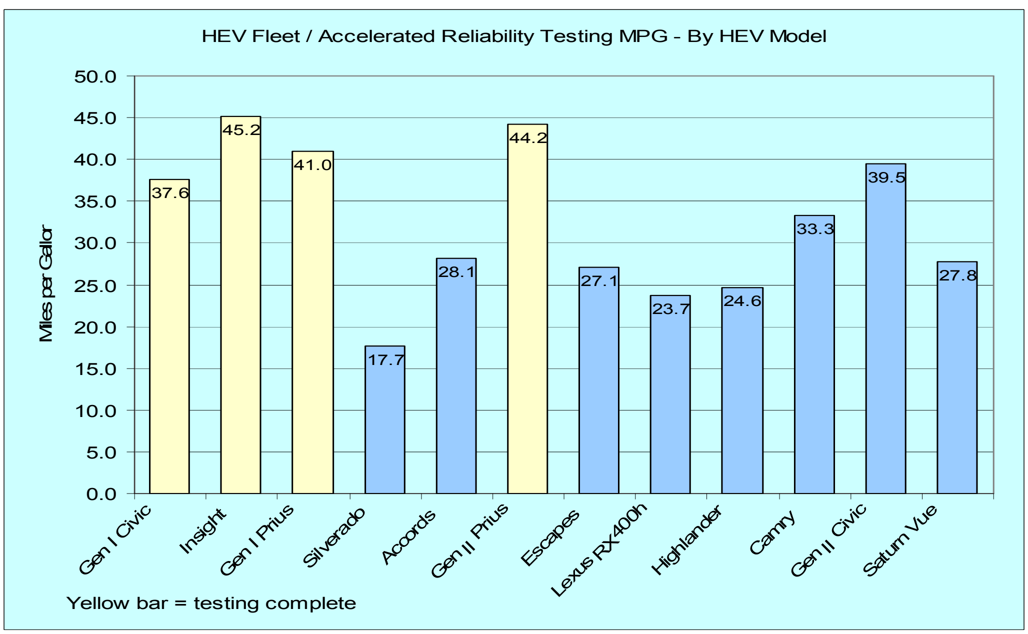


Figure 2. HEV fuel economy (mpg) test results for each HEV model in fleet and accelerated reliability testing.

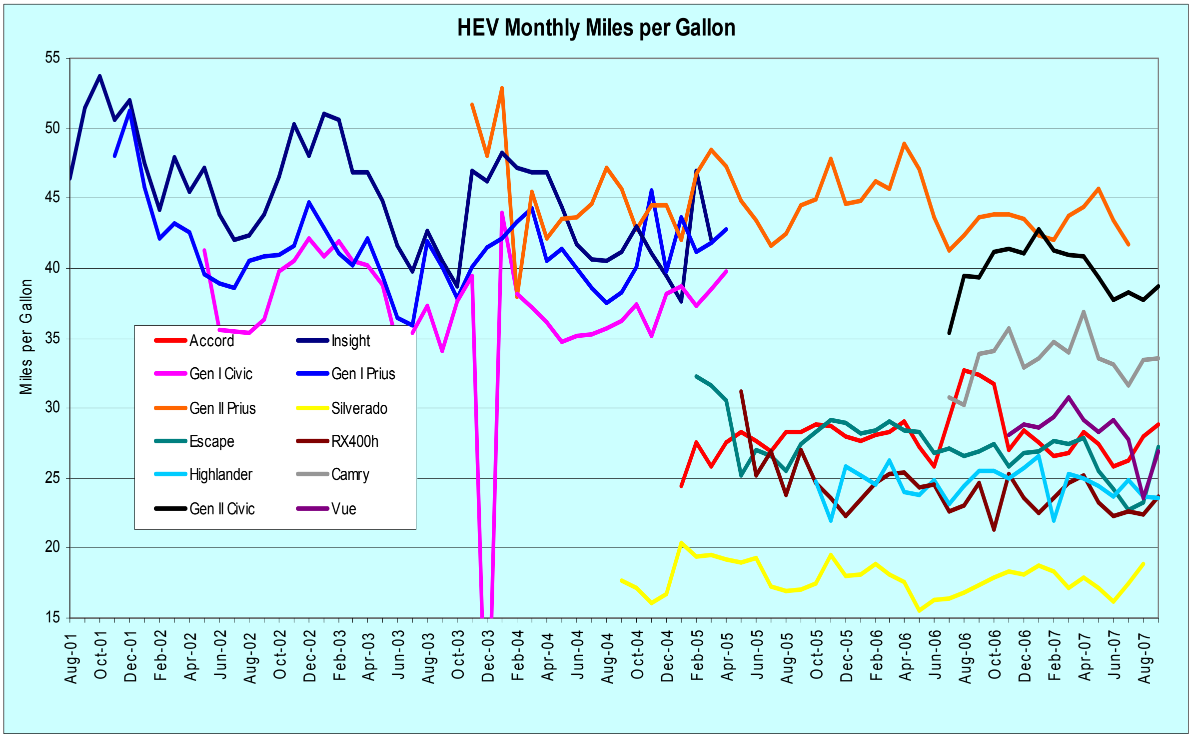


Figure 3. Monthly fuel economy testing results by HEV model.

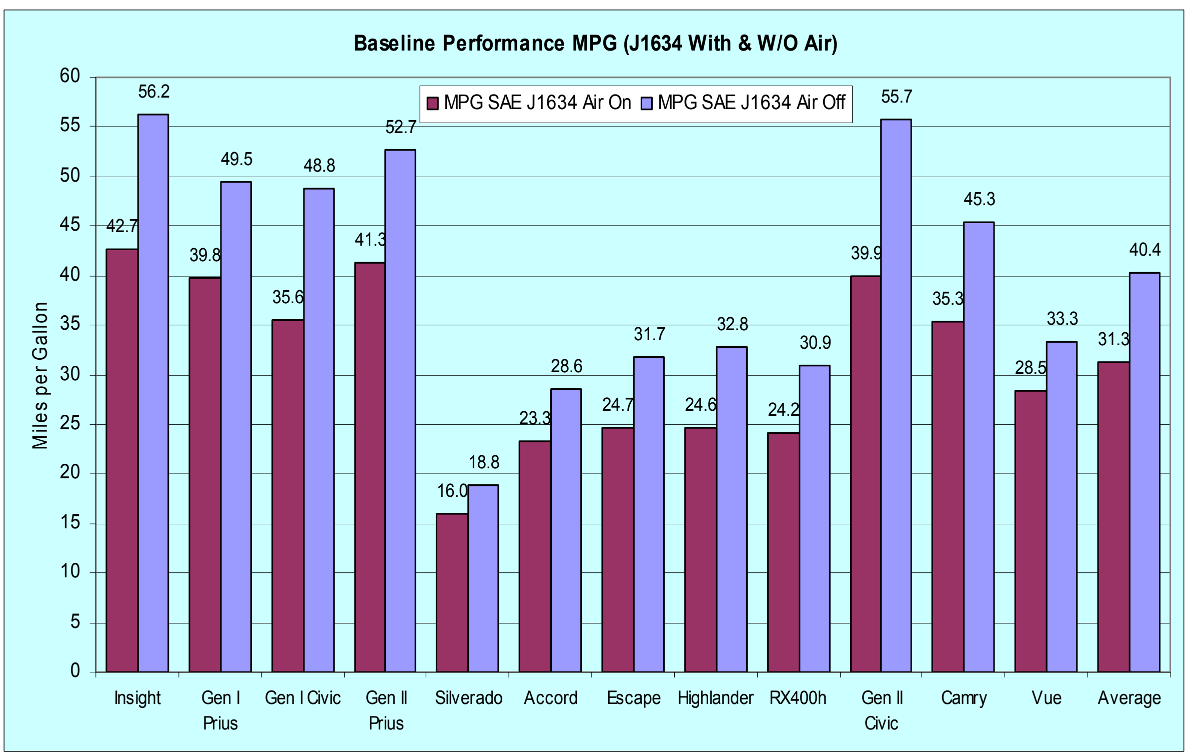


Figure 4. Baseline performance fuel economy test results for SAE J1634 drive cycle testing with the air conditioning on and off.

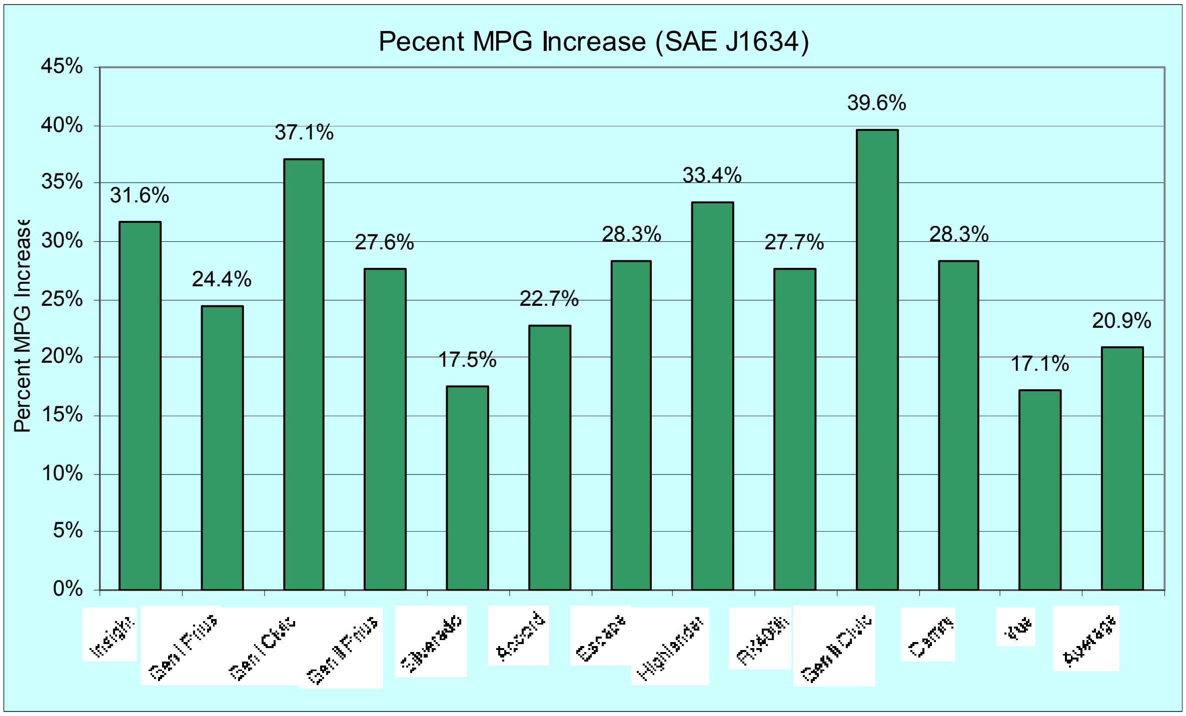


Figure 5. Percentage increase in baseline performance fuel economy test results for SAE J1634 drive cycle testing when the air conditioning is turned off during the testing.

