

annual progress

ADVANCED VEHICLE TECHNOLOGY ANALYSIS AND EVALUATION ACTIVITIES

FREEDOMCAR AND VEHICLE TECHNOLOGIES PROGRAM

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

FY 2006

**Annual Progress Report for
Advanced Vehicle Technology Analysis and Evaluation Activities**

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

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CONTENTS

I.	INTRODUCTION.....	1
II.	MODELING AND SIMULATION	9
A.	Plug-in HEV Component Requirements for Mid-size Car and Mid-size SUV	9
B.	Impact of Drive Cycle Aggressiveness and Speed on HEVs Fuel Consumption Sensitivity.....	19
C.	Data Quality Analysis and Validation of MY04 Toyota Prius.....	31
D.	State of Charge Balancing Techniques.....	36
E.	Government Performance and Results Act (GPRA) Support.....	42
F.	PSAT Maintenance and Enhancements.....	46
G.	Automotive System Cost Modeling	50
H.	Development of Models for Advanced Engines and Emission Control Components.....	55
I.	Heavy Truck Duty Cycle (HTDC) Project.....	61
J.	Plug-in Hybrid Vehicle Systems Analysis	67
K.	Technical Target Tool Enhancements	72
L.	Investigation of Route-based Control for Hybrid Electric Vehicles.....	75
III.	INTEGRATION AND VALIDATION	79
A.	Mobile Automotive Technology Testbed (MATT).....	79
B.	Battery Hardware in the Loop	87
C.	Hydrogen Engine Testing and Calibration	91
IV.	LABORATORY TESTING AND BENCHMARKING.....	97
A.	Benchmarking and Validation of Hybrid Electric Vehicles.....	97
B.	Testing of Plug-in Hybrid Electric Vehicles (PHEV)	102
V.	OPERATIONAL AND FLEET TESTING.....	105
A.	Hybrid Electric Vehicle Testing.....	107
B.	Plug-in Hybrid Electric Vehicle Testing	115
C.	Arizona Public Service (APS) Alternative Fuel (Hydrogen) Pilot Plant Monitoring, Hydrogen and Compressed Natural Gas (H/CNG) Dispenser Testing (real-time fuel blending), and 100% Hydrogen and H/CNG Internal Combustion Engine (ICE) Vehicle Testing.....	118
D.	Neighborhood Electric Vehicle Testing	122
E.	Urban Electric Vehicle Testing	129
F.	Oil Bypass Filter and Diesel Engine Idling Wear-rate Evaluation Testing.....	132
G.	Advanced Technology Medium and Heavy Vehicles Testing	142
VI.	LIGHT VEHICLE ANCILLARY SYSTEMS.....	147
A.	Light Vehicle Ancillary Systems.....	147

I. INTRODUCTION

On behalf of the U.S. Department of Energy's FreedomCAR and Vehicle Technologies (FCVT) Program, I am pleased to submit the Annual Progress Report for fiscal year 2006 for the Advanced Vehicle Technology Analysis and Evaluation (AVTAE) team activities.

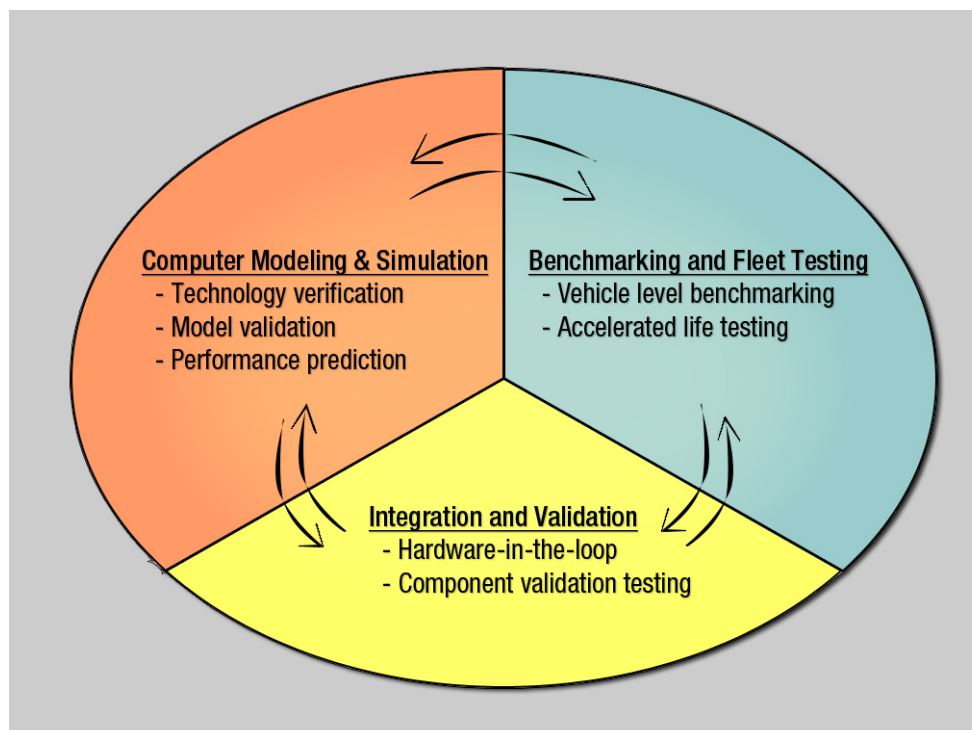
Mission

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 FCVT 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 FCVT Program targets and associated data that will enable the FCVT 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 FCVT Program goals of fuel consumption reduction by developing and evaluating enabling vehicle system technologies in the area of light vehicle ancillary loads reduction.

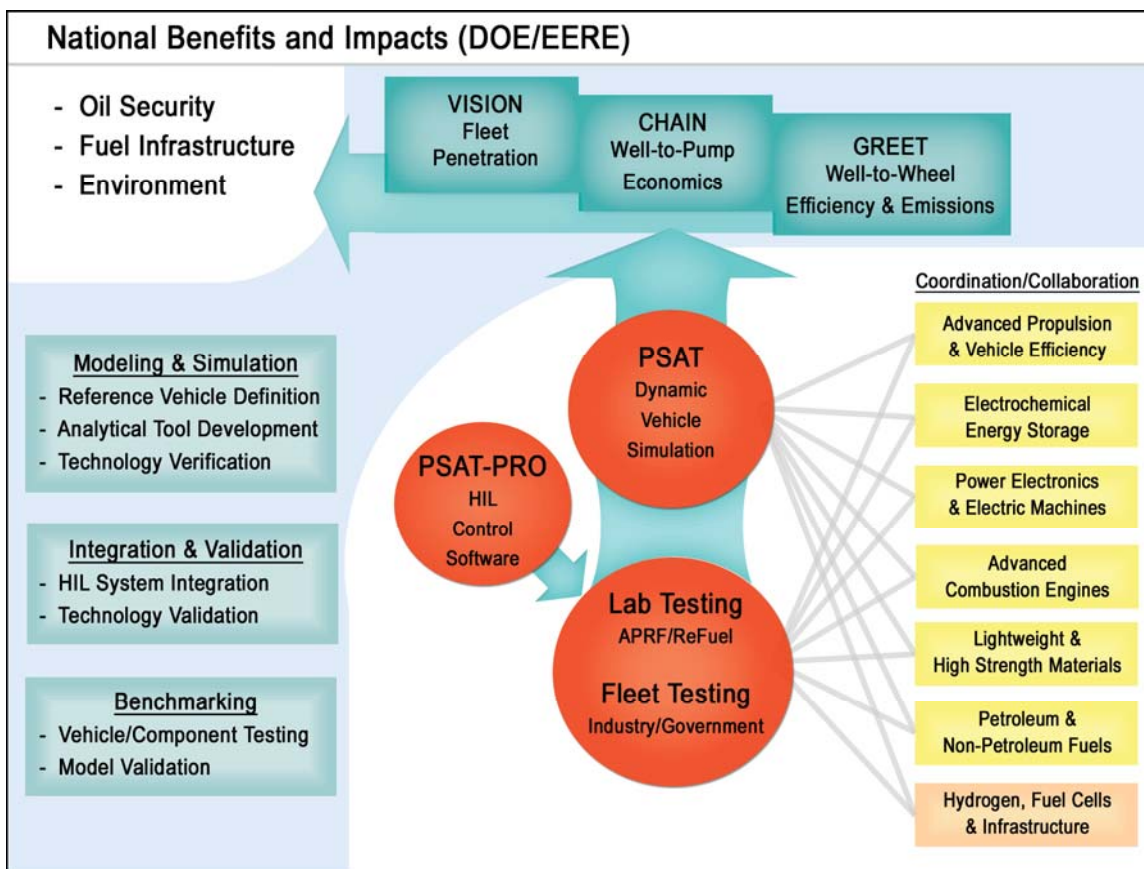
The integration of computer modeling and simulation, hardware-in-the-loop testing, vehicle benchmarking, and fleet evaluations is critical to the success of the AVTAE team. Each respective area feeds important information back into the other, strengthening each aspect of the team. A graphical representation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



Integration of AVTAE computer modeling and testing activities.

FY 2006 AVTAE Activities

AVTAE provides an overarching vehicle systems perspective in support of the technology R&D activities of DOE's FCVT 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 FCVT 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 FCVT and HFCIT Programs is required for both analysis and testing. Analytical results of this sub-program are used to estimate national benefits and 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 five (5) 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 maintained to support FCVT 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 FCVT 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 power 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 real 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, and fuel cell vehicles), development and optimization of energy management strategies, and identification of transient control requirements. In 2004, PSAT received an R&D 100 award, which highlights the 100 best products and technologies newly available for commercial use from around the world. This is the 41st year the technology awards have been given by R&D Magazine to recognize the "100 most technologically significant new products" of the entries the magazine receives.

PSAT-PRO (PSAT rapid control PROotyping software) allows dynamic control of components and subsystems in hardware-in-the-loop (HIL) testing. Real 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 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.

GCTool was developed at Argonne National Laboratory (ANL) for steady state and dynamic analysis of fuel cell systems. Using GCTool architecture, ANL has developed simplified engineering models of fuel cell systems and components for vehicle systems analysis. The engineering model, named GCTool-Eng, can be linked to MATLAB®-based vehicle codes such as PSAT. GCTool-Eng has been successfully used to analyze alternative configurations of fuel cell and hybrid vehicles.

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 FCVT Program matures, the need to evaluate newly developed technology in a vehicle system context will become critical. Through the 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 FY06, the battery HIL will be 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. The ultimate goal is 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 FCVT-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 FCVT 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 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) 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 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 HEV model are tested to 160,000 miles to help ensure accuracy. Ideally, a larger sample than two HEVs would be tested to 160,000 miles, but funding tradeoffs necessitate only testing two of each HEV model.

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.

5. *Light Vehicle Ancillary Systems*

With industry cooperation, the Light Vehicle Ancillary Systems activities develop and test ancillary load solutions to reduce fuel use while maintaining occupant comfort. Focus is on complete system integrated modeling, utilization of advanced measurement and assessment tools, and assessment of the potential of a waste heat cabin cooling system.

Measurement and Assessment Tools - An experimental thermal comfort manikin has been developed and is being validated to measure and predict human response to cabin thermal conditions. The manikin will have realistic physical dimensions and weight as well as controllable surface heat output and sweating rate and breathes warm humid air.

Integrated Modeling - The integrated modeling uses multifaceted numerical tools: vehicle and cabin geometry; cabin thermal properties; cabin air velocity and temperature field; and A/C, thermal comfort, and vehicle models. The objective is to integrate all the factors that impact climate control systems to determine their impact on vehicle fuel economy, tailpipe emissions, and the occupants' response to the thermal environment.

Advanced Climate Control System Assessment - The thermal comfort and integrated modeling tools will be used to assess the level of development of advanced climate control systems for advanced vehicles, such as a fuel cell vehicle. Prototype systems will be developed and tested in the Vehicle Climate Control Laboratory and results will be incorporated into the cooling system integrated modeling tool.

Waste Heat Cabin Cooling Evaluation - The goal is to evaluate the potential, as well as technical barriers to the use of waste heat (coolant and exhaust for ICE) to provide cabin cooling and heating. The challenge is incorporating this approach into HEVs which utilize engine off strategies as well as in FCVs that have little waste heat. Benchtop testing will validate the technical feasibility of prototypes. Manufacturers will be encouraged to incorporate the most promising technologies into a vehicle.

Major projects conducted by the national laboratories in support of these areas in FY 2006 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 2007, AVTAE will complete the specification of representative vehicle platforms, complete baseline performance testing of conversion PHEV's, and validate simulation models on a host of PHEV's at the APRF. Field and laboratory testing will continue to be integrated with modeling/simulation tools. Emphasis will be placed on the fleet evaluation of PHEV conversion vehicles, as well as production PHEV's when available. Test procedures will be developed to account for the nuances associated with PHEV's and models will be validated and enhanced to ensure their usefulness. ANL and INL will be working together to develop a Plug-in Hybrid Test Bed (PHTB) that will allow evaluations of motors, batteries, and control algorithms capable of running full test profiles without mandatory engine starts specific to PHEV applications. 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 FCVT R&D programs, most notably Heavy Vehicle Systems Optimization. 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 FCVT technologies for advanced power electronics, energy storage, and combustion engines will be ongoing as each technology progresses towards the targeted performance. Tests for commercially viable hydrogen fuel cell vehicles are scheduled for FY 2008.

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



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II. MODELING AND SIMULATION

A. Plug-in HEV Component Requirements for Mid-size Car and Mid-size SUV

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Objectives

- The primary focus of this study is to define the battery requirements for Plug-in HEVs.
- Two different vehicle classes (midsize car and midsize SUV) as well as six All Electric Ranges (AER) ranging from 10 to 60 miles have been simulated.

Approach

- A design-specific battery model was developed based on a combination of test data and detailed modeling to represent state-of-the-art Li-ion technology.
- A battery scaling algorithm was implemented to be able to independently select the power and energy of the battery packs.
- Other component models and vehicle assumptions were reviewed by the FreedomCAR Technical Teams.
- Specific post-processing and control strategies were developed to define the most stringent operating conditions of the battery.

Accomplishments

- Vehicles representing the different AER were sized and simulated on several driving cycles.
- Peak charging and discharging powers as well as available energy were recorded.

Future Directions

- Battery test data will be used to refine the initial battery model.
- Vehicle test data will be used to correlate the operating conditions of the battery during different driving cycles.

Introduction

Relatively detailed comparisons between plug-in hybrid powertrains and hybrid powertrains were recently completed [1]. However, these studies did not examine the potential benefit of using a Li-ion battery. To evaluate the battery requirements for different PHEV options, Argonne's vehicle simulation tool, Powertrain System Analysis Toolkit

(PSAT), was used with a battery model designed by Argonne's battery research group.

In this study, we describe the component models and control strategies developed to characterize Plug-in Hybrid Electric Vehicles (PHEVs) for both Midsize and SUV classes. The impact of All Electric Range (AER) on fuel efficiency will be analyzed to provide

direction on the most appropriate sizing strategy. Then, the main battery parameters, including energy, power, current and voltage, will be evaluated.

Approach

Vehicle Definition

Vehicles representative of the compact, midsize and SUV classes were sized for performance times of 8, 9 and 10 seconds. Table 1 summarizes the performance requirements used for this study. For each vehicle class, five types of powertrains were simulated: conventional, mild parallel hybrid, full parallel hybrid, fuel cell vehicle and fuel cell hybrid vehicle. Table 2 clarifies the vehicle and component specifications for the mid-size vehicle configuration. Table 3 summarizes the characteristics of the SUV vehicle for the purposes of this study.

Table 1. Performance Requirements

Parameter	Unit	Value
0–60mph	s	9 +/- 0.1
0–30mph	s	3
Grade at 55 mph	%	6
Maximum Speed	mph	> 100

Table 2. Main Specifications of the Midsize Vehicle

Component	Specifications
Engine	Gasoline based on LK5 data
Electric machine	UQM SR218N
Battery	Li-ion – VL41M
Transmission	5-speed manual Ratios: [3.42, 2.14, 1.45, 1.03, 0.77]
Frontal Area	2.244 m ²
Final Drive Ratio	3.8
Drag Coefficient	0.315
Rolling Resist.	0.008 (plus speed-related term)
Wheel radius	0.3175 m

As shown in Figure 1, the configuration selected is a pre-transmission parallel hybrid, similar to the one used in the DaimlerChrysler Sprinter Van [3].

This study accounts for uncertainty in component specifications by considering two cases: a slow technology advancement case and a fast technology advancement case. Fast technology advancement represents the consequences of achieving the

Table 3. Main Specifications for the Sport Utility Vehicle

Component	Specifications
Engine	Gasoline based on LK5 data
Electric machine	UQM SR218N
Battery	Li-ion – VL41M
Transmission	5-speed manual Ratio: [3.42, 2.14, 1.45, 1.03, 0.77]
Frontal Area	2.46 m ²
Final Drive Ratio	3.83
Drag Coefficient	0.41
Rolling Resist.	0.0084 (plus speed-related term)
Wheel radius	0.368 m

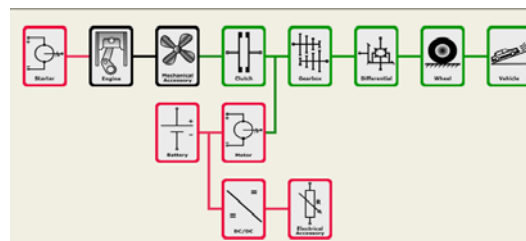


Figure 1. Configuration Selected – Pre-Transmission Parallel HEV

FreedomCAR goals, while slow technology advancement represents the consequences of achieving more conservative improvements.

Battery

In this study, equations were derived for calculating the impedance of a plug-in hybrid vehicle battery for use in simulating the battery behavior under driving conditions. Developing the equations for expressing battery resistance for a plug-in hybrid vehicle battery is more complex than developing those for a standard hybrid vehicle because the plug-in battery may be charged and discharged during vehicle operation for periods lasting several minutes. Ideally, the equations should be able to reproduce the measured voltage curves for a complete discharge and charge at constant current, as well as the battery resistance under conditions of rapidly changing currents. Current and voltage data taken at Argonne National Laboratory were available for a cell fabricated by SAFT, Inc., which is somewhat similar to its 41-Ah lithium-ion cell (designated VL

41M listed on SAFT's web site). The VL41M cell has a capacity of 41-Ah at the 3-h rate and a power of 1,000 W (400 A at 2.5V) at 80% Depth of Discharge (DOD). The data for the cell measured at Argonne were for a 3-h discharge at constant current and for Hybrid Pulse Power Characterization (HPPC) tests. These data were fit to an electronic simulation model with two time constants (Fig. 2) of the form:

$$(OCV - V_L)/I_L = R = R_o + R_{p1} * I_{p1}/I_L + R_{p2} * I_{p2}/I_L$$

In this relationship, OCV and V_L are the open circuit and load voltages; R , R_o , R_{p1} , and R_{p2} , are the total battery impedance, the ohmic resistance, and the polarization impedances; and I_{p1}/I_L and I_{p2}/I_L are the ratios of the polarization currents to the load current. The polarization currents are determined by integration of the equation $dI_p/dt = (I_L - I_p)/\tau$ for each of the polarization impedances (where τ_1 and τ_2 are time constants of 22.8 and 270 s, respectively), as in an earlier study that also used two polarization impedances [4] and in the PNGV Lumped Parameter Model [5] of the United States Department of Energy, which was a similar model with one polarization impedance. The parameters in the equation (OCV , R_o , R_{p1} , R_{p2}) were selected to match the measured data for both the 3-h discharge and the HPPC data for the entire range of the discharge, and these parameters were presented in the form of a lookup table with values from 0% to 100% state of charge at 10% intervals (τ_1 and τ_2 were held constant over the entire discharge). These results were converted to a similar table for the SAFT 41-Ah cell, VL41M, by use of a multiplying factor that matched the calculated impedance at 80% DOD with that given for the VL41M cell.

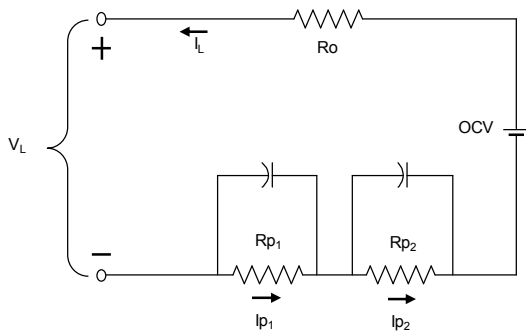


Figure 2. Battery Electric Circuit Model

The utility of the model was further extended to include cells of the same chemistry, but with capacities in the range of 10–100 Ah and capacity-to-power ratios (C/P) of 0.75–3.0 times that of the VL41M cell and for batteries containing any number of such cells. This was done by developing a set of equations used to determine the multiplying factor for converting the lookup table developed for the parameters of the VL41M cell to the appropriate values for the desired cell capacity and power. For instance, some of the equations (with compatible dimensions) are shown here:

$(C/P)_{41}$ = ratio of capacity to power at 80%DOD and 2.5 V for VL41M cell

C_C = capacity of simulated battery cell

F_C = capacity factor for cell = $(C/P)_C / (C/P)_{41}$

M = number of 6-cell modules in battery

N = number of cells in battery = $6 \times M$

R_{41} = resistance of VL41 M cell = $R_o + R_{p1} \times I_{p1}/I_L + R_{p2} \times I_{p2}/I_L$

R_B = resistance of battery = $R_{41} \times F_C \times (41/C_C) \times N$

P_B = power of battery at = $P_{41}/F_C \times C_C/41 \times N$

The model so derived makes it possible to simulate battery behavior for batteries suited to PHEVs with electric ranges of 20–60 miles.

Component Sizing Process

To quickly size the component models of the powertrain, an automated sizing process was developed. A flow chart illustrating the logic of the sizing process is shown in Figure 3. While the engine power is the only variable for conventional vehicles, HEVs have two variables engine power and electric machine power. PHEVs add a third degree of freedom: battery energy. The sizing process defines the peak mechanical power of the electric machine as being equal to the peak power needed to follow the Urban Driving Dynamometer Schedule (UDDS) driving cycle while driving this cycle in all-electrical mode. The peak discharge power of the battery is then defined as the electrical power that the motor requires to produce its peak mechanical power. The sizing process then calculates the peak power of the engine using the power of the drivetrain required to achieve the gradeability requirement of the vehicle.

The 0–60 performance requirement for the vehicle is satisfied implicitly by the constraints on the peak motor power and the peak engine power. The power required by the motor for the vehicle to follow the UDDS cycle added to the power required by the engine for the vehicle to drive up a 6% grade at 55 mph exceeds the power the vehicle needs to go from 0 to 60 mph in 9 seconds.

Finally, the battery energy is sized to achieve the required AER of the vehicle. The AER is defined as the distance the vehicle can travel without starting the engine. It is important to notice that a separate control algorithm is used to simulate the AER. This algorithm forces the engine to remain off throughout the cycle, regardless of the torque request from the driver.

When motor power, engine power and battery energy are changed the mass of the vehicle is recomputed. Using these new values the algorithm checks the vehicle against the performance criteria. If the criteria are met, the vehicle is defined and the algorithm exits. If the criteria are not met, the algorithm executes another iteration adjusting the motor power, the engine power and the battery energy, again. It then rechecks the criteria. The algorithm continues to loop until it converges.

Once it has converged, the battery is oversized to take into account battery aging. The battery power is oversized by 30% and its energy by 20%. This assumption will be modified once more battery data become available.

Seven AER values (7.5, 10, 20, 30, 40, 50, and 60 mi) were simulated. The battery characteristics for each vehicle are provided in Appendix 1. Figure 4 shows three ranges that were defined for each vehicle. The end-of-life (EOL) AER confirms the validity of the sizing algorithm. One notices that an additional AER is available at the beginning of life (BOL).

Excess energy is added to maintain a consistent range throughout the life of the vehicle. At the beginning of life, the control strategy would limit the vehicle range to the value it has at the end of its life, and the additional energy of the battery would not be used. As the battery ages, it loses this excess energy until at the EOL it has enough energy just to

meet the range requirement. Thus, the user of the vehicle would never experience a gradual loss in vehicle AER.

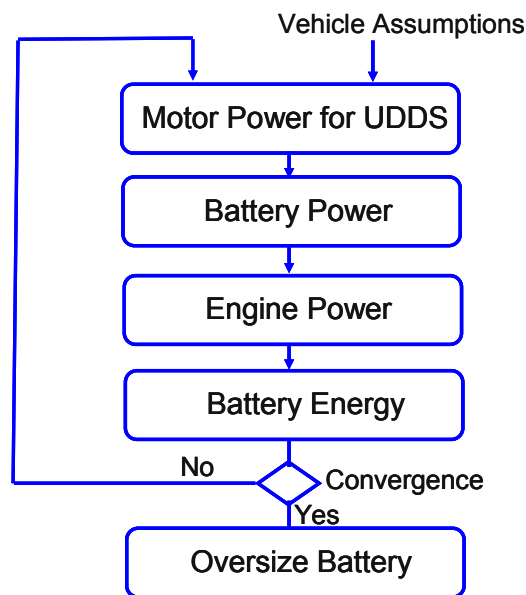


Figure 3. Vehicle Component Sizing Process

During a simulation, the engine is turned on when the driver torque request is sufficient. Turning the engine on expends fuel but conserves battery energy, so that more miles can be traveled before the battery reaches its discharged state. The operating mode that turns the engine on while still depleting the battery is called the Charge Depleting (CD) mode. The additional distance traveled during CD mode depends on the control strategy, which is described in the following section.

Control Strategy

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

- Charge Depleting (CD), during which the battery net discharges - propelling the vehicle.
- Charge-Sustaining (CS), which is similar to that in current HEVs.

Initial state-of-charge (SOC) of the battery, which is also the battery's maximum charge, is 90%, and the final SOC of the battery, which is also the battery's minimum charge, is 30%. 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.

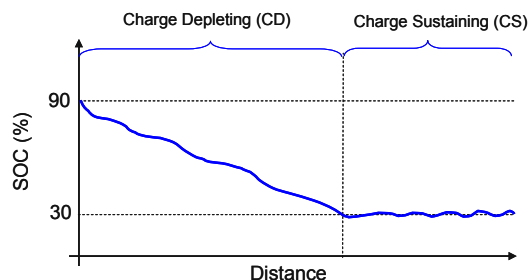


Figure 4. Control Strategy SOC Behavior

Results

Vehicle Level Results

As expected, since the powertrain configurations were identical and the control was similar, the trends for the midsize vehicle and the SUV were the same. Figure 5 illustrates this. As end of life all electric range was increased from 7.5 miles to 60 miles. The Midsize vehicle gained 250 kg and the SUV gained 320 kg. This gain was due almost entirely to the increase in size of the battery pack. As distance is increased pack mass is increased. Since both the Midsize vehicle and the SUV used Li-ion battery packs, the increase was nearly linear from 7.5 miles to 60 miles.

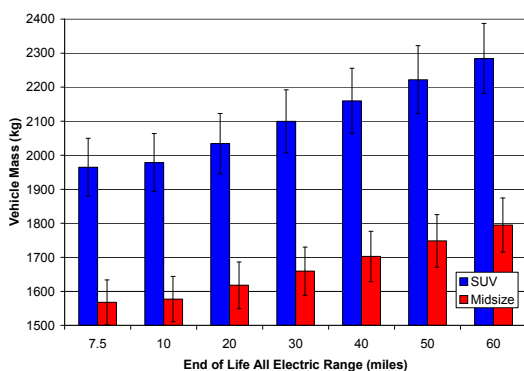


Figure 5. Small Vehicle Mass Increase from 7.5 to 60 Miles All-Electric Range

Figure 6 shows the increase in battery pack mass for each vehicle class. Due to the high specific power of the Li-ion technology, the battery pack is relatively light, especially when compared to other battery chemistries. For the midsize vehicle, the increase in battery mass between a vehicle that has a range of 7.5 miles and a vehicle that has a range of 60 miles is only 220 kg for the SUV the battery pack is only 80 kg heavier. An additional increase in the each vehicle mass results from an increase in the power of the engine and electric motor. As the vehicle get heavier, from the larger battery pack, which is sized to meet the longer range requirement, the engine peak power is increased, so that, the heavier vehicle can satisfy the gradeability requirement. Similarly, the motor peak power is increased in order for the vehicle to meet the all-electric city driving constraint. Thus, all though the battery pack is the greatest contributor to the mass increase, increases in the engine and electric motor also occur.

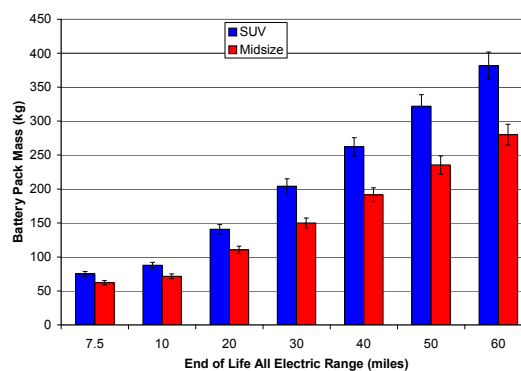


Figure 6. Li-Ion High Specific Power Leads to a Small Mass Increase

The Li-ion battery pack for both the Midsize vehicle and the SUV is a small fraction of the total mass of the vehicle. Referring to Figure 7, for the shortest range PHEV of 7.5 miles, the battery pack is less than 4% of the total vehicle mass. Even for the 60 mile range, the battery pack constitutes only 16% of the total mass of the vehicle. The difference between these percentages for the Midsize vehicle and SUV is about 1%. The powertrain architecture is the same, the control is the same and the battery technology is the same, so the same trend is expected.

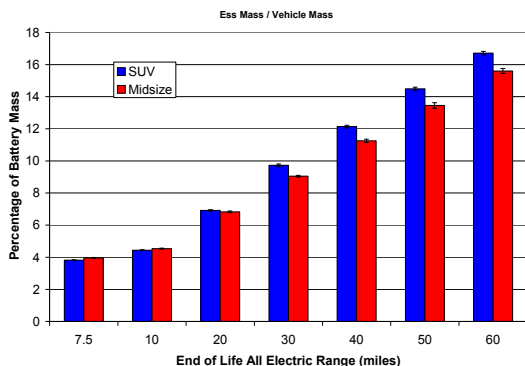


Figure 7. Share of Battery Mass Increases but Midsize and SUVs are Comparable

The electric consumption during the charge depleting operating mode on a UDDS cycle is nearly constant for both vehicle classes. While operating in charge depleting mode, the battery and electric motor propel the vehicle. The battery power is supplemented with engine power only during peak demand. Thus, the entire powertrain has a very high efficiency during this operating mode. A high powertrain efficiency implies that the vehicle has an energy consumption with a low sensitivity to changes in vehicle mass [6]. Thus, the small increase in vehicle mass of 16% results in an even smaller increase in energy consumption as shown in Figure 8.

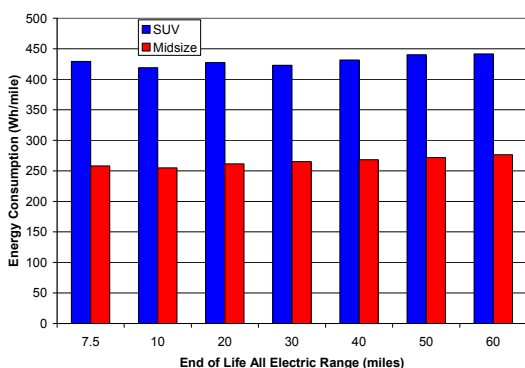


Figure 8. Electrical Consumption Remains Almost Constant

Since the electric consumption is constant regardless of the range that PHEV was designed to travel in charge-depleting mode, the total electrical consumption for this operating mode is a linear function of the charge-depleting range as shown in Figure 9.

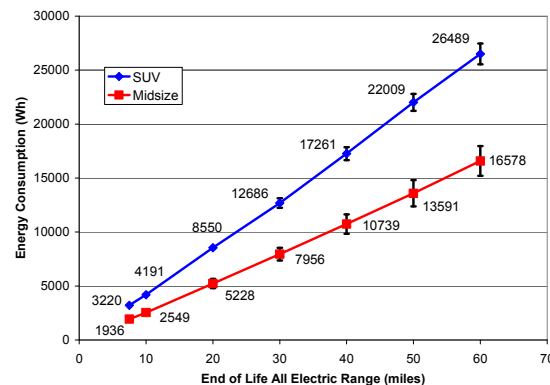


Figure 9. Energy Consumption is a Linear Function of Range

Figure 10 shows the battery peak power required for each vehicle. The SUV consistently requires 20% more power than the midsize vehicle. The sizing algorithm calculated these values assuming that the vehicle could meet the UDDS cycle all-electrically. The algorithm then adds an additional 30% more power to the battery pack to account for aging. The beginning of life power would be limited, so that the driver would not detect a noticeable difference between end of life performance and beginning of life performance.

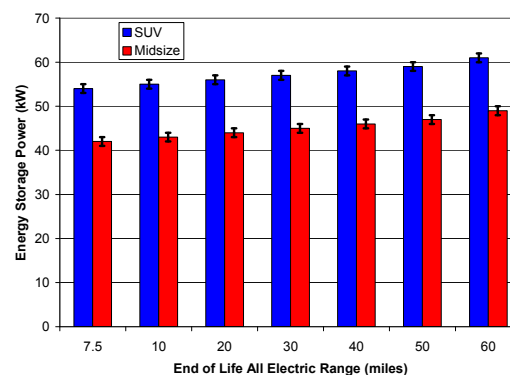


Figure 10. EOL Battery Peak Power (2 sec pulse)

Since battery peak discharge power remains virtually constant as the PHEV range is increased and the battery energy increases linearly with PHEV range, the power-to-energy ratio of the battery varies hyperbolically with range as Figure 11 shows. The x-axis in Figure 11 is to scale between 10 miles and 60 miles; however, between 7.5 miles and 10 miles the axis is dilated, so that the 7.5 mile bar does not appear to fall on the sketched hyperbola.

Figure 11 also shows that for each range, the SUV battery requires a lower power-to-energy ratio than the midsize vehicle. This result agrees with Figure 8, which shows energy consumption, and Figure 10, which shows peak battery power. The SUV peak battery power is 20% greater than that of the midsize vehicle, while the energy consumption is 40% greater.

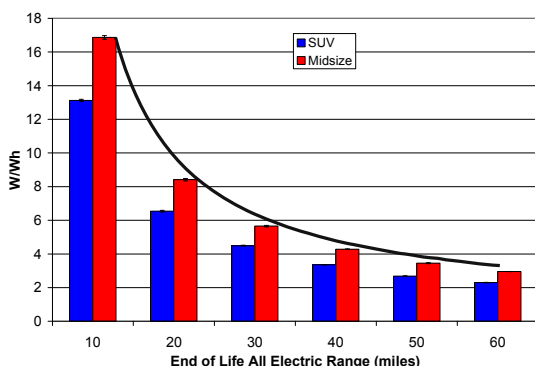


Figure 11. SUV Requires Lower Power to Energy Ratio

Figure 12 shows the cell capacity for each battery pack. To travel the desired range, battery pack energy can be added either by adding more cells or by increasing the charge capacity of each cell. The sizing algorithm, which was used for this study, fixed the battery voltage to 200 volts which is representative of the bus voltage in production hybrids. There are several drawbacks to having a high bus voltage. Increasing the cell voltage requires additional cells in series which increases the complexity of the battery pack. The motor-inverter power electronics have to handle a higher bus voltage. The inverter also has to handle a larger swing in bus voltage as the PHEV discharges its battery pack. There are also safety issues preventing the storage of significant amounts of energy as pack voltage.

Large cell capacity also has disadvantages which over take the disadvantages of higher bus voltage, so the sizing algorithm fixes the maximum capacity of a cell to 90 A-h. Once 90 A-h is reached, energy is added using cells rather than capacity.

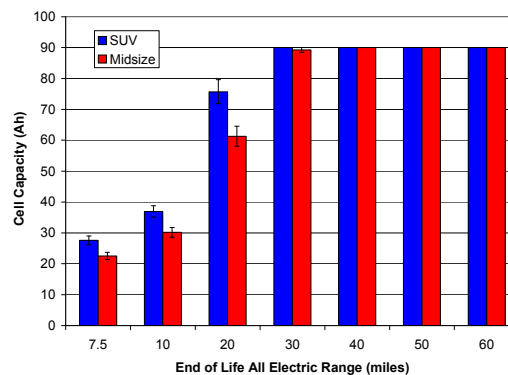


Figure 12. Cell Capacity is Saturated at 90 A-h

By adding additional capacity to the battery, the bus voltage can be fixed at 200 V up to 30 mile range. For this range, the capacity of a cell is at its maximum, thus additional energy is added to the pack by increases the number of cells. Once can see that the bus voltage reaches 600 volts.

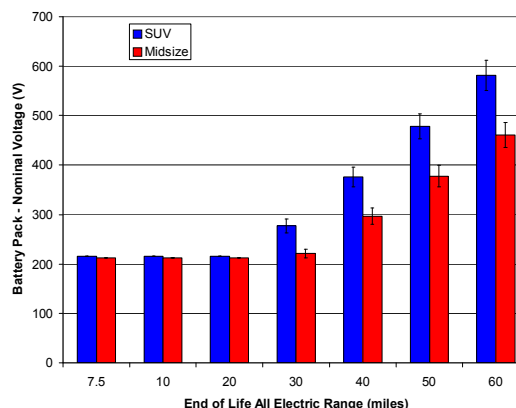


Figure 13. Bus Voltage is Maintained up to 30-Mile Range

Since the SUV requires more energy to satisfy the 40 mile range requirement and since the maximum cell capacity is saturated at 90 A-h for both vehicle classes, the SUV bus operates at a higher average voltage which is shown in the histogram in Figure 14. On the left is the histogram for the midsize PHEV with a 40 mile range and on the right is the histogram for the SUV PHEV with a 40 mile range. It is also evident from these histograms that the SUV bus experiences a wider swing in bus voltage than the midsize vehicle which is expected because the SOC varies from 90 percent to 30 percent for each battery.

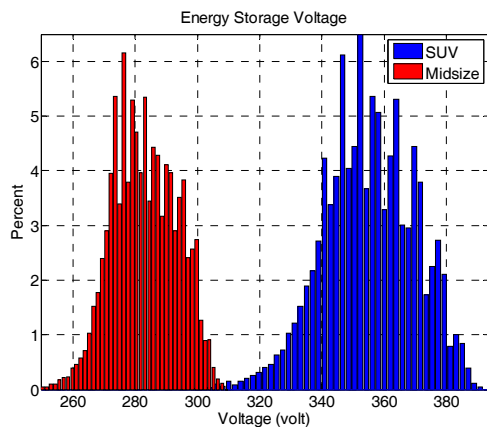


Figure 14. Histogram of Bus Voltage for 40 Mile PHEVs – Fast Technology Case

It is apparent from the current distributions for each 40 mile PHEV, shown in the figure below, that the current supplied in both cases is nearly identical. This is expected. The additional energy and power for the SUV is provided in the form of voltage rather than in the form of current. This is a further consequence of adding energy with cells as opposed to adding energy with capacity.

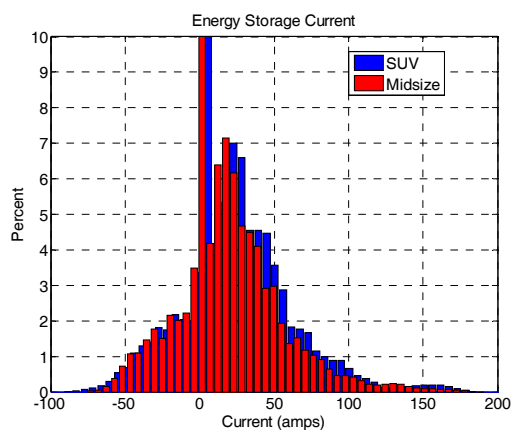


Figure 15. Histogram of Current for 40 Mile PHEVs – Fast Technology Case

The amount of energy recovered during regenerative braking is also an important consideration for PHEVs. Figure 16 shows the histogram for battery power during regenerative braking on a US06 cycle. The histogram indicates that the maximum power necessary for regenerative braking on a US06 cycle is 35 kW.