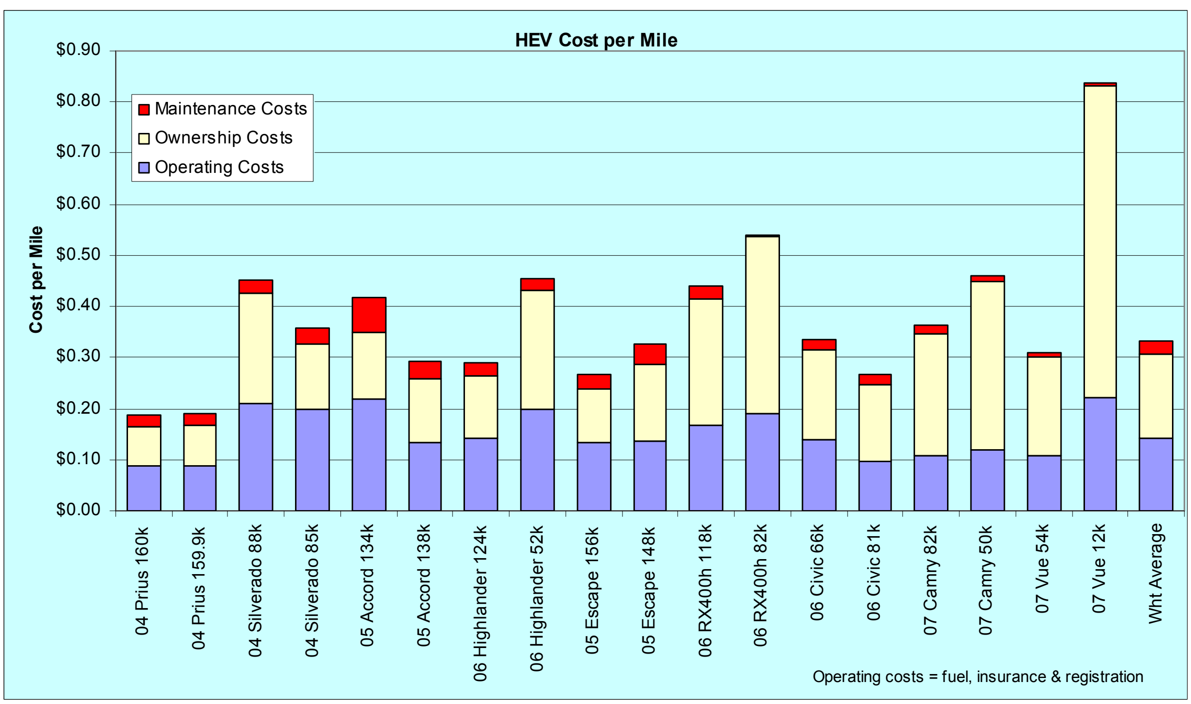


Figure 6. Life cycle costs per mile for the HEVs most recently in testing. The costs include vehicle ownership cost (cost of a new vehicle minus the residual cost per the Kelly Blue Book. When the vehicle is sold, the ownership costs are recalculated based on actual sale prices). The HEV labeling includes the model date, name and test miles to date.

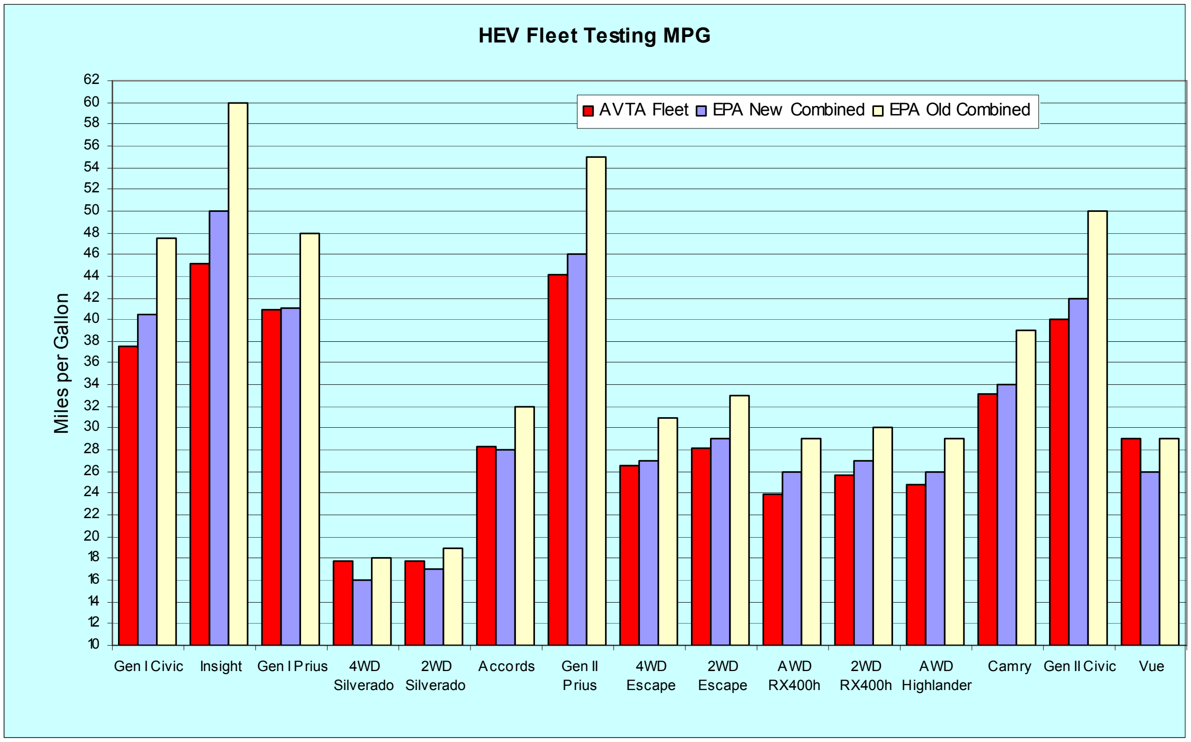


Figure 7. Results for the AVTA fleet testing compared to the results for the old and new EPA mpg testing. The 12 HEV models are broken out into two-wheel, four-wheel, and all-wheel drive categories to match EPA vehicle categories.

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

James Francfort (Principal Investigator), Timothy Murphy (Project Leader)
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-3830
(208) 526-6787, e-mail: james.francfort@inl.gov

DOE Program Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Benchmark early production and prototype plug-in hybrid electric vehicles (PHEVs)
- Reduce the uncertainties about vehicle and battery performance and life, as well as document fuel (petroleum and electricity) use over various distances
- Document PHEV charger performance (profile and demand), charging times, and infrastructure needs, as well as operator behavior impact on charging times and frequencies
- Provide PHEV testing results to vehicle modelers, technology target setters and industry stakeholders.

Approach

- Develop PHEV baseline performance testing specifications and procedures (PHEVAmerica) that are reviewed by industry, national laboratories, and other interested stakeholders
- Obtain PHEVs for testing to the reviewed PHEV baseline performance testing specifications and procedures
- Perform baseline performance tack and laboratory tests, and accelerated onroad tests on PHEVs
- Place limited numbers of PHEVs in demonstration fleet environments for vehicle, infrastructure, and operator testing.

Accomplishments

- Developed 400-page PHEV testing specifications and test procedures
- Received and incorporated appropriate internal and external comments for the 400-page PHEV testing specifications and test procedures document from national laboratories, industry, and stakeholders
- Obtained and tested one PHEV from an original equipment vehicle manufacturer and two PHEVs from two PHEV conversions companies. The three PHEVs tested represented all PHEV models that were viable and operating test candidates in North America during FY07
- Conducted PHEV power electronics and charging infrastructure review
- Signed cooperative testing agreements with non-DOE groups to provide testing access to PHEVs operating in demonstration fleets, with: New York State Energy Research Development Agency (NYSERDA), City of Seattle, King County, Port of Seattle, Puget Sound Clean Air Agency, Tacoma Power, and PHEV conversion companies Hymotion and EnergyCS
- Initiated cooperative testing agreements that will provide additional testing and data collection access to PHEVs operating in California, Florida, Georgia, Hawaii, Indiana, Minnesota, North Carolina, Oregon, and South Carolina
- Performed due diligence on other PHEV models to determine suitability as test candidates
- Initiated processes to obtain five additional PHEV models for testing.

Future Activities

- Incorporate additional PHEV baseline performance testing comments generated both internally and externally
- Continue performing due diligence on potential PHEV suppliers and obtain PHEVs for testing as appropriate
- Test identified PHEV models that were in shipment to the AVTA as FY07 ended, as well as additional PHEV models that are being obtained
- Obtain future PHEV models and battery technologies for testing
- Develop additional PHEV demonstration relationships and support the deployment of PHEVs in these testing fleets
- Evaluate PHEV data loggers and data logging systems for use onboard PHEVs
- Coordinate PHEV and charging infrastructure testing with industry and other DOE entities.

Introduction

Current hybrid electric vehicles (HEVs) combine internal combustion engines (ICEs) and battery storage devices to increase performance and/or fuel efficiency. The batteries commonly used in HEVs have approximately 1 kWh of onboard energy and they are recharged by onboard energy sources such as regenerative braking and motor/generators powered by the onboard ICEs. Many companies and groups are proposing, planning, and have started the introduction of plug-in hybrid electric vehicles (PHEV). Today's PHEVs use a HEV as the base vehicle, and additional or replacement battery packs with 5 to 10 kWh of energy storage are added to the HEVs. 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 systems, but all use onboard chargers connected to the offboard electric grid to fully recharge the PHEV battery packs.

The concept of additional onboard energy storage and grid-connected charging raises questions 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 drive cycles and distances.

Approach

The U.S. Department of Energy's (DOE) Advanced Vehicle Testing Activity (AVTA) supports the introduction of PHEVs by testing the emerging group of PHEV products and documenting vehicle and battery performances, as well as electricity and petroleum use. As a first step, the AVTA has developed a 400-page test plan for inspection, dynamometer, test track, accelerated and fleet testing of PHEVs. In addition, three PHEV models have been obtained and in testing, with at least three models identified and being obtained for testing. The AVTA has conducted a PHEV power electronics and charging infrastructure study and the documenting report was being completed as FY07 ended. The AVTA has also signed testing, demonstration, and data collection agreements with several non-DOE fleets that will operate PHEVs and the AVTA will collect performance and charging data to characterize the performance of the PHEVs and the charging infrastructure.

Results

The 400-page draft test plans were completed during FY06 and they were submitted for review by other National Laboratory groups. During FY07, the plans were further reviewed by a larger group of PHEV industry and stakeholders, and the resulting comments addressed. Three PHEV models were obtained for testing during FY07; the baseline performance (track and dynamometer) and accelerated testing results are discussed below.

The PHEVs that were obtained by the AVTA are the Renault Kangoo (Figure 1), with a Nickel Cadmium battery pack, a Toyota Prius converted by EnergyCS, with a lithium ion battery pack

(Figures 2 and 3), and a Toyota Prius converted by Hymotion, with a lithium ion pack (Figures 4 and 5). As will all vehicles that are baseline performance tested, testing fact sheets are developed for each PHEV (Figure 6).

EnergyCS PHEV Testing - The Prius converted by EnergyCS has completed baseline performance testing, which includes dynamometer testing (conducted by Argonne National Laboratory for the AVTA). This testing includes Urban Dynamometer Drive Schedule (UDDS: 1,372 seconds) testing, during which the EnergyCS PHEV demonstrated gasoline mpg results exceeding well over 100 mpg for each of the first four UDDS test cycles (Figure 7). Note that each UDDS test cycle is 7.48 miles in distance. The test cycles are repeated while the test PHEV continues to operate in charge-depleting mode (pulling electricity out of the PHEV battery pack) until it operates in two charge-sustaining modes (no more additional electricity can be pulled out of the PHEV battery pack). The charge-sustaining results are repeated in the graphs to show the cumulative fuel-use effects if the vehicle were tested for additional cycles.

The EnergyCS Prius is also subjected to Highway Fuel Economy Driving Schedule (HWFEDS; 764 seconds) on the dynamometer, during which the gasoline mpg results were greater than 80 mpg for the first of the three 10.25 mile long test cycles (Figure 8). As with the UDDS cycles, the testing is repeated in charge-depleting mode and then repeated again for at least two charge-sustaining modes.

The EnergyCS Prius has also started accelerated testing, during which the EnergyCS PHEV Prius is driven with a dedicated driver over a series of 10-mile city and 10-mile highway loops. These two loops are repeated in different combinations that range from 10- to 200-mile individual test cycles, which are each followed by a battery recharging period (Table 1). Note that when this vehicle started testing, the three 40-mile cycles were only going to be for 200 miles each (600 miles total for all 40-mile cycles). These 200-mile distances have been subsequently changed to 600-mile distances each as seen in Table 1. However, the 40-mile cycles presented in Table 2 were completed as of the end of FY07 and reported. As Table 2 shows, the EnergyCS PHEV exhibited significant higher mpg test results when driven on the road compared to the 44 mpg results for the stock Prius HEV that the AVTA measured after 320,000 test miles.

Hymotion PHEV Testing - The Prius converted by Hymotion has completed baseline performance testing, which includes dynamometer testing (conducted by Argonne National Laboratory for the AVTA). As with the EnergyCS Prius, the Hymotion Prius testing included UDDS testing, during which the Hymotion PHEV demonstrated gasoline mpg results exceeding over 140 mpg for each of the first three UDDS test cycles (Figure 9). The UDDS results are graphed similarly to the EnergyCS results, with the Hymotion results shown in charge depleting modes and charge sustaining modes, with the sustaining results repeated to show cumulative energy use over longer distances.

The Hymotion Prius is also subjected to HWFEDS testing on the dynamometer, during which the gasoline mpg results were greater than 80 mpg for the first of the three 10.25-mile test cycles (Figure 10). As with the UDDS cycles, the HWFEDS testing is repeated in charge-depleting mode and then repeated again for at least two charge-sustaining modes.

The Hymotion Prius has also started accelerated testing, but it has not completed as many drive cycles as the EnergyCS Prius. This is partially a result of it being obtained later than the EnergyCS Prius and partially due to its use in ride-n-drives and as a display at the DOE sponsored Solar Decathlon in Washington, D.C. However, the few onroad accelerated test cycles it has completed also demonstrate significantly higher mpg results (Table 3) than the stock Prius HEV's 44 mpg.

Renault Kangoo - Both the EnergyCS and Hymotion PHEVs use the Prius's parallel HEV design which allows both the electric motor and the gasoline engine to propel the vehicle. The third PHEV model tested to date is the Renault Kangoo, which uses a series HEV design. In Renault series design, an electrical generator is powered by an internal combustion engine, and the generator charges the vehicle traction battery pack. The generator is not connected directly to the electric drive motor. In a parallel design, electricity can also be generated directly by a fuel cell, but again, it can only be used to charge the battery, it is not connected directly to the electric drive motor. This type of series design is the same design that General Motors has announced for its future Volt PHEV.

While the Kangoo is not of an overly sophisticated design, it is the first, and to date only, series PHEV available. Therefore, the AVTA has benchmarked the performance of the Kangoo and its electric-only switch-able mode. To date, none of the other currently available PHEVs allow the driver to switch to an electric-only mode. Therefore, the Kangoo has been tested in both electric-only and electric-assist modes (Table 4), where during several tests the Kangoo exhibited energy efficiencies of 0.16 to 0.48 alternating current (AC) kWh per mile in electric-only mode, 0.04 to 0.14 AC kWh per mile, and 39 to 42 mpg in electric-assist mode (both the electric motor and gasoline engine propel the Kangoo).

Fleet Testing – As of the end of FY07, there were approximately 85 PHEVs (Table 5) in North America, and most of these were in the United States. In order to collect data on PHEVs in fleet operations, the AVTA has partner with the two PHEV conversion companies that have performed the most PHEV conversions to date. Agreements with Hymotion and EnergyCS are allowing direct access to 74% of the 85 PHEVs. As of the end of FY07, data from onboard data loggers is just starting to be shared and the necessary data storage and dissemination systems are being designed and implemented. These collaborative data-sharing agreements will provide insight into vehicle performance as well as charger performance, charging profiles, and peak charger demand curves. By mid calendar year 2008, this data collection effort will include over 110 PHEVs with onboard data loggers and it will allow a greater understanding of PHEV control and operations (Figure 11).

The AVTA has a testing support agreement with the New York State Energy Research Development Agency (NYSERDA) to test the six PHEV models that NYSERDA has ordered. This agreement provides the AVTA with access to the following PHEV conversions: Prius, Escape and Civic from Hymotion, Prius from EnergyCS, Escape from Electrovaya, and an Escape from HybridsPlus. By testing these PHEVs, the AVTA is supporting NYSERDA's goal to determine which PHEV conversion company(s) should convert some of New York State's several hundred HEVs to PHEVs. As of the end of FY07, NYSERDA's Hymotion and EnergyCS Prius are being tested by the AVTA, the Electrovaya and Hymotion Prius had just arrived for testing, and the other two PHEVs had not been delivered for testing.

During the last month of FY07, the AVTA developed deployment and testing agreements with five Seattle area governmental fleets:

- City of Seattle
- King County
- Port of Seattle
- Puget Sound Clean Air Agency
- Tacoma Power (City of Tacoma).

A total of 17 PHEVs will be deployed in the five fleets by the end of March 2008. Fourteen of the PHEVs will be Hymotion Prius conversions with lithium ion battery packs, and three additional Prius will be Green Car Company conversions with lead acid battery packs. The AVTA has selected data loggers and is supporting the fleets with mission selection and charging infrastructure plans. Both onboard vehicle data and charging data will be obtained monthly and the data will be provided back to the respective fleets and disseminated via the AVTA webpages and at industry conferences.

In addition to the New York State and Seattle, Washington area PHEV demonstrations, other small PHEV fleet demonstrations being developed with several fleets in Hawaii and California, as well as the National Rural Electric Cooperative Association. These agreements that were being put into place at the end of FY07 will allow the AVTA to collect data on PHEVs in the following states by the end of the second quarter of FY08:

- Arizona
- California
- Florida
- Georgia
- Hawaii
- Indiana

- Minnesota
- North Carolina
- Oregon
- South Carolina
- Washington.

Several other groups/vehicle converters have made PHEV product claims, but due diligence suggests that the AVTA has obtained and is obtaining all PHEV models currently available and likely to be produced in at least limited numbers and offered for use by fleets.

Power Electronics and Charging Testing – As of the end of FY07, the AVTA was completing the testing of EnergyCS and Hymotion Prius power electronics and charging profiles (Figures 12 and 13). This testing report will be completed and published during early FY08.

Conclusions

The PHEV industry is in its infancy, with less than 100 light-duty PHEVs deployed in the United States as of the end of FY07. Total independent test miles on any single PHEV battery pack is very limited, so the high-mileage life of PHEV battery packs is unknown. Initial testing of PHEVs suggests there is great potential for reducing petroleum consumption; however, the current cost to convert a HEV to a PHEV ranges from $12,000 to $40,000 per vehicle plus the base cost of the HEV. Therefore, on an economic basis, the cost to the vehicle operator to reduce petroleum consumption with PHEVs is currently considerable. However, the future incremental cost to convert HEVs to PHEVs, or the cost of ground-built PHEVs from original equipment manufacturers, is unknown but is anticipated to be lower.

There is also discussion about PHEVs being able to provide electricity back to the electric grid during periods of peak demand. However, the current group of PHEVs is using 110 volt connectors for recharging from the grid, so this concept may remain theoretical at least for the near future due to limits in the amount of electric energy that can be transfer quickly. Another limiting factor may be battery life, as it is currently unknown what PHEV battery cycle life will be, and if sending electricity back to the grid may significantly lower battery life.

The eventual control systems that future PHEVs will use is also unknown, as some in this infant industry support all-electric ranges while others support greater use of additional electric assist which will theoretically help maximize battery life. Regardless of these questions, the few PHEVs currently in operations have demonstrated the significant potential of PHEVs to reduce the use of petroleum for personnel transportation.

Future Activities

The AVTA will continue to test new PHEV models as they become available as well as previously tested PHEV models that have had significant modifications such as new battery designs or chemistries that are believed to provide significant performance enhancements.

It addition to continued testing of vehicle performance, PHEV charging patterns, demands, and the human influence on charging patterns will be documented on the micro level to better understand charging demands and costs at the individual branch circuit, building, and local distribution network levels.

Consideration is being given to testing additional PHEVs in various modes of operation and battery state of charge (SOC) to determine battery life and vehicle performance if the vehicle is charged in scenarios such as ever other day, or less often; if the battery is continuously discharged and then charged from 50%, 20% or some other SOC; or if the vehicle is continuously operated at very low SOC and rarely charged. These and other operational modes will be considered for additional testing to examine vehicle and battery performance and life.

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

Publications

Given the infancy of the PHEV industry, there have only been limited numbers of PHEV publications to date generated by the AVTA. The PHEV baseline performance testing procedures and vehicle specifications were listed below and are available on the WWW. PHEV reports and papers published during FY07 are listed below. 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.

1. Karner, D., R. Brayer, D. Peterson, M. Kirkpatrick, and J. Francfort. Plug-in Hybrid Electric Vehicle Integrated Test Plan and Evaluation Program. July 2007. INL/EXT-07-12335. Idaho National Laboratory. Idaho Falls, ID.

2. 2007 EnergyCS Prius conversion PHEVAmerica baseline performance testing fact sheet. http://avt.inel.gov/pdf/phev/prius.pdf

3. 2007 Hymotion Prius conversion PHEVAmerica baseline performance testing fact sheet. http://avt.inel.gov/pdf/phev/toyota PriusHymotionFact.pdf

Figure 1. Renault Kangoo PHEV.

Figure 2. Lithium ion battery pack used in EnergyCS conversion of a Toyota Prius.

Figure 3. Lithium ion battery pack placement in the EnergyCS conversion of a Toyota Prius. The pack is in the black box. Note the 110 volt connector cord in the bottom left of the picture.

Figure 4. Prius converted to a PHEV by Hymotion. Note the 110 volt connector cord in the bottom left of the vehicle bumper.

Figure 5. A123 lithium ion battery pack placement in the Hymotion conversion of a Toyota Prius. The pack sits between the rear of the vehicle and the original Prius battery which is retained and used (The Prius battery is to the right of the bright orange cables and only the upper rear side is visible as bright metal.