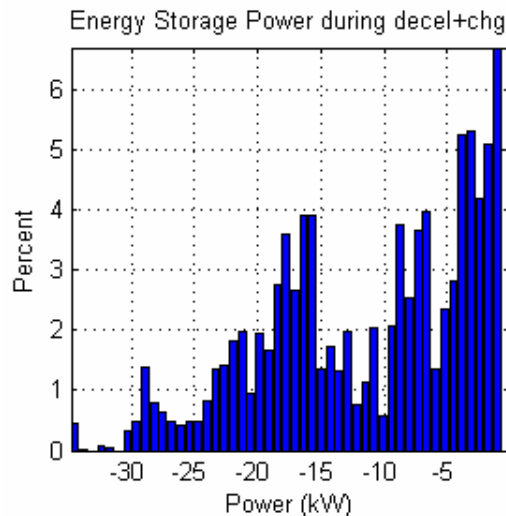


Figure 16. Histogram of Battery Power During Regenerative Braking on US06 Cycle for Midsize 40 Mile PHEV – Fast Technology Case

Electric Machine Requirements

Because the mass increase from 7.5 Mile range to 60 Mile range PHEV is not significant, the peak power needed to propel each class of PHEV does not change significantly. Thus the power of each drivetrain component remains essentially constant. Figure 10 demonstrated this for the battery and Figure 17 demonstrates this for the electric motor. On Figure 17, the FreedomCar goal for the electric machine is shown. Achieving the FreedomCar goal of 55 kW would produce a motor capable of handling all of the midsize PHEV requirements for power; however, this goal would meet the power requirements of about half of the SUVs.

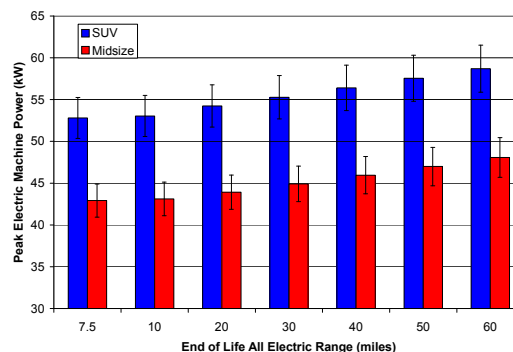


Figure 17. Electric Machine Power Remains Almost Constant

Although more than 55 kW is necessary to meet the peak power demand for the 40 mile SUV PHEV, Figure 18 demonstrates that this power is rarely required for the SUV on the UDDS. The majority of power requests from the motor are below 35 kW. Thus, the FreedomCAR goal of 55 kW would satisfy 90% of the SUV 40 mile PHEV power requirements during its charge-depleting operation. It would be simple just to turn the engine on to satisfy the transient power requests above 35 kW.

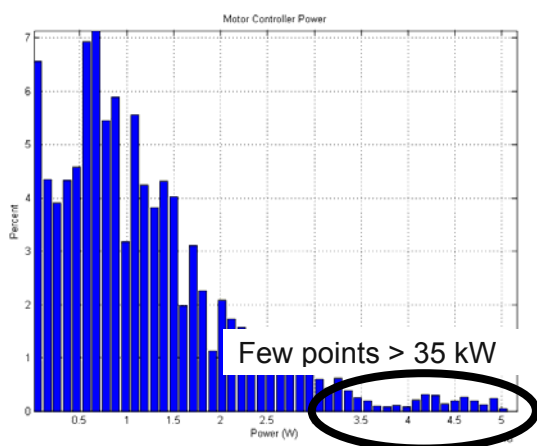


Figure 18. Motor Power for SUV PHEV 40 Mile Range – Fast Technology Case

Figure 19 shows that the midsize PHEV only needs a motor with a peak power of 25 kW to satisfy 90% of its power demand.

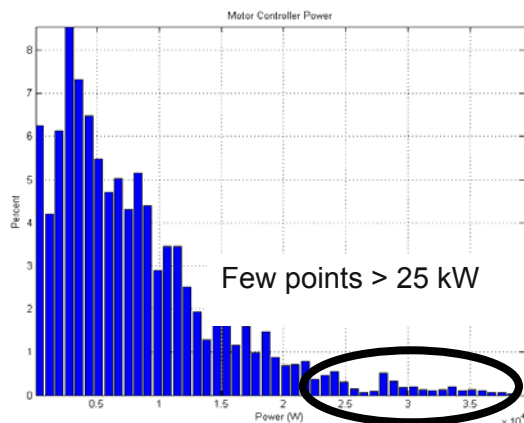


Figure 19. Motor Power for Midsize PHEV 40 Mile Range – Fast Technology Case

As range increases, battery mass is added to the vehicle, because this mass contributes around a 20% increase in total vehicle mass, the component masses do not change radically. Figure 20 demonstrates that between a 7.5 mile range and 60 mile range, the engine power increases by roughly 10%.

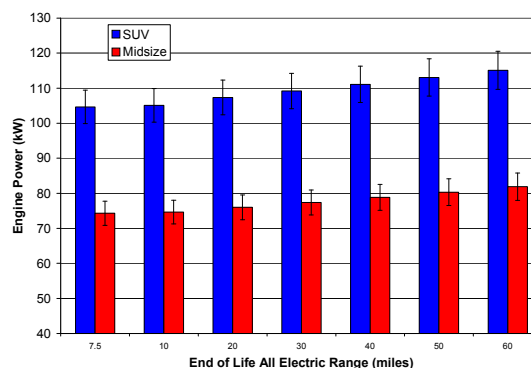


Figure 20. Engine Power Remains Almost Constant

Conclusions

Component models and control strategies have been developed and implemented in PSAT to study the impact of AER, drive cycle, control strategy, and component sizing on the battery requirements. The following conclusions can be stated:

- The Midsize and SUV classes exhibit similar energy consumption trends during charge depleting mode. As would be expected, of the two, the SUV has the greater overall energy and power needs.
- The battery energy is approximately a linear function of the All Electric Range.
- Power requirements are not influenced by the AER as a result of the high specific energy of the Li-Ion battery.
- The high specific power of Li-ion technologies does not have a significant influence on vehicle mass. Specific energy has the greatest affect on vehicle mass.
- Battery pack voltage needs to be taken into consideration for high AER (above 40 mi). Higher capacities or battery packs in parallel might need to be used.

The results of these simulations will be used to define the component requirements of PHEV vehicles implemented in the U.S. DOE R&D Plan.

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B. Impact of Drive Cycle Aggressiveness and Speed on HEVs Fuel Consumption Sensitivity

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Objectives

- The primary focus of this study is to evaluate the impact of drive cycle aggressiveness and speed on HEV fuel consumption sensitivity.
- Explain and quantify the impact of the main powertrain components on the sensitivity.

Approach

- Reproduce the fuel economy trends reported from ANL's APRF testing for two vehicles: Ford Focus and Toyota Prius.
- Define the main parameters influencing the sensitivity.
- Quantify the influence of each parameter.

Accomplishments

- Fuel economy trends from vehicle testing were reproduced in simulation.
- Engine energy is the main parameter influencing the sensitivity.
- An increase in engine efficiency when drive cycles become more aggressive leads to a decrease in sensitivity.
- The high engine efficiency of the Prius and the regenerative braking events tend to minimize the impact of the energy increase.
- For the HWFET driving cycle, both conventional and HEV vehicles behave similarly as a result of the high vehicle speed and the low regenerative braking and vehicle stop events.

Future Directions

- Evaluate the relative impact of each parameter for different HEV powertrain configurations.

Introduction

A preliminary study performed with dynamometer vehicle testing at Argonne's Advanced Powertrain Research Facility [4] demonstrated that hybrid electric vehicles (HEVs) were more sensitive to drive-cycle variations than their conventional counterparts. Several vehicles and drive cycles (Urban Dynamometer Driving Schedule [UDDS],

Highway Fuel Economy Test [HWFET], ATDS, and US06) were considered in the previous paper. The dynamometer testing demonstrated that more aggressive cycles lead to higher fuel consumption.

However, because the vehicles were not heavily instrumented, it was difficult to understand and quantify the reasons behind the differences.

To gain further insight, PSAT [5], Argonne's vehicle simulation tool, has been used to investigate and explain the trends that were observed in testing. PSAT, a forward-looking model, uses the driver outputs to send commands to the different components in order to follow the drive cycle. PSAT is the software of choice for all FreedomCAR and Fuels Partnership activities.

In this study, we will focus on two vehicles (conventional Ford Focus and 2004 Toyota Prius) and two driving cycles used in the initial study: the UDDS and the HWFET. After the trends noticed during vehicle testing are reproduced, each main vehicle parameter will be analyzed to quantify its impact on sensitivity, as well as each parameter's relative importance to overall sensitivity.

Studies by EPA [6] and Honda [7] have demonstrated that parameters other than drive-cycle aggressiveness influenced fuel consumption, such as side wind effects, cold start, and air conditioning loads. As in the initial study performed at Argonne's Advanced Powertrain Research Facility (APRF), this study will only focus on drive-cycle impacts.

Approach

Reproducing Vehicle Fuel Economy Trends from Dynamometer Testing

Six vehicles were initially tested at Argonne's APRF. In this study, only two of them will be studied in detail: a conventional Ford Focus and a 2004 Toyota Prius. Figure 1 has two graphs, the first showing the fuel consumption as a function of cycle scaling factor for the Toyota Prius, and the second showing the fuel consumption as a function of cycle scaling factor for the Ford Focus. These two plots demonstrate the predictive capability of the model when the vehicle load is varied by using a cycle scaling factor.

Both the Ford Focus [8] and the 2004 Toyota Prius [9] were carefully validated for the study. Table 1 summarizes the fuel consumption comparison in PSAT for the Toyota Prius on several driving cycles. The test fuel economies presented in the table are averages from several test results.

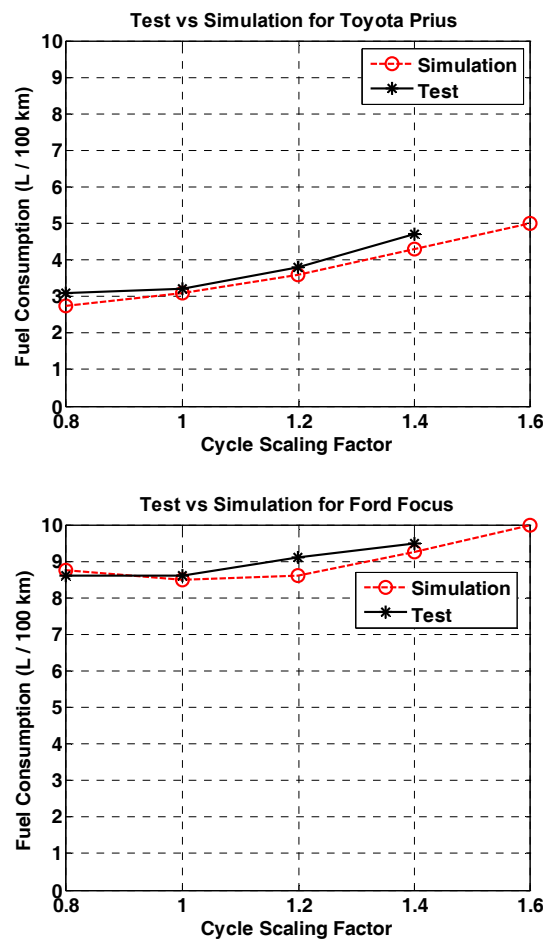


Figure 1. Trends Comparison with Vehicle Testing — UDDS/HWFET Fuel Consumption

Table 2 shows the fuel consumption measured at the APRF and the fuel consumption predicted in simulation by PSAT.

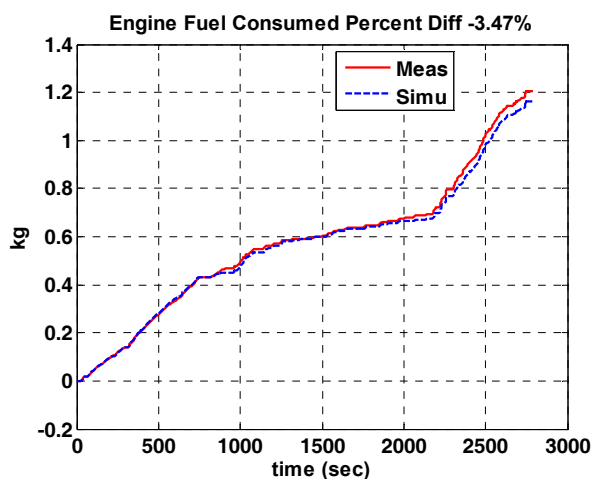
Figure 2 demonstrates the type of analysis done to validate a vehicle model in PSAT. Fuel consumption, total engine on type, and delta State-of-Charge (SOC) are all used as examples in the case of a hybrid to determine the accuracy of the vehicle model. If fuel consumption and delta SOC are each predicted consistently within 5% on numerous cycles, the vehicle model is considered validated. Engine torque, motor torque and generator torque are also compared to determine the accuracy of the vehicle model; however, as in the case of the Focus, such extensive test data is not available. In this case, only the fuel consumption predictive capability of the model is validated. These models were only validated for hot cycles. Thus, all of the results presented in this paper are for a hot vehicle.

Table 1. 2004 Prius PSAT Validation Results

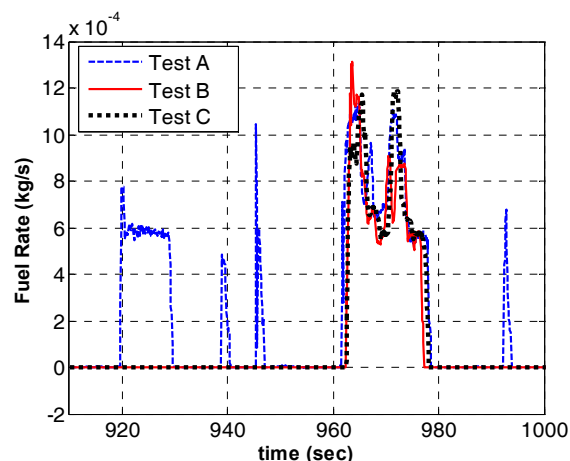
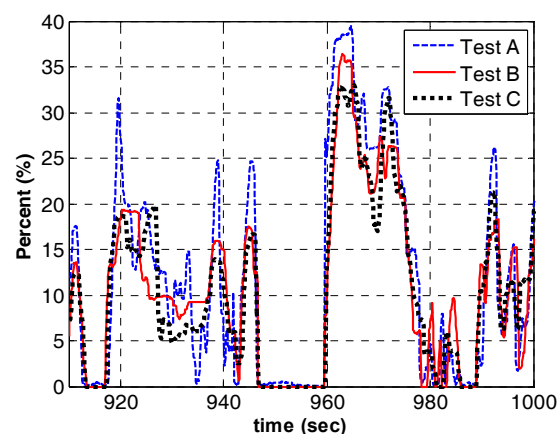
Drive Cycle	APRF Test (L/100 km)	PSAT (L/100km)
UDDS	3.3	3.2
HWFET	3.5	3.5
US06	5.6	5.1
Japan1015	3.1	3.0
NEDC	3.4	3.4

Table 2. 2004 Ford Focus Validation Results for Hot Vehicle Tests

Drive Cycle	APRF Test (L /100 km)	PSAT (L/100 km)
UDDS	8.8	8.9
HWFET	6.2	6.2

**Figure 2.** Example of Plots Used to Validate a Vehicle Model in PSAT

When testing HEVs, a significant issue is testing repeatability. To use battery SOC-corrected values in the initial study, several tests were performed on the same driving cycle. Most of the time, different engine ON timing can be explained by different SOC or thermal conditions. As shown in Figure 3, in several cases, the engine was not turned ON at the same time. Figure 4 demonstrates the impact of the driver on the engine ON/OFF logic. This behavior cannot be reproduced in simulation and, when used to perform SOC correction, will alter the results.

**Figure 3.** Test-to-Test Repeatability Example – UDDS**Figure 4.** Example of Driver Uncertainties Introduced by Vehicle Testing

Similarly to vehicle testing, all of the simulations performed with PSAT are based on hot operating conditions. Both dynamometer testing and simulations introduce uncertainties. The simulations are not able to reproduce component thermal limitations, such as lower battery peak power at elevated temperatures. On the testing side, the driver can have a significant influence on the results.

Sensitivity Parameters

To evaluate the impact of drive-cycle aggressiveness on fuel consumption, the UDDS and HWFET drive cycles were scaled by the following factors: 0.8, 1.0, 1.2, 1.4, and 1.6. Because these cycles are based on the UDDS and HWFET cycles, but are not these cycles, they are referred to in this paper either as (1) xUDDS and xHWFET in a general reference or

(2) 0.8UDDS in reference to a specific cycle scaled by a factor of 0.8.

PSAT predicted the fuel and energy consumption for the Ford Focus and the Toyota Prius on each scaled cycle. The methodology is similar to the one used in the previous Argonne paper. However, the authors recognize that there are many factors, such as thermal behavior, that PSAT does not perfectly replicate in simulation, which leads to differences between the results from testing and the results from PSAT.

Although the method used to define the simulation runs agrees with the one used to define the test runs, a different method was used to define sensitivity and report results. In the previous paper, sensitivity was defined as:

$$\% \Delta = \frac{\% \Delta F}{\% \Delta \gamma} \quad (1)$$

which was appropriate when different vehicles on the same drive cycle were compared. However, using this as the starting point, the definition evolved into Equation 2:

$$\Delta = \frac{\frac{\Delta E_{Fuel}}{d}}{\frac{\Delta E_{Wheel}}{d}} = \frac{\Delta E_{Fuel}}{\Delta E_{Wheel}} \quad (2)$$

There are several reasons for this change in definition. First, because the results are simulated with PSAT, all the signals necessary to calculate power flow in the drivetrain are recorded. Among these signals are those necessary to calculate the load at the wheels of the vehicle in units of energy. Such complete data are nearly impossible to measure from an actual vehicle because of time and cost constraints. Of course, this by itself does not preclude the use of this definition for testing; however, it adds additional complications. Second, the new definition allows comparisons between cycles. Graphing fuel consumption versus γ for a xUDDS is very different than graphing fuel consumption versus γ for the xHWFET cycle. The previous definition of sensitivity calculated for these graphs could not be compared, because γ changes the vehicle load for a xUDDS cycle a lot slower than

it changes the vehicle load for an xHWFET cycle. The vehicle on a xUDDS cycle would demonstrate a lower sensitivity than it would on the xHWFET cycle. Is this the sensitivity of the vehicle or the sensitivity of the cycle to γ ? Equation 3 and 4 illustrate this question.

$$F_{fuel} = f_{veh} (E_{load}(\gamma)) \quad (3)$$

$$\frac{dF_{fuel}}{d\gamma} = \left(\frac{df_{veh}}{dE_{load}} \right) \left(\frac{dE_{load}}{d\gamma} \right) \quad (4)$$

The second term in the equation, $\frac{dE_{load}}{d\gamma}$, changes,

depending on the cycle and is not just a characteristic of the vehicle. This makes comparisons between sensitivity factors on the xUDDS and xHWFET difficult. To address this difficulty, instead of graphing energy consumption as a function of scaling factor, energy consumption was graphed as a function of load at the wheels. The load was expressed in units of energy. Equation 5 demonstrates that the vehicle load changes cubically with the cycle scaling factor.

$$E_{load} = [m_{eff}(\gamma a)(\gamma) + A(\gamma) + B(\gamma)^2 + C(\gamma)^3] dt \quad (5)$$

This cubic variation was the third reason for revising the definition of sensitivity. For small scaling

factors, the term, $\frac{dE_{load}}{d\gamma}$, is changing slowly; for

large scaling factors, the term is changing rapidly. In a sense, if load was plotted versus γ , the second term would dilate the x-axis and lead to a false sense of sensitivity. A cycle with γ equal to 1.2 is not 20% more aggressive than a cycle with γ equal to 1.0. Ultimately, this reason and the second reason stem from the same issue. γ is an artificial parameter introduced for convenience. γ is very useful in creating a consistent measure by which aggressivity of a cycle can be manipulated; however, it leads to difficulty in expressing the results. In addition, there are many different ways to express the aggressiveness of a cycle. Average vehicle speed, peak vehicle speed, average vehicle acceleration, or root-mean-square vehicle acceleration are all candidates for expressing the aggressiveness of a cycle. Vehicle load, in units of energy, encompasses

many of these metrics and allows for comparisons between a vehicle's fuel consumption sensitivity to the cycle and the vehicle's fuel consumption sensitivity to a change in its mass because both of these changes can be represented by a change in vehicle load. Just as fuel consumption is averaged over the distance traveled, the energy consumption and load at the wheels was averaged over distance. This scaling was done for convenience to help facilitate a comparison between test sequences that repeat the same cycle a different numbers of times. This definition for vehicle load is also consistent with the definition for fuel consumption.

Equation 2 can be related to the drivetrain component efficiencies by first expressing fuel consumption as a function of load, as shown in Equation 6, and then second by differentiating Equation 6, yielding Equation 7, which is the instantaneous sensitivity at that average cycle load point.

$$E_{fuel} = \frac{x E_{load}}{\eta_{eng} \eta_{pwt}} + E_{idle} \quad (6)$$

$$\frac{dE_{fuel}}{dE_{load}} = \frac{1}{\eta_{eng} \eta_{pwt}} \left(x E_{load} + x \left(1 - \frac{\dot{\eta}_{eng}}{\eta_{eng}} E_{load} - \frac{\dot{\eta}_{pwt}}{\eta_{pwt}} E_{load} \right) \right) \quad (7)$$

Figure 5 shows that on the UDDS, the sensitivity of the Prius (2.41) is higher than that of the Focus (2.14).

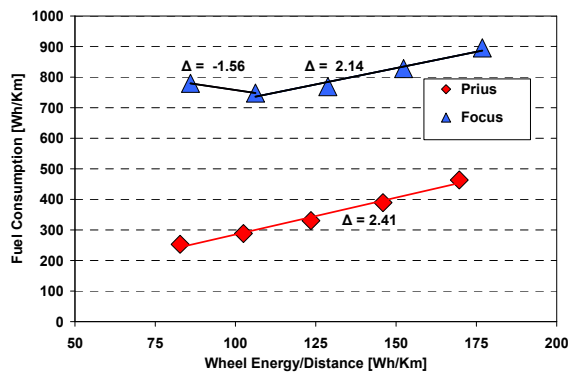


Figure 5. UDDS Sensitivity

In contrast, both vehicles have similar sensitivity on the HWFET, as shown in Figure 6.

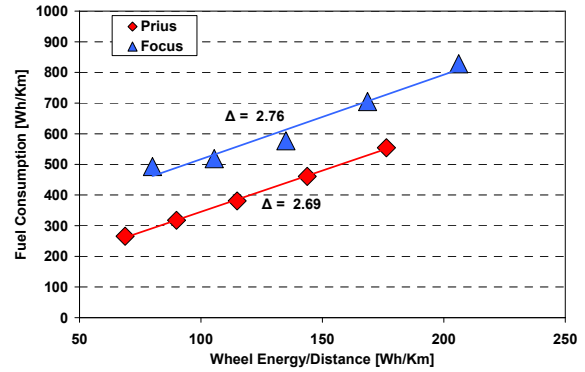


Figure 6. HWFET Sensitivity

The sensitivity trends shown in Figures 6 and 7 are explained in the next sections by using the main powertrain characteristics listed below.

- Engine efficiency and energy loss
- Regenerative braking
- Energy provided at the wheel during acceleration
- Energy required to follow the trace

The influence of each characteristic on the sensitivity will be discussed individually.

Results

Engine Efficiency

Figures 7 and 8 show the engine-operating region for both vehicles on the UDDS driving cycle. As one expects, the Prius is able to maintain its engine-operating region close to the engine's best efficiency curve. As a consequence, its average engine efficiency is higher than that for the conventional vehicle.

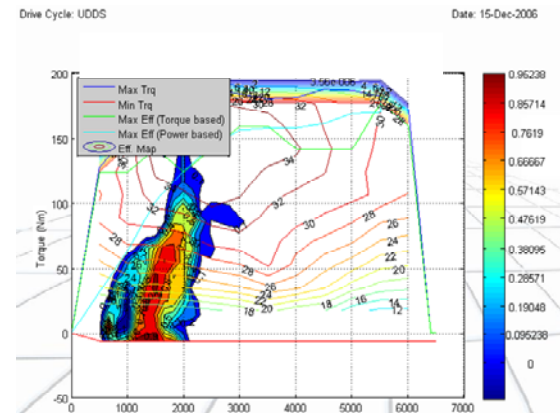


Figure 7. Ford Focus Engine-Operating Conditions on UDDS

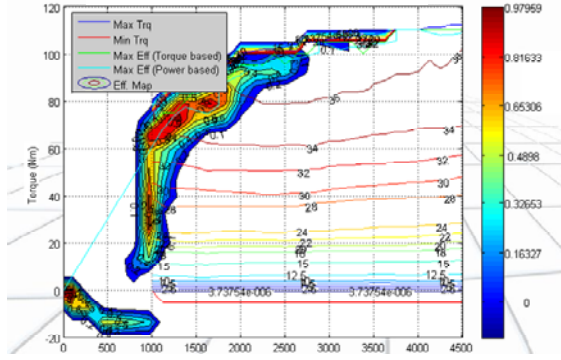


Figure 8. Prius Engine-Operating Conditions on UDDS

Figure 9 shows the average sensitivity of engine efficiency to a change in vehicle load. The Prius average engine efficiency has the same sensitivity on both the UDDS and the HWFET. In contrast, the Focus has a greater sensitivity on the UDDS. In addition, in both cases, the conventional vehicle is more sensitive as its operating region greatly depends on the drive cycle.

An increase in engine efficiency will decrease the impact of the more aggressive driving cycle and decrease vehicle fuel consumption sensitivity. This explains why, in Figure 5, the Focus has negative sensitivity at low vehicle loads, which is also

reflected in Equation 7 by the term $-\frac{\eta'_{eng}}{\eta_{eng}} E_{load}$.

When η'_{eng} is large and positive, the sensitivity can be negative.

In addition, high engine efficiency will also lead to low sensitivity. $\frac{1}{\eta_{eng}\eta_{pwt}}$ is the term in equation 7 that represents this effect.

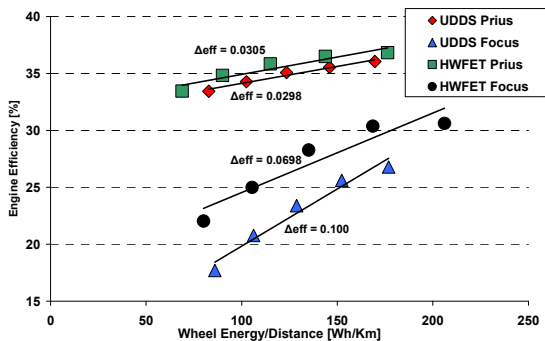


Figure 9. Engine Efficiency – xUDDS and xHWFET

Engine Energy Loss

To fully characterize the impact of the engine, one needs to understand how much the engine is used. Indeed, even if engine efficiency has an impact, its importance is only relative to how often the engine is used.

Figure 10 shows the sensitivity of engine energy losses to vehicle load. As one expects, the energy used by the Prius is smaller than that of the Focus; however, the engine energy increases more for the Prius than for the Focus on the xUDDS, while both vehicles have similar trends on the xHWFET.

xUDDS Driving Cycle

For the Focus, engine efficiency increases at higher vehicle load, which partially cancels the increase in engine losses required by the increase in vehicle load. Figure 10 illustrates that the efficiency of the Focus increases rapidly enough that the engine losses actually decrease. This decrease actually makes the fuel consumption of the Focus less sensitive to a change in load. As for the Prius, the engine efficiency does not increase as much; thus, the engine losses for the Prius increase more than those for the Focus, helping to make the Prius more sensitive to a change in load.

xHWFET Driving Cycle

One notices a similar trend on xHWFET for the Prius but not for the Focus. In fact, the Focus has large engine energy losses and efficiency slopes. The engine energy losses slope should be small. However, the Focus (25%) has a lower efficiency than the Prius (33%). In addition, a change in the amount of regenerative braking energy may also lead to an increase in engine energy.

Figure 11 shows the sensitivity of engine ON percentage of the Prius on both driving cycles. On the UDDS, the engine is used more often as the cycle becomes more aggressive, explaining a greater increase in energy losses. However, on the HWFET, the engine is already used most of the time and, as a consequence, behaves similarly to its conventional counterpart. This conclusion agrees with Equation 7. The parameter x , in Equation 7, captures the effect of engine ON time on sensitivity. The more the engine is on, the greater the fraction of the total

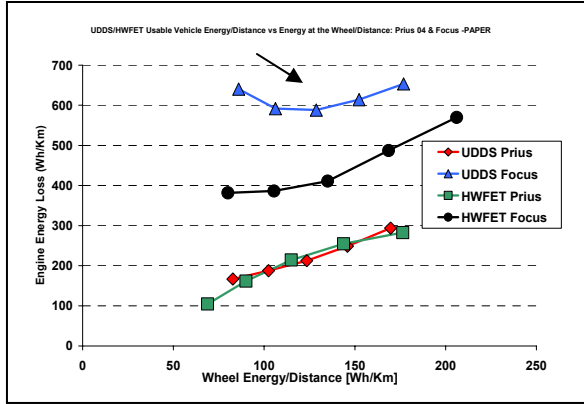


Figure 10. Engine Energy Losses – xUDDS and xHWFET

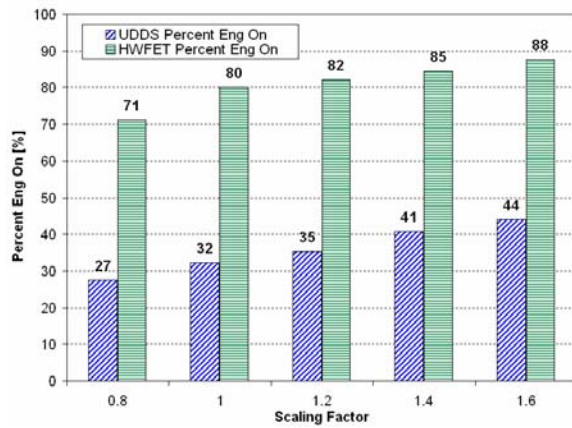


Figure 11. 2004 Prius Engine ON Percentage

vehicle load that the engine supplies and, consequently, the greater the sensitivity. Also, x' captures the rate at which the engine ON time increases and the effect that it has on sensitivity.

Regenerative Energy

PSAT considers the vehicle to be in regenerative mode when the driver torque demand is negative. The regenerative energy is defined by Equation (8):

$$E_{\text{Recovered}} = \int (V_{\text{batt}} I_{\text{batt}}) dt \quad (8)$$

Figure 12 shows the sensitivity of the regenerative energy on both driving cycles for the Prius. As one expects, the HWFET energy does not significantly

increase, in comparison with the UDDS. An increase in regenerative energy will lead to a decrease in sensitivity because less energy will have to be provided to follow the trace.

As shown in Figures 5 and 6, fuel consumption of the 2004 Prius is less sensitive on UDDS ($a = 2.41$) than on HWFET ($a = 2.68$). This could be explained by the regenerative energy plot because we have a greater regenerative energy slope on UDDS ($a = 0.34$) than on HWFET ($a = 0.02$).

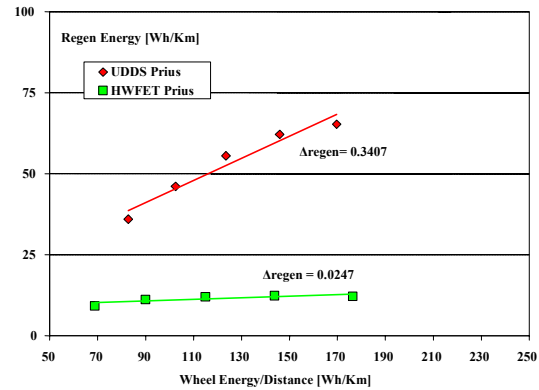


Figure 12. Regenerative Energy – UDDS and HWFET

Energy Provided at the Wheel During Acceleration

The energy provided at the wheel during acceleration is defined by Equation 9:

$$E_{\text{wheel}} = \int (a_{\text{veh}} M_{\text{veh}} V_{\text{veh}} + P_{\text{veh loss}}) dt \quad (9)$$

$$\text{With } P_{\text{veh loss}} = A(V_{\text{veh}}) + B(V_{\text{veh}})^2 + C(V_{\text{veh}})^3 \quad (10)$$

This parameter represents the sensitivity of powertrain efficiency. Indeed, greater sensitivity means that powertrain efficiency remained constant or decreased.

Figure 13 shows the energy provided at the wheel during deceleration. Note that the Prius is more sensitive than the Focus on both driving cycles, and the difference on the HWFET is greater.

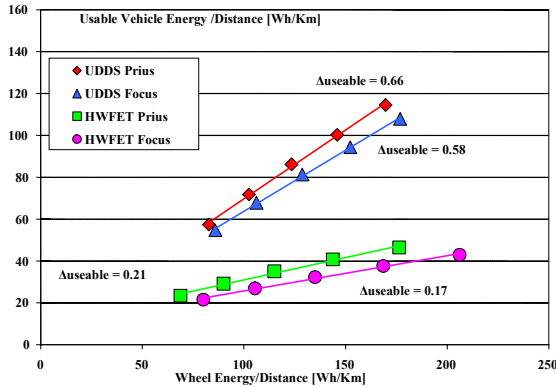


Figure 13. Usable Vehicle Energy – UDDS and HWFET

Sensitivity of the Main Efficiency Parameters for the Prius

Figures 14 and 15 represent the average component (engine, motor, and transmission), as well as the system (regenerative braking and overall powertrain) efficiencies. The powertrain efficiency and the regenerative braking are defined by equation (10) and (11), respectively:

$$\eta_{\text{Regent}} = \frac{E_{\text{recuperated @ batt}}}{E_{\text{recuperable @ wh}}} \quad (11)$$

Concerning the regenerative braking efficiencies, although the total amount captured increased (Figure 12), the proportion of the available energy captured decreases both on the UDDS and the HWFET driving cycles as a result of power limitations on the battery. A vehicle with a more powerful battery would then be able to decrease its sensitivity by increasing its regenerative braking energy.

Figure 9 showed that the average engine efficiency increased with aggressive cycles, decreasing sensitivity. This phenomenon is further amplified on the UDDS by an increase in motor efficiency.

The powertrain efficiency increases on the UDDS up to a 1.2 ratio and then decreases, but it keeps increasing on the HWFET. This is mostly the result of the drop in the share of regenerative energy, in comparison with the energy required to accelerate the vehicle.

As expected, the transmission efficiency, which does not include the electric machine efficiencies, remains constant.

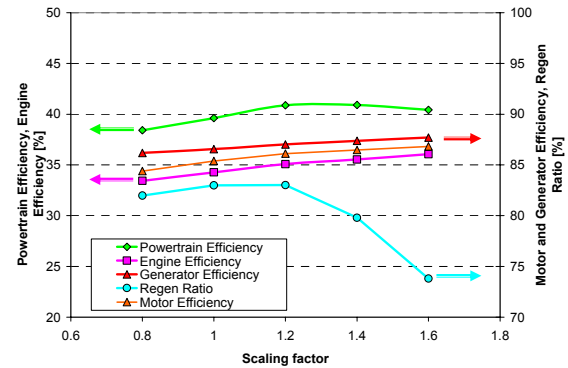


Figure 14. 2004 Prius – Summary of Efficiency Sensitivity on Scaled UDDS

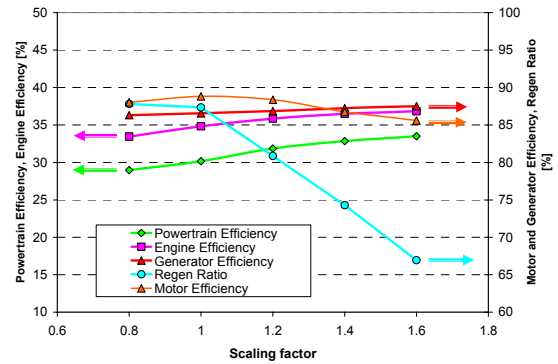


Figure 15. 2004 Prius – Summary of Efficiency Sensitivity on Scaled HWFET

Relative Influence of Parameters on Sensitivity

After studying the influence of each parameter, one needs to look at their relative impact.

Figures 16 and 17 compare the relative importance of each parameter for both vehicles on the UDDS driving cycle. For both vehicles, the engine consumes most of the energy. However, the Prius engine losses significantly increase, in comparison with the Focus. As previously discussed, when the drive cycles become more aggressive, the engine is used more often. For the Prius, the increase in regenerative braking leads to a decrease in the energy required to follow the trace.

Figures 18 and 19 compare the relative importance of each parameter for both vehicles on the HWFET driving cycle.

As in the UDDS, the engine energy losses greatly influence the sensitivity of the Prius. Both vehicles have similar sensitivities because the engine is ON most of the time on the HWFET, and the Prius behaves more like a conventional vehicle.

Table 3 summarizes the impact of each parameter on fuel consumption sensitivity.

Table 3. Summary of the Influence of Each Parameter on the Fuel Economy

	UDDS		HWFET	
	Focus	Prius	Focus	Prius
Engine Peak Efficiency	0	-	0	-
Engine Efficiency Variation	--	-	-	-
Engine Energy	0	++	++	++
Regenerative Energy	NA	-	NA	0
Energy to Follow the Trace	++	+	+	++
Drag & Rolling Resistance	+	+	++	++

+ indicates increase in sensitivity
- indicates decrease in sensitivity

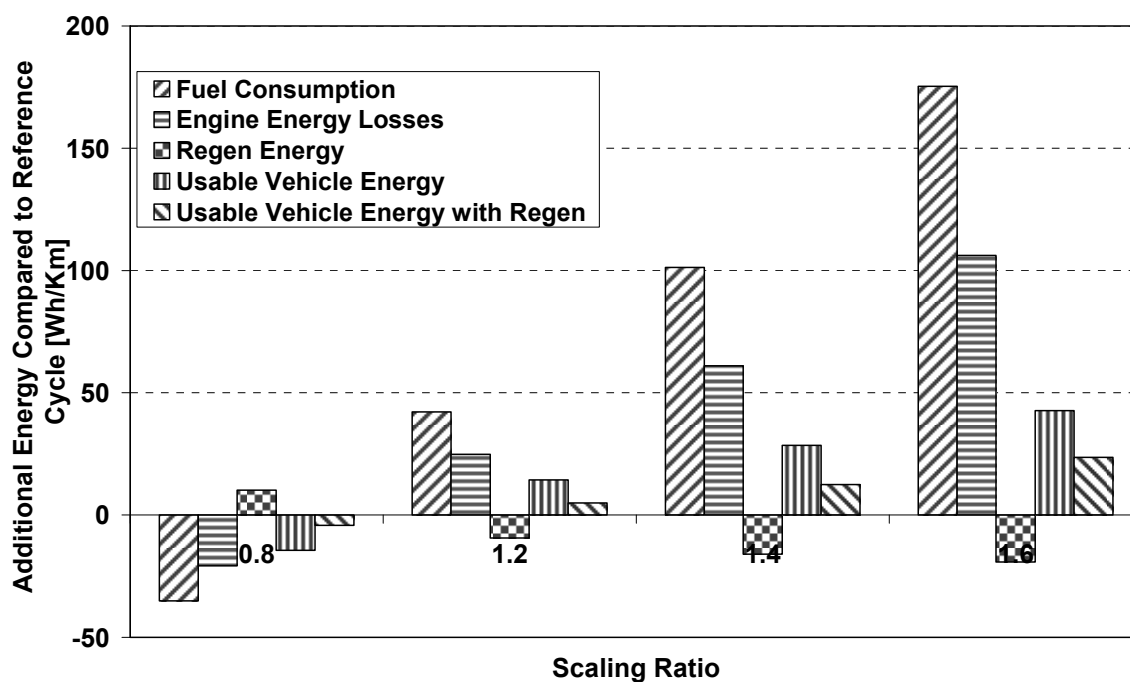


Figure 16. Prius 2004 – UDDS Cycle

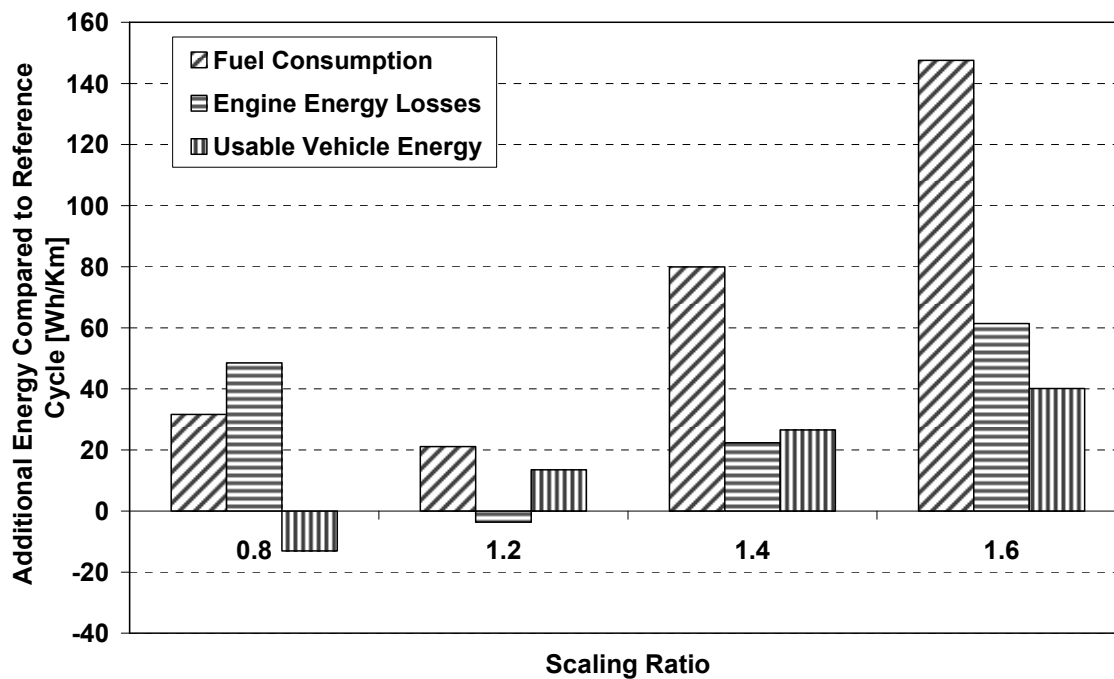


Figure 17. Focus 2004 – UDDS

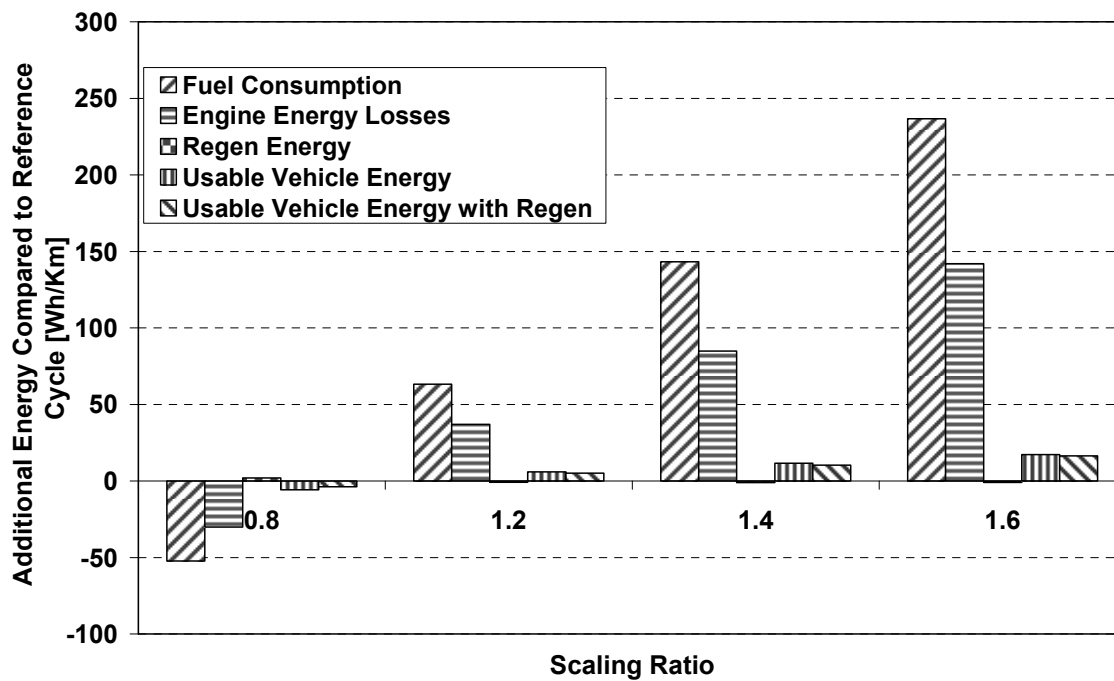


Figure 18. Prius 2004 – HWFET Cycle

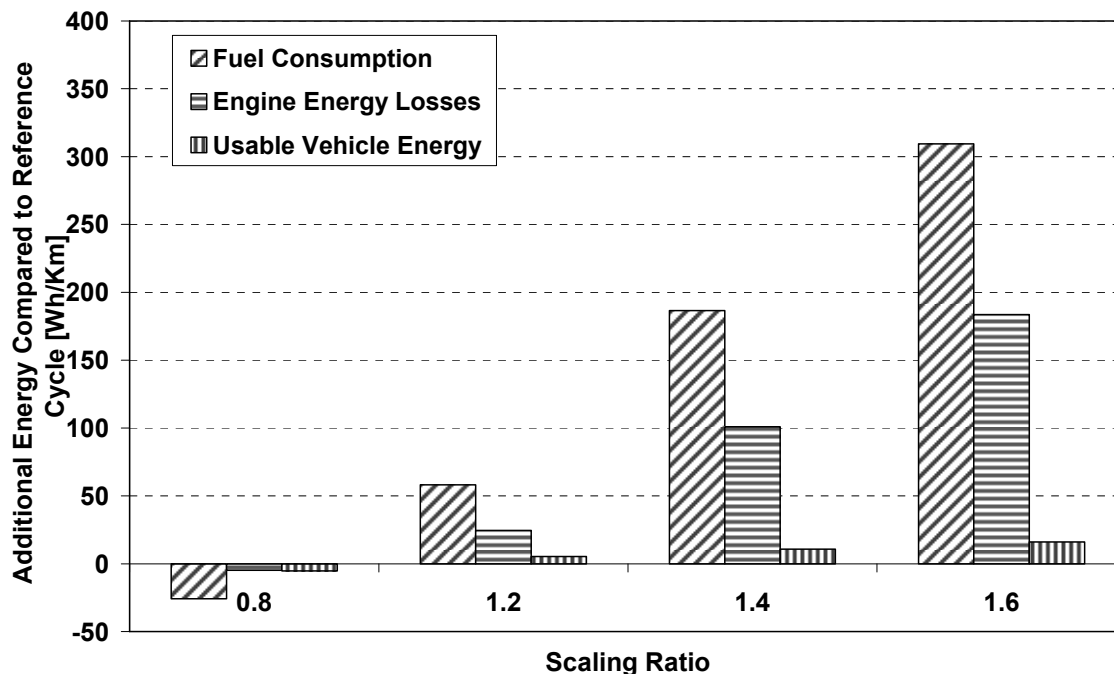


Figure 19. Focus 2004 – HWFET Cycle

Conclusion

The fuel consumption trends noticed during dynamometer testing have been reproduced in simulation by using verified vehicle models. When the aggressiveness of the driving cycles is increased, the Prius appeared to be more sensitive than the conventional Focus on the UDDS and displayed similar behavior on the HWFET. Several parameters can explain these trends:

- The engine energy is by far the main parameter influencing vehicle sensitivity. The more aggressive the driving cycle, the more the Prius will behave as a conventional vehicle and lose the ability to use its electrical components.
- The high engine efficiency of the Prius and the regenerative braking events tend to minimize the impact of the energy increase. However, the importance of regenerative braking in diminishing the input energy required to follow the trace is minimized by very high power during decelerations, and the battery cannot capture that energy.
- An increase in engine efficiency when drive cycles become more aggressive leads to a decrease in sensitivity.
- For the HWFET driving cycle, both conventional and HEV vehicles behave similarly

as a result of the high vehicle speed and the low regenerative braking and vehicle stop events. As a consequence, their sensitivity is very similar.

In conclusion, the Prius is more sensitive to drive cycle conditions than the conventional Focus because of its intrinsic characteristics. HEVs lower their fuel consumption by increasing their engine efficiency at low power requirements, turning the engine OFF when the vehicle stops, increasing their powertrain efficiency by using the electrical path, and recuperating energy during deceleration. The greater the drive cycle characteristics force the HEVs to be used more as conventional vehicles (high power during acceleration and deceleration, no vehicle stops), the greater the fuel consumption sensitivity will be. Even if the reasons behind the differences are similar for other conventional and HEVs, each powertrain and vehicle class will behave differently.

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C. Data Quality Analysis and Validation of MY04 Toyota Prius

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Objectives

- Use laboratory test data to develop a vehicle system controller for the MY04 Toyota Prius model in PSAT that replicates the observed vehicle behavior.

Approach

- Gather relevant 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

- Generic data quality analysis process developed and implemented for the MY04 Prius.
- Component models integrated into PSAT.
- Control strategy developed based on vehicle test data.
- Vehicle model validated on several driving cycles.

Future Directions

- Reuse the data quality analysis process for all vehicles tested at ANL's Advanced Powertrain Research Facility.

Introduction

Because the set of conceivable hybrid electric vehicle powertrains is so large, it is impractical to perform an exhaustive search using fabrication and testing of prototypes to find the ideal powertrain for a given application. Rather a simulation tool can be used instead to provide guidance of similar quality assuming the models accurately predict the behavior of the powertrains under investigation. The simulation tool used to development the model of the MY04 Toyota Prius was the Powertrain System

Analysis Toolkit (PSAT), a state-of-the-art flexible and reusable simulation package developed by Argonne National Laboratory. It was designed to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process from modeling to control. PSAT, the primary vehicle simulation tool to support FreedomCAR and Vehicle Technologies Program, received in 2004 an R&D100 Award, which highlights the 100 best products and technologies newly available for commercial use from around the world.

Test Data Collection

A description of test data collection and quality analysis appears in last year's annual report. For this year, a control strategy was developed that replicates the observed behavior of the MY04 Toyota Prius.

Control Strategy Development

The actual control strategy of the MY04 Toyota Prius is known only to Toyota. Even now, this validation does not reproduce perfectly the MY04 Prius, but rather it provides a control strategy that replicates the observed engine, motor and battery behavior seen on standard drive cycles. The test data was divided into two sets. A tuning set and a checking set. The tuning set was used to determine the controller architecture and controller parameters. The checking set was used to ensure that the control strategy was not over fit to the tuning set.

Several controller architectures were evaluated with varying levels of success. Simple strategies with few degrees of freedom were examined. An example is shown in Figure 1. The advantage of a simple strategy is that it has fewer parameters to tune and thus requires less time to optimize the strategy. The disadvantage is that it may not have enough complexity to fully replicate the vehicle behavior.

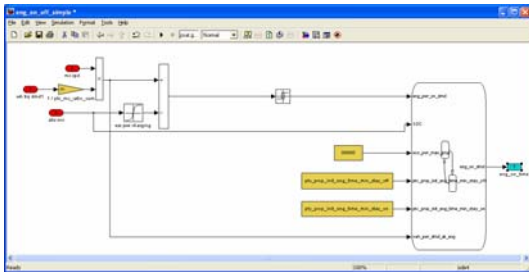


Figure 1. Simple Controller Architecture

More complicated strategies with multiple degrees of freedom were also explored. However, this extra complexity did not add value to the strategy and only increased the tuning time with little added increase in accuracy. A loss of accuracy was more often demonstrated with too much added complexity. The main tool to optimize these strategies, the Matlab Optimization toolbox and the Direct toolbox, would get lost in the higher dimensional space.

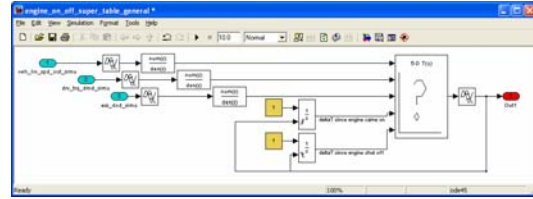


Figure 2. Largest Number of Parameters = Most Degrees of Freedom = Largest Search Space.

Test data was fed into each control strategy, as shown in Figure 3, outside of the PSAT model to determine how well the simulated control strategy could predict the control signals based on input signals that matched perfectly with those in the real vehicle. The optimization algorithm then adjusted the control strategy parameters until a minimum error was reached.

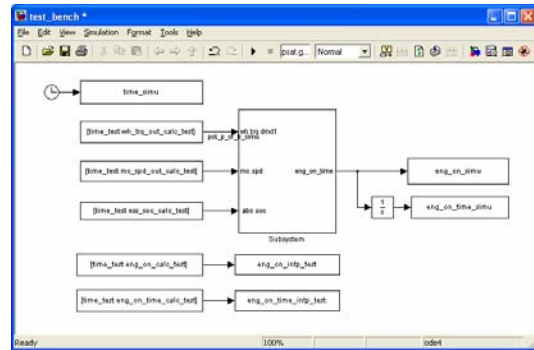


Figure 3. Largest Number of Parameters = Most Degrees of Freedom = Largest Search Space

Validating Component Models

Using test data, a control strategy can be developed in isolation from the rest of the powertrain model. Like the controller, each component model can also be analyzed in isolation. Figure 4 shows a schematic demonstrating the use of test data to validate a battery component model.

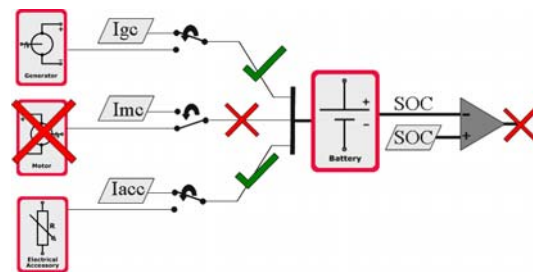


Figure 4. Feeding Measured Data into Component Models

Figure 5 shows SOC for the battery model as test data is spliced in at various points along the powertrain model.

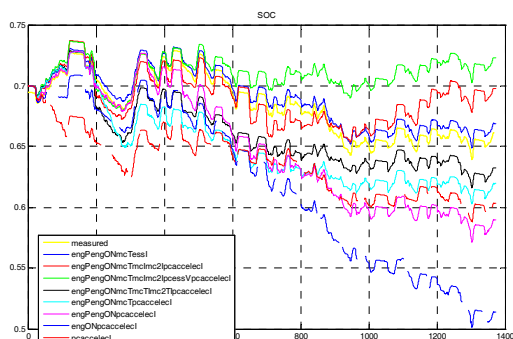


Figure 5. SOC Curves with Different Mixes of Test Data Spliced at Test Points in the Model

From this test, the validation engineer ascertains the accuracy of the battery model by comparing predicted SOC with measured SOC. A large difference in SOC, reveals an inaccuracy in the battery model's SOC prediction. This procedure was also used for the engine, motor and generator. For instance, torque and speed can be fed into the engine to determine how well the model predicts fuel rate.

Validating the Powertrain Model

Once the component models are shown to reasonably correlate with the test data, the powertrain can be joined with the controller and the whole vehicle model can be validated.

Figure 6 and 7 show an example of figures used to analyze the error that builds in the powertrain model over a cycle. The measured and simulated output energies of the engine are compared in Figure 6 for a UDDS, HWFET, US06 cycle. The difference in output energy is roughly 7.4%.

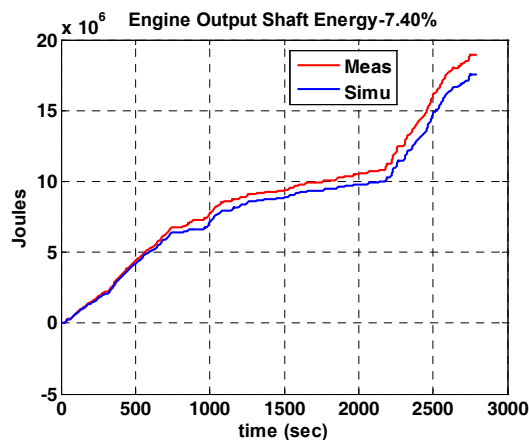


Figure 6. Engine Output Shaft Energy

The measured and simulated total engine on times are compared in Figure 7.

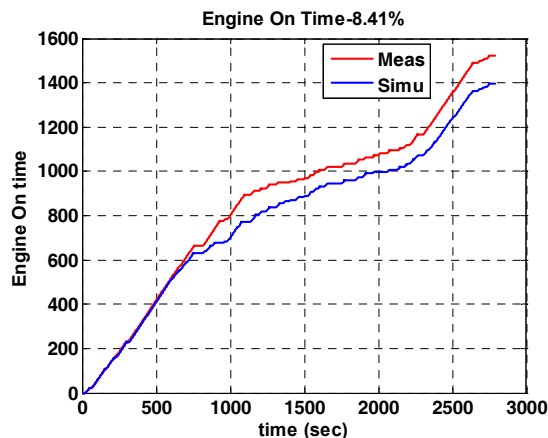


Figure 7. Total Engine on Time

There is 8.4% error between the measured engine on time and the simulated engine on time because of driver behavior shown in Figure 8. The plot on the right shows that the engine stays on during braking events during which the simulated engine shuts off. The reason is evident in the wheel torque. The measured wheel torque is strictly positive, while the simulated wheel torque dips negative. This difference in wheel torque accounts for the simulated engine turning off.

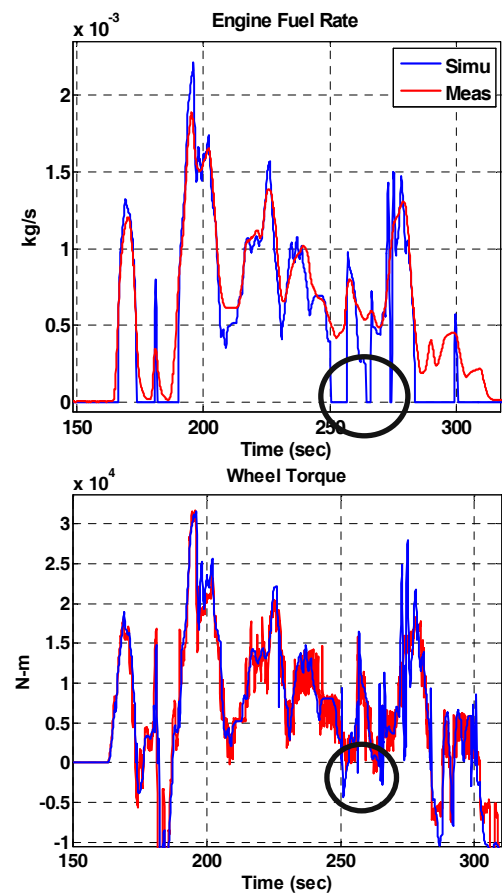


Figure 8. Difference in Engine on Time Explained

The results shown above lead to the question if PSAT ran a more representative driver model or used the measured pedal position as an input signal could all of the engine on events be captured? The answer is that it depends on the logic. Assuming the black box shown in Figure 9 with pedal position, wheel speed and battery SOC as decision inputs, the ON and OFF points can be clustered to determine if there is a surface or a set of surfaces that can be used as boundaries to separate engine on points from engine off points.

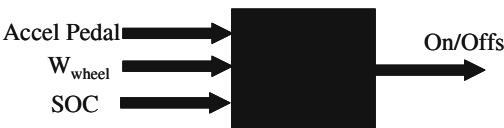


Figure 9. Engine On and Off as a Function of Accelerator Pedal Wheel Speed and SOC

A constellation diagram is shown in Figure 10. Stars represent engine on events. Open circular points represent engine off points. Closed squares represent

engine on points which, based on the above logic shown in Figure 9 and using a single surface, should be engine off points. The closed circles represent engine off points which, also based on the above logic should be engine on points. That is these events are strongly correlated with the group opposite to the one that they are binned in.

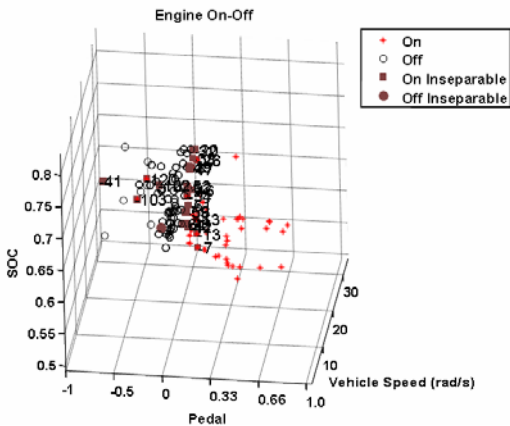


Figure 10. Engine On/Off Constellation Diagram

Figure 11 take these points and shows when they points occur during the cycle. The negative numbers indicated how correlated these points are with their opposing groups.

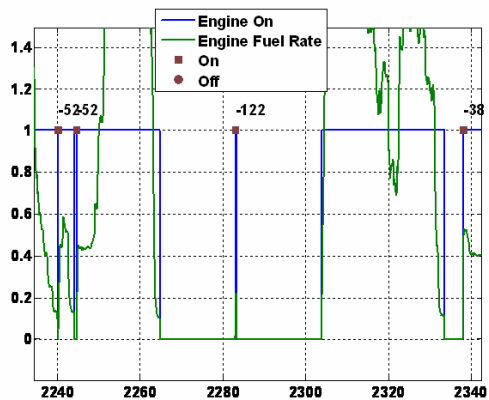


Figure 11. Points That Cannot be Completely Separated Using a Surface

Simulation Results

After assessing the component models uncertainties and tuning the control strategy, the vehicle model was run on several standard drive cycles with different initial conditions. Samples of results for the MY04 Toyota Prius Model are shown below in Table 1.

Table 1. A Selection of Simulation Results for the MY04 Toyota Prius

Fuel Economy			
	Test	Simu	%Diff
UDDS	80.2	78.7	1.8%
UDDS	69.7	70.8	1.5%
UDDS_HWY_US06	61.1	63.2	3.4%
SOC			
UDDS	(0.695) 0.662	0.647	2.2%
UDDS	(0.61) 0.64	0.648	1.2%
UDDS_HWY_US06	(0.63) 0.733	0.745	1.6%

Conclusions

As part of the work for Hyundai and extensive in depth analysis of the Prius MY04 vehicle was done. The control strategy in PSAT was validated.

Publications / Presentations

1. Bourry, A. Rousseau, P. Sharer, S. Pagerit, M. Duoba, "Data QA and Validation of Toyota Prius MY04 Using PSAT," SAE World Congress 2006, Detroit (April 2006)

D. State of Charge Balancing Techniques

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Objectives

- The primary focus of this study is the comparison of the different methodologies used to balance the battery state of charge, and the analysis of results from the simulation of one example on the PSAT software.
- Three test methods which balance the state of charge have been developed for PSAT: dichotomy, linear approximation and continuous repeating mode.

Approach

- Each SOC balancing algorithm was run on several driving cycles including UDDS, HWFET LA92, NEDC and Japan 1015.
- The number of iterations for each algorithm was varied. As the iterations were increased the rate at which each algorithm converged was compared. Also, the limiting value between the algorithms was compared. Ideally, all of the algorithms should converge to the same limit. Depending on the configuration and the control, and, hence, on the distribution of local minima each algorithm may converge to different SOC corrected values.

Accomplishments

- The advantages and disadvantages of each methods were analyzed.
- Results comparing each method on multiple cycles for different types of hybrids were compared.

Future Directions

- A metric showing the margin increase in accuracy for each additional cycle run could be used to better compare methods. That is, a metric showing the rate of converge should be developed.

Introduction

Because the set of conceivable hybrid electric vehicle powertrains is so large, it is impractical to perform an exhaustive search using fabrication and testing of prototypes to find the ideal powertrain for a given application. Rather a simulation tool can be used instead to provide guidance of similar quality assuming the models accurately predict the behavior of the powertrains under investigation. The simulation tool used to development the model of the MY04 Toyota Prius was the Powertrain System Analysis Toolkit (PSAT), a state-of-the-art flexible

and reusable simulation package developed by Argonne National Laboratory. It was designed to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process from modeling to control. PSAT, the primary vehicle simulation tool to support FreedomCAR and Vehicle Technologies Program, received in 2004 an R&D100 Award, which highlights the 100 best products and technologies newly available for commercial use from around the world.

Approach

This study aims to describe and analyze one way used to calculate the fuel economy of hybrid vehicles: by balancing the state of charge of the batteries over a drive cycle. The primary focus of this study is the comparison of the different methodologies used, and the analysis of results from the simulation of one example on the PSAT software. Three test methods which balance the state of charge have been implemented in PSAT: dichotomy, linear approximation and continuous repeating mode.

In this part the three methods will be precisely described in order to have a good idea of their differences, which will be later useful to understand the simulations results. The SAE J1711 which can be considered as another method will be here used as a criterion met or not met in the simulation results. It can be shown that it is a useful indicator of the accuracy of the results

Methodologies Description

Linear Approximation

This method is based on the linear behavior existing between the electricity balance of the energy storage system and the fuel consumption of the HEV. This method consists in measuring different fuel consumptions for different values of this electricity balance (which will be called “ Δ SOC” as the difference between the initial and the final state of charge (SOC) of the HEV’s batteries) and then in performing a linear interpolation of the fuel consumption at the point where Δ SOC equals zero.

It can be observed from the example in Figure 1 that the number of points calculated (blue circles on the graph) and their distance to zero on the x-axis should have an influence on the accuracy of the results.

Dichotomy

This method is focused in searching an initial value of the battery state of charge for which its final value will be very close after performing a simulation on a drive cycle. In other terms the dichotomy is a method based on an algorithm which modifies the initial SOC value and stops when the associated Δ SOC tends towards zero.

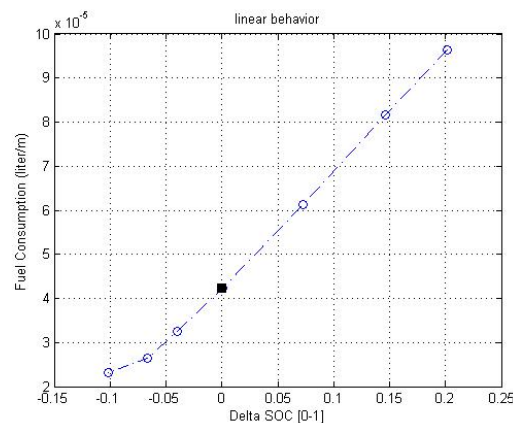


Figure 1. Example of Linear Behavior From the Simulation of the Toyota Prius MY04 on PSAT

This algorithm is an iterative procedure which typically tries to reduce after each test the search area (here the range of value of the initial SOC) as shown in Figure 2.

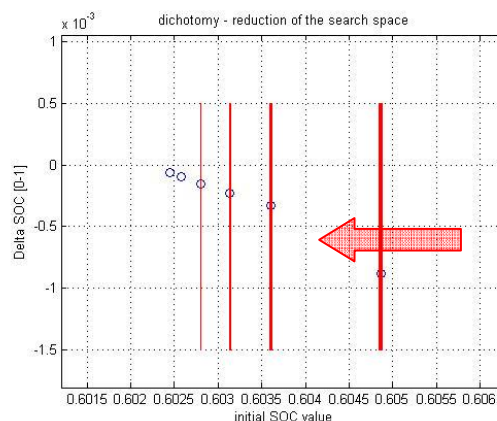


Figure 2. Dichotomy Algorithm

Continuous Repeating Mode

This method is based on the repetition of the drive cycle a certain number of times so that the electricity balance of the energy storage system gets stabilized and the corresponding fuel economy can be measured. The main idea behind this approach is the fact that after a certain amount of time, the final state of charge becomes independent from the initial one. By repeating a cycle many times in a row, the fuel economy will then converge to a value which should be a good result of the fuel economy of the HEV.

Figure 3 shows an example of this independence. After two cycles it can be observed that whatever

the initial value of state of charge is, the behavior of these three simulations becomes similar, following the control strategy here with an SOC target at 70%.

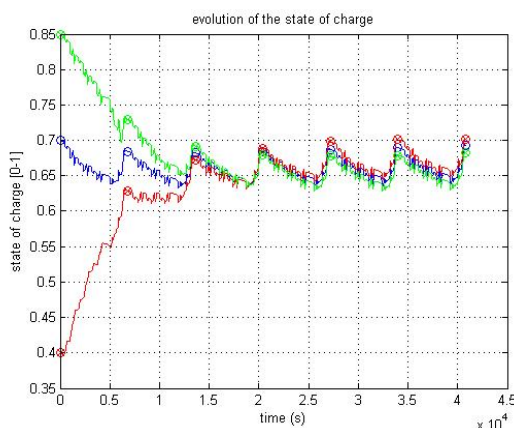


Figure 3. Prius MY04, Japan1015, with Different Initial SOC

SAE J1711

The SAE J1711 mode is another method to measure fuel economy. It consists in adjusting the state of charge and measuring the fuel economy only if the given criterion is satisfied:

$$\left| \frac{\Delta \text{stored electrical energy}}{\text{total fuel energy}} \right| \leq 1\% \quad (1)$$

Where:

$\Delta \text{stored electrical energy} = \text{stored charge} \times \text{voltage of the cell}$

$\text{total fuel energy} = \text{fuel consumed} \times \text{specific weight} \times \text{LHV}$

In this study, the SAE J1711 will not be developed but its criterion will be used as an indicator of the accuracy especially on the continuous repeating mode.

In PSAT when a vehicle is created for simulation and a drive cycle is selected, it is then possible to enable the SOC correction in Graphical User Interface. Then, the SOC correction algorithm has to be chosen in a list which is composed of the three previously described methods:

- linear approximation
- dichotomy
- continuous repeating

Results

The results from simulations on the Toyota Prius MY04 will be used as the base for the analysis of the three SOC correction methods. A large number of simulations were performed on five different drive cycles using the three possible SOC correction methods.

Linear Approximation

Tables 1 and 2 summarize the simulation results from PSAT for the Prius MY04 with linear approximation SOC correction.

The “iterations” line corresponds to the number of points calculated before the linear interpolation; this number can be chosen by the user. The “range” line gives the minimal and maximal state of charge values also chosen by the user and expressed in percents. The fuel economy results are given in mpg (miles per gallon). Finally the “SAE J1711” line shows the results of the 1% criterion.

Over 6 cycles: the SAE J1711 1% criterion is accepted. For a closer range: 4 cycles seem enough. When the SAE J1711 criterion is under 1%, the margin of error is less than 0.5%. It appears more important to be close to the “zero ΔSOC ” point with the pre-defined range of values than to perform many simulations with a large range. This behavior can be explained by the fact that the “extreme” points have a distorting effect on the results.

Dichotomy

Tables 3 and 4 summarize the simulation results from PSAT for the Prius MY04 with dichotomy SOC correction. In this case, the “iterations” line corresponds to the number of drive cycles that needed to be simulated before the algorithm stopped. The “range” line gives the two first state of charge values used in the two first simulations. The tolerance is expressed in percent, the fuel economy in miles per gallon. Finally the “SAE J1711” line shows the results of the 1% criterion.

The 0.5% tolerance is a more demanding criterion than the SAE J1711. The margin of error is less than 1% when SAE J1711 criterion is accepted. There is a difference between the SAE J1711 criterion in the linear approximation and in the dichotomy: in the

linear approximation, the criterion is calculated similarly to the fuel economy with linear interpolation whereas in dichotomy it is a value directly calculated in the simulation.

Continuous Repeating Mode

Tables 5 and 6 summarize the simulation results from PSAT for the Prius MY04 with continuous repeating mode SOC correction.

There is a 2% error on the results within the SAE J1711 criterion for the total cycle and 0.5% error on split results. The first two cycles should not be taken into account especially when a dichotomy is not performed before starting the continuous repeating mode.

Table 1. Linear Approximation Results

Cycle	UDDS	UDDS	UDDS	HWFET	HWFET	HWFET	LA92	LA92	LA92
iterations	5	4	9	4	4	9	4	9	5
range	40-80	60-80	25-90	30-80	50-70	25-90	25-85	25-85	50-75
fuel economy	74.03 (mpg)	74.17	74.14	66.71	66.77	66.74	58.59	58.82	58.82
SAE J1711	0.65	0.18	0.32	0.69	0.38	0.14	1.43	0.72	0.50

Table 2. Linear Approximation Results, Continued

Cycle	NEDC	NEDC	NEDC	Japan*	Japan	Japan	Japan	Japan	Japan
iterations	6	9	4	3	3	5	5	7	4
range	25-90	25-90	60-75	25-90	65-75	65-75	30-80	60-80	65-75
fuel economy	69.30	69.28	69.26	73.68	78.42	78.47	77.88	78.44	78.49
SAE J1711	1.49	1.29	0.53	18.25	2.01	0.61	2.88	0.79	0.35

Table 3. Dichotomy Results

Cycle	UDDS	UDDS	UDDS	HWFET	HWFET	HWFET	LA92	LA92	LA92
iterations	3	3	9	3	3	6	3	3	12
range	40-80	60-80	50-60	60-80	40-80	70-80	60-80	25-90	30-40
tolerance	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
fuel economy	74.41	74.37	73.75	66.76	66.69	66.93	58.85	58.84	58.86
SAE J1711	0.11	0.10	0.14	0.01	0.03	0.11	0.01	0.01	

Table 4. Dichotomy Results, Continued

Cycle	NEDC	NEDC	NEDC	Japan*	Japan	Japan
iterations	3	4	3	3	4	10
range	60-80	25-90	40-80	60-80	40-90	50-60
tolerance	0.5	0.5	0.5	0.5	0.5	0.5
fuel economy	69.08	69.27	69.18	78.52	79.39	76.84
SAE J1711	0.11	0.01	0.04	0.02	0.45	0.71

Table 5. Continuous Repeating Results

Cycle	UDDS	UDDS	UDDS	HWFET	HWFET	HWFET	LA92	LA92	LA92
iterations	4	3	6	3	5	9	6	6	3
Init soc	65	70	70	65	65	65	65	70	65
total fuel eco.	73.98	75.49	74.83	66.36	66.46	66.54	58.30	58.66	57.70
split fuel economy	74.38	73.67	73.87	66.42	66.68	66.75	58.91	58.89	58.84
SAE J1711	0.12	0.63	0.27	0.22	0.19	0.17	0.35	0.13	0.73

Table 6. Continuous Repeating Results, Continued

Cycle	NEDC	NEDC	NEDC	Japan	Japan	Japan	UDDS
Iterations	6	6	2	6	6	2	3
Init soc	65	70	65	65	70	70	dicho.*
total fuel eco.	68.15	68.85	66.78	75.99	78.48	80.74	72.55
split fuel economy	68.94	68.92	67.99	77.07	77.66	78.86	73.84
SAE J1711	0.58	0.21	1.34	0.97	0.17	1.16	0.82

First Interpretations

These results show mainly that the SAE J1711 criterion allows guaranteeing results with a maximum of 2% error. One issue is the difference between results depending on the state of charge correction method used.

Analysis

One major aspect is to consider the time needed in order to get a result with certain accuracy. With much time, a linear approximation with many cycles or a dichotomy with a very small tolerance would give precise results but that is not the purpose.

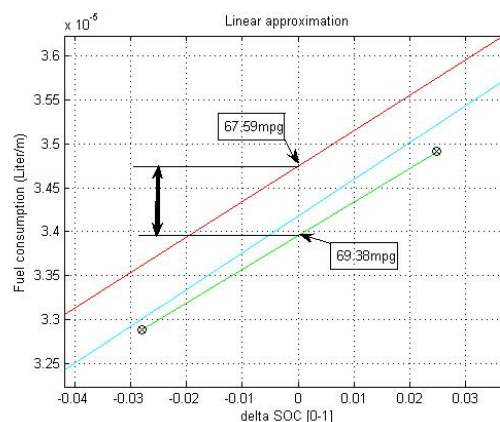
Linear Approximation

The results using linear approximation depend on the extreme values and the number of cycles chosen by the user. For a broad range of values between the extremities more simulations are needed than for a closer range around the “zero Δ SOC” point.

Considering the simulation time, simulating the ten cycles of this previous example gives a fuel economy of 69.4 miles per gallon whereas the only red line, as shown in Figure 4, corresponding to only two simulations gives after linear interpolation a fuel economy value of 67.6 miles per gallon. In the middle, the result from the blue line is a value of 68.8 miles per gallon.

In general, the gain in time increases the error in the results. In this particular case, the error between the “red” results and the “green” result is about 2.5%. One way to avoid it is by narrowing the range of values.

With the linear approximation SOC correction method, it is not possible to guarantee a result within a pre-defined accuracy without knowing in advance

**Figure 4.** Linear Approximation Results

some characteristics (like the target state of charge for example) but this method gives always a result with good precision with at least six simulated cycles.

Dichotomy

The dichotomy mode with its algorithm and the tolerance has the advantage of guaranteeing on the last simulation a Δ SOC value which corresponds to a desired precision range. By default, this value is set at 0.5% in PSAT which insures that the SAE J1711 criterion is accepted.

In the case of the NEDC drive cycle, as shown in Figure 5, this tolerance allows staying in a close range of results. After calculation the maximum error on fuel economy within the tolerance is 0.5%.

Another point is the choice of the two first state of charge values used at the beginning in the algorithm, as shown in Figure 6: the example shows in these three cases a maximal error of 0.25% corresponding to the choice 50% and 90% for the two first SOC values.

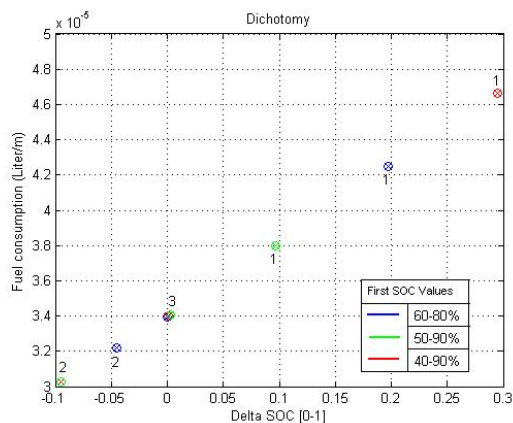


Figure 5. Prius MY04, NEDC, Dichotomy, in 3 Cases

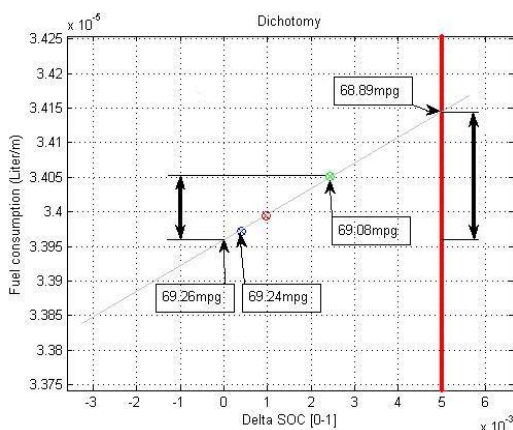


Figure 6. Magnification of NEDC, Dichotomy from Figure 5

Considering the simulation time, the advantage of the dichotomy mode is that the whole number of simulations chosen by the user will not necessarily be performed since the algorithm stops when the tolerance is reached. Moreover, when the two first state of charge values defined by the user are one over and one under the “zero Δ SOC” point, three simulations are enough in many cases for an acceptable tolerance (like 0.5%).

Continuous Repeating Mode

It can be observed from Figure 7 that whatever the initial state of charge value is, after two cycles, there is a stabilization of the behavior. That is why if the fuel economy is calculated from the beginning of the third cycle, the results converge.

In this example, three simulations were started with different initial SOC values: 40%, 60% and 80%. The results after four cycles and after six cycles give an error range of less 0.5% which shows that this method behaves well independently from the starting values.

The choice of the number of cycles does not have a huge influence since the behavior after four, six or ten simulations remains similar.

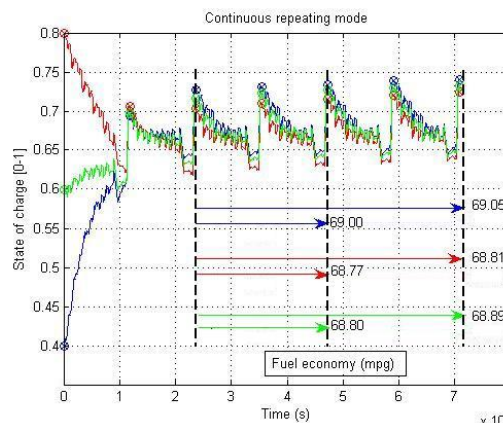


Figure 7. Prius MY04, NEDC, 6 Cycles Continuous Repeating Mode, in 3 Cases

Conclusion

The three SOC balance procedures evaluated give similar results. They all yield results that satisfy the criteria specified in J1711.

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1. Kenji Morita, Kazuki Shimamura, Nobuo Iwai, Ken-ichi Shimizu, “Fuel Economy and Exhaust Emissions Test Procedure for Hybrid Electric Vehicles – Comparison of Continuous Repeating Mode, Linear Approximation and SAE J1711,” EVS 18 Berlin, 2001
2. Shigeru Seimiya, Ken-ichi Shimizu, “Test Procedure to evaluate Fuel Consumption of HEVs – Universal Procedure to Secure Accuracy,” EVS 18 Berlin, 2001

E. Government Performance and Results Act (GPRA) Support

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Objectives

- The goal is to simulate multiple vehicle platforms, configurations and timeframes in order to support GPRA by providing the fuel economy for analysis.

Approach

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

Accomplishments

- 224 vehicles were sized and simulated.
- New vehicles were simulated when updates were made to the assumptions or new vehicle or when additional configuration or timeframe were requested.