PHEVAMERICA

U.S. DEPARTMENT OF ENERGY ADVANCED VEHICLE TESTING ACTIVITY

Base Vehicle Description
Make: Toyota
Model: Prius Year: 2007
VIN: JTDKB20U577558820
Number of Passengers: 5
Hybrid Configuration: Series/Parallel

Hymotion Plug-In Hybrid

VEHICLE SPECIFICATIONS

Weights
Design Curb Weight: 3037
Vehicle Test Weight: 3337 lbs
GVWR: 3795 lbs
GAWR F/R: 2335/2250
Distribution: 54.2%/45.8%
Payload: 758 lbs
Performance Goal: 400 lbs

Engine
Model: 1NZ-FXE
Output: 76 HP @ 5000 RPM
Configuration: 4 Cylinder In-line
Displacement: 1.5L
Fuel Tank Capacity: 11.9 gal
Fuel Types: Unleaded

Electric Drive System
Battery Manufacturer: A123
Battery Type: Li-Ion
Number of Cells: 616
Nominal Cell Voltage: 3.3V
Nominal System Voltage: 184.8V
Nominal Pack Capacity: 4.7 kWh
Measured Useable Capacity: 2.96 kWh

Charge System:
Input Voltages: 120V
Required Breaker Currents: 15-Amp
Charger Power Output: 1.2 kW
Charger Plug Type: NEMA 5-15
Estimated 80% Charge Time: 4.4 Hrs
Estimated 100% Charge Time: 5.5 Hrs

VEHICLE TEST RESULTS

Charge Depleting:
Acceleration 0-60 MPH
Time: 13.28 seconds
Acceleration 1/4 Mile
Time: 20.27 seconds
Maximum Speed: 74.34 MPH
Acceleration 1 Mile
Maximum Speed: 103.4 MPH

Charge Sustaining:
Acceleration 0-60 MPH
Time: 13.41 seconds
Acceleration 1/4 Mile
Time: 20.42 seconds
Maximum Speed: 74.82 MPH
Acceleration 1 Mile
Maximum Speed: 104.0 MPH

Brake Test @ 60 MPH
Distance Required: 153.0 ft

Fuel Eonomy with A/C Off[1]
Cold Start Charge Depleting[2]:
Fuel Economy: 146.72 MPG
A/C kWh Consumed[7]: .147 kWh/mi
Charge Depleting[3]:
Average Fuel Economy: 167.2 MPG
A/C kWh Consumed[7]: .148 kWh/mi
Charge Sustaining[4]:
Fuel Economy: 60.8 MPG

Fuel Eonomy with A/C On[1,5]
Cold Start Charge Depleting[2]:
Fuel Economy: 128.9 MPG
A/C kWh Consumed[7]: .199 kWh/mi
Charge Depleting[3]:
Average Fuel Economy: 153.2 MPG
A/C kWh Consumed[7]: .197 kWh/mi
Charge Sustaining[4]:
Fuel Economy: 46.5 MPG

UDDS Fuel Economy[6]			HWFET Fuel Economy[6]		
Distance (miles)	Fuel Economy (mpg)	A/C Energy Consumed (kWh)[7]	Distance (miles)	Fuel Economy (mpg)	A/C Energy Consumed (kWh)[7]
10	154.8	1.65	10	87.48	1.30
20	160.3	3.31	20	95.27	2.64
40	117.4	3.58	40	86.11	3.92
60	99.40	3.58	60	75.79	3.92
80	88.88	3.58	80	70.52	3.92
100	83.71	3.58	100	67.36	3.92
200	72.26	3.58	200	61.05	3.92

TEST NOTES:

1. Cumulative fuel economy over EPA standard urban drive cycle.
2. Vehicle soaked at ambient temperature while off for a minimum of 12 hours prior to testing.
3. Average non-cold start charge depleting fuel economy.
4. Value determined from average charge sustaining fuel economy tests with appropriate energy correction calculations.
5. A/C on coldest setting with full blower power.
6. Calculated cumulative fuel economy values, includes cold start.
7. A/C energy based on measured charge efficiency.

This vehicle meets all HEV America Minimum Requirements listed on back of this sheet
Values in red indicate the Performance Goal was not met. All Power and Energy Values are DC unless otherwise specified.

Figure 6. Hymotion PHEV fact sheet used as an example of a baseline performance testing fact sheet.

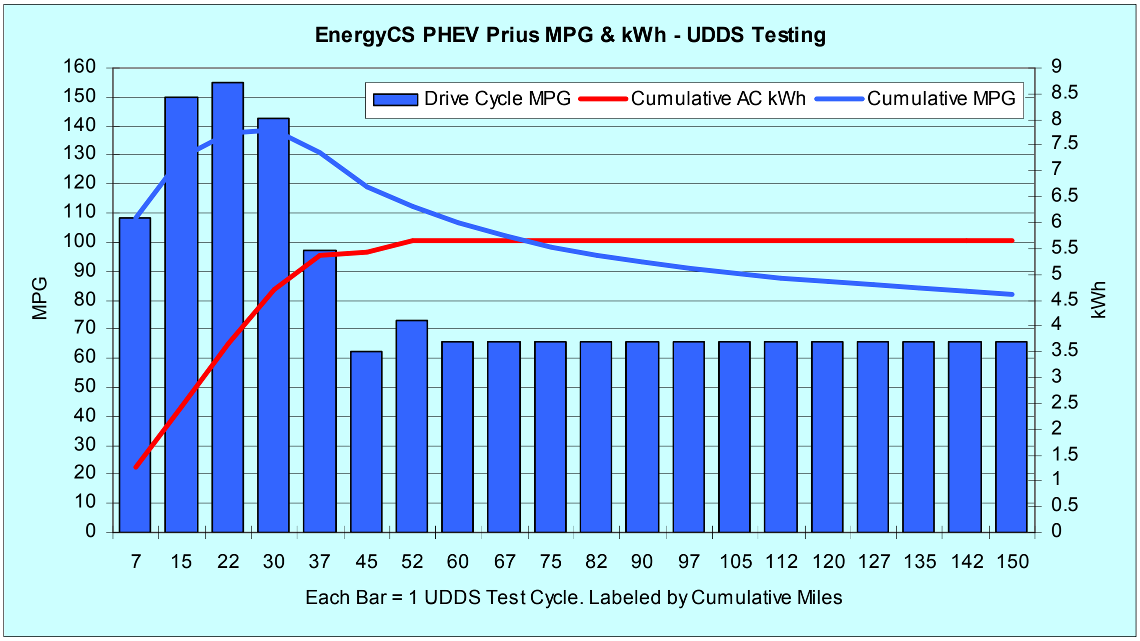


Figure 7. EnergyCS PHEV UDDS testing results. The blue line is the cumulative mpg and the red line is the cumulative kWh used.

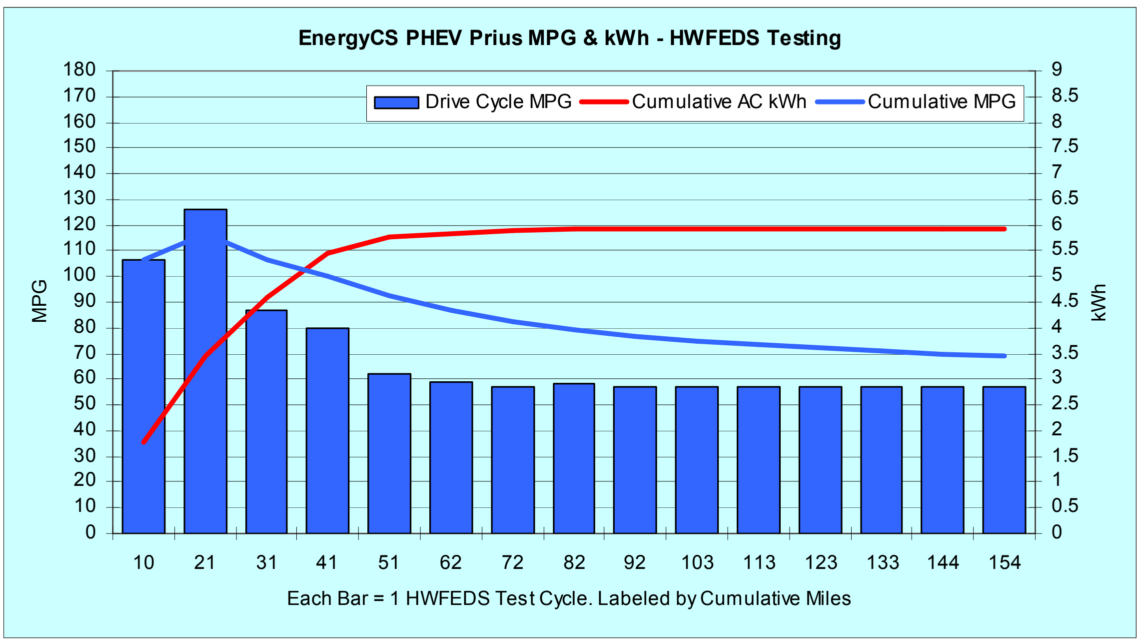


Figure 8. EnergyCS PHEV HWFEDS testing results. The blue line is the cumulative mpg and the red line is the cumulative kWh used.

Table 1. Revised PHEV accelerated testing distances as of the end of FY07.

Cycle (mi)	**Urban (10 mi)**	**Highway (10 mi)**	**Charge (hours)**	**Repetitions (N)**	**Total (mi)**	**Repetitions (%)**	**Miles (%)**	**Cumulative (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
Average	43%	57%	8.3	18.0				

Table 2. EnergyCS PHEV accelerated testing results to date. Note that when this vehicle started testing, the three 40-mile cycles were only going to be for 200 miles each. These 200-mile distances have been subsequently changed to 600-mile distances each as seen in Table 1. However, the 40-mile cycles are presented below as they were completed as of the end of FY07.

Cycle	**Urban**	**Highway**	**Charge**	**Reps**	**Total**	**Electricity**	**Gasoline**	
(mi)	**(10 mi)**	**(10 mi)**	**(hours)**	**(N)**	**(mi)**	**kWh**	**Gals**	**MPG**
10	1	0	4	60	600	115.58	4.78	125.6
20	1	1	8	30	600	86.21	7.95	77.9
40	4	0	12	15	200	17.37	1.61	126.4
40	2	2	12	15	200	29.00	1.42	145.1
40	0	4	12	15	200	30.00	2.43	85.5
60	2	4	12	10	600	65.00	5.90	103.7
80	2	6	12	8	640	39.04	10.09	65.8
100	2	8	12	6	600	22.67	8.81	70.8
200	2	18	12	3	600	12.98	10.46	57.8
Total	1,740	2,500	984	132	4,240	Weighted Average		88.4

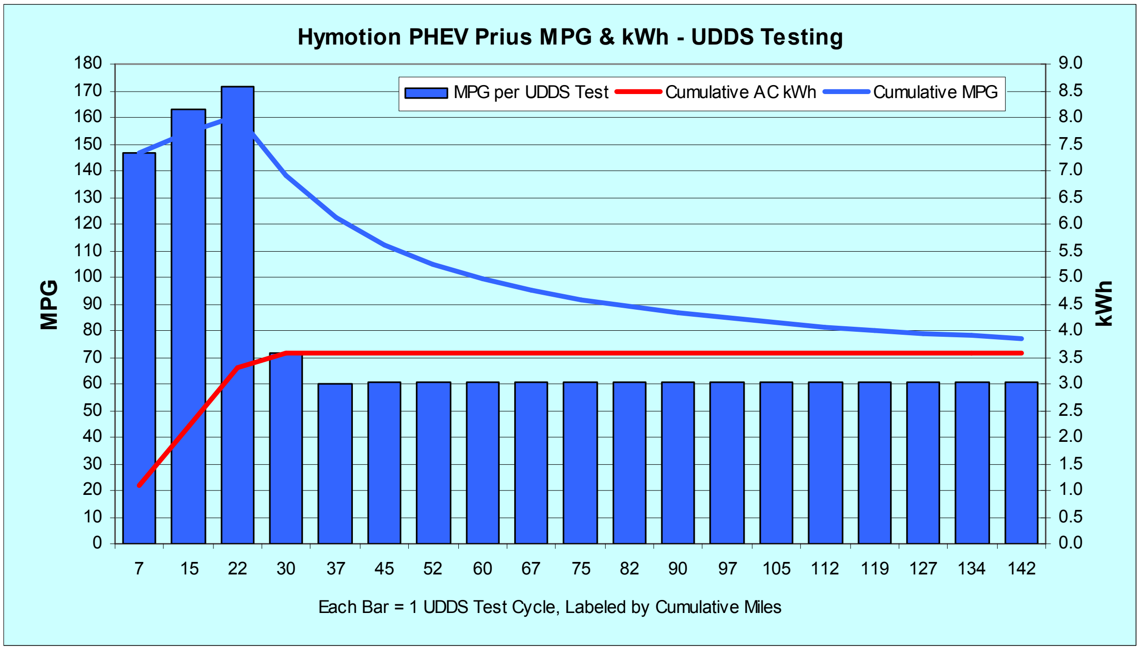


Figure 9. Hymotion PHEV UDDS testing results. The blue line is the cumulative mpg and the red line is the cumulative kWh used.