Future Directions

- Continue to support GPRA in 2007.

Introduction

DOE management is interested in a side-by-side review of alternative pathways to reducing U.S. oil use and GHG emissions from the light-duty vehicle fleet, and the National Research Council 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, i.e. combinations of pathways) with more evaluation criteria (including cost).

Methodology

The goal of the Multi-path Transportation Futures Study is to compare multiple fuel and vehicle pathways in as fair a fashion as possible. The realization of this goal is not straightforward and unambiguous, however. One way to satisfy the goal, for example, might be to optimize each pathway's vehicle design for the specific fuel and vehicle technology combination embodied by the pathway; this may lead to "competing" vehicles being quite different from one another. Pathways with low energy density fuels (hydrogen or electricity) have onboard energy storage challenges because high pressure storage tanks (or cryogenic tanks, or adsorption tanks) and batteries are heavy and expensive; vehicles in these pathways will gain

higher benefits (in terms of increased range or reduced storage system costs) from load reduction than would vehicles using energy-dense liquid fuels. This implies that an “optimal” electric vehicle or hydrogen vehicle would likely use expensive weight reduction (and other load reduction) technologies that might not be used by vehicles powered by liquid fuels. This interpretation of the goal, though reflective of what might actually occur in the marketplace, would create substantial analytical difficulties, because of the large uncertainties in the estimated cost of future load reduction technologies and in the complex tradeoffs that would be made in designing the vehicles.

To avoid the problems this interpretation would cause, we have chosen instead to design the vehicles in each pathway to be as similar as possible consistent with the differences in their fuels and drivetrains. The vehicles must satisfy the same core set of performance standards, and will have virtually identical “gliders” (a “glider” is a vehicle minus its powertrain and fuel storage system). Consequently, these vehicles will appear to their drivers and passengers to be virtually identical to each other, except where differences are made inevitable by the pathway differences (e.g., differences in the time spent refueling or in the location of refueling, small performance differences caused by the high low-end torque of electric motors and diesel engines, and so forth).

The fuel economy evaluations were conducted using the Powertrain Analysis System Toolkit (PSAT) vehicle simulation model. The vehicles modeled are considered “leading edge” vehicles assumed to be introduced to the fleet in limited numbers at the modeled date. The overall vehicle designs and technology performance assumptions are based on technological optimism and an assumed strong design preference for fuel economy over performance. This preference flows from the assumed political context, which is one of urgency from the failure of world oil production to keep pace with continued growth in transportation demand. It is assumed that there is strong government and consumer demand for increased vehicle efficiency and perhaps alternative fuels, and general acceptance of the idea that vehicle acceleration performance will no longer increase with every new model redesign.

Due to the number of vehicles to size and simulate for this year GPRA, an automatic component sizing routine was developed and used to run this study. The sizing of the 224 vehicles now takes about an hour using the Distributed Computing Platform.

Assumptions

The following assumptions have been defined for 2 vehicle classes: midsize car and midsize SUV. Six configurations are proposed for the study:

- conventional gasoline
- conventional diesel
- full hybrid gasoline (no AER, 20 and 40 miles)
- full hybrid diesel (no AER, 20 and 40 miles)
- fuel cell hybrid
- electric vehicle

Three driving cycles were used: UDDS, HWFET, US06.

Additional assumptions:

- All Electric Range (AER) will be defined on UDDS.
- Hydrogen storage tanks will be sized for 320 miles range (UDDS, HWFET combined).
- For fuel cell HEV configurations, only batteries will be considered. However, it has been shown that ultra-capacitors would achieve similar fuel economy than Li-ion for lower hybridization degrees configurations.
- When possible, specific engines will be used, meaning the engine powers will not be changed.

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

Results

After several modifications to the assumptions and sizing of the vehicles following the different feedback from the original runs, these are the last results provided to DOE.

Figure 1 shows the fuel economy ratios for the timeframes considered (2015, 2030 and 2045) for the midsize car compared to the conventional gasoline 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 as 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 the midsize SUV compared to the conventional gasoline of the same year. Similar trends and values are noticed than for the midsize vehicle.

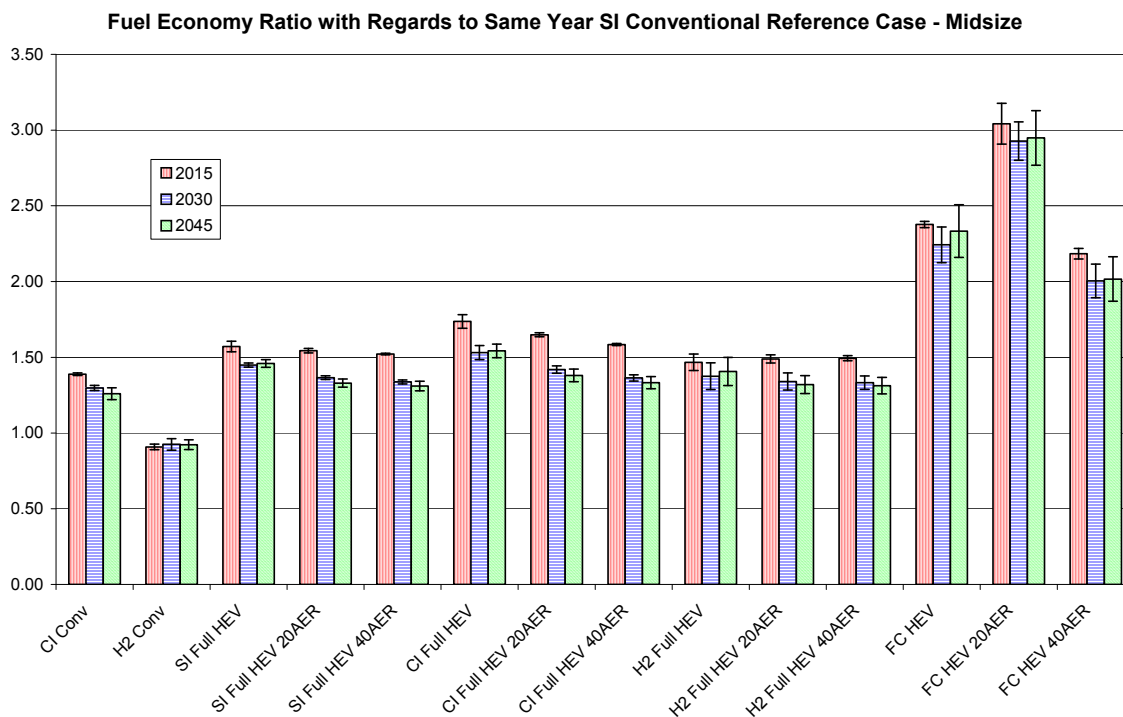


Figure 1. Fuel Economy Ratio with Regards to Same Year Midsize Car Conventional Vehicle

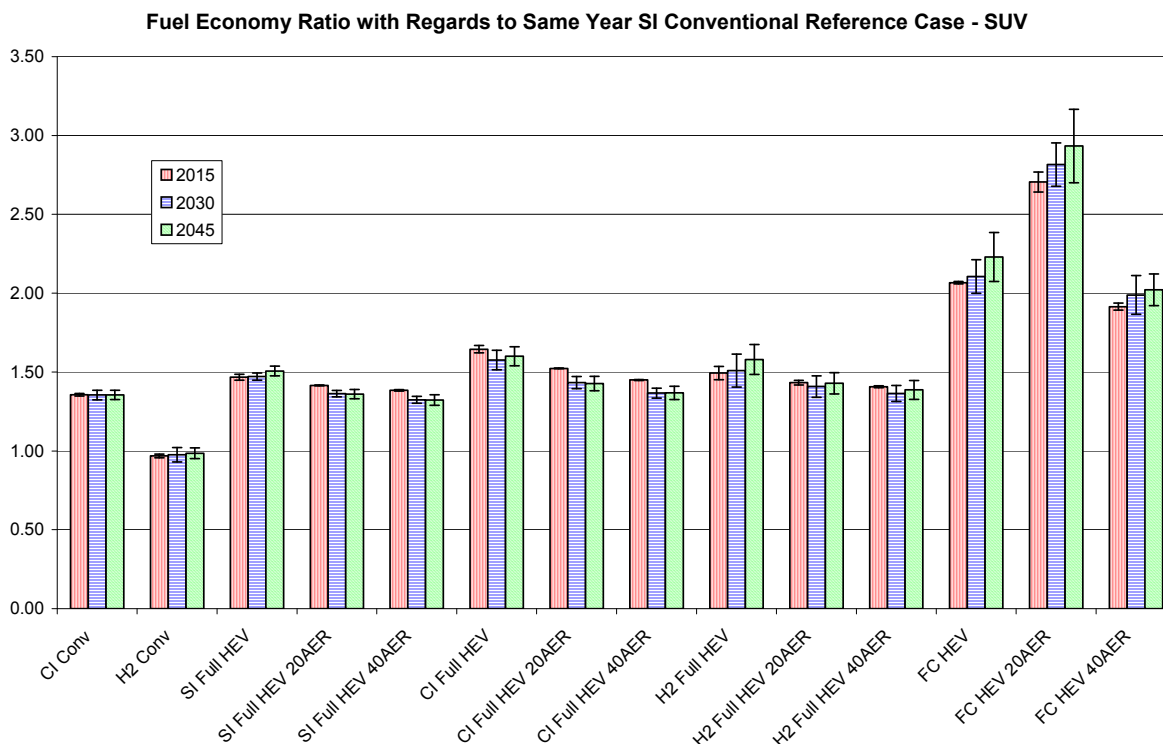


Figure 2. Fuel Economy Ratio with Regards to Same Year Midsize SUV Conventional Vehicle

Conclusions

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

Publications / Presentations

1. A. Rousseau, S. Pagerit "MultiPath / GPRA results – Run 1" E-mail to DOE (May 2006).
2. A. Rousseau, S. Pagerit "MultiPath / GPRA results – Run 2" E-mail to DOE (June 2006).
3. A. Rousseau, S. Pagerit "MultiPath / GPRA results – Run 4" E-mail to DOE (July 2006).
4. A. Rousseau, S. Pagerit "MultiPath / GPRA results – Run 5" E-mail to DOE (August 2006).
5. A. Rousseau, S. Pagerit "MultiPath / GPRA results presentation and assumptions definition for next run," ANL-DOE, Washington (September 2006).
6. A. Rousseau, S. Pagerit "MultiPath / GPRA results – Run 6" E-mail to DOE (October 2006).

F. PSAT Maintenance and Enhancements

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Objectives

- The goal is to enhance and maintain PSAT and PSAT-PRO as needed to support DOE, the user community and HIL projects. This includes 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

- PSAT V6.1 to be released in November 2006.
- Improved Graphical User Interface.
- More detailed documentation of the software post processing.
- Developed Heavy Duty version of PSAT.
- Designed an automatic component sizing for studies.
- Implementation of hydraulic systems.
- Addition of control strategies for plug-in HEV (PHEV).
- Addition of post-processing capabilities.

Future Directions

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

Introduction

To better support DOE and its users, several new features have been implemented in PSAT. Some of the most significant accomplishments are described below.

Results

ANL's vehicle systems analysis team will release the newest version of its vehicle simulation modeling

software in November 2006. The latest Powertrain System Analysis Toolkit (PSAT V6.1) includes many new features and improvements. These changes were based on feedback from people in industry and universities who use the software as well as the needs expressed by staff at DOE and ANL. PSAT V6.1 runs with Matlab R14SP3 or above.

Numerous new features were implemented based on user's feedback and to support DOE activities.

New Opening Screen

A new opening screen has been developed for the users to be able to select between light and heavy duty simulations. This feature supports the greater emphasis by DOE on Heavy Duty modeling. By selecting different options, users will then have access to different component data, drive cycles and powertrain configuration.

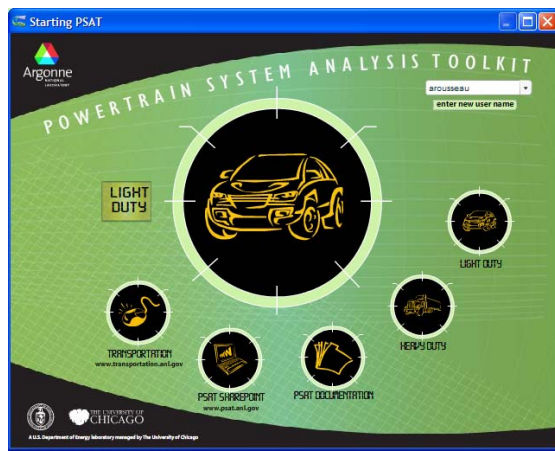


Figure 1. New Opening Screen

Additional Powertrain Configurations for Heavy Duty

For medium and heavy duty powertrain configurations, users need to select the number of axles. Additional options were integrated as shown in Figure 2.

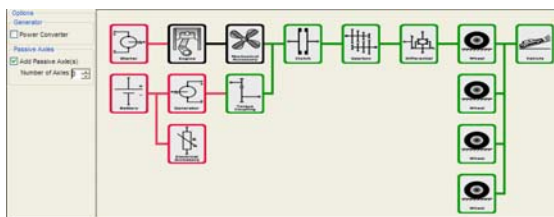


Figure 2. Multi-axle Selection

Additional SOC Correction Techniques

Researchers are still debating which vehicle test procedure should be used to measure Hybrid Electric Vehicles fuel economy. Modeling engineers share the same concerns. To evaluate the uncertainties introduced by several proposed

methodologies, additional options were implemented in the Graphical User Interface. Figure 3 shows an example of a new option called "repeating sequence". This additional feature has been implemented to support a DOE study.

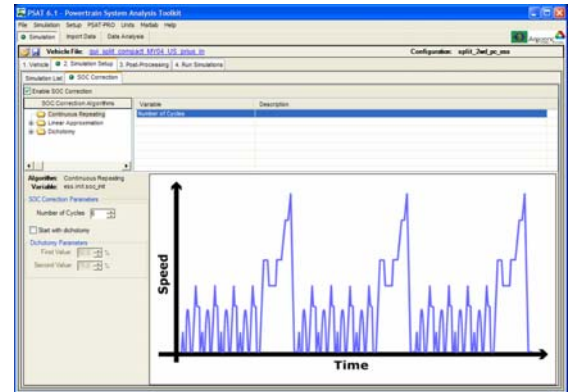


Figure 3. Additional SOC Correction Techniques

Automated Simulation Report

To accelerate the time required to analyze a simulation and easily share the results with experts, a process to generate automated reports was developed. To maximize the flexibility, users have the ability to independently select the figures to be implemented in the final report. The report is currently an HTML document with hyperlinks allowing each figure to be opened in the Matlab Workspace.

In addition to the figures, all the initialization parameters (e.g., data, cycle type...) as well as the results (e.g., fuel economy, efficiency, power...) are provided in separate tables.

Provide Easy Access to PSAT Structure

In previous versions of PSAT, only the main results were accessible from the Graphical User Interface. This list was set and pre-defined. A new Tab in the GUI now allows the users to easily navigate through the PSAT structure that contains all the results.

Figure 4 shows an example with the engine energy. In the initial version, only the total input, output and losses engine energy would have been easily accessible from the GUI. Users can now view the energy repartition when the vehicle is accelerating, decelerating or stopped. For hybrid electric vehicles,

one would also be able to look at the distribution when the battery is charging or discharging.

energy		
accmech		
cpl		
gb		
fd		
vwh		
veh		
ess		
gc		
tc_gc		
accelecc		
eng		
E_in_zero_veh_spd	VWh	37.85
E_out_zero_veh_spd	VWh	0.81
E_loss_zero_veh_spd	VWh	37.05
E_in_pos_vwh_trq	VWh	495.25
E_out_pos_vwh_trq	VWh	119.87
E_in_neg_vwh_trq	VWh	108.85
E_out_neg_vwh_trq	VWh	-4.06
E_loss_pos_vwh_trq	VWh	375.38
E_loss_neg_vwh_trq	VWh	112.91
E_in_tot	VWh	604.1
E_out_tot	VWh	115.81
E_loss_pos	VWh	436.6
E_loss_neg	VWh	0
E_loss_tot	VWh	488.29

Figure 4. Easy Access to PSAT Structure

Analyze Several Test Data in Batch Mode

PSAT V6.0 included a new utility to be able to quickly import and rename test data from a text file into the Matlab environment. Once in Matlab, the same post-processing routines than for the simulations could be used to calculate the efficiencies, power and energy of the different components. Because many vehicle tests are performed with the same set of sensors, a new feature was added to be able to post-process all the tests at once.

Improved Test and Simulation Comparison

Several Tabs were modified to be able to easily compare results between several tests and/or simulations. Figure 5 shows a comparison of the main results of two simulations.

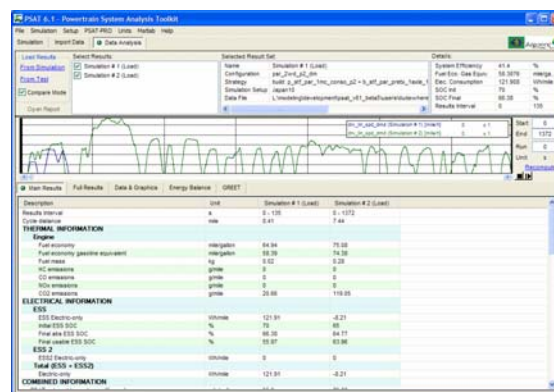


Figure 5. Simulation Comparison

Linkage with GREET

With numerous fuels being compared, the necessity to analyze the entire Well-to-Wheel (WTW) becomes more and more important. A new Tab was implemented in PSAT to be able to open GREET after a simulation has been performed. The fuel economy results are then imported to GREET and the Well-to-Tank (WTT) parameters calculated. All the final results from GREET are then imported back into PSAT to be able to visualize WTT, TTW and WTW.

Component Models

Hydraulic Systems

To fulfill the requests from our heavy duty 21st Century Truck partners, a hydraulic hybrid configuration and generic hydraulic component models were added to PSAT. Two entirely new component models were defined in PSAT: the hydraulic pump and the hydraulic energy storage system, also known as the accumulator.

PHEV Battery Model and Data

The Argonne battery group supplied the vehicle systems team with state-of-the-art Li-ion battery data and also a scaling procedure, which scales a Li-ion battery in both power and capacity. The new data and algorithm was successfully integrated into PSAT and was used during the Plug-in Hybrid Electric Vehicle Battery Requirements study to support the FreedomCAR Energy Storage Tech Team. Results were produced for both midsize vehicles and SUVs. The scaling procedure was also used to design PHEVs for the Multipath study,

which supports the Department of Energy's yearly GPRA process.

New Controllers for PHEV

A representative Plug-in Hybrid Electric Vehicle control strategy was developed to support the Plug-in Hybrid Electric Vehicle Battery Requirements study for the FreedomCAR Energy Storage Tech Team and the Multipath study.

This strategy has two modes: a charge depleting mode and a charge sustaining mode. This PHEV strategy also formed the basis for the HIL strategy used on Argonne's battery HIL test stand.

New Post-Processing Functionalities

To improve PSAT capabilities and with the addition of new models and configurations, the following functionalities were added:

- MOVES calculation for EPA, this calculation was extended to include PHEVs and a paper was published assessing the uncertainty in using the MOVES calculation to predict fuel consumption.
- PHEV computation for the Fuel Economy equivalent based on utility factors and J1711 standard. Several calculations were developed in Matlab to calculate an equivalent fuel economy for PHEVs, including variants of the SAE procedure. The PHEV post-processing is run offline in batch mode. There is still a requirement to integrate the calculations as part of a PHEV test procedure.

- ESS usage reporting. As part of a Tech Team request, simulations were performed to study the ESS requirements for PHEV application. As part of this analysis, a new processing plot was defined to characterize the use of the battery, in term of Power and Energy, for different vehicles and different cycle. An example of this plot is provided below.

Conclusions

PSAT V6.1 will be released with numerous new features based on DOE and user's feedbacks.

Publications / Presentations

1. Rousseau, J. Kwon, P. Moon "Prius MY04 Test analysis."
2. Rousseau, J. Kwon, B. Ble, "Honda Accord Test Analysis."
3. Rousseau, "ESS Requirement for PHEV Application," VSATT and ESS Tech Team.
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G. Automotive System Cost Modeling

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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.
- 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.
- 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 validated and database updated using four latest commercial hybrid vehicles. The cost model integration into the performance model PSAT is nearing completion.
- Life cycle cost estimation capability beyond light-duty vehicles was completed with the initial focus on Class 8 heavy-duty trucks.

Future Directions

- Continue the validation of cost data assumptions and approach by coordinating and providing the cost assessment of advanced technology vehicles using ASCM to various DOE program offices.
 - Validate the light-duty life cycle cost model integration into PSAT and initiate the heavy-duty life cycle cost model integration into PSAT.
 - Enhance the heavy-duty life cycle cost modeling capability to include other medium- and heavy-duty truck classes.
-

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 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 seven different types of advanced vehicle designs including hybrid and fuel cell vehicles. The focus of this year's work has been to validate and update the light-duty ASCM model by estimating the life cycle cost of four commercial hybrid vehicles. Integration of the cost model into the performance model PSAT was also initiated which is nearing completion. In addition, life cycle cost estimation capability beyond light-duty vehicles was demonstrated by considering an illustrative Class 8 heavy-duty truck.

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

Light-Duty Vehicles

Automotive system cost model (ASCM) for light-duty vehicles was validated and database updated using four latest light-duty commercial hybrid vehicles. The database was updated by collecting information on current hybrid vehicle system components, and sizing relationships. The database update was broad enough to allow in the future the life cycle cost estimation of nine commercial light-duty hybrid vehicles available in the market today. The following four hybrid vehicles representing the breadth of vehicle sizes and hybrid technology options were chosen for the vehicle life cycle cost estimation:

- Toyota Prius
- Honda Accord
- Ford Escape, and
- Chevy Silverado

Life cycle cost comparisons were made not only among these four hybrid vehicles but also corresponding conventional, non-hybrid vehicles. Conventional vehicles considered were closest in performance and trim to the hybrid version. Only major changes were assumed to occur in powertrain components, since same vehicle platform is used for both hybrid and conventional vehicle cases.

Actual component sizing data of commercial vehicles was considered, whenever available. Data collection focused mainly on different hybrid powertrain components, and component sizing and cost relationships were developed using the collected data. Maintenance and repair cost data used for the life cycle cost estimation were updated using the latest AVTA data, supplemented for most other operation cost data using Intellichoice. Assumptions for OEM overhead and dealer cost were based on its prevalent real differences in margins, marketing pricing strategies, and state of technology development among various vehicle types.

Figure 1 shows the life cycle cost comparisons among four light-duty commercial hybrid vehicles considered here. Estimated hybrid vehicle MSRPs are significantly higher in some cases but less than \$2300 max./vehicle. Higher estimated MSRPs

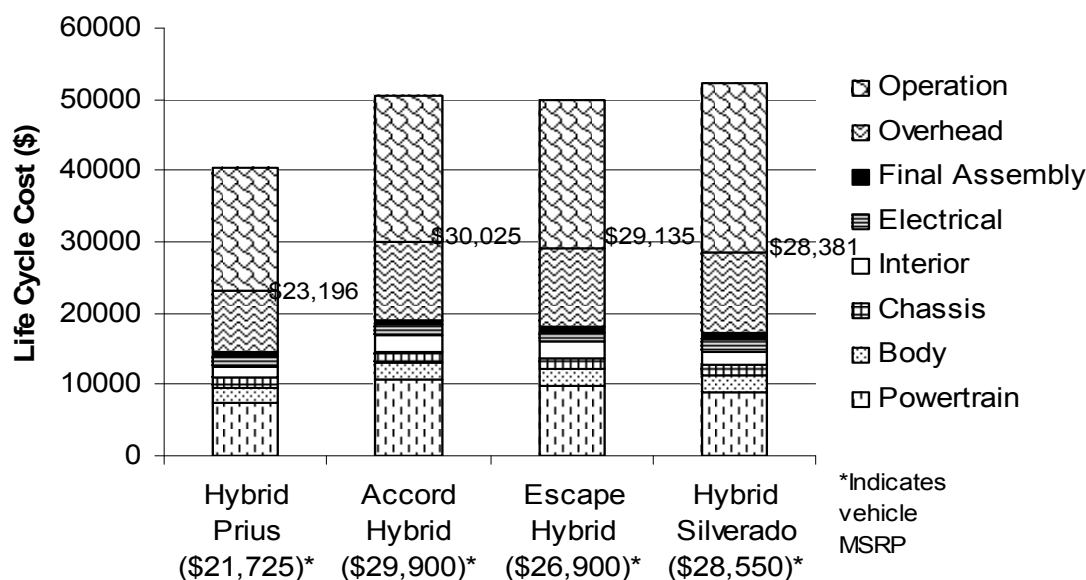


Figure 1. Life Cycle Cost Comparisons of Commercial Hybrid Vehicles

indicate that prevalent profit margins (which varies by vehicle type) and vehicle development/engineering costs are not being recovered in some hybrid vehicle cases. MSRP difference between the estimated and actual is maximum in the case of Escape hybrid, indicating a relatively low production volume and early hybrid technology development stage, thereby it is likely that the supplier may not be recovering its total cost today. The difference is the least in the case of hybrid Silverado, which is less of a hybrid. Overhead (i.e., OEM and dealer) cost contributes to 36%-39% of MSRP, reasonable assumptions made of which in this analysis are critical in the overall cost estimates. Life cycle costs of hybrid vehicles were estimated to be higher, in the range of 6%-9% than corresponding conventional vehicles. These results thereby indicate that fuel economy benefits of hybrid vehicles are not sufficient enough to negate the effect of higher initial purchase and non-fuel operation costs.

ASCM integration into PSAT is nearing completion. The cost model integration into PSAT would facilitate in the quick turn around of the life cycle cost estimation of advanced technology vehicle configurations simulated by PSAT using the output file generated by PSAT. The cost model integration uses Microsoft Visual Studio as the user-friendly front-end, whereas XML database and Matlab

software are used for input data management and cost calculations, respectively.

Heavy-Duty Trucks

A systems-level, stand-alone spreadsheet-based technical cost modeling tool has been developed for heavy-duty vehicles. It considers in detail both the purchase cost of the vehicle and the operation costs over the service life of the vehicle. Initial focus in this model has been on Class 8 heavy-duty trucks using a similar framework developed for light-duty vehicles. The model allows researchers to assess purchase cost for a range of specific vehicle designs at the resolution of major vehicle systems, subsystems, and components, considered for light-duty vehicles. Important system interactions, such as power, torque, and load rating requirements, are accounted for in the model's simulated vehicle design. The basic model design is based on two primary elements: (a) a framework of equations and relationships used for component sizing, and (b) the database that populates this framework.

The model can be used to determine the cost-effectiveness of the broad range of options for improving fuel economy being considered today. For changes to fuel economy for target scenario (i.e., a high-end, long-haul class8 tractor-trailer with an annual mileage of 130,000 and four-year life) relative to a 5 mpg baseline, the total net present

values of operation costs based on a 4-year vehicle life are shown in Figure 2. The current value (calculated by maintaining the baseline net present value of life cycle cost) of these improvements is shown in Figure 3, where it is negative at mpg values less than baseline value of 5 mpg. By comparing the cost of a given technology for its resulting fuel economy relative to the value shown on the curve, the cost-effectiveness of the solution can readily be assessed.

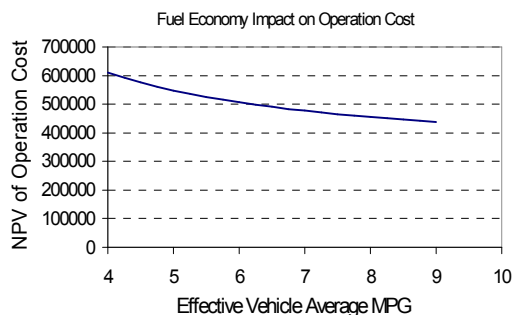


Figure 2. Operation Cost vs. MPG

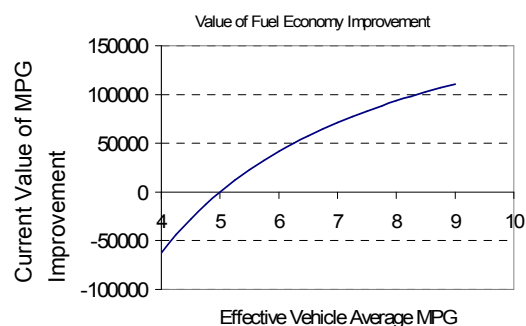


Figure 3. Value of MPG Improvement

Figures 2 and 3 also show that between 5 and 6 mpg, the value of fuel economy improvement is \$41,500, or \$4,150 per 0.1 mpg improvement, over a four-year operation period. Aerodynamics, engine modifications, transmissions, tires, etc. that can provide this improvement at this cost or below are cost-effective. It has been reported that improvements in aerodynamics and rolling resistance, and the use of lightweight materials can provide mpg improvements in the range of 7-10%, 7-12%, and 10-15%, respectively. A 7-10% mpg improvement for the target vehicle can be cost-effective for the additional component if costs do not exceed the range of \$14,525 to \$20,750.

Similarly, the cost-effectiveness of vehicle weight reduction can also be estimated using this model. Reduction of the empty vehicle weight has a two-fold advantage with respect to fuel economy improvements: energy requirements are lessened for a lighter vehicle, and rolling resistance is also lowered since it is a function of vehicle weight. The use of high strength steels, composites, aluminum, and selected polymers can reduce vehicle weight without sacrificing structural integrity. Lower vehicle weight will allow more payload in weight-limited vehicles, whereas fuel economy improvements will result in volume-limited vehicles. For the same target scenario as considered above in Figures 2 and 3, the value of vehicle weight savings has been estimated to be about 7 cents/ton/mile.

Future Directions

With the completion of cost model integration into the performance model PSAT, and model documentation planned during the coming year, the model should 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. Cost assessment of plug-in hybrids using ASCM will also be completed during the coming fiscal year.

It is proposed that with the completion of life cycle cost estimation capability demonstration for Class 8 truck category, the modeling framework be enhanced to include other major vocations of Class 7 and 8 heavy-duty trucks having the most fuel-savings potential during the coming year. This would facilitate consideration of affordability as one of the criteria in establishing system and component targets to guide the heavy vehicle R&D programs. It is also proposed that the heavy-duty truck cost model be integrated with PSAT as the performance modeling component of heavy-duty trucks is developed in the latter model.

Publication

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

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Objectives

- 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 as functions of configuration and operation with advanced combustion modes and emerging fuels.

Approach

- Develop and validate low-order, physically consistent computational models for oxidation catalyst (OC), lean NO_x trap (LNT), diesel particulate filter (DPF), and selective catalytic reduction (SCR) aftertreatment devices 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 essential performance and exhaust characteristics of advanced diesel engines operating in both conventional and high efficiency clean combustion (HECC) modes.
- Develop and validate appropriate strategies for linking engine and aftertreatment simulations in order to accurately account for their system interactions (including specifically engine modulation strategies for regeneration and desulfation).
- Translate the above models and strategies into a form that is compatible with direct insertion into the PSAT framework.
- Leverage the above activities as much as possible through inclusion of experimental engine and aftertreatment data generated by other DOE activities.

Accomplishments

- A preliminary performance map representing the altered fuel consumption and exhaust composition engine states for LNT regeneration has been added to the existing multi-mode engine map for emerging diesel technology that accounts for both conventional and “high-efficiency clean combustion” (HECC).
- The previously developed LNT model has been upgraded to include additional kinetics from the literature and bench reactor data and converted fully to Simulink format.
- Simulink ‘supervisor’ modules and an associated operating strategy have been developed that allow direct interaction between the engine and LNT simulations in PSAT, thereby capturing the fuel penalty and emissions associated with realistic LNT device performance.
- Additional validations and improvements have been made to the previously developed Matlab DPF model, and the model is now being coded in Simulink format.

- A DPF supervisor module analogous to the LNT supervisor is currently under construction and is being linked to the engine map in a similar fashion for DPF regeneration.

Future Directions

- Expand multi-mode diesel engine map database to include the 1.9-L GM standard platform.
- Begin development of engine performance map for Honda Accord with cylinder activation.
- 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 LNT and DPF models in PSAT under FTP 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 NO_x 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 FY2006, the ORNL work in this component of VSATT has continued to address both engine and emissions control modeling. For the former, an engine map previously constructed for the 1.7-liter Mercedes diesel engine was further updated to reflect the engine capability for shifting to a so-called regeneration state to reduce and remove stored NO_x in LNT's. A similar process is used to remove accumulated particulate matter (via oxidation) in DPF's. In an LNT regeneration state, the engine is briefly operated under transient rich conditions to cause the release and subsequent reduction of stored NO_x. It is during this altered operating state that the primary fuel penalty associated with LNT-based NO_x control occurs. In order to minimize this penalty, advanced LNT control strategies use some type of sensor feedback (e.g., exit NO_x sensor) for actually triggering the regeneration. The regeneration control process also has to take into account the fact that the engine speed and load demands may sometimes not permit it to switch to a rich fueling condition and that the engine may also have to be switched to a different transient operating state for desulfating the LNT or regenerating the DPF.

In addition, to improving the basic LNT device model, most of the effort during this period has been directed toward getting the model fully integrated

into the PSAT environment with appropriate links to the engine map so that the combined system functions as intended. The resulting interlinked system configuration appears to be readily adaptable to both DPF and SCR simulations as well. In addition, the approach used for extending the existing engine maps to LNT regeneration conditions appears suitable for application to LNT desulfation and DPF regeneration.

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 NO_x and particulate matter (PM).

Both NO_x 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 LNT's and oxidize the carbonaceous particulate matter in DPF's. 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 constraints 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. We have modified the previously developed Mercedes 1.7-liter engine map to accommodate inclusion of alternative operating states appropriate for LNT regeneration. The map extensions are based on data from engine-dynamometer-LNT experiments at ORNL. The extended map specifically includes information about the transient engine exhaust composition and temperature that are achieved by briefly altering the fueling and injection according to the most successful modulation strategy (the so-called delayed extended main injection strategy) evaluated in the ORNL experiments. At least approximately, the engine speed and torque are maintained constant through the regeneration transient. While the exhaust properties during the transient are fixed, the user can specify the duration of the regeneration transient as an adjustable control parameter. This regeneration adjustment makes it possible to evaluate trade-offs between fuel penalty and emissions performance.

Although the available data for the engine LNT regeneration operating state are currently very limited, we anticipate adding numerous additional points to the map in the coming year based on a combination of new experimental data and engine simulations from WAVE. We also expect that for certain regions of speed and load it will not be possible to achieve regeneration, and these regions will be flagged in the engine map as unavailable for regeneration activity.

We expect that the above comments will apply equally to LNT desulfation and DPF regeneration strategies as well. As described below, the ultimate utilization of the regeneration maps will be placed under the control of the so-called engine supervisor, which will account for all of the engine operating constraints and other system priorities in controlling the overall system.

Specific plans have also been made between ANL and ORNL to develop a joint engine map suitable for simulating the performance of a Honda Accord gasoline engine with cylinder deactivation. Preliminary discussions were held between John Green, Dean Edwards, and Mike Duoba in late September to define an experimental plan to collect

vehicle measurements at ANL's Advanced Powertrain Research Facility (APRF) which can be used to calibrate ORNL simulations using Ricardo WAVE. As illustrated in Fig. 1, this model would then be used to supplement the experimental data base and complete a sufficiently detailed engine performance map. Green and Edwards may join the ANL team in November to participate in some of the experiments and data collection.

Aftertreatment Devices. The original LNT model was upgraded this year to incorporate improved kinetics and also reduce execution time in PSAT. The current Simulink version (depicted schematically as it is linked to the engine map in Fig. 2) includes both the basic NO_x storage and reduction kinetics proposed by Blint and Olsson [Olsson *et al* (2005)] and additional components from ORNL modelling to account for CO and H₂ impact on regeneration, oxygen storage, NH₃ formation, and calibration with the kinetic measurements made for the commercial Umicore reference LNT catalyst used as a benchmark by CLEERS [www.cleers.org, Pihl (2005), and Pihl *et al* (2006) and Larson *et al* (2006)].

Inclusion of CO and H₂ in the regeneration process is a critical feature because these components are known to be the dominant reductants under many conditions in the ORNL engine-dynamometer experiments. Oxygen storage is also known to be a major feature of commercial LNT catalysts (although it is often neglected in laboratory experiments), and it is also known to be a major contributor to reductant (and thus fuel) consumption. Ammonia formation is receiving increased attention because it can be an undesirable pollutant, it can potentially increase the fuel penalty, and is now being seriously considered as a component of combined LNT-SCR systems.

While providing important new information, these additional components in the LNT model have created new challenges in maintaining execution speed. As time and other priorities permit, we are continuing to try to minimize the computational penalties. As of now, two key features that remain to be added to the LNT model are inclusion of the rate and performance impact of sulphur poisoning, and the capability to model the desulfation process.

The simplified 0-D DPF model initially developed last year was upgraded this year with improved assumptions for the filter and PM physical properties and has been validated in its Matlab format. Important improvements this year also included adjustment of the basic oxidation rate parameters and inclusion of kinetics for carbon oxidation by NO₂. Additions of kinetic effects associated with soluble organic fraction are also needed to account for the regeneration kinetics of PM from HECC-type combustion and unconventional fuels such as biodiesel.

Due to the effort required for engine map development and LNT and DPF modeling, no additional work has been done this year on completing the urea-SCR device model or the improving the existing oxidation catalyst model to include PM occlusion/oxidation and NO to NO₂ oxidation. These features are currently recognized to play very important roles in the efficiency performance of lean exhaust emissions controls, so they have been assigned a high priority in plans for the coming year.

System Integration

As noted above, all of the aftertreatment devices must be linked to the engine via both the exhaust and the overall engine management system. It is ultimately the global interaction of these individual components that determines the overall fuel efficiency and emissions performance of the engine propulsion system. Although the detailed system configuration and control strategies used by various the OEM's are highly proprietary, we expect that it should still be possible to define publicly shared benchmarks for comparing various engine and aftertreatment technologies consistently in PSAT. Hopefully, input from OEM's and suppliers through collaborative effort such as CLEERS can aid in defining such benchmarks.

As a starting point for LNT's, we have defined the overall system configuration depicted in Fig. 3 as our baseline. As indicated, the basic logic sequence starts with an LNT out NO_x sensor that indicates when the breakthrough from the LNT begins to exceed a critical user-defined level. A logic device (referred to as the LNT supervisor module) then requests the engine supervisor module to provide

regeneration when it is able. The engine supervisor will ultimately evaluate requests from other system devices as well as status signals from the engine to decide when an LNT regeneration event can be scheduled. When regeneration is complete, the engine will automatically be returned to its nominal combustion state at the demanded speed and load.

Figure 4 illustrates example simulated performance results for a Umicore-like LNT when operated in an integrated implementation of the above configuration and control strategy with different degrees of regeneration. As illustrated, incomplete regeneration results in significant NO_x breakthrough. Conversely, continued regeneration beyond that needed to completely remove the stored NO_x results in significant ammonia release at temperatures below 350°C (not shown here). Thus there is a need to optimize regeneration such that the fuel penalty is minimized while still meeting emissions regulations.

Also as noted above, we expect to define similar configurations and strategies for both DPF regeneration (see Fig. 5) and LNT desulfation (not shown). The engine operating requirements for each of these different types of regeneration are known to be significantly different so managing them in a reasonably optimal way during highly transient drive cycles will be a significant challenge.

Future Directions

Progress in implementing the engine and aftertreatment models described above continues to be limited by funding delays. As in the previous year, the FY06 work was not able to start until well after the middle of the fiscal year. For FY07 the most critical issues remaining to be addressed are:

- Expand multi-mode diesel engine map database to include the 1.9-L GM standard experimental platform.
- Begin development of engine performance map for Honda Accord with cylinder activation.
- 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 the oxidation catalyst model to account for PM effects and NO oxidation as they impact downstream LNT/DPF performance.
- Complete integration and testing of LNT and DPF models in PSAT under FTP 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.

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I. Heavy Truck Duty Cycle (HTDC) Project

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Objectives

- Collect real-world heavy vehicle performance data from fleets engaged in normal vocational activities.
- Compile and archive the real-world vehicle performance data as a research asset for use by the Department of Energy, other federal agencies, and other organizations interested in heavy truck energy efficiency research.
- Develop characteristic duty cycles based on the collected real-world data and usable within the Argonne National Laboratory's (ANL's) Powertrain System Analysis Toolkit (PSAT).
- Provide data and information gathered within the field test to support the development, calibration, and evaluation of ANL's Class-8 module of PSAT.
- Develop a duty-cycle generation tool that will allow a user to develop a customized duty cycle based on the real-world data collected within the field test and from future field tests.
- Provide an analysis of the field-test data to characterize heavy vehicle performance as reflected during the field test.
- Develop a plan for collecting additional duty cycle data and information for additional vehicle types (e.g., vocational vehicles), different routes (freeway, two-lane rural, etc.), and various situational circumstances (congestion, weather, large vs. small fleets, etc.).

Approach

- Identify relevant PSAT and other vehicle performance measures to be collected in the field test.
- Identify and procure sensors and data acquisition systems capable of collecting identified performance measures.
- Identify industry and federal partners interested and willing to leverage resources for the conduct of the field tests.
- Work with ANL to assure that PSAT data needs will be satisfied.
- Identify a volunteer fleet willing to allow a 12-15 month on-going data collection effort on two-to-ten of their class-8 tractor trailers.
- Conduct pilot testing on a volunteer tractor-trailer to field-harden instrumentation, identify data collection protocols, demonstrate the feasibility of generating heavy truck duty cycles, and initially characterize heavy truck performance.
- Identify specific field test vehicles.
- Instrument identified vehicles.
- Develop data downloading protocols and a data archive.

- Conduct field testing over a 12-15 month period of time, gathering real world performance data for regular vocational activities.
- Develop duty cycles and analyze/characterize the class-8 performance during the field test.
- Provide data, information and duty cycle input to ANL for their class-8 module development efforts.
- Reserve a portion of the collected data to be utilized for an independent evaluation of the PSAT class-8 module.
- Conduct an independent PSAT evaluation based on reserved field data.
- Develop a prototype duty-cycle generation tool based on data collected in the pilot and field tests, and capable of accepting future field test data.
- Demonstrate the duty-cycle tool and present papers on results.
- Prepare a final report.
- Plan for future associated efforts.

Accomplishments in FY2006

- Completed Pilot testing with the instrumented Dana's 1999 Peterbilt 379 Tractor and 2004 Wabash dry-freight Trailer. The tractor, trailer, engineering support and some specialized test equipment was loaned to the pilot test by Dana at no charge. Michelin provided specialized instrumentation and the cost of two sets of tires (a standard set of dual tires and a set of new-generation single-based wide tires (NGSBWTs). ORNL, Dana shared in the fuel and toll costs.
- Collected 104 channels of data for two East-West runs and two North-South runs. Nearly 17,700 miles were driven. 47 Gbytes of data were collected.
- Significant lessons learned were obtained from the Pilot Test related to data collection rates, sensor quality, and the handling of huge amounts of test data.
- A Pilot Test final report was prepared and submitted to DOE.
- Successful generation of customized duty cycle information from the Pilot Test data was demonstrated.
- Analysis of the fuel consumption data for segments of the trips made with the standard dual tires and NGSBWTs was conducted. A 2.9% fuel savings was experienced with the NGSBWTs. When the data was corrected for congestion, a nearly 8% fuel savings was experienced (same driver, same tractor-trailer, same road segment, same pay-load, same weather conditions). This benefit will be studied further in the Field Test portion of this project.
- A data mapping utility was developed to support data analyses, and provide the basis for the duty cycle generation tool that will be developed in CY2007.
- A paper on the Pilot Test and the fuel consumption analysis was presented at the International Truck and Bus Safety and Security Symposium, November, 2005, Alexandria, VA. The paper was one of four papers (out of 70 papers) selected as "Best Paper" at the symposium.
- From the Pilot Test, the data collection system was redesigned to reduce cost, size, complexity and increased reliability.
- Defined the performance measures, data acquisition systems and sensors required for the Field Test. Determined that within the project budget, it was feasible to instrument four-to-six tractor-trailers.
- Worked with industry partner Michelin for the donation of five sets of new tires for tractor-trailer combinations; three sets of new standard dual tires and two sets of NGSBWTs. Rims for the NGSBWTs were also loaned to the project by Michelin.
- Worked with industry partner Dana Corp., for the donation of five sets of tire inflation monitoring systems.

- Identified several class-8 long-haul fleets that would be good candidates as the “test fleet.” Because of the need for trailer weight data and the need to “marry” instrumented tractors with the instrumented trailers (given the fact that most of the reliable carriers engage in drop-and-hook strategies), selection of a viable fleet that could meet the needs of the project was difficult.
- Schrader Trucking Co., Inc., located in Greeneville, Tennessee about 45 miles from the National Transportation Research Center (NTRC) was selected as the test fleet. They have 82 tractors and 180 trailers. This decision was based on the level of cooperation received from Schrader Truck during the discussion phase; their forward thinking relative to technology displayed during discussions; the fact that their vehicle pool was large enough that all test vehicles could be the same make and model, thus removing a large variable from the data analysis; our DAS as designed was able to communicate with their vehicle’s data bus; and Schrader already had experience using NGSBWTs on their tractors and trailers.
- Procured, tested and integrated more than \$100K of instrumentation for use within the field test.
- Developed and tested six integrated data acquisition systems (DASs) for use in the field tests. Versions of the DAS were tested on volunteer passenger vehicles, DOE vehicles, and several tractor-trailers for shake-down purposes.
- A data collection and handing protocol was defined
- A data archive server was established at the ORNL Campus to protect data in the event of a catastrophic event at the NTRC.
- Plans for the initiation of the field test in October, 2006 were engaged in.

Future Directions

- Engage in a staged deployment of the instrumented tractor-trailers.
 - Collect 12 months of data for each instrumented tractor.
 - Develop a prototype duty-cycle generation tool based on real-world vehicle performance data. This tool will allow an analyst to generate custom duty cycles for very specific applications; urban, city, rural, freeway, arterial, hilly, flat, wet, dry, congested, etc.
 - Assess the impact of NGSBWTs on fuel economy within the field test.
 - Determine the ‘true’ percentage of engine ideal time for this sample of vehicles.
 - Conduct additional field-testing to collect performance data not collected, to include data on vocational vehicles, busses/motor coaches, data from major freight corridors, short-haul, small fleets, metropolitan/city, etc.
 - Establish a heavy vehicle performance data archive as a resource for DOE heavy vehicle research.
 - Seek stronger alignment with the 21st Century Truck Initiative, the DOE “Super Truck” concept, and the National Transportation Research Center, Inc.’s “Safe Truck” concept.
 - Seek integrative energy efficiency and safety research including cross-agency research.
 - Collect and analyze vehicle performance and duty cycle data on advanced vehicles.
-

Introduction

Nearly 80% of the U.S. domestic freight revenue involves the use of heavy trucks. Current trucking industry issues encompass a fine-balance of concerns related to the economical, safe, and secure operation of heavy trucks on our highways. In order to move toward an effective solution-set that optimally balances such concerns, a firm understanding of the nature and characteristics of heavy truck driving and their associated duty cycles in the U.S. is critical.

The trucking industry in the U.S. involves considerable use of class-8 trucks, operates in relatively small fleets (50% of the fleets in the U.S. are less than 100 trucks, and 25% of the fleets in the U.S. are less than 10 trucks), operates on small profit margins, and is faced with considerable regulatory and economic pressures (e.g., issues related to hours-of-operation, and reduction of truck idling time). Making heavy trucks more efficient through new technologies or fleet management protocols is a goal that would contribute to larger profit margins and would also contribute to a reduced dependence on oil, and reduced emissions. Since efficient systems are also typically more inherently safe, lives could also be saved.

A practical dilemma involves knowing what the true benefits of new energy efficient technologies are. Most benefit assessments are based on existing information on heavy truck operation. Much of this information is stylized and based on duty cycles that are meant to test various emission or fuel economy measurements. For example, the FTP Transient Cycle is a transient engine dynamometer cycle for heavy-duty truck and bus engines. It includes segments designed to simulate both urban and freeway driving and used for emission certification testing of heavy-duty diesel engines in the U.S. Another example is the Urban Dynamometer Driving Schedule (UDDS) which is an EPA transient chassis dynamometer test cycle for heavy-duty vehicles. While cycles such as these are based on an understanding of the vehicle technology and how best vehicles might be tested to assess emissions and fuel economy, they do not really reflect real world driving and the real demands placed on the vehicle, driver or vehicle systems.

Despite common beliefs, knowledge of how trucks actually operate on our highways is not well known. With new hours-of-operation rules, recurring congestion in urban environments, anti-idling regulations, differing fleet management philosophies, weather, the need to deal with incidents of non-recurring congestion, and encountering various topological conditions, only the most highly experienced heavy truck driver has a true situational awareness of the characteristics of driving on our nation's highways. A better understanding of the effects of these impacts on driving, as captured via a field test of heavy vehicle driving would provide a valuable asset to DOE, other federal agencies, as well as the trucking industry in evaluating technologies for energy efficiency, safety, emissions, fleet management, etc.

For DOE, such data and information would provide a basis on which to make decisions related to new technologies being developed to reduce fuel consumption, provide alternative power sources (e.g., fuel cells and hybrid engine technologies), transition to alternative fuels, and to reduce emissions. In particular, a database that reflects true driving experiences across various parameters such as geographic terrain, fleet size, fleet type, driving environment, driving protocols, etc., can provide a rich source of information that could be utilized to make sound energy efficiency-based technology decisions.

These and similar complimentary data needs of various agencies of the Department of Transportation and the trucking industry require data and information on how trucks are actually utilized and driven in real-world environments, the geography over which they are operated, information related to the driving situation and the protocols and regulations that govern their operation. In addition, much of the current thinking, and research related to long-haul and urban/city driving are based on anecdotal information. A quantitative profile of the driving behavior of heavy trucks does not currently exist. A thorough understanding of the operation of heavy trucks within duty cycles that reflect real-world conditions is an asset that would have great benefit to DOE, other federal agencies, and the overall trucking industry.

Approach

This Project will involve efforts to collect, analyze and archive data and information related to heavy-truck operation in real-world highway environments. Such data and information will be usable to support technology evaluation efforts, and provide a means of accounting for real world driving performance within heavy truck analyses. Additionally, the data collected will generate data, information, and duty cycles that will support Argonne National Laboratory's (ANL's) development of a class-8 module for their Powertrain System Analysis Toolkit (PSAT). Industry partners will include Michelin Americas Research and Development Corp., of Greenville SC, Dana Corporation of Kalamazoo, MI, and Schrader Trucking of Jefferson City, TN. These partners are interested in the vehicle dynamics of real world long-haul driving (to support their interests in vehicle dynamics, vehicle stability, tire performance, tire-road interface and operational efficiency improvements. Significant in-kind contributions were provided in the pilot testing phase of this project (more than \$400K of in-kind resources were contributed by Dana and Michelin, and similar resource contributions are expected from Michelin, Schrader and Dana in the field test portion of this work). Figure 1 shows a wheel torque transducer loaned by Dana to support the pilot testing portion of the project. Figure 2 shows one of six Volvo tractors to be used in the field testing portion of the Heavy Truck Duty Cycle (HTDC)



Figure 1. Wheel Force Transducer Loaned to Support HTDC Pilot Testing, from Dana Corporation



Figure 2. One of Six Class 8 Tractors to be Used in the HTDS Field Test Owned by Schrader Trucking

Program. The Program will be conducted in two phases. These phases are:

Phase 1: Design, Testing and Evaluation of a Duty Cycle Data Collection System (initiated in January 2005 and concluded in March 2006).

Phase 2: Fleet Instrumentation, Data Collection and Analyses (initiated in March 2006 and will be concluded in December 2007).

Pilot Test Overview

The primary objectives of the Pilot Test (Phase 1) included partnership formation, identification of performance measures, procurement of instrumentation, conducting a pilot test, demonstrating duty cycle data generation capabilities, characterization of heavy truck performance, planning for Phase 2, and final Phase 1 report preparation. This phase of the work prepared the hardware, software and research team for conduct of the field testing.

Pilot Test Results

Numerous lessons learned were identified and documented in a Pilot Test Final Report. A prototype mapping utility tool was developed to generate duty cycle data and information from the pilot test data. This tool will be further refined in FY2007 to generate duty cycles for a variety of selectable parameters (terrain, weather, congestion, urban/rural, etc.). Analysis of the fuel consumption data collected during the pilot testing indicated a 2.9% fuel savings when the same vehicle, with the

same driver and the same payload traveled the same segments of highway, but utilizing Michelin's New Generation Single-Based Wide Tires (NGSBWTs) on one run, and new Michelin standard dual tires on another run. When this data was corrected for congestion effects, an 8.0% fuel savings was seen when the NGSBWTs were used. This fuel efficiency will be focused on in the field test efforts. Figure 3 shows the NGSBWTs mounted on the Dana Trailer used in the Pilot Test.



Figure 3. NGSBWTs Mounted on the Dana Trailer Used in the HTDC Pilot Test

Pilot testing was concluded by demonstrating the capability to generate duty cycle information that could be utilized by PSAT.

Field Test Overview

The Field Test (Phase 2) will involve instrumenting a fleet of from six tractors and ten trailers from the Schrader Trucking Fleet located in Jefferson City, TN. Instrumentation of the tractors and trailers will be completed in October, 2006 and will collect 54 channels of data related to engine performance, vehicle performance, location, topology, weather conditions, and road conditions. The tractors and trailers will engage in normal Schrader-based vocational activities. The trucks will enter the field test in a staged manner to assure that there is no equipment or experimental weaknesses, and data will be collected for each tractor-trailer for a period of 12 months. Half of the instrumented portion of the test fleet will use Michelin's NGSBWTs while the other half will use new Michelin standard dual tires. The routes traveled by Schrader trucking will provide a diversity of topology; city, urban and rural highways; with various weather and road conditions.

A data archive will be developed to manage and archive the significant amount of data that will be collected. In addition, an easy-to-use duty cycle tool will be developed that will allow for the generation of duty cycles based on the desired characteristics needed by researchers. Phase 2 will also involve supporting the continuing development of ANL's PSAT for its class-8 module and for doing an independent evaluation of the class-8 module based on a portion of the field test data. Analysis of the fuel efficiencies of the NGSBWTs will be conducted along with other interesting analyses as funding allows. A final report will be prepared, papers will be prepared and presented, and plans for additional duty cycle data collection for other truck configurations will be developed.

Future Directions

This project will provide a valuable asset for making heavy truck energy efficiency technology decisions based on real-world performance data. In particular, it will provide input for developing, calibrating, testing and evaluating ANL's class-8 module for PSAT, and will result in the development of a duty-cycle generation tool capable of generating custom duty cycles for various long-haul characteristics. Future directions for this work will be to enrich the database with data that provides greater breadth and depth to analysis capabilities. That is, to collect and analyze data on other vehicle types, situational circumstances, operational protocols, etc. Such a capability would support the establishment of a national data archive for heavy truck performance data, and would be a valuable national asset for heavy truck energy efficiency research. Inclusion of safety data and information might also be a long-term goal that could receive cross-agency attention and support. Lastly, a future goal is to gain a deeper understanding of heavy truck operations on our nation's highways. The availability of a national archive of heavy truck performance data could support the establishment of a Center of Excellence in Heavy Truck Performance Research.

J. Plug-in Hybrid Vehicle Systems Analysis

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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

- Proposed improvements to the existing test procedure for reporting PHEV fuel economy that will provide more uniform comparisons across technology options.
- Conducted a thorough exploration of the PHEV design space, including evaluation of the tradeoffs between cost and fuel consumption leading to definition of component performance requirements.
- Applied real-world driving data to quantify impacts of travel behavior on the potential benefits of PHEVs and showed that PHEVs can achieve significant petroleum savings with limited electric range.
- Explored optimization of PHEV energy management strategies focusing on petroleum displacement and concluded that an electric-centric or blended strategy will likely provide a robust solution.

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 FY06 to objectively assess PHEV technology, support the larger DOE PHEV assessment effort and complement activities at other national laboratories, and share 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 key contributions of this activity include:

1. Proposed improvements to the existing test procedure for reporting PHEV fuel economy
2. Thorough exploration of the PHEV design space, including evaluation of the tradeoffs between cost and fuel consumption
3. Application of real-world driving data to quantify impacts of travel behavior on the potential benefits of PHEVs
4. Optimization of energy management strategies focusing on petroleum displacement.

The NREL research team has participated in many key industry meetings and NREL research has been documented in eight formal presentations and five technical papers that have been published or have been submitted for publication within the next 6 months. A compilation of these papers and presentations was submitted as a milestone report and the following is a summary of the important insights that emerged from the four areas of emphasis listed above.

PHEV Fuel Economy Reporting Methods

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. The SAE J1711 Recommended Practice was created in 1999 and provides the fundamentals for measuring fuel economy of off-vehicle charge-capable vehicles (i.e., plug-in hybrids and electric vehicles). Seven years later, with a much better understanding of how PHEVs will likely operate, some improvements to the original procedure are recommended. The team's specific recommendations follow.

- Report gasoline and electricity consumption separately
- Revise the end-of-test criteria to more accurately determine the distance driven in charge-depleting
- Assume that vehicles will be fully charged once per day

The recommended improvements to the fuel economy reporting methods have been adopted in our analyses and the team intends to work with other labs and regulatory agencies to enact similar improvements in their procedures. The analysis also identified the need to develop a new utility factor relationship, based on the best available travel survey data, and to explore the implementation of a driving-type specific utility factor to account for the fact that most short-distance travel will be urban in nature and most long-distance travel will be highway in nature. Finally, it has been determined that the current EPA certification cycle adjustment factors provide an inaccurate prediction of real-world PHEV consumption and should also be revised.

PHEV Cost and Consumption Analysis

NREL recently developed a rapid design exploration methodology and applied the methodology to an expanded PHEV analysis spectrum that includes PHEVs with a wide range of power and energy capabilities. In particular, the unique scope included PHEVs with limited all-electric capabilities that are still able to realize tangible petroleum displacement by operating in a "blended" charge-depleting mode.

Key conclusions from the analyses follow.

- The PHEV_x definition should be based on the energy equivalent all-electric range of the energy storage system, rather than on actual all-electric range (distance before first engine turn-on event).
- The expected petroleum reduction of a PHEV is substantial, but the incremental costs may present a barrier to broad market penetration.
- To provide equivalent cycle life performance, the usable state of charge window of a short-range PHEV must be significantly less than that of a long-range PHEV given the state of current technology.

- To provide a payback relative to an HEV within 10 years, based on fuel cost savings and purchase cost alone, PHEVs will require battery costs to reach long-term high-volume cost estimates (<\$300/kWh) and gasoline costs to increase to more than \$4.00/gal.

The analysis thus far has not allowed vehicle platform engineering as a strategy for reducing costs and improving fuel economy. Aerodynamics and vehicle light-weighting will likely have a more pronounced impact on PHEVs than any other configuration. Future analysis will focus on vehicle platform enhancements and their impact on the relative costs and benefits of PHEVs. Additionally, design options and alternative business models will be explored to address the high cost of batteries for PHEVs.

PHEV Real-World Performance Expectations

The consumption of electricity and petroleum by a PHEV will be strongly influenced by the daily distance traveled between recharge events and the aggressiveness of driving. Rather than rely on standard test profiles for a prediction of PHEV fuel consumption, we have collaborated with municipalities to use existing drive cycle databases as an input to simulation models. The simulation results provide key insights into consumer travel behavior and quantify the real-world potential for PHEVs to displace petroleum. The first dataset was from the St. Louis, Missouri, metropolitan area and includes 227 unique driving profiles with daily travel distances ranging from less than a mile to more than 270 miles. Conclusions from the travel survey data follow.

- Approximately 50% of the vehicles traveled less than 29 miles a day. Because many vehicles drive less than 30 miles a day, the battery of a PHEV with 30 or more miles of electric range capability would likely be under-utilized on a daily basis.
- The travel survey data provide evidence that the UDDS (Urban Dynamometer Driving Schedule) and HWFET (Highway Fuel Economy Test) driving profiles used for fuel economy reporting today fall short of capturing the typical driving behavior of today's consumer.
- Contrary to experience with HEVs that typically deliver fuel economies significantly less than their rated values, simulations of real-world driving suggest that a large percentage of drivers of PHEVs will likely observe fuel economies in excess of the rated fuel economy values. However, due to high power requirements in real-world cycles, drivers are unlikely to experience significant all-electric operation if PHEVs are designed for all-electric range on the UDDS.
- If all vehicles in the travel survey "fleet" were PHEV20 vehicles designed for all-electric range on the UDDS, the petroleum consumption would be reduced by 56% relative to a conventional vehicle fleet. The PHEV40 reduced consumption by an additional 12% and was equivalent to ≈ 1 gal/vehicle/day of petroleum savings.
- The time-of-day usage pattern obtained from GPS travel survey data and the recharge requirements from simulation will be extremely valuable for determining the impact of PHEV recharging scenarios on the electric utility grid.

Since completing the St. Louis analyses, data from five other metropolitan GPS travel surveys have been obtained. The driving profile database will expand from 227 to more than 2,000 vehicles. Additional analyses will be completed using the full collection of more than 2,000 driving profiles. Real-world travel simulations will be executed considering variations in platform, aerodynamics, performance, control, and recharge scenarios. In addition, the database will be used to explore the emissions control implications of potential engine cold-starts and the fuel consumption impacts of location-specific air conditioning usage.

PHEV Energy Management Strategies

NREL's vehicle systems analysis team has a long history of applying optimization tools to explore HEV energy management strategies. During the past fiscal year two parallel efforts were initiated. The first was to explore the extensive PHEV design space and identify promising regions (using the modeling techniques developed for the Cost-Benefit study above). The second effort applied dynamic programming techniques to determine the "near optimal" power distribution between the engine,

motor, and battery in a PHEV for a known driving profile. NREL's energy management strategy work is critical for maximizing the petroleum savings while protecting the batteries of future hybrid vehicles. The conclusions from these analyses include the following.

- A strategy in which a PHEV x travels x miles on electricity only is one strategy option but it is not the only strategy. As long as the strategy is achieving a net discharge of the battery, petroleum will be displaced regardless of whether the vehicle is operated on battery only or a combination of battery and engine power (known as a "blended" control strategy).
- The selection of strategy and component sizing are not entirely independent. Reducing the rated power and size of the electric traction components is one way to reduce the cost of a PHEV. Reducing electric components also necessitates the use of a "blended" strategy.
- Dynamic programming optimization of PHEV energy management strategies indicated that optimum control based on *a priori* knowledge of the driving cycle provided marginally better petroleum savings than a strategy that used stored electric energy to the greatest extent possible.

As PHEV technology evolves, energy management strategy will become increasingly important. It will be used to ensure satisfactory battery life, maximize petroleum displacement, gain performance improvement, and manage vehicle thermal and emissions transients. NREL's future work will apply optimization to more varied driving scenarios and include aspects beyond fuel displacement in the objective function.

Conclusions

NREL's assessment of PHEV technology has added to the body of knowledge and continues the Vehicle Systems Analysis team's long history of timely, innovative, objective, and quality contributions to advanced vehicle technology development. The President's Advanced Energy Initiative defines 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 FY06 explored this and many other

potential PHEV design scenarios. PHEV technology has great potential to transition our nation's transportation energy demand away from petroleum. However, finding ways to address the high component costs and narrowing the gap between vehicle design and consumer behavior through technology optimization will be critical to achieve the petroleum displacement potential of PHEVs.

NREL will execute a continuation of its PHEV research in FY07. The goal will be to develop and demonstrate potential solutions to technical barriers identified by past research. Emphasis will be placed on fuel economy and emissions test procedures and reporting methods, real-world travel behavior analysis, exploration of alternative economic scenarios, and engine and emissions control system modeling for PHEV duty cycles. These tasks will contribute to the overall FreedomCAR PHEV research plan in the areas of analysis, research and development, and test and validation. Finally, the team plans continue strengthening our collaborative relationships with industry colleagues. With NREL's contributions and the contributions of others, the auto industry and DOE can lead to way toward widespread introduction of PHEV technology.

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K. Technical Target Tool Enhancements

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Objective

- Assist DOE with the evaluation of advanced vehicle technologies to help DOE and industry find feasible pathways to reduce oil consumption and find which areas (technical targets) are the most important to the success of oil reducing new technology vehicles.

Approach

- Link a vehicle model, cost model, and marketability model to solve for the best component sizes and vehicle architectures for a given set of DOE technical targets.

Accomplishments

- Verified that a fast high level vehicle model that uses inputs from PSAT can provide valid component and vehicle level results in a timely manner.
- With guidance from ANL, linked AVID, a vehicle choice model, into the Technical Target Tool and updated the coefficients so AVID would predict actual past vehicle sales.
- Ran the Technical Target Tool comparing the marketability and fuel economy of conventional, electric hybrid, and plug-in electric hybrid vehicles from 2005 to 2015 using three technical target and fuel price scenarios.

Future Directions

- Discuss the results with DOE and industry to determine additional scenarios and assumptions to evaluate.
 - Explore different combinations of DOE technical targets that make PHEVs successful at improving energy security.
 - Add ethanol, electric, and other advanced architectures to the list of fuel saving vehicles to evaluate.
 - Add functionality to the marketability model to determine if consumers will reduce their vehicle size or pay more for advanced higher fuel economy vehicles.
-

Introduction

The conventional vehicle systems analysis approach is failing to predict actual hybrid electric vehicle component sizes. The approach assumes that sizing components to meet conventional vehicle performance will provide a marketable vehicle. The hybrids actually being sold do not reflect similar conventional vehicle performance. Instead, components are sized to take advantage of the unique characteristics that an advanced powertrain offers. For example, the Prius is the slowest vehicle in its class but gets a spectacular 55 miles per gallon (MPG). The Technical Target Tool offers a new approach that can more closely match reality.

Approach

The Technical Target Tool combines a vehicle, cost, and marketability model to size components, as seen in Figure 1. It evaluates hundreds of different component sizing combinations to find an architecture's most marketable combination of vehicle characteristics. This process is repeated for multiple architectures and years and the resulting vehicles are then compared to see which would be most successful. Market success is critical for making an impact on reducing petroleum use.

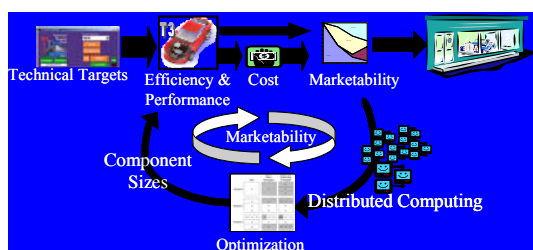


Figure 1. New Component Sizing Approach

In order to have confidence in the approach, all of the individual pieces to the approach must be validated. The high level vehicle component models were created from PSAT runs and validated against full PSAT component models. The component models were then run in vehicles and validated with real conventional and hybrid electric vehicles. Similarly, the cost and marketability model were created, adjusted and validated to match the trends of today's market.

Three scenarios were run with the Technical Target Tool, as seen in Table 1.

Table 1. Analysis Scenarios

	Baseline (Achieve targets)	Scenario 1	Scenario 2 (Pro PHEV)
Battery	NiMH to Li-Ion	NiMH to Li-Ion	NiMH to Li-Ion
Gas price	AEO 2006 (Low)	2002-2005 trend (High)	2002-2005 trend (High)
Glider mass reduction	0%, 50% 2006, 2015	Current Status	Current Status
Engine efficiency	35% to 45% 2006 to 2010	35% to 45% 2006 to 2010	Current Status

Results

The results highlight several improvements of the new approach, the struggle facing PHEVs, and unforeseen impacts that technical targets may have on energy security.

The results show that the new approach has important advantages. First, they show that component sizing strategies should change for different technology improvements and gasoline prices. The conventional approach only changes component sizing with changes in mass. The new approach finds more marketable sizing by taking advantage of improvements in efficiency and cost, as seen in the battery energy increase in Figure 2.

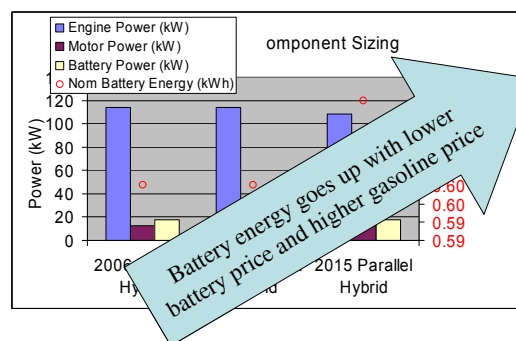


Figure 2. Battery Size Increases with lower Battery Cost and Increasing Gasoline Price

Second, the better component sizes from the new approach have an impact on the marketability analysis. In scenario 1, the conventional sizing approach led to the conventional vehicle looking more marketable than the HEV. The new approach took advantage of the unique architecture characteristics, technology improvements, and gasoline prices and found a fuel saving HEV

solution that was more marketable than any conventional vehicle.

While HEVs may find wide market success, PHEVs struggled for all three scenarios. The analysis predicts efficient conventional vehicles will dominate for the baseline scenario, and hybrid electric vehicles (HEVs) will dominate for the other two scenarios. Plug-in hybrid electric vehicles (PHEVs) struggle due to the initial high cost of the large battery that is needed to survive the deeper discharges seen by the PHEV compared to the HEV.

Conclusions

The new component sizing approach is critical for component sizing and vehicle architecture comparisons. It captures all DOE technical target improvements, takes advantage of the unique characteristics of advanced vehicle architectures, and improves market analysis predictions of advanced vehicle success and energy security impacts.

Finding the DOE R&D that makes PHEVs marketable may be essential for energy security. Although fuel economy improved for all of the scenarios, none of them eliminated today's level of petroleum imports for light duty vehicles. Today's average fuel economy would have to be 55 MPG to eliminate light duty imported oil. In the baseline scenario, the dominant conventional vehicle fuel economy inches slightly above 40 MPG. In scenario one and two, the dominant HEV fuel economy is around 45 MPG. More concerning is that this analysis only included the efficient compact car class. Other classes will have even lower fuel economies. This underscores the importance of further DOE R&D research to make petroleum displacing vehicles such as PHEVs successful to improve energy security.

Future enhancements and analysis could focus on answer the following questions:

- What technical targets help provide the most energy security?
- How much can we expect ethanol and other advanced vehicles to help improve energy security?
- Would people downsize rather than hybridize if fuel costs rise?

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L. Investigation of Route-based Control for Hybrid Electric Vehicles

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Objective

- Investigate the possibility of using information about the upcoming route to improve the fuel efficiency of hybrid electric vehicles (HEVs).

Approach

- Consider the sources of possible fuel efficiency improvement and the potential ways to adapt hybrid control strategies based on route information.
- Analyze existing related work in literature to quantify potential benefits and identify areas where further contribution is needed.
- Begin implementing a novel route-based control approach to achieve efficiency improvements.

Accomplishments

- Identified the control decisions made by hybrid vehicles to respect battery state-of-charge (SOC) limits in the face of unknown driving as the source of potential route-based control improvements.
- Categorized the range of potential route-based control approaches, citing literature examples.
- Demonstrated that efficiency improvement potential exists from route-based control, but that establishing good baseline strategies for comparison and eventually implementing the strategies in hardware are important steps to better quantify the achievable gains.
- Identified ‘look-ahead’ strategies (using real-time route predictions from GPS, etc) as providing the most promising combination of fuel efficiency and cycle flexibility. This approach category also has the fewest literature examples, offering an opportunity for novel contribution.
- Added two base strategy improvements to minimize SOC control related losses: utilizing vehicle kinetic energy information to improve SOC forecasting, and affecting SOC adjustments in a least-fuel-use manner.
- Initiated look-ahead control implementation steps:
 - Dividing a predicted route into segments, categorized using driving type characteristics.
 - Evaluating vehicle performance using modified control settings over range of segment characterizations.
 - Utilizing the characterization-based performance estimates to predict actual simulation results over a full cycle.

Future Directions

- Improve efficiency-based SOC adjustment base strategy.
- Complete look-ahead implementation with variable control scheduling.
- Simulate look-ahead control improvements over standard and real-world cycles, and cycles that are poorly predicted.
- Continue related analysis of real-world driving cycles, and quantify frequency of off-cycle conditions (extreme grades, congestion, etc).
- Possibly implement and test look-ahead control strategy in hardware.

Introduction

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 with good driveability), the hybrid controller must also respect battery 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 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

Having identified the above-described source for potential efficiency improvements, the next step was to evaluate the array of possible adaptive HEV control approaches, and to cite supporting examples from literature. The last approach step for FY06 was to then initiate novel contribution in the most promising approach category identified.

Results

Figure 1 provides a visual context in which to categorize the range of ‘adaptive’ or ‘route-based’ control approaches. In the approach category assuming no cycle knowledge, the strategy may only

‘adapt’ to instantaneous cycle requirements. As such, strategies in this category will need a general or ‘all-purpose’ set of control parameters to provide decent performance on all cycles. However, vehicle fuel efficiency may be sub-optimal on any given cycle, with the amount of unrealized efficiency potential variable from cycle to cycle. Due to the need for SOC control, the inputs to the decision logic must include a function that biases greater battery discharging as SOC increases above the target level and encourages less battery use (or more battery charging) as the SOC drops below the target. A simple concept to help minimize unnecessary application of the SOC control function is to use information about vehicle speed and regenerative braking efficiency to improve SOC estimation – i.e., assume the battery will capture a fraction of the vehicle’s kinetic energy (KE).

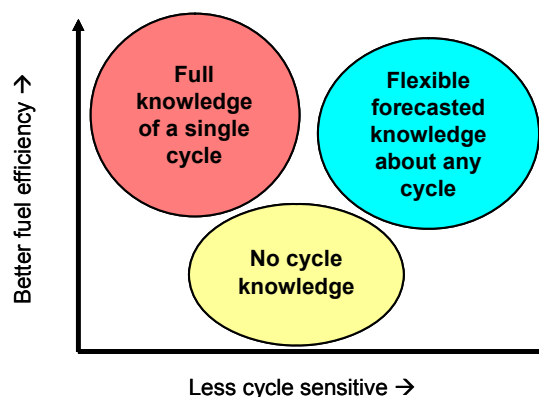


Figure 1. Range of ‘Adaptive’ Control Approaches

In the approach category with full *a priori* knowledge of the cycle to be driven, various (computationally intensive) methods can help determine the ideal control parameter tuning for that particular cycle. Relative to using a baseline control strategy over the same cycle, many previous studies

show significant improvement potential from cycle-specific tuning, although in several cases some of the perceived benefit may result from comparing to baseline approaches that could have been better to begin with. One study by Wipke, et al [1] compares four different cycle-specific parameter tunings by simulating multiple repetitions of each cycle using a different control parameter tuning each time. Excluding the results for parameter sets tuned and run on the same cycle, the comparison showed that the parameter set tuned for the NEDC cycle provided the next best fuel efficiency on each of the other three simulated cycles. However, the fuel economy using cycle-specific parameter tunings was still significantly higher than the ‘all-purpose’ NEDC tuning (e.g., as much as 13% higher for the US06 cycle-specific tuning).

The final approach category considers using real-time route forecasts to make control decision improvements. Within this category, a ‘look-ahead’ control procedure (making predictions based on inputs such as from a GPS trip planner) provides the best combination of cycle flexibility and improvement potential. The scarcity of literature examples for this adaptive procedure also suggests an opportunity to make novel contributions.

The first step in implementing a new look-ahead controller is to develop a solid baseline strategy into which predictive cycle inputs can be fed (and with which the look-ahead control improvements can be compared). One of the first components added to the base strategy was the ability to improve SOC estimation based on current vehicle KE. The next component was to ensure that when the SOC estimate deviates from the target level, any control adjustments to bias SOC movement back towards the target are made in a least-fuel use manner.

A typical approach for imposing SOC control adjustments is to add a battery charging or discharging request (based on the distance from the target SOC) on top of the road load power requirement. Figure 2 shows an example impact of such a fixed charging power request imposed at two different engine operating states. At road load level ‘A,’ the power increase results in an increased engine efficiency, whereas at ‘B’ the power increase actually decreases engine efficiency. To minimize inefficient battery charging (such as shown for ‘B’),

the newly-developed base strategy makes SOC-related control adjustments so as to preference high ratios of delivered battery charging per increase in fuel use (more along the lines of the ‘A’ adjustment).

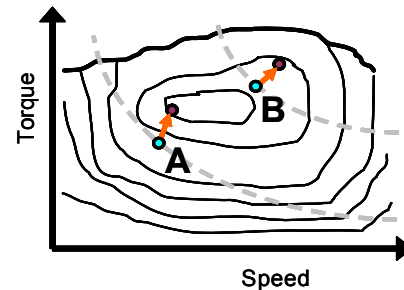


Figure 2. Example Engine Map Showing Impact of a Given Battery Charging Power Request at Two Different Operating Points

The novel look-ahead component under development begins with the assumption that second-by-second predictions of the upcoming route are not possible, but that it is possible to characterize the anticipated driving type over upcoming route segments. Different control settings can be used for each segment, allowing more frequent control variation than with parameter tuning approaches for specific cycles made of many different segment types. Decisions to choose one setting over another for a particular segment are based on pre-processed predictions of fuel and battery energy use for simulations over similarly characterized segments. The results so far have shown a smooth correlation to predict fuel and energy use based on segments categorized by average velocity and acceleration characteristics.

Conclusions

Of the range of promising route-based control approaches, ‘look-ahead’ strategies offer the best combination of fuel efficiency improvement and cycle flexibility, and represent an area where further novel contribution is needed. An efficiency-based SOC adjustment strategy was developed to provide a solid baseline for the new approach. The baseline also uses a KE adjustment to SOC estimation, which offers a simple way for any strategy to reduce unnecessary SOC control adjustments using readily available information. The novel look-ahead

implementation approach is well underway, with good correlation shown so far between fuel and energy use estimates and the selected cycle segmentation and characterization approaches.

Continued work will include enhancing look-up tables for both the base and look-ahead strategy, and scheduling look-ahead control variation over predicted cycles. Simulations will be performed using a detailed vehicle model over standard as well as real-world cycles, which will include investigating the impact of the actual cycle deviating from the look-ahead prediction.

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III. INTEGRATION AND VALIDATION

A. Mobile Automotive Technology Testbed (MATT)

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Objectives

- Develop a research platform providing the flexibility to integrate, test and validate DOE-sponsored subsystem hardware in an emulated vehicle environment.
- Enable easy control strategy development for different hybrid configurations and components with testing and validation of efficiency, emissions and performance.

Approach

- Build a mobile test fixture with a modular component plates enabling easy swap of powertrain components.
- Develop an emulated hybrid vehicle environment with the possibility to vary the degree of hybridization
- Control all the components to a representative degree.
- Design a generic control system which can be adapted to the powertrain changes.
- Validate the emulated environment.

Accomplishments

- Completed the construction of the Mobile Automotive Technology Testbed (MATT), a portable test fixture enabling Hardware-In-the-Loop (HIL) system integration and technology validation.
- Completed the installation and validation of a “virtual inertia” scalable electric machine providing the flexibility to vary the degree of hybridization.
- Developed, implemented, tested in simulation, and validated in HIL testing PSAT-PRO control software.
- Operated MATT in different mode including hybrid mode while improving individual components and their control.

Future Directions

- Operate MATT in Advanced Powertrain Research Facility’s (APRF) 4 wheel drive chassis dynamometer.
 - Compare the conventional results to the base line vehicle (Ford Focus).
 - Perform a degree of hybridization study.
 - Implement and evaluate the hydrogen internal combustion engine in a hybrid environment.
-

Introduction

DOE asked Argonne National Laboratory (ANL) to leverage its expertise in HIL testing to quantitatively validate the potential of DOE-sponsored subsystem hardware in an emulated vehicle environment. In this initiative, ANL researchers need to investigate different hybrid configurations, different level of hybridization, and different control strategies to evaluate their impacts on the potential of the technologies.

ANL has developed a unique, flexible, Hardware-In-the-Loop (HIL) platform for advanced powertrain technology evaluation: the Mobile Advanced Technology Testbed (MATT). MATT has the flexibility to easily test advanced components in various hybrid configurations. In addition, MATT has the capability of emulating any size of motor and battery. Therefore, the powertrain under test can be evaluated with different levels of hybridization. The versatile control system software developed by ANL provides rapid evaluation of control options associated with each hybrid configuration and each level of hybridization.

Approach

MATT consists for a frame on wheels with different component plates bolted to it. Each component is mounted on a bedplate with the supporting systems required for its operation. This modular approach allows easy swap in components and hybrid powertrain architectures. Figure 1 illustrates the MATT concept.

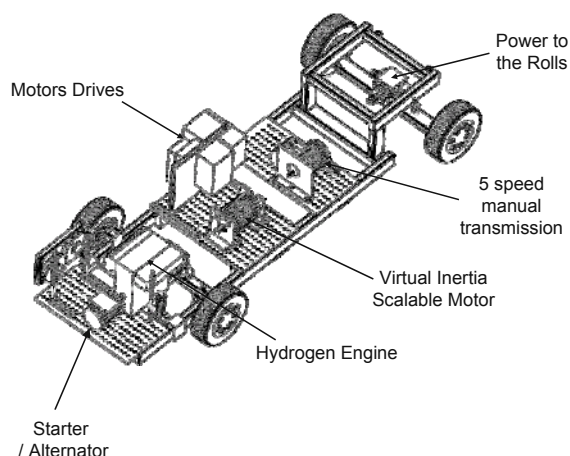


Figure 1. A Schematic of the MATT Concept

The heavy instrumentation of each component is used to evaluate the component efficiency and performance in the system context. The control strategy impact on the cycle efficiency of the components is also assessed. A torque sensor is located between each power component, thus enabling the efficiency analysis. This platform is tested in the APRF's 4WD chassis dynamometer for fuel economy, emissions and performance.