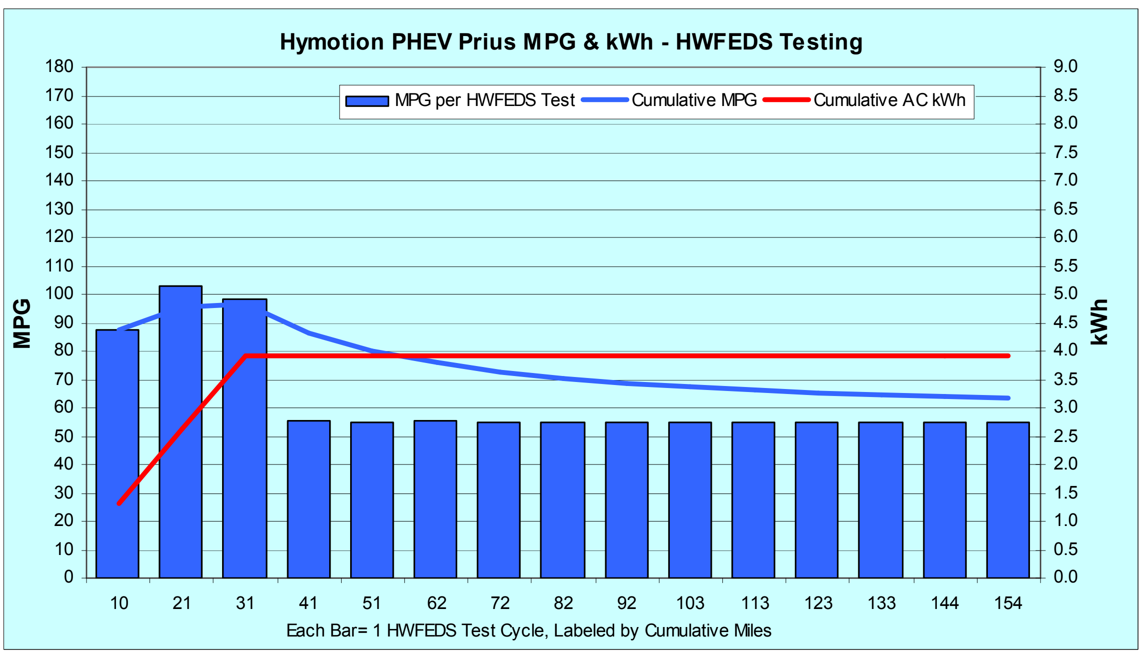


Figure 10. Hymotion PHEV HWFEDS testing results. The blue line is the cumulative mpg and the red line is the cumulative kWh used.

Table 3. Hymotion PHEV accelerated testing results to date. Note that when this vehicle started testing, the three 40-mile cycles were only going to be for 200 miles each. These 200-mile distances have been subsequently changed to 600-mile distances each as seen in Table 1. However, the 40-mile cycle is presented below as it was completed as of the end of FY07.

Cycle	**Urban**	**Highway**	**Charge**	**Reps**	**Total**	**Electricity**	**Gasoline**	
(mi)	**(10 mi)**	**(10 mi)**	**(hours)**	**(N)**	**(mi)**	**kWh**	**Gals**	**MPG**
10	1	0	4	60	600			
20	1	1	8	30	600	122.02	5.37	115.9
40	4	0	12	15	600	29.84	1.87	108.9
40	2	2	12	15	600			
40	0	4	12	15	600			
60	2	4	12	10	600			
80	2	6	12	8	640			
100	2	8	12	6	600	35.98	8.43	73.23
200	2	18	12	3	600			
Total	1,740	2,500	984	132	4,240	Weighted Average		

Table 4. Energy use test results for the Renault Kangoo baseline performance testing and the onroad 10-mile accelerated test cycle

Test Cycle	**kWh AC per Mile**	**Miles per Gallon**
Battery only—UDDS	0.268	
Battery only—HWFEDS	0.155	
Battery only at constant 45 mph	0.271	
Battery and ICE cold start UDDS	0.144	42.3
Battery and ICE hot start UDDS	0.110	39.4
Battery and ICE hot start HWFEDS	0.042	40.9
Sixty - Battery Only 10-mile Accelerated Test Cycle	0.481	

Table 5. PHEVs deployed in North America by PHEV conversion company.

Conversion Company	**# Units Converted To Date**	**State**	**Battery Technology**	**Latest Cost**
Hymotion	50 Mostly Priuses with some Escapes	Canada	Lithium	$12k
Electrovaya	1 Escape	Canada	Lithium	Proposed $6k to $10k.
EnergyCS	13 Prius	CA	Lithium	$40k
Green Car Co.	3 Prius	WA	Lead acid	$12,000 for lead
HybridsPlus	8 Prius	CO	Lithium	Prius - 4.5kWh $24k, 9kWh $32k, Escape – 12kWh $36k
Cal Cars	8 assorted	CA	Lead, NiMH, Lithium	Conversions start <$6k
Advanced Vehicle Innovations	1 Prius	WA	Lead acid	Unknown
AllCell	1 Escape	IL	Lithium	Unknown
Total	85 light duty PHEVs reported deployed to date			

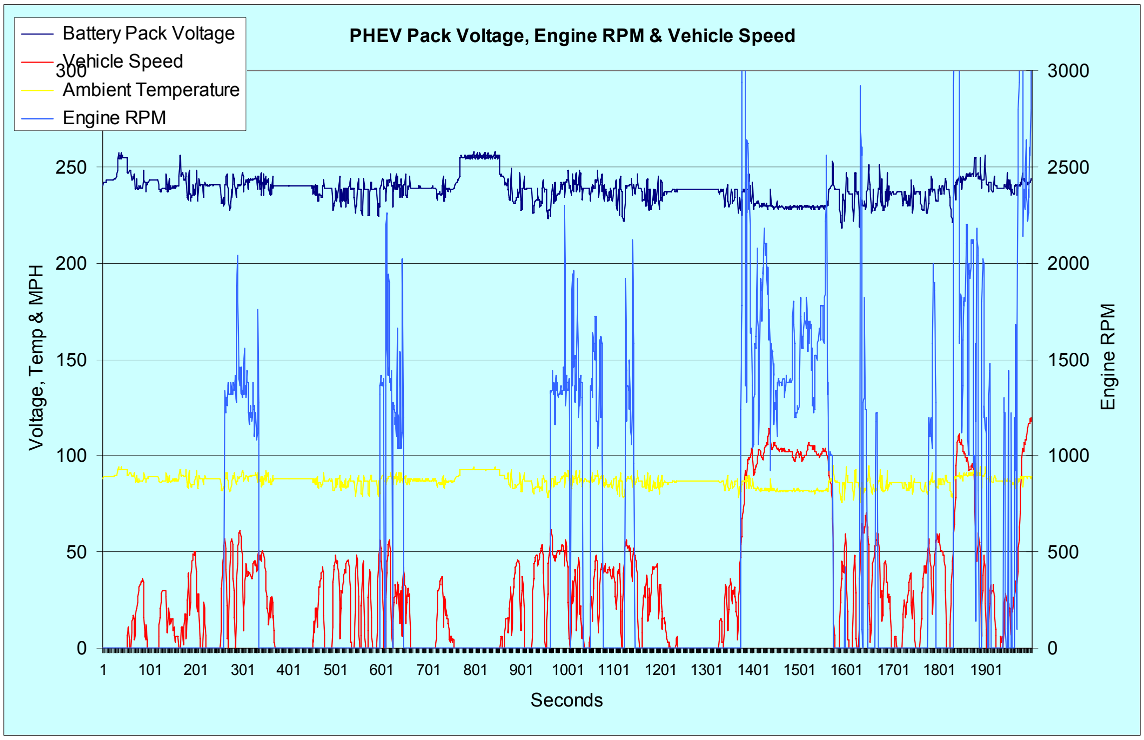


Figure 11. Sample of EnergyCS PHEV onboard data, including engine RPM, vehicle speed, ambient air temperature, and battery pack voltage.

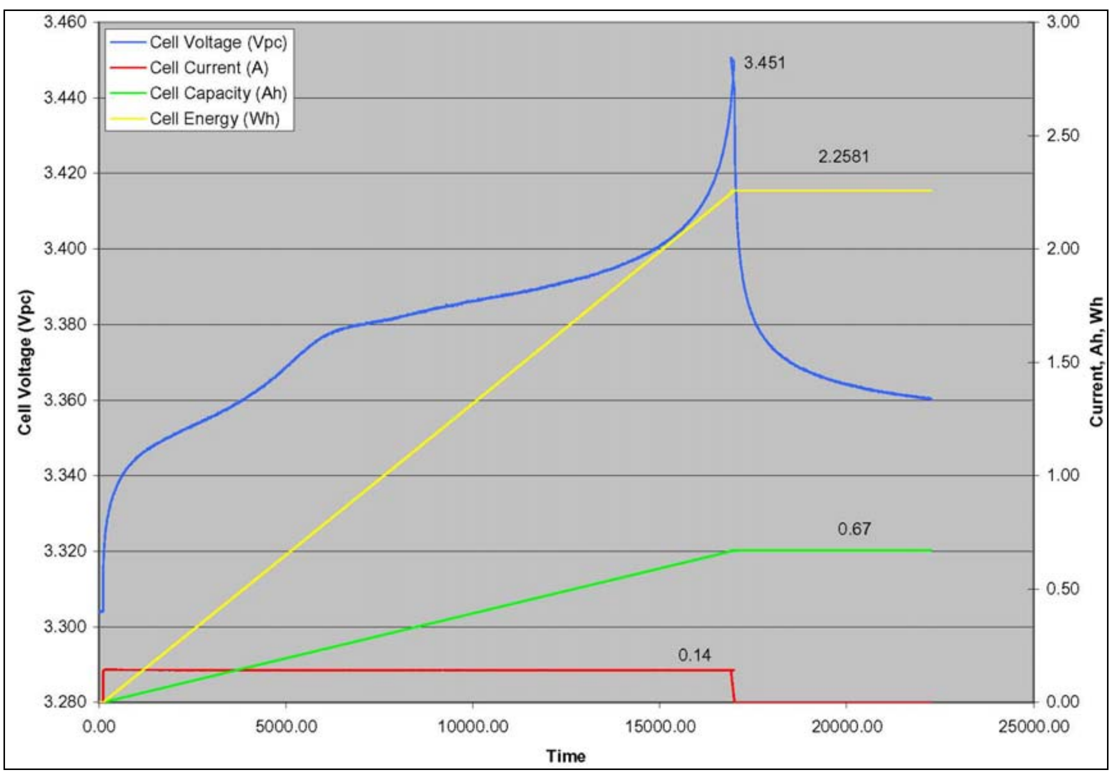


Figure 12. Typical PHEV charge profile on the cell level.