The current configuration is a pre-transmission parallel hybrid with engine start-stop capabilities. MATT is powered by a Ford 2.3 liter 4 cylinder gasoline engine. A complete stock exhaust system has been installed on the platform. The electric motor is an 100kW AC induction machine. The transmission is an automated 5 speed manual transmission. This configuration serves as a baseline for the future work in particular the comparison between the gasoline and the hydrogen engine. Figure 2 shows a picture of the current configuration.



Figure 2. A Picture of the Current Pre-transmission Hybrid Configuration

The future configurations include a hydrogen internal combustion engine hybrid and a Plug-in hybrid with a physical battery pack.

The virtual scalable inertia motor enables different degree hybridization studies of the different hybrid architectures. The motor-drive combination emulates any motor smaller than 100 kW. The motor cancels its own inertia while adding its virtual inertia on top of the request motor torque, thus replicating the dynamics real time of the emulated system. Figure 3 is a picture of the virtual scalable inertia motor.



Figure 3. The Virtual Inertia Scalable Motor

In order to control each component of the powertrain, ANL developed a set of integrated tools (PSAT; PSAT-PRO). This set of tools provides the flexibility adapt the control system to the sub-systems hardware being evaluated. It also eases modifications to the emulated environment and testing of multiple hybrid control strategy.

PSAT-PRO[®] is a control software developed by ANL and based on PSAT[®]. In combination with dSpace[®], PSAT-PRO links the PSAT simulated environment to actual subsystems control. PSAT-PRO allows the combination of computer models and actual hardware for HIL testing and has been developed to test subsystems in virtual vehicle environment. Control strategies and components models developed in simulation can be evaluated in the laboratory. Figure 4 illustrates the link between PSAT and MATT.



Figure 4. PSAT-Pro Links PSAT to Hardware in the Laboratory

Results

This section will present the hardware results as well as some accomplishments starting with the engine, moving to the motor and then addressing the rest of the components.

The engine clutch control was upgraded this year. Although a few iterations have been made to improve the clutch control, a lack of resolution in the chosen actuators was still present. First matching master-slave hydraulic cylinders with the appropriate clutch were selected for the engine. The engine is used in different vehicles of the Ford lineup; the Ford Ranger is the most heavy duty application, thus its hydraulic clutch system was selected for use on MATT. Second the clutch housing of the provided engine had to be extended since the initial Ford design never included an operation clutch mechanism. This precision job required to replicate the engine bell housing bolt pattern and align the support bearing for the output shaft while including the clutch slave retaining features. The hardware result is shown in Figure 5.



Figure 5. The New Extended Bell Housing

Then the new hydraulic clutch system was used with the existing air actuator. The result was an operational clutch system. The control system was able to launch the vehicle in a conventional mode. Yet, the launch was rough and inconsistent. Argonne National Laboratory turned to a professional dynamic motion control company to design the new position control actuation mechanism. The system is based on a oversize screw actuator with an encoder position feedback. This system is schedule for commissioning in October 2006.

In the mean time, the launches of the MATT platform are performed with the electric motor in first gear while the gasoline engine is started. Once the motor and the engine speed are matched the clutch is closed. The speed matching between the engine and motor had to be precise into order to avoid large torque spikes in the driveline due to

clutch closing to fast. This is referred to as “first gear electric launch”. Figure 6 shows time plot of measured data from at first gear electric launch. The data also show the large torque fluctuation as the clutch closes.

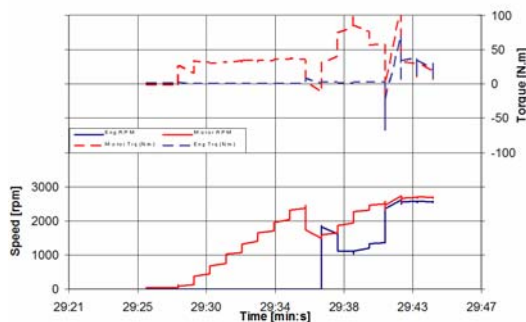


Figure 6. 1st Gear Electric Launch with Large Torque Spikes at Clutch Engagement

The gasoline engine came with a stock cable throttle body with integrated idle air motor controller. Several throttle actuation mechanism were implemented. All the systems fell short of the required dynamics or the resolution for control of the engine. Thus an electronic automotive throttle was required. Two different models were selected. The BMW throttle exhibited the best controllability, yet it was mismatch in its size. The 2.3 liter engine required a much smaller throttle, the large BMW throttle made the low load control and idle control difficult. The final hardware is an electronic throttle body from the Ford Escape which is employed in a version of the 2.3 liter engine.

This electronic throttle still required a driver. A Mototron controller is used to transform an analog throttle position control signal from PSAT-Pro into the appropriate physical position. The Mototron has been programmed with an integrated PID controller. The team spent much time to tune the system to obtain a good response, first on the bench then on the running engine. The low load condition and idling required the most attention. Figure 7 illustrates the control achieved over the throttle. The yellow line is the commanded position and the blue line is response of the system. Since the throttle position feedback is inverted the graph also show the inverted throttle position in orange.

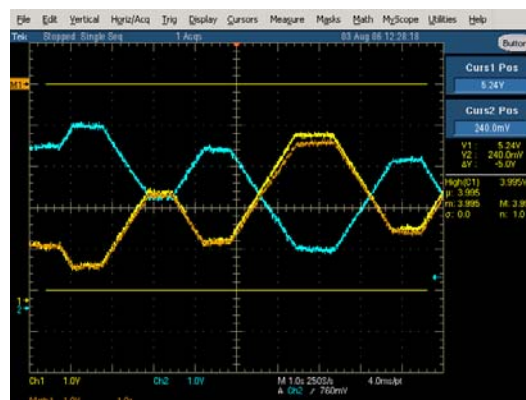


Figure 7. Throttle Control Tuning Using a High-Speed Oscilloscope

During the characterization of the engine, the ECU (Engine control unit) reported certain error code. Some of these trouble codes could be easily solved by replacing sensors or fixing connections. A handful of errors are related to the fuel system and evaporative emissions control which do not apply to the MATT setup. The engine received its fuel from a fuel scale with integrated booster pumps and a metering system. After the trouble shooting period a few minor trouble codes persisted. Argonne National Laboratory hired Mahle Powertrain, who worked with Ford on the 2.3 liter DURATEC engine development. Mahle is going to insure that the ECU is running stock calibrations despite of the fuel system errors. This is necessary before the base line testing is started with MATT to assure that emissions data from the engine is representative. Mahle is schedule to come to Argonne in late October.

Upon the resolution of all major trouble codes of the ECU, the team performed a full characterization of the gasoline engine. The electric motor was used as an engine dynamometer by putting the transmission to neutral. The engine was exercised against the motor running at a constant speed. The engine torque sensor between the engine the motor was recorded along with other data using the data acquisition system. Figure 8 shows an example of engine data collected at 2000 rpm.

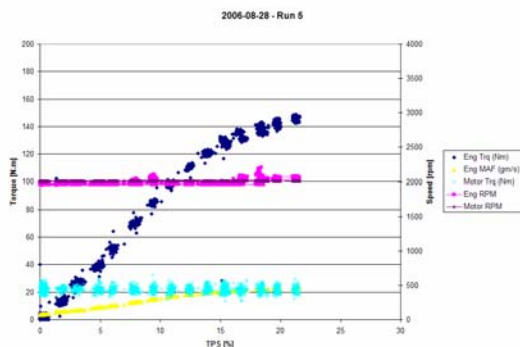


Figure 8. Engine Data at 2000 rpm

The characterization includes sweeps through loads at different speeds. A correlation between engine speed, throttle position and resulting torque was established as shown in Figure 9. The correlation table was integrated in the PSAT-Pro controller and verified to result in the open loop request engine torque for different speeds.

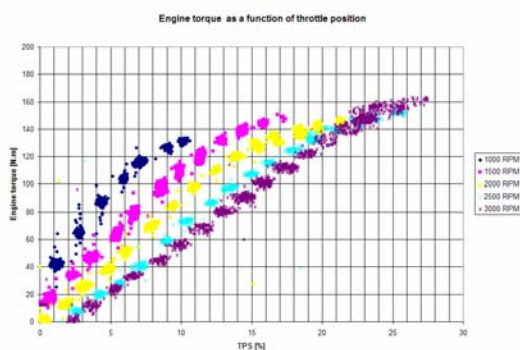


Figure 9. Torque to Throttle Position Correlation for the 2.3 Liter DURATEC Engine

The characterization also tested the support system of the engine such as the coolant system and the fuel supply pressure and flow. Some minor improvements were implemented, now all the systems show adequate operation. MATT completed some drive cycles in conventional mode thus using the engine only (except of the 1 gear electric launch). Figure 10 show the test results from a Japan1015 drive cycle. Notice that the motor provided traction torque in the electric launch and after that the engine provides all the torque.

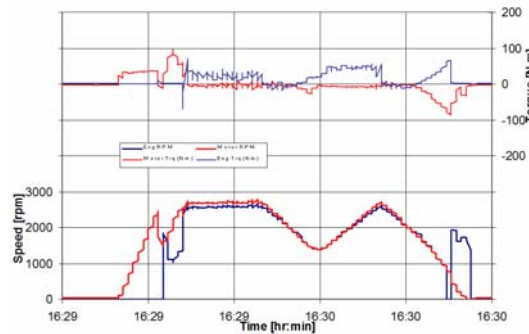


Figure 10. Engine-Only Operation on a Japan1015 Drive Cycle

The electric motor has been upgraded from the Ballard to a NEMA AC induction machine. The upgrade was necessary to implement the virtual scalable inertia concept. The Ballard motor did not match well enough with the drive system installed on MATT to obtain the required dynamics for the virtual inertia concept.

Table with New Motor Characteristics

The NEMA machine needed to be modified to a double ended shaft. Argonne National Laboratory pressed out the original shaft, machined a new double ended shaft and repressed the new shaft in. The new shaft in the rotor is shown in Figure 11. The double ended shaft receives the torque sensors. One torque sensor is couple to the engine shaft and the other sensor attaches to the transmission shaft. Furthermore the motor needs forced cooling, thus two squirrel cage fans were retrofitted on the motor. The entire system is properly guarded for safety.



Figure 11. New Double-Ended Shaft Pressed in the NEMA Machine Rotor

With the new motor in place, the drives had to be retuned to the specific motor characteristics. The motor is a perfect match for the drive. Full torque has been extracted from the motor to propel MATT forward. The motor can launch the platform in any gear. The motor can propel MATT through all the drive cycles in electric only mode as shown in Figure 12.

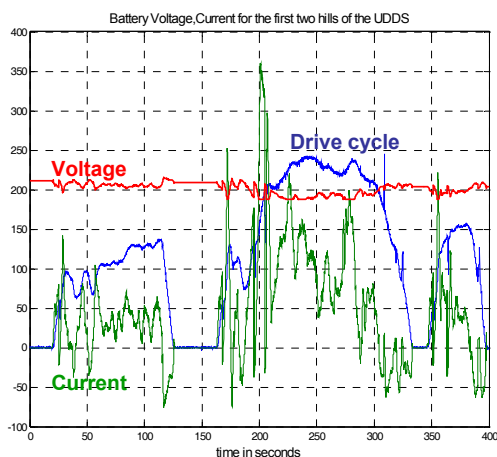


Figure 12. Voltage and Current Plot for the Start of the Urban Cycle

The improved response time enable the team to validate the virtual scalable inertia concept. The emulation of different electric machines has been achieved. However, during our validation process, we were not satisfied by the emulation program code embedded in the motor drive. The time response during gear shifting (highest dW/dt) was too long. To overcome this issue, we developed our own control algorithm using PSAT-PRO to provide the additional inertial torque required. Figure 13 shows the code structure implemented in the PSAT-Pro controller.

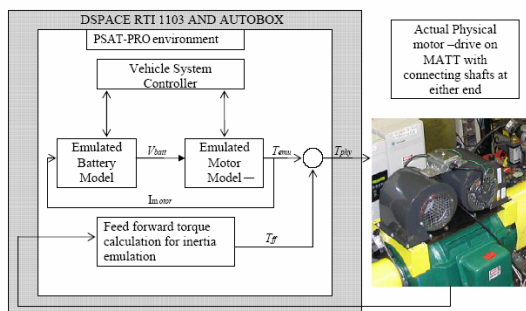


Figure 13. Emulation of Different Degrees of Hybridization in the PSAT-PRO© Environment on MATT

Figure 14 shows the emulation of motors with different inertia. The smaller motor (red) requires less torque than the larger motor (turquoise). The explanation of the physics and further results are published in a paper at EVS 22.

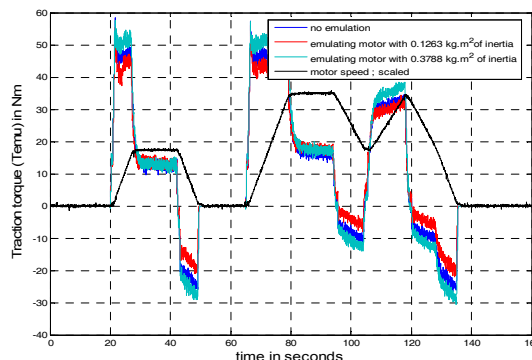


Figure 14. Different Size Motor Emulated on the Japan 1015

The transmission is still the automated 5 speed transmission. During the shake down process, a few rough shifts caused by aggressive control occurred and the transmission differential got damage. The differential was rewelded. The shifting process was slightly improved with speed match of the motor.

The next transmission has been identified for MATT: the 5R55 automatic transmission from Ford. This transmission is a 5 speed used in mid size sedans and SUVs. An aftermarket company developed a controller for this transmission. The transmission can provide reverse torque through it for regenerative braking from 5th gear to 2nd gear. Two transmissions have been received at Argonne National Laboratory.

Picture of Next Transmission

The mechanical brakes were also calibrated. The hydraulic system of the brakes is actuated by an air solenoid. Infrared temperature sensors provide feedback of the fading. The controller can apply a set brake torque to the brakes.

The data acquisition system is independent of the PSAT-Pro controller. It records the sensors from the subsystems and the test cell. It does not perform any control task, but has the ability of triggering the emergency stop system in case a sensor report out of range readings. All three torque sensors on MATT

have been calibrated. Pressure sensors, speed sensors, thermocouples among other sensors are all recorded in the DAQ to allow post test analysis.

Appendix of Sensor List

The data acquisition system is composed of three levels: the safety system, the basic component instrumentation and the test specific instrumentation. The safety system on MATT from software to hardware components is operational. The basic component instrumentation includes sensors required for fundamental understanding of the component performance in the vehicle system and trace component losses. These sensors are all in place and calibrated. The final level is component and test specific were a particular part of the system needs to be instrumented to answer a very specific question. Some engine parts have been instrumented for that purpose.

The DAQ has a user interface which displays some essential data in real time such as component speeds and torques as well as temperatures. Figure 15 shows the data acquisition system interface.



Figure 15. Screen Shot of the Data Acquisition Interface From the First Conventional Drive

PSAT-Pro has been updated for the component control. An interface screen for individual control was created. This mode enables to individually operate a component to test and calibrate the control signals.

The PSAT-Pro controller also logs data from components as well as emulated signals which are not available on the NI data acquisition system. Post processing allows merging of the real component data and the emulated vehicle data.

MATT ran cycles for shake down in electric only, hybrid mode, conventional with 1st gear electric launch and plug-in hybrid mode. All these modes required a specific control code from PSAT-Pro.

For the emulated Plug-in tests, different control strategies were tested in order to assess impact of engine on decisions on the all electric range (AER). In the selected control, a Charge Depleting mode (CD) has been defined where the electric motor is the prime mover of the vehicle but the engine is allowed to assist when the motor power is too limited to follow the cycle. During the test, the engine was only providing the supplemental power to follow the cycle (typically during the second hill of the urban cycle).

Figure 16 below depicts our preliminary test results. Our emulated P-HEV was tested for two consecutive urban cycles. The SOC of the emulated battery decreased from 90% to 50% for the consecutive urban cycles (UDDS).

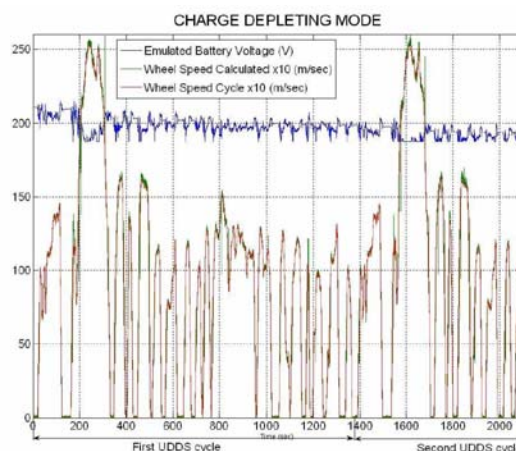


Figure 16. Emulated Plug-in Hybrid Results

The team is also preparing to upgrade MATT to a physical plug-in hybrid electric vehicle as request by DOE. In order to run MATT with a real battery pack an appropriate inverter-motor combination is needed. A UQM motor was selected based on the voltage range of the battery pack and power requirement.

Table of the UQM Characteristics

The motor has been received by Argonne National Laboratory. The new Plug-in motor plate is being

design and built. The battery pack has been received at the end of September. PSAT-Pro has been modified to run a Plug in hybrid control strategy.

During FY06 MATT has been operated as a Plug-in hybrid via emulation of the battery-inverter-motor combination. The work focuses on control development and all electric range insight. Since the engine did not operate on the stock calibration on fuel economy or emissions results were derived.

Conclusion

The MATT platform has been completed and operated in hybrid mode while the component and their control were improved. MATT is a tool providing the ability to integrate and test DOE-sponsored subsystem hardware in an emulated environment. As such, MATT enables technology validation in a vehicle system context and provides a vehicle system view to the various FreedomCAR technical teams.

As an example of MATT capability utilization, our team is evaluating H2-ICE technology potential and technical limitations. But our team also leverages MATT to evaluate H2-ICE potential in a hybrid vehicle environment. By identifying the additional potential of vehicle hybridization and engine control adaptation, our team will provide an independent evaluation from a vehicle system perspective. The hydrogen internal combustion engine is scheduled to be tested on MATT at the end of 2007 calendar year.

In addition, the scalable electric machine allows studying degree of hybridization impact on vehicle performances. The virtual scalable inertia motor concept was validated.

Finally the team is preparing MATT to evaluate the plug-in battery pack in a vehicle system context. By utilizing this concept, our team is able to evaluate various advanced battery for different hybrid applications.

Publication

1. EVS 22 Paper, 10/13/06, Innovative approach to vary degree of hybridization for advanced powertrain testing using a single motor, N. Shidore.

B. Battery Hardware in the Loop

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Objectives

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

Approach

- Build a battery test stand in which the battery is connected to a bi-directional power supply (ABC-150), which acts as a power source /sink.
- Control the ABC-150 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 to emulate a plug-in hybrid vehicle and control the ABC-150, so that the battery can be evaluated in a closed loop, real battery – virtual vehicle scenario (concept of H.I.L).

Accomplishments

- Construction of battery test stand complete.
- Plug-in hybrid vehicle model and controller developed in PSAT-PRO.
- First charging of the battery according to manufacturer recommended charging profile mid-October.
- Shake-down tests to follow.

Future Directions

- Emulate different vehicle configurations / vehicle class in PSAT-PRO and evaluate plug-in batteries for those configurations/ vehicle classes.
 - Implement different control strategies for the emulated vehicle and evaluate impact of change in control strategies on the battery.
 - Validate simulation model(s) of battery (ies).
 - Perform the above experiments at different ambient temperatures to see the impact of temperature on the battery.
-

Introduction

Plug-in hybrid electric vehicles (PHEVs) have been identified as an effective technology to displace petroleum by drawing 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 large 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 development of PHEVs for a mass market.

The most significant technical barrier to commercially viable PHEVs lay in the energy storage system. The challenge resides in developing batteries 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 system 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

Concept of Battery H.I.L

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 using the Powertrain Systems Analysis Toolkit (PSAT).

The concept of battery H.I.L, as it applies to the present experiment, can be explained using the classic control theory –block diagram (plant,

controller, feedback) closed loop system. Figure 1 shows Battery H.I.L in a plant-controller-feedback scenario. The plant consists of a real battery connected to a virtual vehicle through a D.C. Power supply; 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.

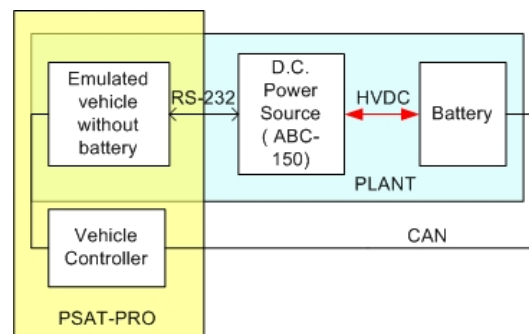


Figure 1. Battery H.I.L Represented as a closed Loop Plant-Controller-Feedback System

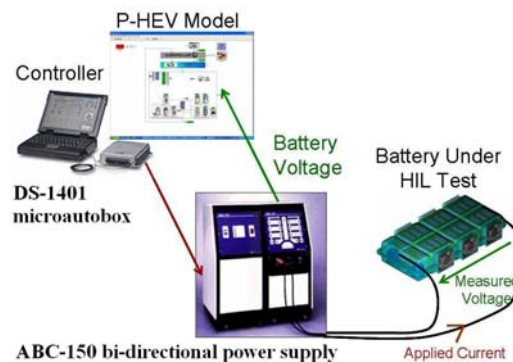


Figure 2. Implementation of Battery H.I.L in Hardware

Figure 2 shows the causal effort-flow relationship between the battery and the virtual vehicle, which is central to the H.I.L. 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 like S.O.C, temperature e.t.c affect the battery current capability and can be

sensed by the virtual vehicle in-directly in the form of battery voltage/power available to the traction motor. For example, low battery S.O.C due to heavy discharge events results in low battery voltage. The traction motor now has to run on low voltage, and with limited current, this limits electrical power available to the motor. This limitation in electric power then affects the overall virtual vehicle performance.

Various vehicle level parameters, for e.g. drive cycle, vehicle configuration, vehicle class, vehicle control strategy and vehicle components can be changed in the virtual vehicle. Impact of changes in all the above, on the battery, can be evaluated.

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 micro-autobox. The Dspace MicroAutobox (DS1401-RTI) is an automotive grade real-time controller, typically used as a prototyping tool for engine development. The ABC-150 bi-directional power supply is capable of sinking or sourcing power upto 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 Ah Li-ion battery. An AutoCAD drawing of the battery is shown in Figure 3; Figure 4 shows the actual picture of the battery.

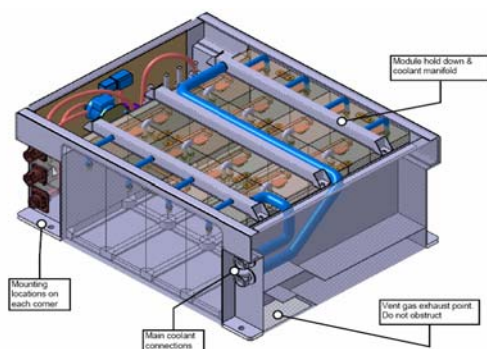


Figure 3. Drawing of the JCS 41 Ah Li-ion Battery

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 weight restrictions.



Figure 4. JCS 41 Ah Li-ion Battery

Some battery level specifications are stated in Table 1.

Table 1. JCS 41Ah Battery Specifications

Cell Capacity	41 Ah nominal
Nominal voltage	259.2 V
Voltage Range	194.4 V – 288 V
Continuous Current	150 A at 30 degrees Celsius
Operating temp	10 to 40 degrees Celsius

Emulated Vehicle

A plug-in hybrid electric vehicle is emulated in PSAT-PRO. The vehicle is a pre-transmission parallel hybrid, similar to the present configuration of the mobile advanced technology test bed.

Major components of the virtual vehicle are outlined in Table 2:

Table 2. Virtual Vehicle for Battery H.I.L

Engine	2.3 L Ford Duratek gasoline
Motor	75 kW peak UQM P.M. motor
Transmission	5 speed manual
Vehicle Platform	Ford Focus -2005

Plug-in Control Strategy

To start with, the control vehicle control strategy used in PSAT has been implemented in PSAT-PRO. An important part of the Battery H.I.L project is to make modifications to the control strategy and observe its impact on the real battery.

The PSAT control strategy for plug-in hybrids comprises of two distinct modes:

Charge depleting mode (C.D): the engine turns on at high vehicle load demand. Otherwise, the vehicle runs as a ZEV.

Charge sustaining mode (C.S): The vehicle operates like a conventional hybrid.

The controller switches from the C.D. mode to C.S. mode based primarily on battery S.O.C.

Accomplishments

Work on the battery H.I.L project began in August, 2006. The battery arrived at ANL on 28th July, 2006. Since then, following progress has been made:

Hardware set-up complete

The hardware –set up for battery HIL, using the concepts described in the ‘Approach’ section, is now complete.

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

The contactor box has 4 contactors (2 per channel, 2 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 lab process water regulated to ~5 psi at a flow rate not to exceed 0.8 gpm.

Plug-in Vehicle Model and Controller Implemented in PSAT-PRO

The plug-in vehicle model was transferred from PSAT to PSAT-PRO. Modifications were done to the PSAT simulation model so that the model can be implemented on battery H.I.L. CAN and serial communication was established with the Battery Management Controller (BMC) for control and communication purposes, respectively.

The vehicle model and control strategy have been briefly described in the ‘approach’ section.

Initial Charging and Shake-down Tests

The battery arrived with the SOC at 18%, and by the time the hardware was set-up, the battery SOC was down to 4%. As a part of the initial shake-down tests, the battery was charged to 35%. Currently, shake-down tests are being conducted on the battery HIL set-up to debug the vehicle control system and CAN communication errors between the BMC and the vehicle controller/virtual vehicle model. As a part of the shake-down tests, the virtual vehicle is being tested on the Japan 1015 cycle with the battery in the loop.

Future Directions

Vehicle-level test cycles will be “driven” according to PHEV-specific test protocols. Using the HIL testing set-up, the battery performance capabilities are measured for different energy management strategies, different vehicle platforms, different performance goals, different off-board charging profiles/schedules, and different temperature conditions. Further research involves comparison to other battery technologies leading to energy storage recommendations for PHEV technology. Running as many as standard six to ten cycles in a row will show the dynamic nature of the PHEV controls as the battery energy is depleted to the minimum level. Tests are conducted until charge-sustaining behavior is observed. The maximum battery usage is observed for the AER strategy, other charge-depleting strategies will be investigated given the larger power available from a PHEV pack compared to a typical HEV. In the analysis utility factors will be used to give favor to more electric operation in the earlier cycles in the sequence.

The above tests will be conducted at different emulated ambient temperatures, to quantify the impact of temperature on battery performance.

Conclusion

The battery HIL test stand set-up is complete and evaluation of the battery for plug-in applications will be conducted for various vehicle parameters, control strategies and temperatures.

C. Hydrogen Engine Testing and Calibration

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Objectives

- Develop a fully controllable hydrogen fuelled internal combustion engine with stand alone operating capability to be integrated in MATT (Mobile Automotive Technology Testbed).

Approach

- Adapt an existing test cell to allow testing of hydrogen internal combustion engines.
- Set up engine in hydrogen test cell.
- Equip test engine with aftermarket Engine Control Unit (ECU) to provide full engine control ability.
- Take baseline engine data.
- Develop advanced efficiency optimized operating strategy and stand-alone operating capability.
- Fully map engine with advanced operating strategy.
- Transfer engine to MATT.

Accomplishments

- Completed the engine test cell reconstruction and upgrade.
- Completed the engine setup.
- Operated the engine on aftermarket ECU and ran shake-down tests.
- Completed baseline engine testing.
- Completed engine data analysis and derived advanced operating strategy.
- Stand alone operating feature implemented in ECU.

Future Directions

- Complete mapping of hydrogen engine with advanced operating strategy.
 - Ensure stand-alone operating capability including idle control.
 - Transfer engine to MATT.
-

Introduction

DOE asked Argonne National Laboratory (ANL) to leverage its expertise in HIL testing to quantitatively validate the potential of DOE-sponsored subsystem hardware in an emulated vehicle environment. ANL has developed a unique, flexible, Hardware-In-the-Loop (HIL) platform for advanced powertrain technology evaluation: The Mobile Advanced Technology Testbed (MATT). MATT has the flexibility to easily test advanced components in various hybrid configurations.

To further extend the testing capability of above mentioned platform a hydrogen powered internal combustion engine is being prepared to replace the gasoline engine currently used on MATT for certain studies. To allow for comprehensive testing in a vehicle environment the hydrogen engine has to be capable of reliable, safe stand-alone operation.

Approach

An engine test cell is being adapted to allow testing of hydrogen fuelled internal combustion engines. This test cell is being used to run a baseline mapping of the hydrogen engine and based on the gathered information derive an efficiency optimized operating strategy. A schematic of the hydrogen engine test cell is shown in Figure 1.

The engine test cell is equipped with a double ended dynamometer and also holds a single-cylinder engine operated on hydrogen. The two engines share the hydrogen safety and metering system, the high-

and low-speed data acquisition system as well as the emissions analysis equipment.

Several mixture formation concepts for hydrogen engines exist. They mainly differ in terms of power output, complexity, availability and durability of the mixture formation components. In order to keep the complexity manageable and to allow for extended periods of engine operation the strategy of choice is hydrogen port injection. To compensate for the lack of power output inherent to this operating mode a belt driven supercharger is used to boost the engine.

The engine used for these investigations is a Ford 2.3l Duratec engine that had been converted to hydrogen operation by Ford Motor Company. The fact that the engine is identical to the gasoline counterpart currently used on MATT will allow for a fast and straightforward exchange of engines on MATT. The main engine specifications are summarized in Table 1.

Table 1. Hydrogen Engine Specifications

Engine Manufacturer	Ford Motor
Cylinders	4
Bore (mm)	89
Stroke (mm)	79.6
Displacement (l)	2.3
Compression ratio	12
Valvetrain	4V Dual Overhead Cam (DOHC)
Speed range (RPM)	6000
Injector	Quantum PFI
Hydrogen	Coriolis Meter

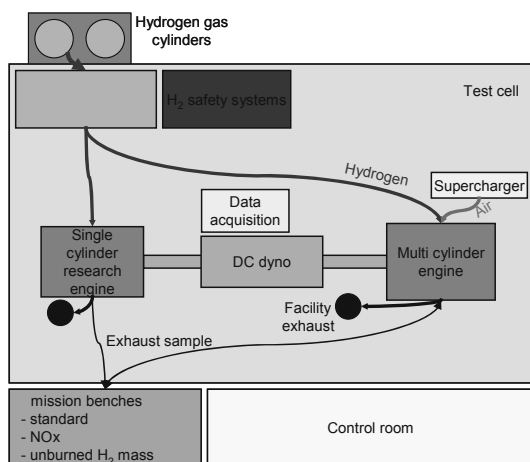


Figure 1. Schematic of Hydrogen Engine Test Cell

Figure 2 shows a picture of the hydrogen engine fully operational in the hydrogen test cell. A hood on top of the engine with continuous air flow guarantees that hydrogen is captured and transported out of the building in the unlikely event of a hydrogen leakage. In addition a hydrogen sensor is mounted inside the hood. If a measurable concentration is detected an E-Stop will automatically be triggered and the dyno as well as the hydrogen supply system are being shut down. As an additional safety feature a hydrogen flame camera that is tied into the E-Stop systems as well monitors the engine.



Figure 2. Hydrogen Engine and Test Cell

Full control of the engine as well as the stand-alone capability are being accomplished by use of an aftermarket Engine Control Unit (ECU). In the case of the hydrogen engine a M800 system manufactured by MOTEC is used. This ECU allows full control of fuel injection as well as ignition.

Results

Previous experiments with hydrogen port injected engines have shown that the air/fuel ratio has crucial influence on the engine performance, efficiency and emissions behavior. Due to high NO_x emissions without after treatment air/fuel ratios close to stoichiometric have to be avoided. Based on that knowledge the hydrogen engine was operated at four different air fuel ratios to determine the effects on efficiency performance and emissions.

Figure 3 shows this trend for an engine speed of 1500 RPM. Increasing the air/fuel ratio from $\lambda=2$ to $\lambda=2.5$ results in an increase in brake thermal efficiency in the range of 1 - 2 %. A further increase of air/fuel ratio to $\lambda=3$ only shows a minor further increase in efficiency. Similar trends with a peak efficiency in the range $2.5 < \lambda < 3$ can be seen at other engine speeds.

Due to the leaner mixture the peak engine torque decreases significantly with increased relative air/fuel ratio (from $T_{\text{max}} \sim 180 \text{ Nm}$ at $\lambda=2$ to about 120 Nm at $\lambda=3$). Consequently high engine output requires mixtures with the lowest air/fuel ratio possible. An operating strategy optimized only for efficiency where the engine is solely run in these lean regimes ($2.5 < \lambda < 3$) would result in an unacceptable loss in power density.

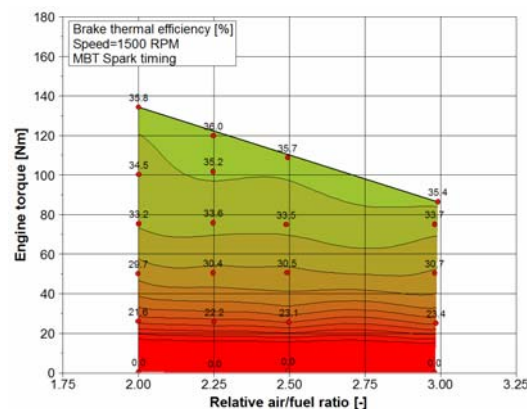


Figure 3. Influence of Air/Fuel Ratio on Efficiency

Figure 4 shows the efficiency maps (brake thermal efficiency) for the four different air/fuel ratios. The spark timing for each individual operating point was set to MBT (maximum brake torque). The peak efficiency in all cases is reached at full load (wide open throttle) and it varies between 35 and 37%. For identical engine load the brake thermal efficiency increases as expected with leaner engine operation (see Figure 3).

The only critical emissions component in hydrogen operation is nitric oxide. The target set by the Department of Energy for hydrogen engines is NO_x emissions as low as 0.07 g/mile (Tier II Bin 5). Similar trends concerning air/fuel ratio and NO_x emissions have been published by several authors. According to those publications the critical air/fuel ratio at which NO_x emissions increase significantly is around $\lambda \sim 2$.

Figure 5 shows the dependency of NO_x emissions on air/fuel ratio at a speed of 1500 RPM. As mentioned before an increase in air/fuel ratio results in a reduction in NO_x emissions. Figure 6 shows the NO_x emissions maps for the four different air/fuel ratios tested in this study. For the richest of the mixtures ($\lambda=2$) the amount of nitric oxides produced is in a range of several hundred ppm in almost the entire load and speed range. Increasing the air/fuel ratio to $\lambda=2.25$ already results in a significant reduction of emissions. The peak NO_x value is only slightly more than 100 ppm , in a wide load and speed range the NO_x emissions are well below 100 ppm . A further increase in air/fuel ratio to $\lambda=2.5$ results in NO_x emissions as low as 20 ppm in almost the entire operating range. At an air/fuel ratio of $\lambda=3$

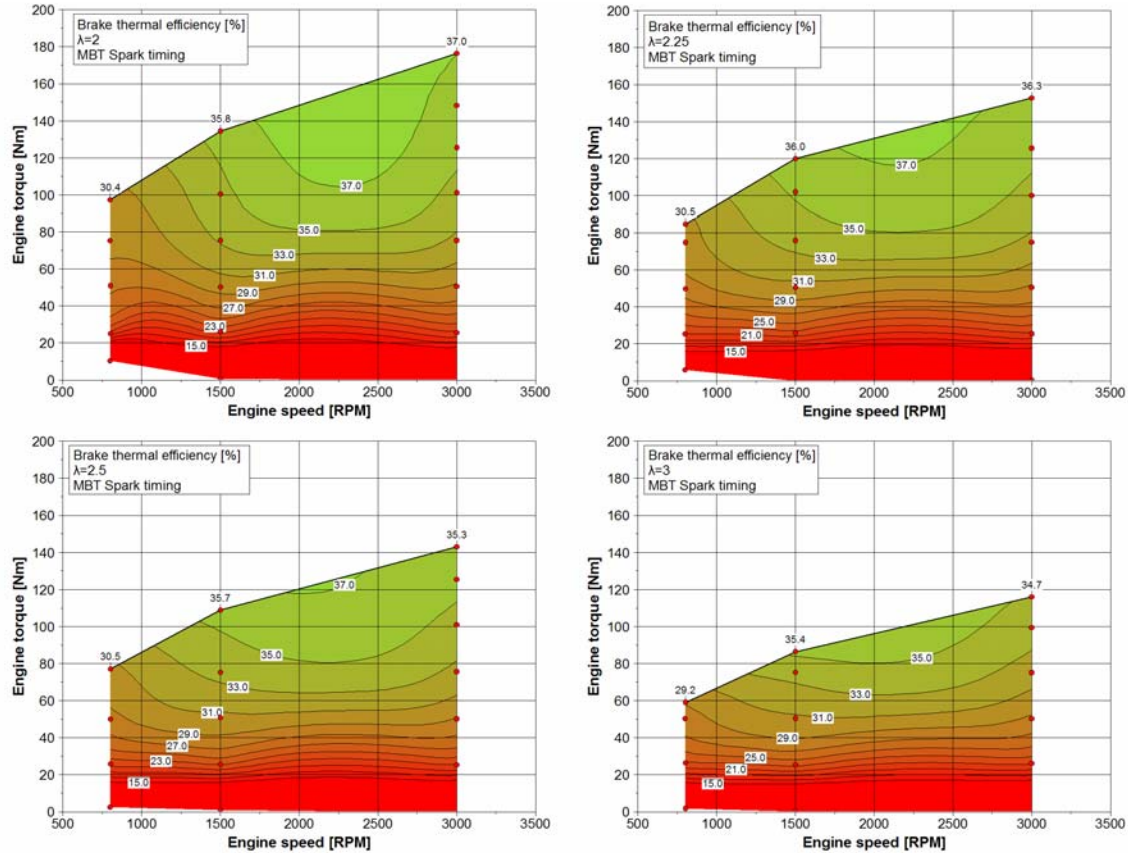


Figure 4. Efficiency Maps for Relative Air/Fuel Ratios λ of 2, 2.25, 2.5 and 3

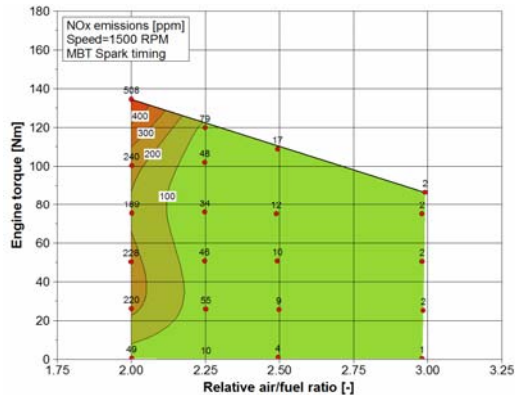


Figure 5. Influence of Air/Fuel Ratio on NOx Emissions

the emissions are below 3 ppm, an emissions level that is already within the accuracy limit of the analyzer.

Due to lower combustion speed lean engine operation usually results in a decrease in combustion

stability. In automotive application this is perceived as rough engine operation and has to be avoided. One important measure of cyclic variability, derived from pressure data, is the coefficient of variation in indicated mean effective pressure. It is standard deviation in IMEP divided by the mean IMEP, and is usually expressed as:

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{IMEP} \times 100 \quad (1)$$

It defines the cyclic variability in indicated work per cycle, and it has been found that vehicle drivability problems usually result when COV_{IMEP} exceeds about 10%. Figure 7 shows the coefficient of variation in indicated mean effective pressure as a function of engine torque for the four different air/fuel ratios at an engine speed of 1500 RPM. For each operating point the spark timing is set to achieve maximum torque (MBT spark timing).

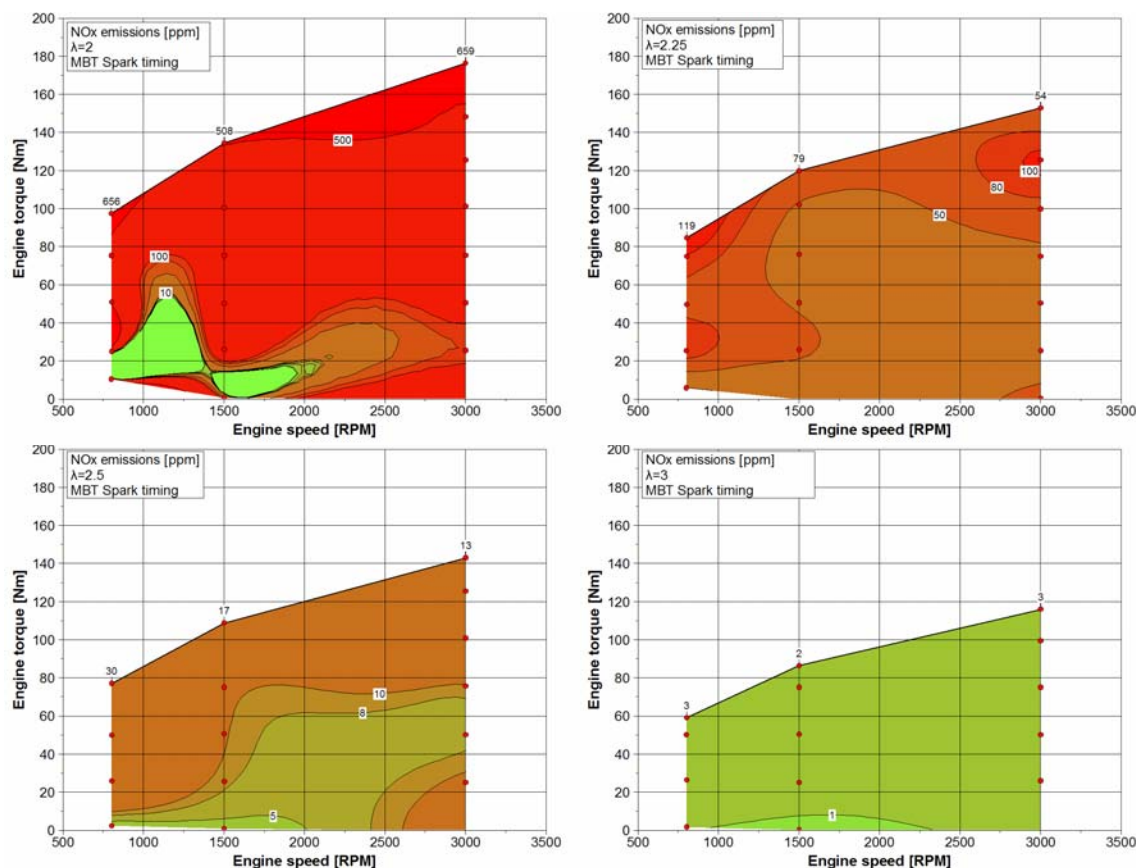


Figure 6. NO_x Emissions Maps for Relative Air/Fuels Ratios λ of 2, 2.25, 2.5 and 3

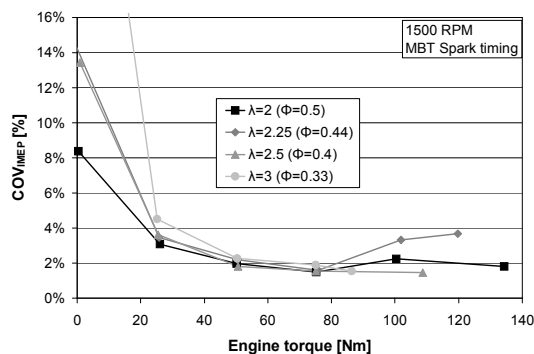


Figure 7. Combustion Stability versus Torque

Within a wide range of operation the combustion stability is well below the critical limit. Although leaner operation is said to negatively affect the combustion stability, this trend can not clearly be seen in the range of air/fuel ratios tested. The only critical operating situation is lowest torque (0 Nm), where a significant increase in COV_{IMEP} can be seen for all air/fuel ratios.

Based on above mentioned results in terms of efficiency behavior, emissions trends, power output and engine stability an efficiency-optimized operating strategy for the supercharged hydrogen engine with port fuel injection was derived. This optimized hydrogen engine operating strategy consists of several operating modes. The first mode for idle and low engine loads is an extremely lean combustion at a constant air/fuel ratio with high engine efficiency and practically zero NO_x emissions. A conventional throttle is used to adjust the load at a preset air/fuel ratio value and thereby keep the engine from running too lean which would result in unacceptable combustion instabilities. With increase in load beyond the wide-open-throttle position at the preset lean air/fuel ratio value the second mode at variable equivalence ratio is employed. The engine load in this mode is controlled by changing the air/fuel ratio with the throttle being fully open. This operating mode can be extended up to a certain air/fuel ratio limit at which NO_x generation increases exponentially. For

high engine loads and full load the engine can be operated in a third mode with stoichiometric combustion, thereby providing maximum power output. This mode requires an exhaust gas after treatment system and is therefore not further explored at this point. Figure 8 schematically illustrates the dependency of air/fuel ratio on torque request and shows the different operating modes.

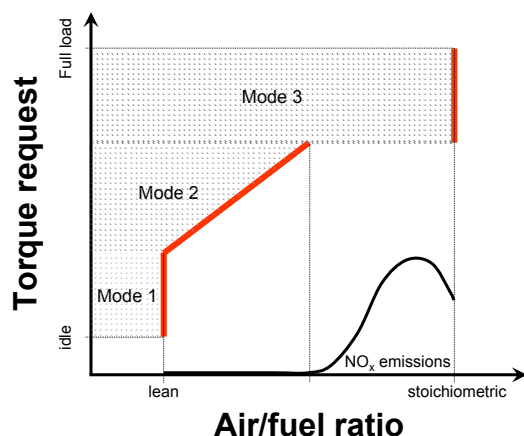


Figure 8. Schematic of Torque Request versus Air/Fuel Ratio and Operating Modes

Based on the available results and the derived operating strategy the engine can be fully mapped using only the torque request as an input. The engine control unit (ECU) also needs to compensate for several environmental parameters, e.g. hydrogen pressure, engine temperature as well as dynamic engine operation.

Conclusions

An engine test cell was upgraded to allow operation and testing of hydrogen powered internal combustion engines. This upgrade is completed and the cell is fully operational and commissioned.

A supercharged hydrogen-powered 4-cylinder engine was set up in the hydrogen test cell and equipped with an aftermarket engine control unit (ECU). The engine is fully operational, shake-down testing and baseline engine mapping has been performed.

Based on the results of the baseline testing an advanced efficiency optimized engine operating strategy has been derived. The strategy consists of

several operating modes that are employed based on the load demand.

To allow the engine to operate in stand-alone mode the engine control unit has been adapted such that the only external input required to run the engine is a load demand. These features as well as the fact that the engine is identical to the gasoline engine currently used on the MATT platform guarantee an almost seamless transition from gasoline to hydrogen operation on the hybrid platform.

Final mapping of the hydrogen engine with the advanced operating strategy has to be completed. After the stand-alone capability has been proven the engine is ready to be transferred to MATT.

Publications / Presentations

1. Wallner, T.; Lohse-Busch, H. "Light Duty Hydrogen Engine Application at Argonne National Laboratory." Conference "Bridging the Technology...Hydrogen Internal Combustion Engines." San Diego/CA. Feb. 2006.
2. Wallner, T. "Overview of American and European Hydrogen Research Activities." International Conference on Safety in Transportation (ICOSIT). Benevento/Italy. Sept. 2006.

In Preparation

1. Wallner, T., Lohse-Busch, H. "Performance, emissions and efficiency evaluation of a supercharged hydrogen-powered 4-cylinder engine." SAE Fuels and Emissions Conference. Cape Town/South Africa. Jan. 2007.
2. Lohse-Busch, H.; Wallner, T. "Efficiency Optimized Operating Strategy of a Supercharged Hydrogen-Powered 4-Cylinder Engine for hybrid environment." 2007 JSAE/SAE International Fuels and Lubricants Meeting. Kyoto/Japan. July 2007.

IV. LABORATORY TESTING AND BENCHMARKING

A. Benchmarking and Validation of Hybrid Electric Vehicles

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Objectives

- Provide operational data during chassis dynamometer using novel instrumentation for,
 - 2005 Accord HEV (Level II)
 - Lexus RX400h, two (2) vehicles (Level I)
 - Highlander HEV (Level I)
 - “End-of-Life” 2002 Prius (Level I) and 2001 CVT Insight (Level I)

Approach

- Vehicle, manufacturer’s service manuals, and diagnostic’s tool are purchased for the vehicles tested.
- In the case of the Level II testing, axle torque sensors are installed and experimental custom engine (transmission input) torque sensor is designed and developed with instrumentation suppliers.
- Vehicles are wired for instrumentation of major components for speed and easily found stock sensors.
- Tests are run on vehicles for cycle fuel economy, performance testing and steady-state load testing for all the vehicles.

Accomplishments

- APRF data acquisition system improved for higher productivity, more modular and higher quality data.
- Accord transmission input torque sensor was successful using state-of-the-art digital telemetry system that with earlier generations would have not been possible.
- Lexus and Highlander were tested, first data available from the 4WD Lexus hybrid system (motor assist in rear wheels).
- First high-mileage HEV data available for industry and DOE analysis.

Future Directions

- The digital telemetry system is an encouraging direction for other hybrid systems.
 - ANL will address hybrid test-to-test variability with an industry-standard robot driver.
 - Engine torque data will be augmented with indicated torque measurements made possible with a high-speed data acquisition system, non-intrusive cylinder pressure transducers and a compact crankshaft encoder.
-

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 is applicable to virtually every effort in the FreedomCAR partnership and all the “Tech Teams” benefit from the data collected in the APRF.

Approach

The APRF design has evolved to be more productive by using a more modular approach to advanced data acquisition. In the figure below, a cart rolls up to a test vehicle. On the cart is the battery analyzer (Hioki power analyzer) and the data acquisition system. Mass termination is retained in the vehicle so to connect to the labs data acquisition system entails connecting two or three large connectors each bundled with 32 channels of signals. Vehicles can now be swapped over in under an hour, compared an entire day or more with previous methods.

The Hioki power analyzer is now integrated with the Host computer to make battery power analysis more robust. It is the standard in measurement throughout HEV testing.

Other improvements include a new optical character recognition system employed to collect detailed vehicle parameters from the manufacturer’s diagnostic system. Because of the APRF’s custom Host computer system, this new vehicle network reading system was implemented to provide network data alongside all the rest of the signals acquired for testing.

Level 2 - Model Year 2005 Accord HEV

The Accord HEV was tested last year at the Level I detail. A new torque sensor was designed and successfully implemented in the Accord, as shown in Figure 1 and Figure 2.

The major obstacle to overcome for the torque sensor is the fact that the location of the sensor puts in the worst conditions for electromagnetic interference (EMI). From the photographs, it can be noticed that the antenna is located within a centimeter from the stator coils. Torque sensor

technology for vehicles is developed with conventional vehicles in mind. FM signal telemetry is adequate where no source of interference is near and as was found in the Prius application, the FM frequencies can be on the order of the inverter frequencies. It is believed that this torque sensor application for the Accord would simply not have worked if not for the new digital telemetry system. This telemetry system is a new technology just now making into challenging sensor applications like this one.



Figure 1. Digital Telemetry Torque Sensor Antenna (left) and Sensing Flexplate (right)



Figure 2. Torque Sensor Installed in Flexplate Location

The axle torque sensors and electric power readings provide adequate accuracy for all the major power flows in the Accord hybrid system, a schematic of which is shown in Figure 3.

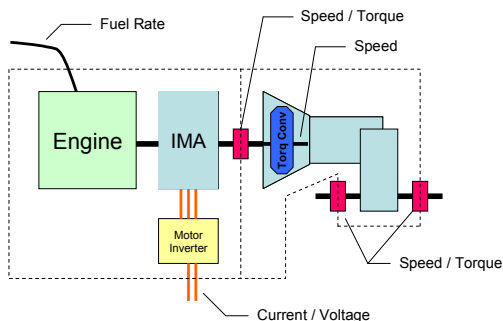


Figure 3. Location of Axle Torque Sensors in Honda Accord Hybrid

Level 1 – Johnson Controls RX400h

Using ANL's close working relationship with Johnson Controls, ANL borrowed their Lexus RX400h hybrid to test for mutual benefit and took roughly two and one half weeks to complete. Of primary interest to JCI was of course battery conditions and performance. Figure 4 shows a team of JCI engineers working hand in hand with ANL researchers.



Figure 4. JCI Engineers Observing Testing of Their RX400h Test Vehicle at APRF

Level 1 – ETEC RX400h and Highlander HEV

ANL is part of DOE's Advanced Vehicle Testing Activity (AVTA) by providing the chassis dynamometer testing before and after fleet service. Another RX400h was testing in the lab alongside the Highlander HEV. Both vehicles have nearly identical powertrains however, the RX400h is a

4WD design (rear electric motor) and the Highlander was 2WD.

Accord HEV Test Results and Analysis

The benchmark testing is broken down into three different types of tests; 1) Maximum Performance, 2) Steady-state Loads/Speeds, and 3) Cycle Fuel Economy.

Maximum performance looks at component and systems behavior under a full acceleration up to 80 MPH and also passing maneuvers; various combinations of cruise followed by a full accel to higher speeds.

Steady-state testing comprises of driving the vehicle at various speeds with the dynamometer set at various grade levels. The test included stepping up in speeds and then stepping back down to include a dead-band control changes. In Figure 5 below, the measured fuel economy is plotted for the speeds and loads tested. Note that at 30 MPH and 30% grade, different operational conditions made for significantly different fuel economy values.

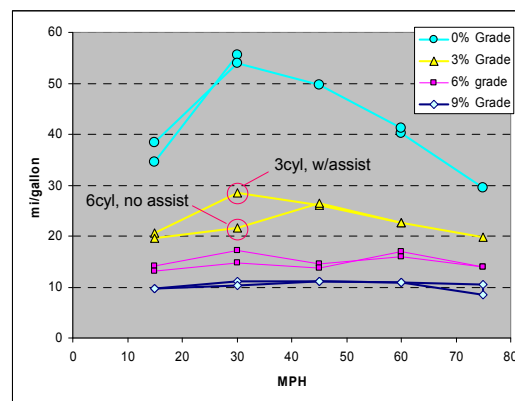


Figure 5. Accord HEV Fuel Economy Results from Steady-State Speed Testing

Component efficiencies can be directly calculated with the torque sensors installed. For example, Figure 6 shows the transmission efficiency for the speed and grades tested. Note that at 0% grade that the first two efficiency measurements are different than the step down measurements; this was traced back to inefficient warm-up conditions at startup.

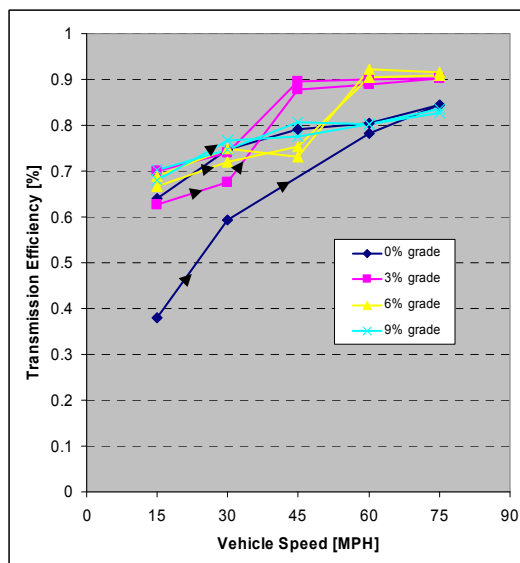


Figure 6. Transmission Efficiencies (including Torque Converter) of Accord HEV

One particular feature of the Accord HEV that was analyzed was engine cylinder shut-down (also called “Deactivation”). Under light load the engine valvetrain has the ability to deactivate one bank, or three (3) cylinders by keeping the valves shut. Load conditions for when this occurs is shown in the Figure 7.

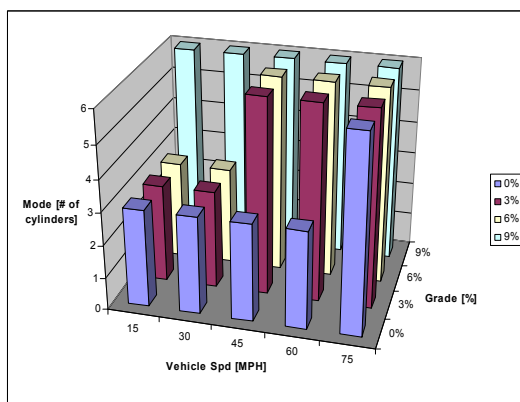


Figure 7. Accord HEV Engine Cylinder Deactivation Conditions

For fuel economy cycles, the objective is to find characteristic charge-balancing cycles to observe operational behavior without net influence of the battery. In order to accomplish this, it usually requires that any particular cycle needs to have the same cycle run beforehand to condition the battery to the charge-sustaining state-of-charge (SOC). To

illustrate the vehicle’s ability to control SOC levels, Figure 8 represents a graph of three different tests with varied initial SOC levels are shown with the vehicle’s SOC plotted over the cycle. Note that the ending SOC levels nearly match even with such highly varied initial SOC levels.

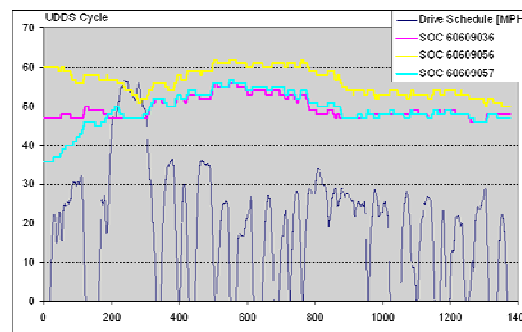


Figure 8. Accord HEV SOC Control in Three UDSS Tests With Varied Initial SOC Levels

“End-of-Life” 2002 Prius (Level I) and 2001 CVT Insight (Level I)

Two vehicles were available for benchmarking from the AVTA program for “End-of-Life” (EOL) benchmark testing. Although ANL did not test the vehicles before they were put into high-mileage service (both EOL vehicles have over 170,000 miles), in the case of the Gen I Prius, ANL does have an identical low-mileage Prius that is useful to compare.

The conclusion of many fuel economy tests were that the operation of the vehicle was not significantly diminished by high mileage. In fact, all the fuel economy tests showed only a 1-2% drop in fuel economy. Preliminary testing of the battery capacity change in-vehicle was inconclusive. The battery will be removed and tested under controlled conditions to find if indeed a capacity loss can be found.

The 2001 CVT Honda Insight EOL vehicle was in a remarkably different operational condition compared to the Gen I Prius. The transmission suffered from multiple failures and in its current condition, still had transient events that indicate that it may be slipping belt or suffering from another condition that provide harsh torque fluctuations events. This is shown graphically in Figure 9.

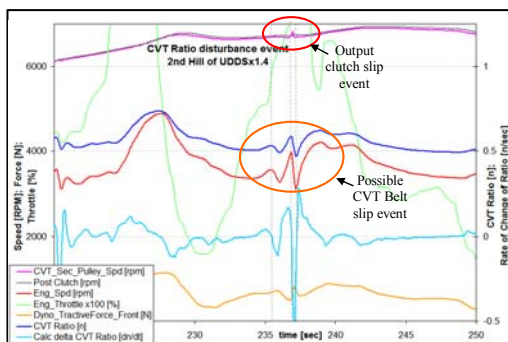


Figure 9. Speed and Load Data Revealing Possible CVT Belt Slip Event

The vehicle was coast-down tested on a track prior to shipment to ANL, there showed significant losses compared to certification dynamometer setting. Compared to EPA certification fuel economy, the results from testing on the dynamometer showed a 11-12% drop in fuel economy.

However, the vehicle also experienced several Diagnostic Trouble Codes (DTC) that essentially disabled the hybrid control system. There was essentially zero current flow into or out of the battery pack. With these DTC's present, there was no assist, no engine start stop, or regenerative braking. The only significant battery utilization was starting the engine at the beginning of the test. Three DTC were present in this condition. DTC P58 is labeled as "Charge Discharge Balance Problem". DTC P1447 and P1448 are labeled as "Battery Module Deterioration". In these conditions, the fuel economy dropped 40% on the "cold-start" UDDS cycle.

Conclusions

The Advanced Powertrain Research Facility has become a powerful tool for gathering data of the most advanced powertrains at a level of detail not available anywhere else in industry. The OEM partners in FreedomCAR have become close collaborators in sharing time and equipment in order get the most out of the testing programs and studies.

"Level 2" testing of the Accord HEV produced extensive data that reveal how the vehicle operates and the component-level efficiencies. And with a more prominent role in the AVTA program, many more hybrids are be tested with a "Level 1" of instrumentation. Also, as EOL vehicles become available, DOE's research partners have highly detailed information about technology performance and degradation. Level 1 testing of the Lexus RX400h, Highlander HEV, EOL Prius and EOL Insight were a great success.

Supporting DOE's basic hardware development and simulation studies, in either case having a solid foundation of current technology is a critical aspect of any research and development program.

Publications / Presentations

1. Draft Accord HEV Level 2 Test Report SAE.
2. "Demonstration of Current Production Hybrid Vehicle Component Technologies" invited speaker Hybridfest, Madison, WI, July 2006.

B. Testing of Plug-in Hybrid Electric Vehicles (PHEV)

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Objectives

- Provide operational data during chassis dynamometer using novel instrumentation for a Hymotion PHEV Prius and determine the fuel displacement, energy usage and emissions impact of the vehicle as compared to a production Toyota Prius.

Approach

- Retrofit a 2004 Toyota Prius, which is previously instrumented for Level II testing, is with the Hymotion PHEV battery system.
- Tests are run on vehicles for cycle fuel economy, performance testing and steady-state load testing.
- Experiment with different test approaches. No recent formal procedure yet exist.

Accomplishments

- APRF acquired the first detailed data of a low volume production PHEV.

Future Directions

- Test the Energy CS Prius.
- Test the Renault Kangoo series PHEV.
- Test the Hymotion Ford Escape Hybrid.

Introduction

Plug-in Hybrid Electric Vehicles (PHEV) are an emerging technological development in the effort to reduce foreign oil dependency. A PHEV makes current HEV technology even more complex. Current HEVs on average do not use net energy from the battery, the objective of the PHEV strategy is to use net battery energy. The Hymotion PHEV Prius is a low volume production PHEV system. Even though the system is not optimized, it does offer significant petroleum reduction. One of these Hymotion systems was installed in the 2004 Toyota Prius that was previously instrumented at Argonne National Lab for Level II testing. The Hymotion

PHEV Prius was dynamometer tested for fuel economy, energy usage, and emissions.

Approach

The APRF dynamometer facility is used to test the is extensively instrumented Hymotion Prius system. Detailed information is collected from torque sensors on the engine output and the axles, a power analyzer measures current and voltage from the Prius battery, the Hymotion battery, the DC/DC converters, and the electrical usage of the powertrain system. CAN data logging devices allow recording of Hymotion control functions and Prius control functions. This instrumentation is used to record

vital data while testing during the drive cycles as well as during recharging the Hymotion battery system. The APRF direct fuel scale and the Pierburg emissions bench are both used to calculate fuel economy and emissions.

The Hymotion battery system consists of a Li Ion battery pack that is installed in parallel to the production Prius pack to provide an additional 5 kWhrs of electrical energy storage. This system also includes a clever control system to enable the Prius to operate in a charge depletion (CD) mode. CAN communication is used to communicate with the production Prius controller and operate the vehicle in EV mode up to 40 mph or until a power requirement threshold is exceeded. This results in the powertrain predominantly utilizing electrical energy which minimizes engine operation. This in turn reduces fuel consumption.

The vehicle was tested in 2WD mode for best repeatability and the test class weight was adjusted up to 1452 kg for the additional 73 kg mass of the Hymotion system. The dynamometer coefficients used for this testing, as shown in Table 1, are the same as the production Toyota Prius.

Table 1. Hymotion Prius Dynamometer Coefficients

Coefficients	A	B	C
Target	19.918	0.1393	0.0164
Dyno Set	3.604	-0.1538	0.0179

Results

Hymotion Prius Test Results and Analysis

Testing of the Hymotion Prius included the UDDS, HWY and the US06. Starting from 100% State of Charge (SOC), multiple cycles were driven in charge depletion mode until the vehicle entered charge sustaining operation.

Charge Depletion UDDS Cycles

Beginning from a cold start, the Prius PHEV charge depleted for nearly 25 miles. Charge sustaining was observed during the 3rd “hill” of the fourth consecutive UDDS. During those cycles, the powertrain operated predominantly in EV mode. The engine turned on above 40 mph and when the EV mode power threshold is exceeded. Table 2

shows the unadjusted results from the five consecutive UDDS cycles. Comparing the fuel usage of the charge depletion mode to the charge sustaining mode, electrical energy displaces roughly two thirds of the fuel usage as compared to the charge sustaining mode for the first 25 miles driven on the UDDS cycle.

Table 2. Hymotion Prius Consecutive UDDS Cycle Results

UDDS	#1	#2	#3	#4	#5
Fuel used [gallons]	0.051	0.037	0.040	0.101	0.113
Miles driven [miles]	7.48	7.48	7.48	7.48	7.47
Fuel Economy [mpg]	148	200	187	74	66
Elec energy [DC kWhrs]	.93	.96	.94	.23	.12

Figure 1 shows the consecutive UDDS cycles. Note the accumulated fuel consumed is much lower for the charge depletion PHEV Prius (CD PHEV) as compared to the production charge sustaining (CS HEV). This results in electrical energy usage displacing gasoline consumption. After the vehicle fully charge depleted the usable battery energy, it operated in the standard charge sustaining mode as a production Prius does.

Charge Depletion HWY Cycles

The Hymotion Prius was also tested on the HWY cycle. Six consecutive HWY cycles were conducted in the charge depletion operation, starting from a full battery charge. The vehicle operated in charge depletion mode for about 33 miles into the fourth HWY cycle. Table 3 shows the results of the consecutive HWY cycles. Comparing the fuel usage of the charge depletion mode to the charge sustaining mode, electrical energy displaces roughly half of the fuel usage as compared to the charge sustaining mode for the first 30 miles driven on the HWY cycle. This is less fuel displacement than the UDDS cycle because the required power for the HWY is greater than the UDDS and since the Hymotion max power output is only 6 kW, the extra power required for the HWY cycle is achieved from fuel power.

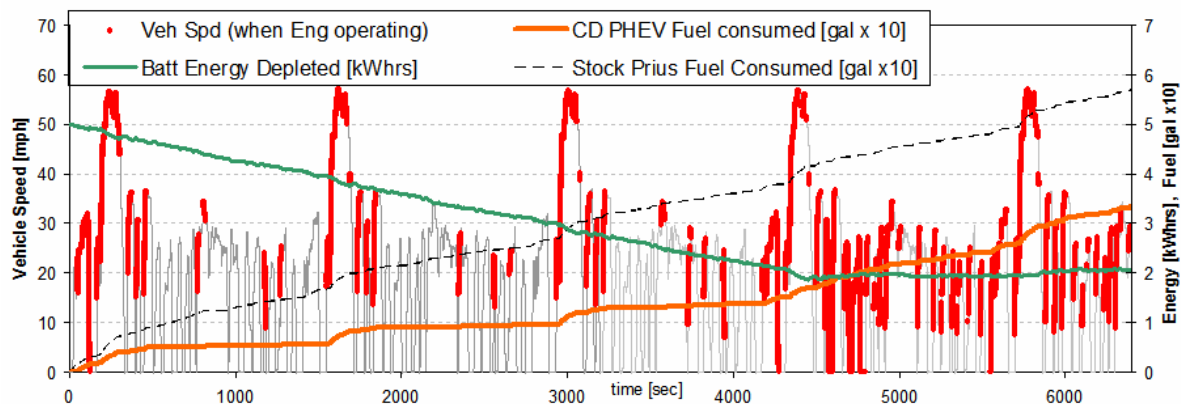


Figure 1. Charge Depletion UDDS Cycles - Hymotion Prius on Chassis Dynamometer

Table 3. Hymotion Prius Consecutive HWY Cycle Results

HWY	#1	#2	#3	#4	#5
Fuel used [gallons]	0.092	0.084	0.096	0.142	0.165
Miles driven [miles]	10.27	10.27	10.27	10.27	10.27
Fuel Econ. [mpg]	112	122	107	72.2	62.4
Elec energy [DC kWhrs]	1.0	1.0	0.94	0.24	-0.04

Figure 2 shows the consecutive HWY cycles. Note the accumulated fuel consumed is again much lower for the charge depletion PHEV Prius (CD PHEV) as compared to the production charge sustaining (CS HEV). This results in electrical energy usage displacing gasoline consumption.

Fuel consumption is shown during the HWY cycles, but above 40 mph the engine is always spinning due to speed limitations of the generator MG1 but fuel is not always being consumed. During deceleration and some mild accelerations and steady state operation are performed with electric power only.

One very important observation is that the Prius configuration is not well suited for quickly depleting battery energy – especially during highway driving. The efficiency of the engine suffers when it is used for power, but unloaded by using the electric motor for propulsion. It would be preferred to use the engine only at high power points to maintain higher average efficiency. The Prius has a engine torque sensor that allows investigation into this issue. Figure 3 compares engine-on operation and the associated efficiency of both charge-sustaining and

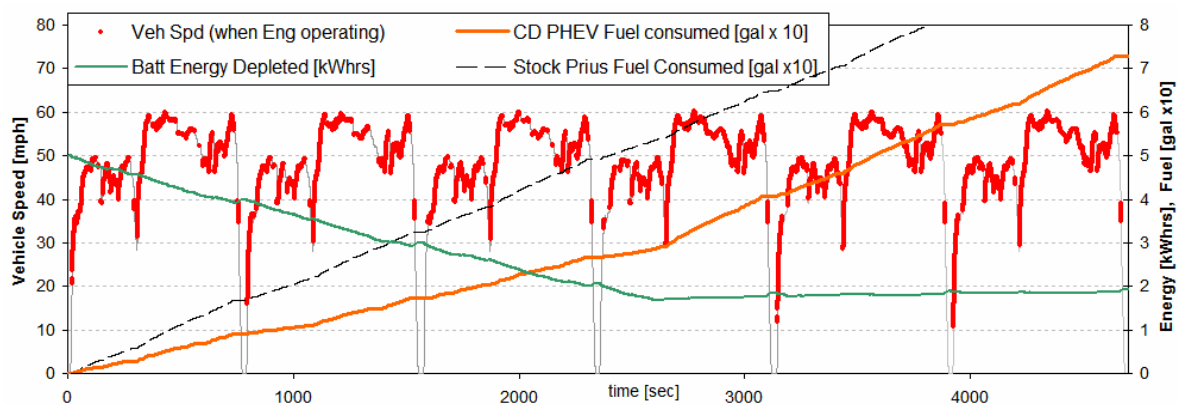


Figure 2. Charge Depletion HWY Cycles - Hymotion Prius on Chassis Dynamometer

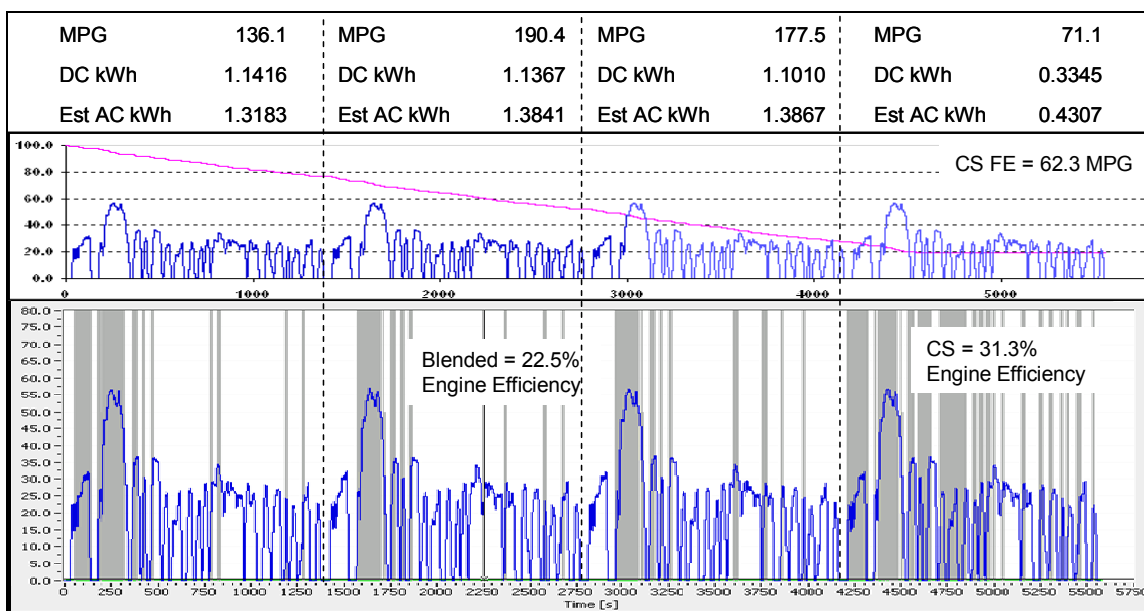


Figure 3. Engine Efficiency Comparison – Depleting vs. Sustaining

charge-depleting operation. Note the significant difference between 22.5% and 31.3% engine efficiency.

Conclusions

The Advanced Powertrain Research Facility produced the first data from a production, commercially available PHEV system. The system, which was installed in a Toyota Prius, showed significant petroleum displacement for 25 to 30 miles depending on driving conditions.

Supporting DOE's initiative to develop vehicles technologies for petroleum displacement is essential and testing the Hymotion Prius is the first viable PHEV system to be extensively tested at a full dynamometer facility.

Publications / Presentations

1. Draft Report SAE 07PFL-375.

V. OPERATIONAL AND FLEET TESTING

A. Hybrid Electric Vehicle Testing

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Objective

- 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 11 HEV models.
- Operate at least two of each HEV model 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 33 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, 28.4 mpg for the 2 Honda Accords, 44.5 mpg for the 2 Gen II Prius, 17.7 mpg for the 2 Chevrolet Silverado HEVs, 27.5 mpg for the 2 Ford Escapes, 24.3 mpg for the 3 Lexus RX400h, 24.7 mpg for the 2 Toyota Highlanders, 32.5 for the 2 Toyota Camrys, and 38.7 for the 2 Gen II Honda Civics.
- As of September 2006, 2.2 million HEV test miles have been accumulated.
- Completed end of life vehicle and battery testing on Honda Insight, Gen I Toyota Prius, and Honda Civic HEVs.
- Provided HEV testing results to industry, the U.S. Department of Energy, and other National Laboratory via the FreedomCAR & Vehicle Technologies Program's Vehicle Simulation and Analysis Technical Team.

Future Activities

- Benchmark new HEVs available during FY07.
 - 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 onboard energy storage that is never connected to the grid for charging the battery. The batteries are charged by the onboard ICE powered generator, as well as by regenerative braking system. Most of today's HEVs use nickel metal hybrid chemistries as the onboard traction battery. One current HEV uses a lead acid battery. Future HEVs may use lithium battery technologies.

Future HEV onboard energy storage systems may include combinations of multiple battery technologies employing different charge and discharge methods, and ultracapacitors. Future HEV ICEs may operate on alternative fuels such as hydrogen, methane, compressed natural gas (CNG), ethanol, or blends of hydrogen and CNG. In addition to providing benchmark data to modelers and technology target setters, the 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 FY06, the AVTA has performed accelerated reliability and fleet testing on 33 HEVs, comprised of 11 HEV models: Generation (Gen) I and II Toyota Priuses, Honda Insight, Honda Accord, Chevrolet Silverado, Gen I and II Honda Civics, Ford Escape, Lexus RX400h, Toyota Highlander, and Toyota Camry. In addition, baseline performance testing has been completed on nine of the 11 models, with the Gen II Civic and Camry undergoing baseline performance testing as of the end of FY2006. 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 reliability testing, two of each HEV model will each accumulate 160,000 onroad miles in 36 months.

Also during FY06, end-of-life (at 160,000 miles per vehicle) baseline performance testing was performed on two each Gen I Civics, Gen I Priuses, and Insights. The testing included rerunning the fuel economy (SAE J1634) tests and conducting battery testing.

Results

As of September 2006, the 33 HEVs have accumulated 2.2 million accelerated reliability and fleet test miles (Figure 1). The fuel economies ranged from 17.7 to 45.2 mpg in the onroad fleet and accelerated reliability testing (Figure 2). All of the HEVs that have been tested for accelerated reliability 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).

In addition to the HEV fuel economy and total test miles data being collected, all maintenance events, including the costs or if under warranty, dates and vehicle miles when a maintenance event occurred, is collected to compile life-cycle vehicle costs. This data is also 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.

During baseline performance testing, the AVTA uses two dynamometer drive cycles to test fuel economy. The two AVTA drive cycles combine city and highway driving patterns into a single identical test cycle (SAE J1634), but one AVTA test is performed with the air conditioning (AC) on maximum and the other AVTA test is performed with the AC turned off. It should be noted that the AVTA's fleet and accelerated reliability fuel economy results fall within the bounds of the two AVTA drive cycles (Figure 6), which suggests the AVTA baseline performance dynamometer testing is a good predictor of actual onroad HEV gasoline use.

At HEV end-of-life (defined as 160,000 miles per vehicle), SAE J1634 fuel efficiency testing were rerun on the six 160,000 miles HEVs (2 Insight, 2 Gen I Civics, 2 Gen I Prius) with the AC on and off. The AC on and off test results are compared to new vehicle AC on and off fuel efficiencies for each HEV model. The six HEVs were all end-of-life tested using new-vehicle coast down coefficients (Phase I). In addition, one of each HEV model was also subjected to fuel efficiency testing using coast down coefficients obtained when the vehicles completed 160,000 miles of testing (Phase II). Traction battery pack capacity and power tests were

also performed on all six HEVs during the end-of-life testing in accordance with the FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles procedures.

When using the new-vehicle coast down coefficients (Phase I testing), 11 of 12 HEV tests (each HEV was tested once with the AC on and once with the AC off) had increases in fuel efficiencies compared to the new vehicle test results (Figures 7 and 8). The end-of-life fuel efficiency tests using the end-of-life coast down coefficients (Phase II testing) showed decreases in fuel economies in five of six tests (three with the AC on and three with it off).

During Phase II fuel efficiency testing, the vehicle's onboard fuel efficiency display was recorded and compared to the actual Phase II fuel efficiency findings (Table 1). For every case and vehicle tested, it was observed that the on-board vehicle computer displayed fuel efficiencies higher than the actual measured SAE J1634 fuel efficiency.

All six HEVs experienced decreases in battery capacities (Figure 9), with the two Insights having the highest remaining capacities and the two Priuses having the lowest remaining capacities.

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 fairly robust; as of the end of FY06 and 2.2 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 NiMH second pack failed at 147,000 miles. In addition, there was a lead acid HEV traction pack failure at 36,000 miles.

The results for the end-of-life (160,000 miles) static battery testing suggest that the two Civics have remaining battery capacities of 68%, the two Insights have remaining battery capacities of 85%, and the two Priuses have remaining battery capacities of 39%.

Future Activities

New HEVs available from U.S., Japanese and European manufacturers will be benchmarked during FY06. 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. HEV reports and papers published during FY06 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. and J. Francfort. June 2006. *US Department of Energy Hybrid Electric Vehicle Battery and Fuel Economy Testing*. Power 7858 1-5. Journal of Power Sources. Elsevier. London, United Kingdom.
2. Francfort, J.E. June 2006. *Hybrid Electric Vehicle and Lithium Polymer NEV Testing*. INL/CON-05-01003 42nd Power Sources Conference. Philadelphia, PA.
3. Francfort, J., D. Karner, R. Harkins, and J. Tardiolo. April 2006. *Hybrid Electric Vehicle Fleet and Baseline Performance Testing*. INL/CON-05-00415. SAE World Congress - Paper Number 2006-01-1267. Idaho National Laboratory. Idaho Falls, ID.
4. Francfort, J., D. Karner, R. Harkins, and J. Tardiolo. February 2006. *Hybrid Electric Vehicle End-of-Life Testing On Honda Insights, Honda Gen I Civics and Toyota Gen I Priuses*. INL/EXT-06-01262. Idaho National Laboratory. Idaho Falls, ID.
5. Francfort, J.E. December, 2005. *Hybrid Electric Vehicle Testing*. INEEL/CON-05-00964. Electric Drive Transportation Association Conference. Vancouver, Canada.