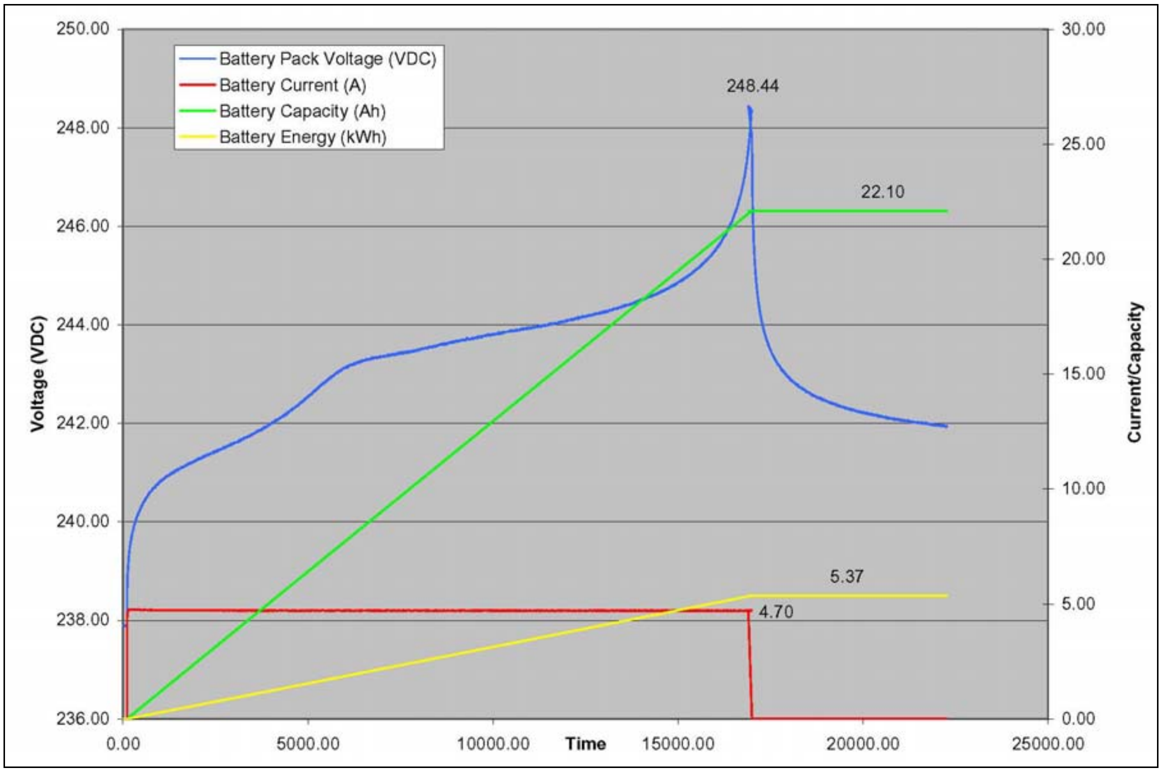


Figure 13. Typical PHEV charge profile on the pack level.

C. Hydrogen Internal Combustion Engine (ICE) Vehicle Testing

James Francfort (Principal Investigator), Timothy Murphy (Project Leader)
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-3830
(208) 526-6787; james.francfort@inl.gov

DOE Program Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Assess the safety, reliability and operating characteristics of 100% hydrogen fueled internal combustion engine (ICE) vehicles
- Identify any engine and vehicle system degradations when operating ICE vehicles on 100% hydrogen
- Perform independent testing on candidate 100% hydrogen ICE vehicles

Approach

- Use the Integrated Waste Hydrogen Utilization Project (IWHUP) in Vancouver, British Columbia as a source of inexpensive and high volume hydrogen to fuel eight 100% hydrogen ICE pickups converted from natural gas fuel to 100% hydrogen fuel
- Perform baseline performance (closed test track and dynamometer) testing on appropriate test vehicles

Accomplishments

- Fleet testing of eight vehicles fueled at the IWHUP demonstrated no safety problems during vehicle fueling and operations as the vehicles demonstrated consistent, reliable behavior
- The fleet vehicles demonstrated faster exhaust gas oxygen sensor degradation and an increased presence of water in the engine oils
- A 100% hydrogen ICE pickup successfully completed baseline performance testing

Future Directions

- Continue to operate the eight vehicles and document fuel use, vehicle performance, and any effects hydrogen has on vehicle subsystems
- Continue to evaluate candidate test vehicles and when appropriate, perform baseline performance and fleet testing on them

---

Introduction

The APS Alternative Fuel Pilot Plant, shown in Figure 1, is a hydrogen, compressed natural gas (CNG), and H/CNG-blends production and fueling system. The plant distinctly separates the hydrogen system from the natural gas system, but can blend the two fuels at the station's fueling system.

The AVTA, along with Electric Transportation Applications (ETA) and Arizona Pubic Service (APS), has monitored the operations of the APS Alternative Fuel (Hydrogen) Pilot Plant to determine the costs to produce hydrogen fuels (including 100% hydrogen as well as H/CNG blends) for use by fleets and other operators of advanced-technology vehicles.

Along with the station, the AVTA and its testing partners have operated two dozen internal combustion engine (ICE) vehicles on 100% hydrogen and blends of H/CNG. As a follow up to this testing, the AVTA is now collecting test data on eight 100% hydrogen ICE pickups that are fueled at the IWHUP in Vancouver, British Columbia. The IWHUP is being utilized because the hydrogen, which is emitted as a byproduct of a sodium chlorate manufacturing plant in North Vancouver, is both plentiful and inexpensive.

Figure 1. APS Alternative Fuel (Hydrogen) Pilot Plant, with fuel dispensing island in the foreground.

Approach and Results

Normal fleet operations and vehicle subsystem examinations have identified several consequences from lean-burn operations. Given hydrogen's very wide flammability limits, very lean burn is used to minimize the presence of NOx in the exhaust stream. This large use of intake air relative to hydrogen, results in cooler engine operations. As a believed result, water is appearing in the engine oils, which has the potential to shorten engine life. A second finding is the short life of exhaust gas oxygen sensors, the operation of which is required for CARB certification. It is unknown if the cooler exhaust gas is failing to burn off contaminates, but this is one possible theory. In early testing, these eight vehicles are averaging between 12 and 13 miles per gasoline gallons equivalent (GGE) of hydrogen.

A compressed natural gas Chevy Silverado base vehicle was converted to operate on 100% hydrogen fuel by Roush Industries and Electric Transportation Engineering Corporation (ETEC). This is the same vehicle model used for fleet testing in Vancouver and it is of a "crew cab" configuration, with six seat belt positions. It uses three Dynetek carbon-fiber-wrap aluminum-lined tanks installed in the bed of the pickup (Figure 2) 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 is 10.5 GGEs. In addition to the fuel tanks, other modifications included a supercharger, hydrogen fuel rails, hydrogen injectors, and significant engine control testing (Figure 3) and modifications.

Figure 2. Dynetek hydrogen fuel tanks in the bed of the pickup.

In track testing, the vehicle demonstrated an acceleration time from 0 to 60 mph of 22 seconds, a quarter mile top speed of 60 mph, and a constant speed fuel economy of 27 miles per GGE at 45 miles per hour. During dynamometer testing, the fuel use was 17.7 miles per GGE during the SAE J1634 testing with the air conditioning off, and 15.2 miles per GGE during the same SAE J1634 testing with the air conditioning turned on maximum.

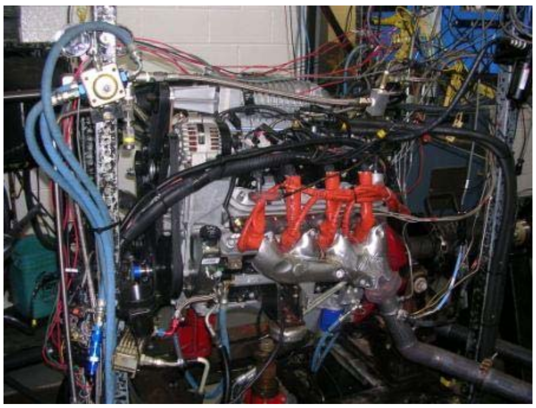


Figure 3. Hydrogen ICE testing on a Roush engine dynamometer.

Publications and Presentations

Various publications document pre-FY07 hydrogen ICE testing as well as the hydrogen station design and monitoring efforts. These reports can be found at: http://avt.inel.gov/hydrogen.shtml During FY07, the baseline performance testing fact sheet was published and its www location is listed below.

1. 2005 6.0 Liter Roush/Chevrolet Hydrogen ICE Pickup Truck baseline performance testing fact sheet. http://avt.inel.gov/pdf/hydrogen/roush_hev_fact.pdf

D. Neighborhood Electric Vehicle Testing

James Francfort (Principal Investigator), Timothy Murphy (Project Leader)
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415-3830
(208) 526-6787, e-mail: james.francfort@inl.gov

DOE Program Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objectives

- Support the California Air Resource Board's (CARB) decision process to require all neighborhood electric vehicle (NEV) models sold in California be tested by DOE's Advanced Vehicle Testing Activity (AVTA) in order to be eligible for CARB incremental funding and credits.
- Maintain documented test procedures and capabilities to support the continued introduction and operations of neighborhood electric vehicles in fleet environments, and expand the NEV test base.

Approach

- Answer all CARB questions regarding NEV testing history, test procedures development, conduct of testing, and AVTA objectives
- Conduct NEV testing as requested by industry and other NEV stakeholders.

Results

- CARB has chosen to require all NEV models sold in California be tested to the AVTA NEVAmerica baseline performance testing procedures.
- Initiated the testing of a new NEV from Global Electric Motors (GEM), a Chrysler subsidiary.
- Wisconsin has also elected to require any NEV models that are eligible for licensing in Wisconsin be tested by the AVTA NEVAmerica test procedures by the AVTA
- Respond to questions and inquires from numerous NEV manufacturers and perspective manufactures as to the testing process, costs, and schedules.

Future Activities

- Given the potential of this market and the expanding use of NEVs, when additional NEVs are introduced by manufacturers, the AVTA will continue to test new entrants.

Introduction

Neighborhood Electric Vehicles (NEVs) are defined by the National Highway Traffic Safety Administration as low-speed electric vehicles with attainable speeds of more than 20 miles per hour (mph), but not more than 25 mph. NEVs are generally allowed to operate on public streets with posted speeds up to 35 mph and are licensed as a motor vehicle.

NEVs are growing in popularity among fleets and the public because of improvements in technology and their inherently low operating costs. In response to this increasing popularity, the AVTA continued to maintain testing procedures and to update them based on past testing experience.

Approach

Conduct numerous conference calls with CARB regarding their process to adapt the NEVAmerica test procedures as their standard requirement. Answer NEV inquires as to testing processes, schedules and costs. One NEV was delivered for testing by Chrysler subsidiary Global Electric Motors (GEM) during late FY07. This testing was initiated as the fiscal year ended, so a testing report is not yet available.

Results

There were many new NEVs from new manufacturers shown at industry conferences, but there were no new testing inquires made by NEV manufacturers until CARB mandated that all NEVs be tested by the AVTA. This mandate was driven by CARB's experience that, in the past, some NEVs sold and operated in California were of substandard quality. Primarily for this reason, CARB has required all NEV models be tested by AVTA to the NEVAmerica test procedures. Successful completion of the NEVAmerica testing qualifies each NEV model for incremental funding and credits from CARB.

During the fourth quarter FY07, a single NEV from GEM started testing. It is anticipated that GEM will place two of three additional models in testing with the AVTA during FY08.

Future Plans

AVTA personnel have answered requests for testing information from approximately six NEV manufacturers and anticipate several NEV models will be introduced for testing during FY08.

E. Advanced Technology Medium and Heavy Vehicles Testing

Kevin Walkowicz (Principal Investigator)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
(303) 275-4492, e-mail: kevin_walkowicz@nrel.gov

DOE Technology Manager: Lee Slezak
(202) 586-2335, e-mail: Lee.Slezak@ee.doe.gov

Objective

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

Approach

- Work 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; and
- Provide updates on current applications to DOE and other interested organizations, as needed.

Results in FY07

- Published final results on New Flyer / GM Allison Hybrid Electric Buses operating in King County, WA.
- Published final results on Orion VII / BAE Hybrid Electric Buses operating in New York, NY.
- Analyzed 12 months of in-service data and prepared a draft final report on all 12 months for an evaluation of gasoline hybrid electric buses in Long Beach, CA.
- Began an evaluation with UPS and Eaton Corporation to evaluate an Lithium Battery HEV Delivery Truck in Dallas, TX.
- Completed final report detailing testing of the thermal performance of a Volvo Sleeper Cab and completed testing of International Pro-Star sleeper cab under the Cool Cab project.

Future Activities

- Complete evaluations on current fleet vehicles, initiate new evaluations;
- Coordinate modeling and testing activities with other DOE projects such as 21CT and AHHPS; and
- 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 2007 included:

- Fleet evaluations
- Short term technology evaluation – Cool Cab

Fleet Evaluations

In FY2006, AVTA worked with 4 fleets to evaluate the performance of advanced technologies in service. They are:

1) New York City Transit (NYCT) has been investigating clean fuel technologies for several years. AVTA is finishing its work with this fleet to evaluate the next-generation Orion VII/BAE hybrid bus. NYCT has purchased 325 of these hybrids in the initial two orders. The first order of 125 (Gen I) is an upgrade from the fleet's prototype Orion VI hybrids. The second order of 200 (Gen II) has several additional modifications to further improve the system performance.

In addition to the hybrid buses, NYCT is also operating Orion VII CNG buses. These natural gas buses were included in the 125 evaluation.

In FY2007, AVTA published the analysis on the fleet of CNG and Hybrid (125 order) buses in an NREL Technical Report (November 2006). Also in FY2007, AVTA submitted a draft final report on the fleet of 200 hybrids which compared both the generations of hybrids. Highlights of these reports are as follows:

- *Usage:* NYCT quickly integrated both the CNG and Gen I hybrid buses into the fleet, achieving a similar usage rate of approximately 2,300 monthly miles per bus. The Gen II hybrids averaged about 2100 miles per month per bus, mainly due to depot speed differences.

- *Reliability:* Both the CNG and Gen I hybrid bus fleets experienced miles between roadcalls (MBRC) rates above NYCT's required 4,000 MBRC (average 6,000 MBRC for CNG, 5,000 MBRC for Gen I hybrid). Gen II hybrids averaged just over 5,400 MBRC.

- *Fuel Economy:* The Gen I hybrid buses had an average fuel economy that was 34-40% higher than the diesel baseline buses. The Gen II hybrids fuel economy decreased slightly from the Gen I hybrids 3.00 mpg versus 3.19 for the 1st year of each generation. This could be attributed to the addition of EGR on the Gen II hybrids. (Figure 1)

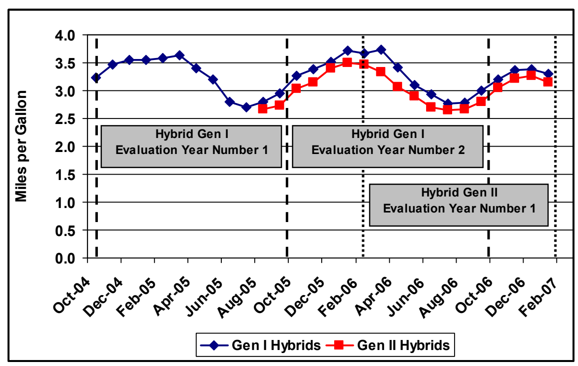


Figure 1. Fuel Economy Summary of Gen I and Gen II Bus Groups

- *Maintenance Costs:* The CNG buses had an average total maintenance cost higher than that of the hybrid buses: CNG buses had 5% higher total cost than the Gen I hybrid buses; Gen II hybrids had 39% lower maintenance costs than the Gen I buses. For the propulsion system only maintenance costs, the CNG buses were 5% lower than the Gen I hybrids and the Gen II hybrids were 55% lower than the Gen I hybrids. (Figure 2)

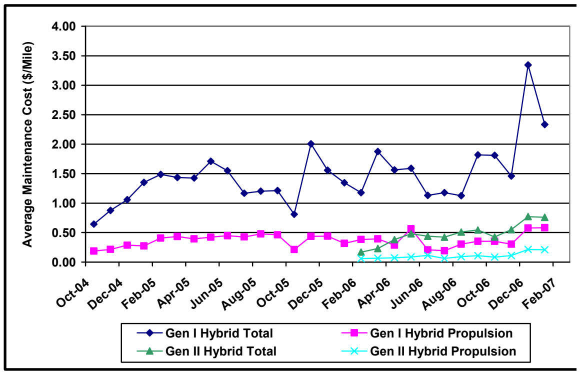


Figure 2. Propulsion System Maintenance Costs

- NYCT has shown their commitment to hybrid technology by placing an order for an additional 500 buses from Orion with the BAE Systems hybrid propulsion system.

2) King County Metro in Seattle, Washington (KC Metro) has replaced a large fleet of older technology buses with New Flyer articulated (60-ft) buses using the GM-Allison parallel hybrid system. AVTA worked with the fleet in FY07 to finish the evaluation of this new hybrid system in comparison to conventional diesel buses from the same order. The diesel buses used the same platform and engine, making this the closest “apples-to-apples” comparison that AVTA has conducted.

In December 2006, AVTA published a final project report for 12 months of data on the buses in service. These results for the evaluation were presented to the industry at the SAE Hybrid Symposium in February 2007 and at the Hybrid Truck Users Forum in February 2007. Highlights of this report are as follows:

- _Fuel Economy:_ Figure 3 shows the fuel economy comparison between the hybrid and diesel buses. These results show an overall increase of 27% in fuel economy for the hybrid buses when compared to the diesel buses in a similar service.

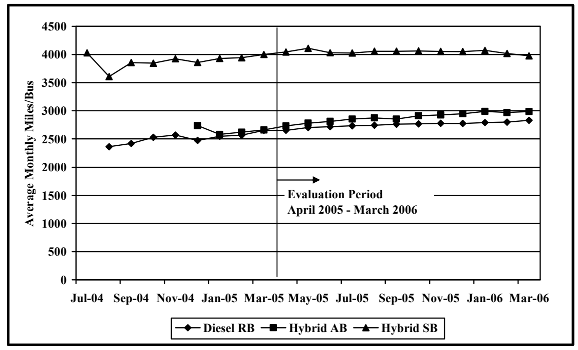


Figure 3. Fuel Economy for Hybrid and diesel buses at KC Metro in similar duty cycle.

- _Maintenance Cost:_ Figure 4 shows the total maintenance cost for both types of buses. The hybrids averaged $0.44/mile and the diesels averaged $0.46/mile – a 4% decrease. Figure 5 shows the maintenance cost for the propulsion system only. The hybrids averaged $0.13/mile and the diesels averaged $0.12/mile – a 5% increase. These propulsion system costs do not include warrant related costs.

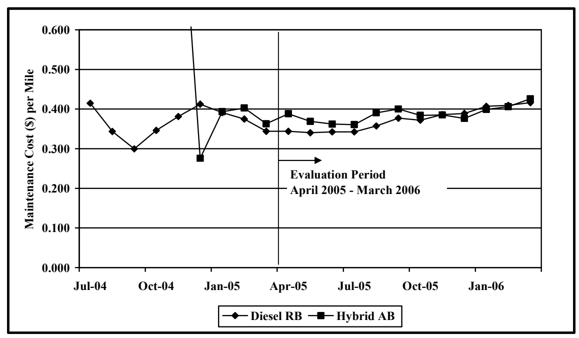


Figure 4. Total maintenance costs/mile

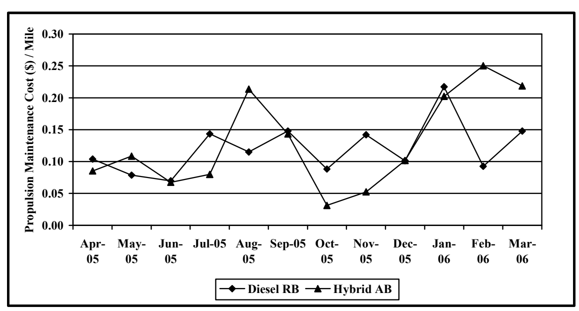


Figure 5. Propulsion only maintenance costs/mile

- *Propulsion System Failures:* Warranty costs for both vehicles were calculated but do include 6 failed Dual Power Inverter Modules (DPIM's) for the hybrid buses. As the replacement costs of these are unknown at the time of the report, they were not included in the reported warranty costs. There were no battery failures and no drive unit failures for these buses during the evaluation period.
- *Reliability:* Figure 6 shows the MBRC's for both bus groups for all systems and also for propulsion system only. Propulsion system MBRC's for the hybrids averaged 10,616 miles and the diesel buses averaged 12,199 miles (13% more miles between road calls).
- *Operational Costs:* Total operational costs for the diesel buses (fuel and maintenance costs) were $1.25 per mile. The total operational costs for the hybrid buses were $1.06 per mile – a 15% decrease overall.
- Overall, KCM Transit was satisfied with the buses and recently ordered more.

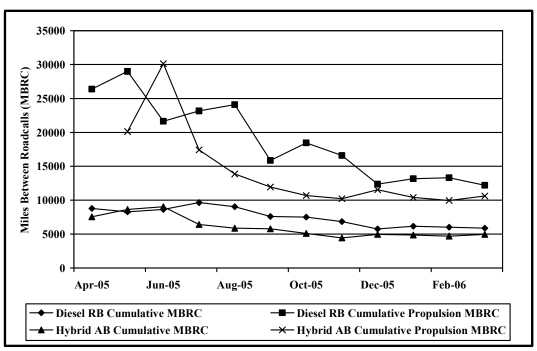


Figure 6. MBRC for both bus groups

3) Long Beach, CA – ISE Gasoline Hybrid - AVTA is finishing its work with this fleet to evaluate 10 of the gasoline hybrid buses which are currently operating in the city of Long Beach, CA (Long Beach Transit - LBT). LBT currently has forty-seven 40-ft hybrid gasoline-electric buses equipped with Maxwell ultra capacitors for energy storage that arrived in June – August 2005. These buses were expected to operate more cost effectively than CNG in terms of infrastructure, fuel economy and maintenance savings and offer a clean option for LBT as gasoline was qualified as an alternative fuel for transit buses by the California Air Resources Board (CARB).

In September 2007, AVTA produced a draft final project report for 24 months of data on the buses in service (June 2005 – June 2007). These buses were compared with the conventional diesel buses that were also in operation in the LBT fleet. A final published report is expected in December 2007. Highlights of this report are as follows:

- *Fuel Economy:* Figure 7 shows the fuel economy comparison between the hybrid and diesel buses. When compared to the conventional diesel buses, the results show an overall decrease of 4.3% in fuel economy (on a straight per gallon basis) and an 8.5% increase in fuel economy (if the fuel consumption is adjusted for the energy content on a volumetric basis).

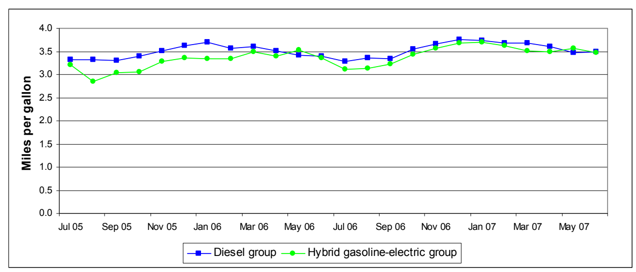


Figure 7. Fuel Economy for Hybrid and diesel buses at LBT in similar duty cycle.

- *Maintenance Cost:* Figure 8 shows the total maintenance cost and propulsion system maintenance cost for both types of buses. For total maintenance cost, the hybrids averaged $0.31/mile and the diesels averaged $0.54/mile – a 42% decrease in costs for the hybrids. For propulsion system only maintenance costs, the hybrids averaged $0.08/mile and the diesels averaged $0.19/mile – a 63% decrease. These propulsion system costs do not include any warranty related costs.

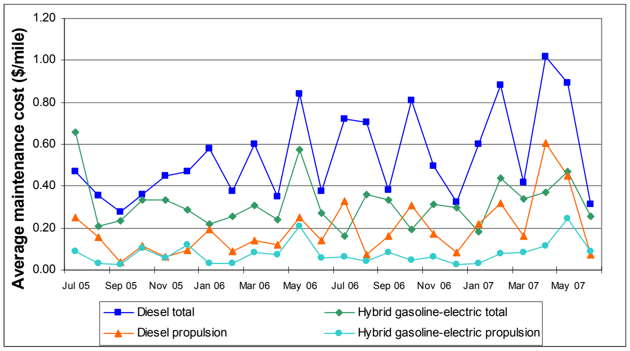


Figure 8. Maintenance costs/mile

Ultra capacitors: During the evaluation period a manufacturing issue was identified; acetonitrile was leaking from some of the ultra-capacitors. ISE corrected the issue with a warranty campaign based on serial numbers of suspect batches of ultra-capacitors. The correction was to apply an epoxy coating over the ultra capacitors, sealing them. Two incidents of ultra-capacitor dry cell overheating were attributed to this leakage within the fleet, but were not part of the study group.

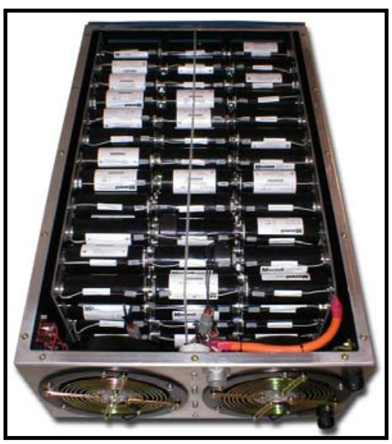


Figure 9. Maxwell Ultra capacitor Pack

- *Reliability:* Figure 10 shows the MBRC's for both bus groups for all systems and also for propulsion system only. Total MBRC for the hybrids averaged 9,000 miles and the diesels averaged 11,040 miles (an 18% decrease in MBRC for the hybrids). For the propulsion system MBRC's for the hybrids averaged 15,000 miles and the diesel buses averaged 19,118 miles (22% less MBRC for the hybrids.

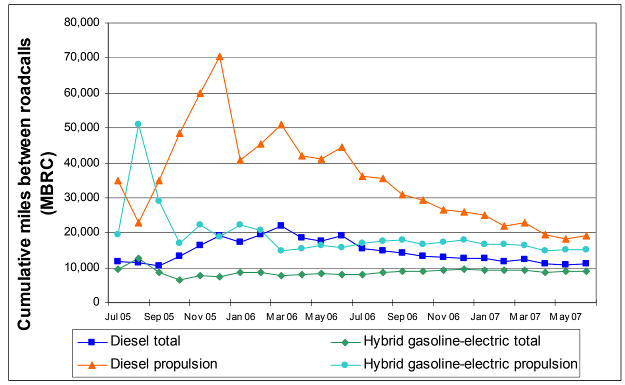


Figure 10. MBRC for both bus groups

- *Operational Costs:* Total operational costs for the diesel buses (fuel and maintenance costs) were $1.19 per mile. The total operational costs for the hybrid buses were $1.05 per mile – a 12% decrease overall for the hybrids.
- Overall, LBT has been satisfied with the buses.

4) UPS Hybrid Package Delivery

A new fleet evaluation was initiated in FY2007. AVTA will be evaluating trucks in a UPS fleet in Dallas, TX to evaluate the performance of their MD package delivery vehicles equipped with an advanced battery powered Eaton parallel hybrid systems. The intent of the project is to compare these lithium battery parallel hybrid trucks with conventional diesel powered trucks. An evaluation to assess the performance and feasibility of this technology was initiated. Duty cycle data acquisition was completed in May of 2007 in Dallas and a composite duty cycle was created for testing. (Figure 11) Chassis Dynamometer Testing (funded by the Advanced Heavy Hybrid Program) was also completed and managed by the AVTA team to ensure continuity with the 12 month evaluation.

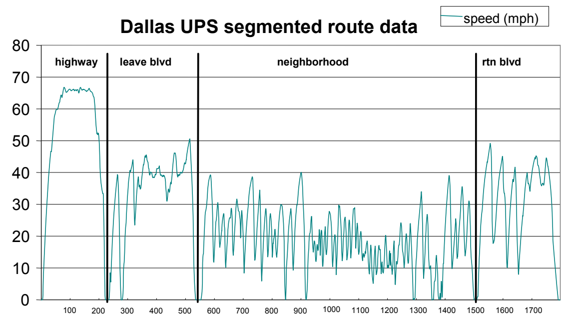


Figure 11. UPS route data

Short Term Technology Evaluations

Cool Cab

The AVTA team completed a thermal analysis of a two Class 8 sleeper cabs in order to quantify options for reducing air conditioning load. Reducing air conditioning load will allow for advanced, energy saving idle reduction technologies to be implemented.

Volvo: In October 2006, the AVTA team completed testing of a Volvo Model 770 tractor and was able to quantify the average heat transfer coefficient for the cab as well as the R-value of the truck. Modifications to the cab were completed and the UA and R-values with these changes were determined.

- 2 kW required for Volvo truck heating
- UA calculated: 65 w/K for Volvo, 84 w/K for FL (baseline comparison)
- Curtain test = 15% reduction for bunk area
- Windows = 20% reduction in UA possible

Infrared images were also analyzed to identify specific areas of the truck that could benefit from improved sealing or insulation. (Figure 12).

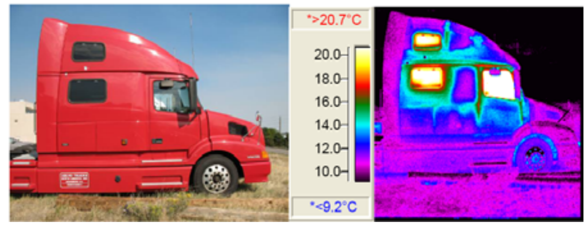


Figure 12. Infrared analysis of Volvo

International: In May 2007, the AVTA team completed testing of a 2007 International Prostar tractor and was able to quantify the average heat transfer coefficient for the cab as well as the R-value of the truck. Modifications to the cab were completed and the UA and R-values with these changes were determined. A milestone report was submitted in September of 2007 which summarized the work on this (see Figure 13):

	Base or Unmodified case	Sleeper Curtain Closed	Arctic Curtain Closed	Windows Insulated
UA Test	50 W/K	20% reduction from base	25% reduction from base	13% reduction from base
Solar Soak	ΔT = 11°C	3% reduction from base	28% reduction from base	38% reduction from base

Figure 13. UA results for International Pro-Star

Infrared images were also analyzed to identify specific areas of the truck that could benefit from improved sealing or insulation. (Figure 14)

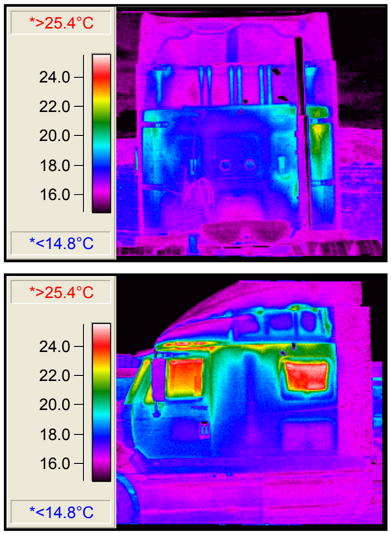


Figure 14. Infrared Images of Pro-Star

Overall AVTA Results

Results from AVTA fleet evaluations have been anticipated and well received by the industry. Specific results for each evaluation are described as a part of the project sections above.

Future Plans

The team will continue working with fleets to investigate the latest technology in heavy-duty vehicles. The team will track the latest developments in advanced vehicles and select those most promising 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.

FY2007 Publications / Presentations

1. Barnitt, R.; Chandler, K. (November 2006). New York City Transit Hybrid and CNG Transit Buses: Final Evaluation Results – 125 order. 62 pp.; NREL Report No. TP-540-40125

2. Barnitt, R. (September 2007). New York City Transit Hybrid and CNG Transit Buses: Final Evaluation Results -200 order - Final Draft. 62 pp.; NREL Report No. TP-540-42217

3. Chandler, K.; Walkowicz, K. (December 2006). King County Metro Transit Hybrid Articulated Buses: Final Evaluation Results. 60 pp.; NREL Report No. TP-540-40585

4. Hayes, R. R.; Williams, A.; Ireland, J.; Walkowicz, K.; Black, S. (November 2006). King County Metro -- Allison Hybrid Electric Transit Bus Testing. SAE Paper No. 2006-01-3570. SAE 2006 Commercial Vehicle Engineering Congress and Exhibition, 31 October - 2 November 2006, Chicago, Illinois. 10 pp.; NREL Report No. CP-540-40607.

5. Proc, K. (September 2007). CoolCab Truck Testing Project Update / Milestone Report (Presentation). 14 pp.; NREL Report No. PR-540-42396.

6. Walkowicz, K. (November 2006). DOE Heavy Duty Field Test Program (Presentation). 20 pp.: Presented at the Hybrid Truck User Forum, San Diego, CA. NREL Report No. PR-540-40859

7. Walkowicz, K. (February 2007). DOE Sponsored Heavy Duty Hybrid Work (Presentation). 24 pp.: Presented at the SAE Hybrid Vehicle Symposium, San Diego, CA. NREL Report No. PR-540-40983

8. Lammert, M. (September 2007). Long Beach Transit Two-Year Hybrid Gasoline Electric Evaluation –Final Draft Milestone Report. 28 pp.: NREL Report No. TP-540-42226

9. Barnitt, R. (November 2006). NREL Fleet Test and Evaluation Team Activities (Presentation). Presented at the American Public Transit Association, Pittsburgh, PA. NREL Report No. PR-540-40877

Printed on recycled paper

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

For more information contact:
EERE Information Center
1-877-EERE-INF (1-877-337-3463)
www.eere.energy.gov