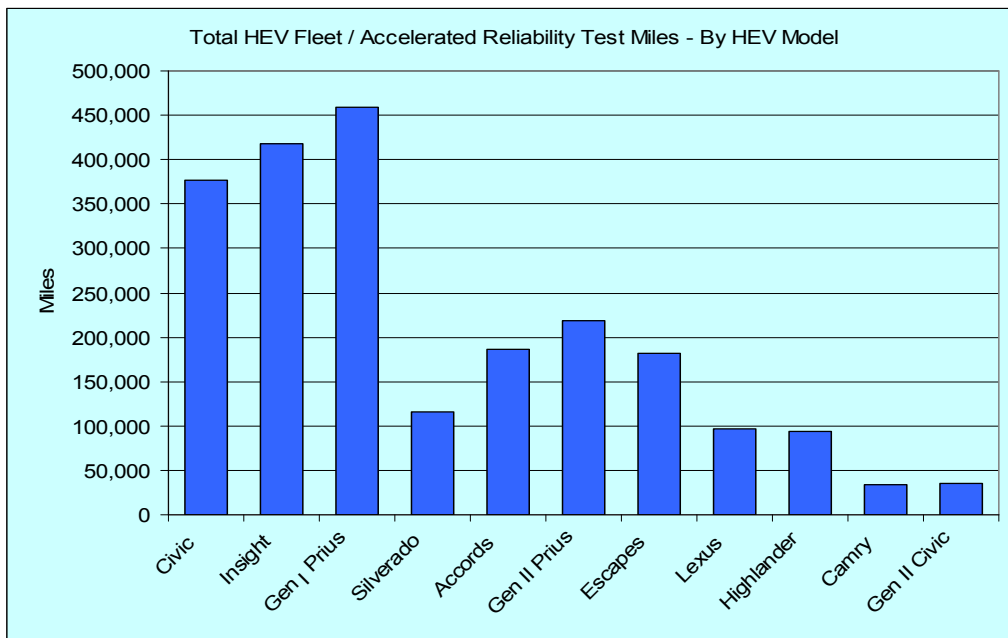


Figure 1. Total HEV Test Miles by Vehicle Model

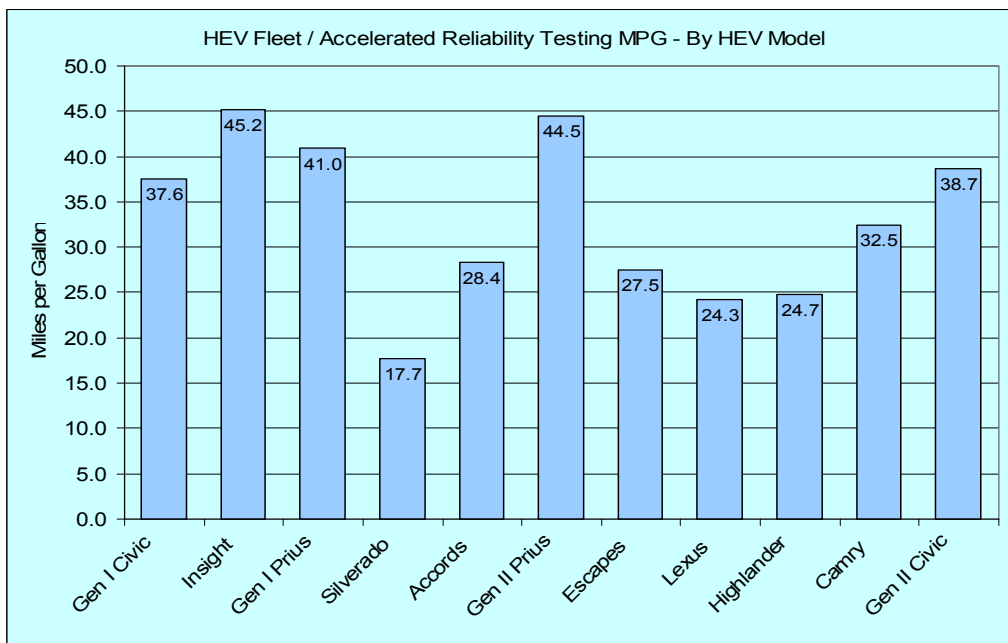


Figure 2. HEV Fuel Economy (mpg) Test Results for Each HEV Model in Fleet and Accelerated Reliability Testing

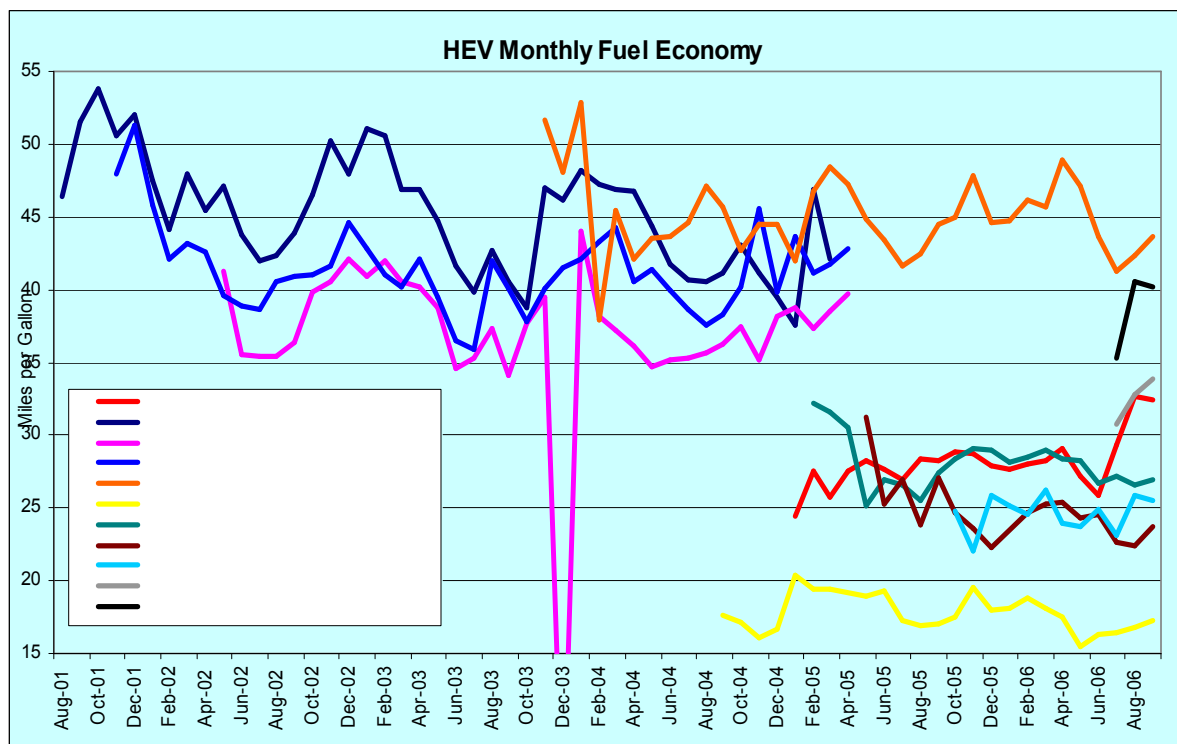


Figure 3. Monthly Fuel Economy Testing Results by HEV Model

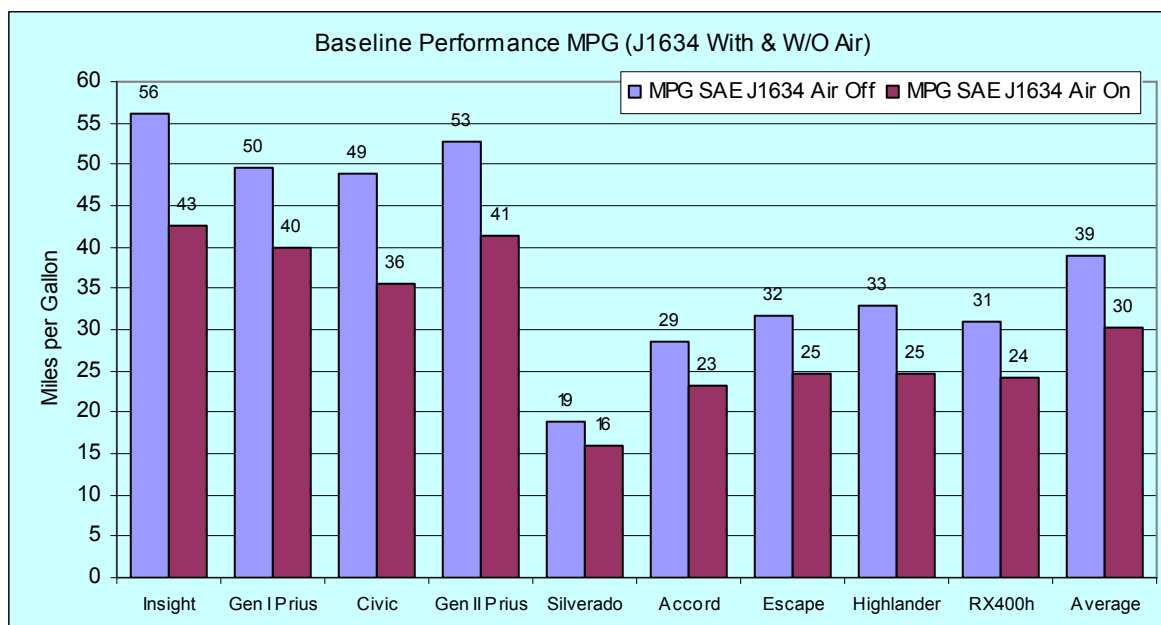


Figure 4. Baseline Performance Fuel Economy Test Results for SAE J1634 Drive Cycle Testing With the Air Conditioning On and Off

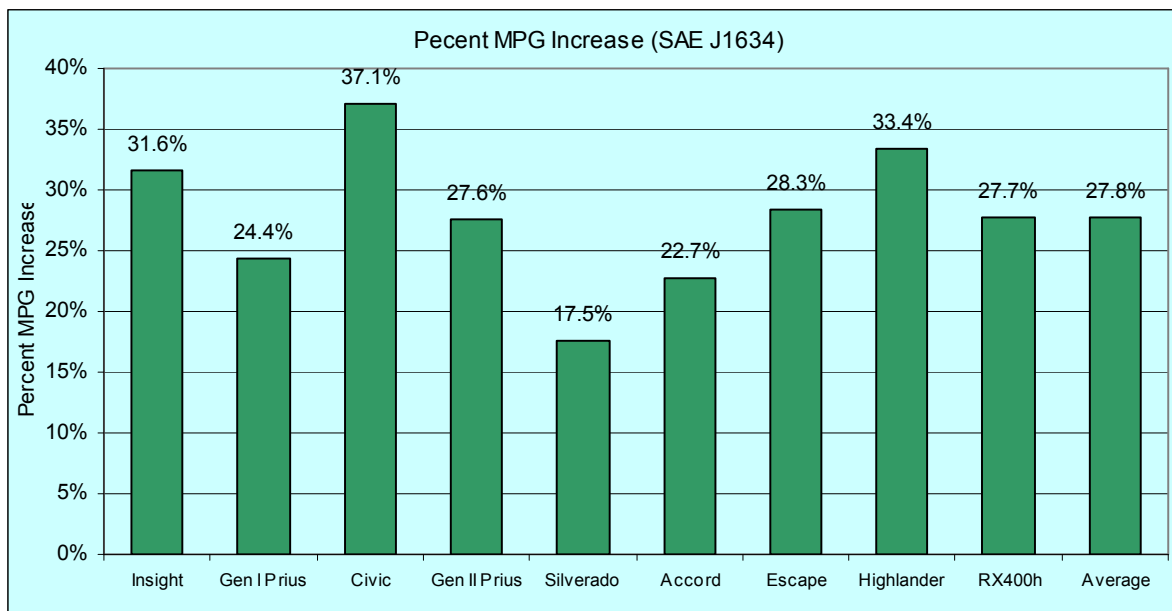


Figure 5. Percentage Increase in Baseline Performance Fuel Economy Test Results for SAE J1634 Drive Cycle Testing When the Air Conditioning is Turned Off During the Testing

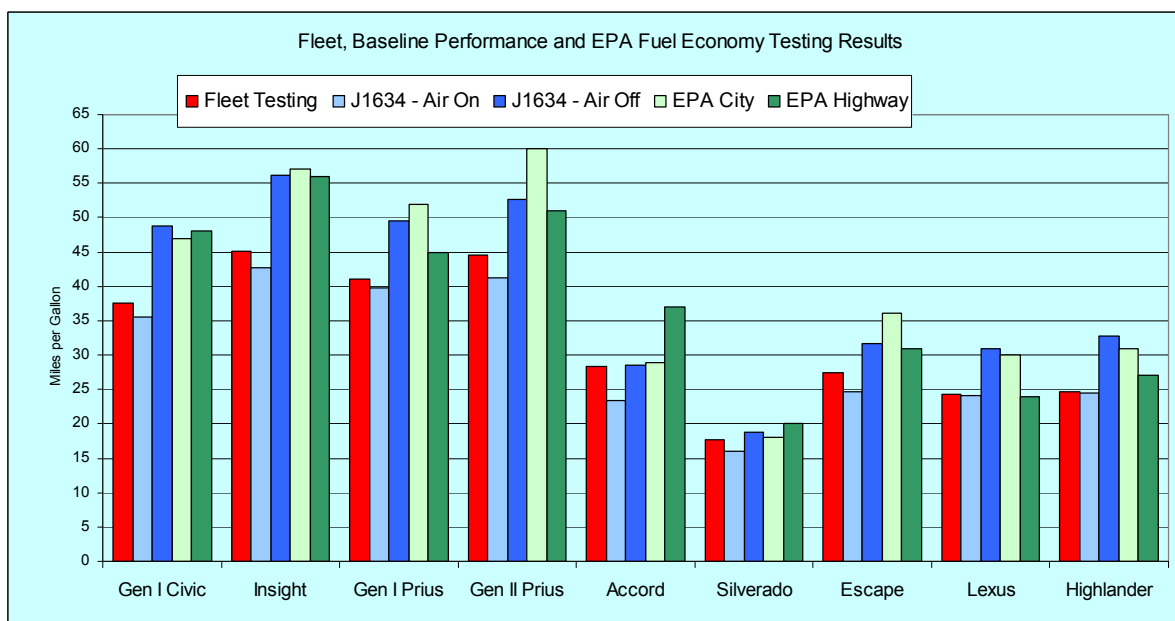


Figure 6. EPA and AVTA Fuel Economy Testing Results for the Civic, Insight, Gen I Prius, Gen II Prius HEVs, Accord, Silverado, Escape, and Lexus HEVs

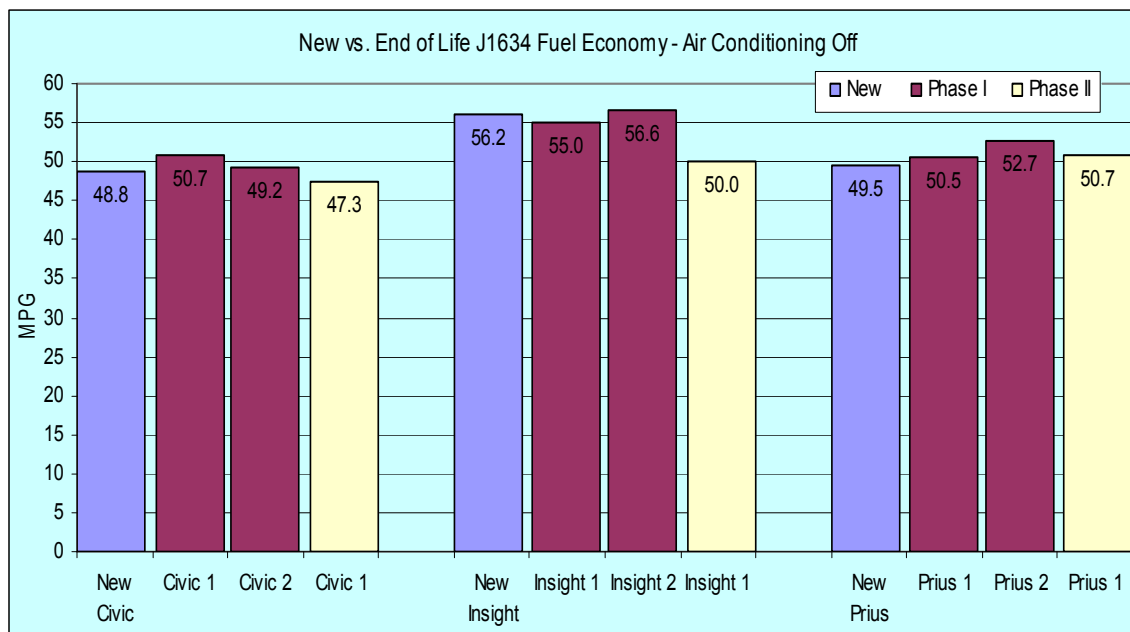


Figure 7. New Versus End-of-Life HEV SAE J1634 Fuel Efficiency Results with the AC Off

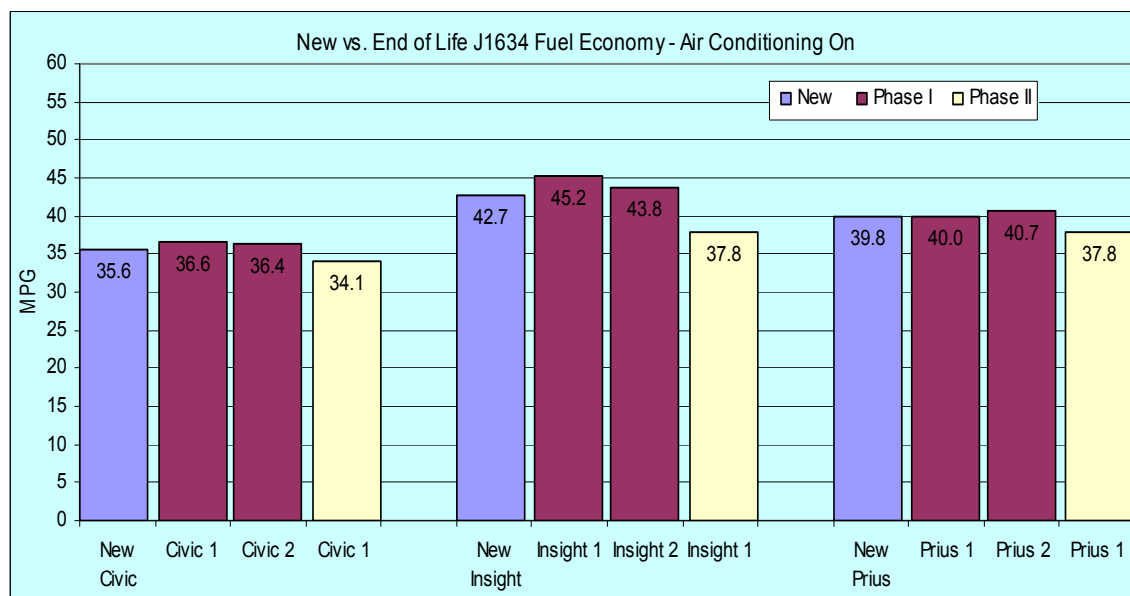
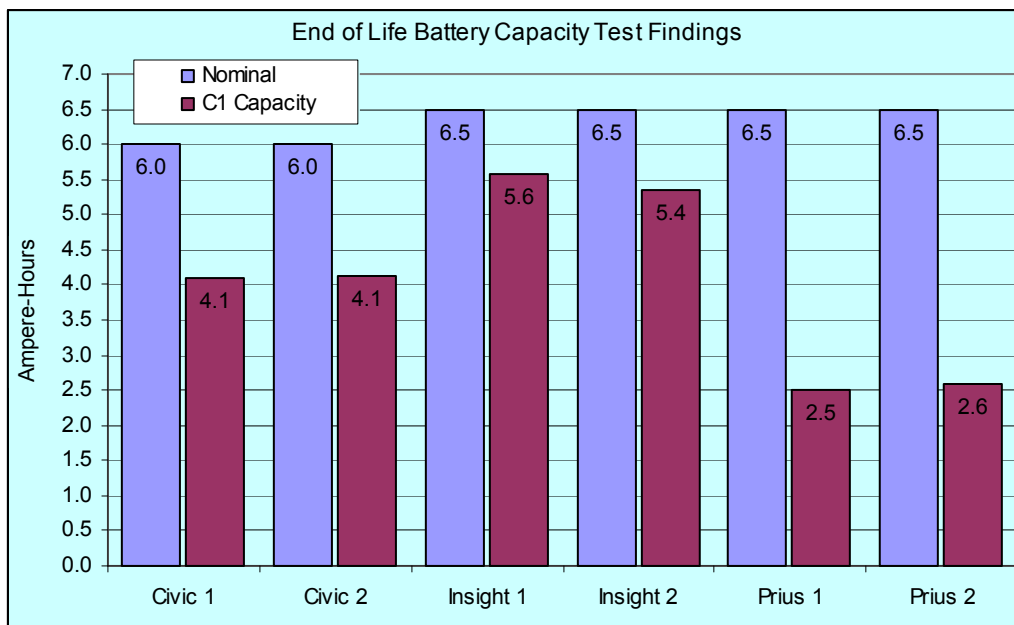


Figure 8. New Versus End-of-Life HEV SAE J1634 Fuel Efficiency Results with the AC On

Table 1. Phase II SAE J1634 Fuel Efficiency Compared to the Onboard Computer Reported Fuel Efficiency

End-of-life Phase II Test HEV	Onboard computer fuel efficiency percentage above the SAE J1634 fuel efficiency results
Civic 1 AC off	+21.7%
Civic 1 AC on	+21.0%
Insight 1 AC off	+11.0%
Insight 1 AC on	+11.7%
Prius 1 AC off	+15.7%
Prius 1 AC on	+14.7%

**Figure 9.** End of Life Battery Capacity Findings

B. Plug-in Hybrid Electric Vehicle Testing

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Objective

- Benchmark commercially available and prototype plugin hybrid electric vehicles (PHEVs).
- Reduce the uncertainties about PHEV battery performance and life, as well as document fuel (petroleum) use over various distances.
- Provide PHEV testing results to vehicle modelers and technology target setters.

Approach

- Develop PHEV baseline performance testing specifications and procedures (PHEV America) that are reviewed by industry, national laboratories, and other interested stakeholders.
- Obtain prototype PHEVs for testing based on the reviewed PHEV baseline performance testing specifications and procedures.
- Perform baseline performance tests and fleet tests on PHEV models.

Accomplishments

- Developed baseline performance testing specifications and test procedures.
- Submitted the test specifications and procedures to other national laboratories for review.
- Obtained one prototype PHEV from a original equipment vehicle manufacturers and one prototype PHEV from a vehicle converter. Ordered a third PHEV from a second PHEV converter.
- Performed due diligence on other entities claiming to have PHEVs for sale.

Future Activities

- Incorporate PHEV baseline performance testing comments and send to a larger industry/stakeholder audience for second review.
 - Continue performing due diligence on potential PHEV suppliers and obtain PHEVs for testing as appropriate.
 - Coordinate PHEV testing with industry and other DOE entities.
-

Introduction

Current hybrid electric vehicles (HEV) combine internal combustion engines (ICE) and battery storage devices to increase performance and/or fuel efficiency. The batteries commonly used in HEVs have approximately 1 to 2 kWh of onboard energy and they are charged by onboard energy sources such as regenerative braking and motor/generators powered by the onboard ICEs. Many groups are proposing and planning introductions of plugin HEVs (PHEV) that use battery packs with 5 to 10 kWh of onboard energy storage that are charged by the onboard systems as well as by onboard chargers connected to the electric grid. The concept of additional onboard energy storage and grid-connected charging raises questions that include the life and performance of these larger batteries and the actual amount of petroleum displaced over various drive cycles and distances.

Approach

The 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 200 page draft baseline performance test plan for dynamometer, test track, and inspection testing of PHEVs. In addition, two new PHEV models have been obtained with a third model ordered.

Results

The draft test plans were completed during FY06 and they were submitted for review by other National Laboratory groups. During FY07, the plans will be further reviewed by a larger group of PHEV industry and stakeholders, and the resulting comments addressed. The first two PHEV models were obtained as FY06 ended, so no testing results were yet available. The PHEVs that were obtained by the AVTA are the Renault Kangoo (Figure 1), with a Nickel Cadmium battery pack, and a Toyota Prius converted by EnergyCS, with a lithium ion

battery pack (Figures 2 and 3). The third PHEV that is on order will be another Toyota Prius converted by Hymotion, equipped with a lithium polymer battery pack.

Several other groups/vehicle converters have made PHEV product claims, but due diligence suggests that the AVTA has obtained and is obtaining all three PHEV models currently available.

Conclusions

Because of the inception state of this technology, there are not yet any vehicle testing results to report. Due diligence investigations suggests that while there are many claims of available PHEV products, the availability of fully functioning PHEV products is still very limited.

Future Activities

After incorporating all appropriate testing procedure comments, PHEV testing will commence on the first three PHEV models. As additional PHEVs become available, they will enter testing.

Publications

Because the test procedures are still in draft form and not yet available publicly, they are not referenced.



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.

C. Arizona Public Service (APS) Alternative Fuel (Hydrogen) Pilot Plant Monitoring, Hydrogen and Compressed Natural Gas (H/CNG) Dispenser Testing (real-time fuel blending), and 100% Hydrogen and H/CNG Internal Combustion Engine (ICE) Vehicle Testing

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Objectives

- Gain an understanding of hydrogen infrastructure requirements, including hydrogen production, storage, blending and delivery.
- Assess the safety, reliability and operating characteristics of using hydrogen and hydrogen / compressed natural gas (H/CNG) blended fuels for fueling and operating internal combustion engine (ICE) powered vehicles.
- Provide hydrogen vehicle, production, storage, and operations testing results to vehicle modelers and technology target setters.

Approach

- Use the APS Alternative Fuel (Hydrogen) Pilot Plant in Phoenix, Arizona to fuel two 100% hydrogen ICE Ford pickups converted by Electric Transportation Engineering Corporation (ETEC), one 100% hydrogen ICE General Motors pickup converted by ETEC/Roush, and one ETEC converted H/CNG ICE Ford F150.
- Fleet test additional H/CNG-powered ICE test vehicles to provide H/CNG ICE vehicle operating knowledge in fleet applications in the greater Phoenix area.
- Operate and test a 100% hydrogen and H/CNG fuel dispenser that blends hydrogen and CNG in real-time instead of in batch mode.
- Continue to use monitoring sensors to measure energy and water use by the Pilot Plant subsystems and components to document plant capacities and energy efficiencies.

Accomplishments

- The Pilot Plant has been operated since June 2002 with no unusual events, having fueled 100% hydrogen, H/CNG, and CNG vehicles approximately 11,500 times while producing 9,000 kilograms of hydrogen.
- No safety problems were encountered with vehicle fueling or operations.
- The vehicles demonstrated consistent, reliable behavior.
- Hydrocarbon and carbon monoxide emission levels were reduced and documented below levels observed with pure CNG vehicles and gasoline vehicles.
- Hydrogen production costs at the Pilot Plant have been documented.
- Demonstrated that vehicles equipped with ICEs can safely operate on 100% hydrogen and H/CNG fuels with varying amounts of modifications.

Future Directions

- Test additional hydrogen and H/CNG vehicles that become available.
- Continue to monitor the Pilot Plant efficiencies as an aid to setting DOE hydrogen goals.

Introduction

The APS Alternative Fuel Pilot Plant, shown in Figure 1, is a model 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 Public Service (APS), is monitoring 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. The hydrogen fuel cost data will be used as benchmark data by technology modelers as well as research and development programs.

Twenty-five H/CNG blended fuel vehicles have been operating in the APS fleet and fueling at the Pilot Plant. In addition, four different 100% hydrogen ICE vehicle models have operated out of the Pilot Plant, including a Mercedes van, two Ford pickups converted by ETEC, and a General Motors pickup converted by ETEC and Roush. These activities provide knowledge of and experience with handling and fueling hydrogen and H/CNG fuels.

Approach and Results

Alternative Fuel (Hydrogen) Pilot Plant

Hydrogen has been produced since June 2002 through electrolysis of purified water and the Pilot Plant can produce up to 18 kilograms (kg) of hydrogen per day by operating a fuel cell in reverse. The hydrogen is compressed to 6,400 PSI and stored in a storage tank. As much as 155 kg of hydrogen is stored at various pressures up to 6,000 PSI. In addition to producing hydrogen, the plant also compresses natural gas to 5,000 PSI from street service. The hydrogen production, compression and storage equipment are physically located in a large

open-air building; and the water purification, nitrogen, and helium equipment are located in an adjacent building.



Figure 1. APS Alternative Fuel (Hydrogen) Pilot Plant, with Fuel Dispensing Island in the Foreground

The fueling island is located in the forefront of the Pilot Plant. At the fueling island, hydrogen, CNG, and H/CNG dispensing are performed in the same manner. One hose dispenses hydrogen into the vehicle with a pressure rating of up to 5,000 PSI. The other hose dispenses H/CNG and 100% CNG at a vehicle pressure rating of up to 3,600 PSI.

APS Pilot Plant Monitoring

The monitoring system was designed to track hydrogen delivery to each of the three storage areas and to monitor the use of electricity on all major equipment in the Pilot Plant, including the fuel dispenser island. In addition, water used for hydrogen production is monitored to allow calculation of the total cost of plant operations and plant efficiencies. The monitoring system at the Pilot Plant allows for analysis of component, subsystems, and plant-level costs.

The monitoring software is mostly off-the-shelf, with a custom interface. The plant can be monitored over of the Internet, but the control functions are restricted to the control room equipment.

The monitoring system has identified several areas having the potential to lower costs, including using an reverse osmosis system with a higher efficiency, improving the electrolysis power conversion efficiency, and using air cooling to replace some or all chiller cooling. In addition, the knowledge gained from the monitoring system is being used to investigate hydrogen production options and costs from nuclear generated electricity.

100% Hydrogen and H/CNG Dispenser Testing

The AVTA has continued to test a prototype gaseous fuel dispenser developed by ETEC. The dispenser, shown in Figure 2, delivers three types of fuels: 100% hydrogen, 100% compressed natural gas (CNG), and blends of H/CNG using two independent single nozzles. The nozzle for the 100% hydrogen dispensing is rated at 5,000 PSIG and used solely for 100% hydrogen fuel. The second nozzle is rated at 3,600 PSIG and is used for both CNG and H/CNG fuels. This nozzle connects to both a CNG supply line and a hydrogen supply line and blends the hydrogen and CNG to supply H/CNG levels of 15%, 20%, 30%, and 50% hydrogen by volume.

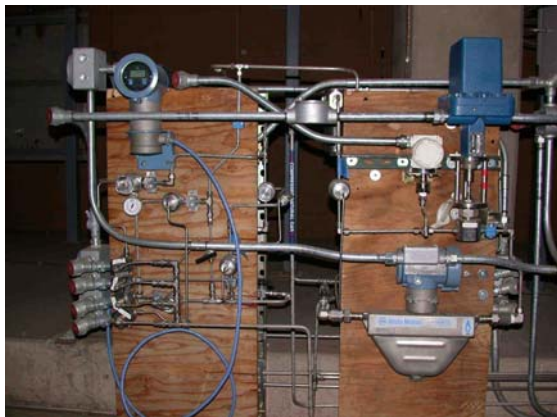


Figure 2. 100% Hydrogen, CNG, and 15, 20, 30, and 50% Blended HCNG (by volume) Prototype Dispenser Brassboard Design

The dispenser incorporates proportional flow control valves for both the hydrogen and CNG gas streams to control gas flow rates from 100 to 40,000 SCFH. These flow rates support fast fueling times—less than 5 minutes for typical light- and medium-duty vehicles. The control valves are trimmed by a digital dispenser controller using mass flow signals provided by coriolis mass flow transducers in each

of the hydrogen and CNG gas streams. The dispenser controller adjusts the control valves to provide real-time ratio control of blended fuels. The dispenser testing is ongoing. This dispenser is being commercialized by Clean Energy.

Hydrogen and H/CNG Vehicle Testing

The Arizona Public Service meter fleet of bifuel vehicles used 10,600 GGE of 15% H/CNG while being operated 190,000 miles and fueled 1,600 times. In addition, various private groups and individuals fueled at the Pilot Plant 350 times, using 1,800 GGE of mostly 15% H/CNG blends.

Two 100% hydrogen ICE pickups were previously converted to run on 100% hydrogen by ETEC and baseline performance testing was completed during FY06. The two vehicles are both Ford pickup trucks with 5.4 liter V-8 ICEs. One pickup was equipped with a 32-valve engine and the other with a 16-valve engine. The 32-valve engine produced energy efficiencies of greater than 40% on the engine dynamometer while the 16-valve engine was designed as a low-cost option.

In fleet testing, the 16-valve pickup (Figure 3) has accumulated 5,000 miles and it averaged 17.4 miles per gasoline gallon equivalent (GGE).



Figure 3. Baseline Performance Tested 100% Hydrogen, 16-Valve, 5.4 Liter Internal Combustion Engine Pickup

The changes for the 32-valve, 5.4 liter, 100% hydrogen ICE pickup (Figure 4) include changing the engine compression to 10.5 to 1 compression, using a supercharger to achieve 12 pounds of boost, and installing 3 Dynetek hydrogen tanks with an aluminum inner vessel and carbon wrap rated for

5,000 PSI operations that store 15 kilograms of hydrogen onboard.

This vehicle has started fleet testing, and it is averaging 14.4 mile per GGE on 100% hydrogen after 9,000 test miles.



Figure 4. Baseline Performance Tested 100% Hydrogen, 32-Valve, 5.4 Liter Internal Combustion Engine Pickup

ETEC and Roush Industries converted a Chevrolet 1500HD crew cab base vehicle with a 6 liter V8 CNG engine to 100% hydrogen. This vehicle has a total of 10.5 kg of 100% hydrogen stored onboard in three 5,000 psi tanks. The vehicle has a range of 14 miles per GGE in city driving and 20 miles per GGE in highway driving, giving it a range of 140 to 200 miles. It has 200 horsepower and 260 lb-ft of torque, while using lean combustion so all emissions are either ULEV or SULEV. Nine of these vehicles have been produced, with eight operating in Vancouver, British Columbia.

Publications and Presentations

1. Francfort, J.E. September, 2005. Advanced Vehicle Testing Activity – Hybrids, Hydrogen, and other Alternative Fuel Vehicle Activities Brayer. R., D. Karner, and J. Francfort. Hydrogen and Hydrogen/Natural Gas Station and Vehicle Operations – 2006 Summary Report. INL/EXT-06-11689. Idaho National Laboratory. Idaho Falls, ID.
2. Francfort, J. and D. Karner. April 2006. Hydrogen ICE Vehicle Testing Activities. INL/CON-05-00414. SAE World Congress - Paper Number 2006-01-0433. Idaho National Laboratory. Idaho Falls, ID.
3. Francfort, J.E. February 2006. Hydrogen Station & ICE Vehicle Operations and Testing INL/CON-06-01109. WestStart CALSTART Hydrogen Internal Combustion Engine Symposium. San Diego, CA.

D. Neighborhood Electric Vehicle Testing

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Objective

- Develop documented guidelines for fleet managers to follow in order to successfully introduce and operate neighborhood electric vehicles (NEVs) in fleet environments.

Approach

- Use ongoing NEV operations data and fleet experience from four NEV fleets to document NEV costs, and fleet introduction and operations experiences. Also incorporate NEV testing and operational experience of AVTA personnel from Electric Transportation Applications and the Idaho National Laboratory.

Results

- The subsequent report identified methods to improve operator and vehicle success when introducing NEVs into a fleet application. Some findings are listed below.
- Identified charge infrastructure requirements for fleets.
- Identified fast charging advantages for fleets of NEVs, including additional range that can be obtained per minute of fast charging.
- Documented preventative and corrective maintenance requirements.
- Identified operator responsibilities and training requirements.
- Documents NEV fuel costs on a per mile basis and compared this to other transportation options.

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 analyzed the potential of NEVs to reduce the use of imported petroleum and the requirements for successful fleet introduction.

During FY06, NEV operations data and the lessons learned from NEV testing in various fleets was

documented. The key questions that needed to be addressed to support successful NEV deployment included:

- What are the requirements of the different vehicle missions within my fleet?
- What NEVs are available on the market and how do I assess what will work best?
- How will NEV maintenance be performed?
- What charging infrastructure will be required?
- What training will be required to support NEV deployment?
- What will capital and operating costs be?

It is from the experience gained from testing NEVs and operating them in fleets that the issues relevant to successfully introduce and operate NEVs in fleet operations are examined.

Approach

Luke Air Force Base

Luke Air Force Base (LAFB) is located 20 miles west of Phoenix, Arizona and the facility encompasses 4,200 acres with its maximum speed on the base of 25 mph, it is an ideal application for NEVs.

LAFB is home to numerous training squadrons, each with its own command structure. Prior to participation in AVTA fleet testing, LAFB command ordered that small electric vehicles (golf carts and NEVs) would be owned by each individual squadron, rather than provided by a central motor pool as is done with full-size vehicles. Therefore, no single fleet manager was responsible for the operation of the NEVs at LAFB.

AVTA data collection was coordinated with the LAFB environmental group, which monitors all electric vehicle activity for environmental reporting purposes. Having multiple squadrons at LAFB, managing their individual NEV resources, emulates multiple small autonomous fleets operating without an automotive fleet manager. This situation would be typical of a small to medium size business in which transportation was only incidental to the business operations.

A total of 55 NEVs were tracked in the LAFB fleet and Global Electric Motors (GEM – a wholly owned subsidiary of DaimlerChrysler) was the manufacturer of all of these vehicles. Twenty-one of the NEVs were equipped to operate from a fast charger installed at a centrally located parking lot (Figure 1). Each squadron determined the necessary charge infrastructure needed to support its NEV fleet. Typically, this consisted of 120 Volt (V) alternating current (AC) single phase outlets installed at NEV parking locations (Figure 2). However, many times it consisted of the use of long extension cords reaching across an existing parking lot. Late into AVTA fleet testing at LAFB, base command established a NEV parking lot equipped with 120 V electrical outlets. This parking lot was intended to allow overnight charging of the NEVs at LAFB regardless of squadron assignment.

Mission selection was the prerogative of the individual squadron or department funding the NEV purchase, and no mission guidelines were provided other than the typically optimistic claims of range, charge time, and maintenance requirements provided by vehicle salesmen. Missions were typically categorized as on-base personnel transportation in a “motor pool” type environment. A few specific missions (e.g., flight line fire suppression system maintenance) were employed that often required vehicle modifications for hauling and/or towing equipment required for that assignment.

Maintenance was also left up to the individual funding the NEV purchase. A GEM dealer located in northwest Phoenix, approximately 20 miles from LAFB, typically performed maintenance. At various times throughout AVTA fleet testing at LAFB, NEV maintenance was also available at the base “auto shop.”

Marine Corps Recruit Depot San Diego

One of two countrywide basic training bases used for training all new United States Marine Recruits is the Marine Corps Recruit Depot San Diego (MCRDSD), which is the location for all Marine Corp basic training on the west coast. The base, located in San Diego, California, encompasses 385 acres. The posted speed limit on the base is 20 mph, making this another ideal application for

the implementation of a NEV fleet for speed-limited, short-range transportation.

The MCRDSD NEV test fleet consisted of 10 GEM vehicles. One of the GEMs was used by the administration group, and the remaining nine GEMs were modified with a “police-package” consisting of code lights located on the windshield, a siren, horn, and specialized bumpers with towing capabilities. The Military Police Force used the modified police-package GEM NEVs for a variety of functions, including base patrol, speed and traffic enforcement, the towing and placement of traffic control signs and monitors, and the transportation of the canine units (in their carriers) to assigned work areas.

City of Palm Springs

The goal of the Palm Springs NEV program was to demonstrate the potential for low-speed electric vehicles to substitute for gasoline-fueled vehicles, in a local municipality, while driving on designated (35 mph or less) roadways in the City of Palm Springs. The California Energy Commission asked the city to keep track of mileage and maintenance for a period of 1 year. Another objective of the program was to reduce vehicle emissions.

Twelve of the 31 GEM NEVs were allocated by the City of Palm Springs as follows; five for airport services, two for the Police Department, two for the City Yard and one vehicle each to the Chamber of Commerce, Information Services/Print Shop, and City Hall. Palm Springs Unified School District used three GEMs as part of an operating fleet.

Agua Caliente Spa Hotel and Casino in Palm Springs operated a fleet of six GEMs. Administrative, Building Maintenance, Computer IT, and Security staff used these vehicles.

An innovative businessman initiated a rental business, GEM Rentals of Palm Springs, located in the downtown area. The 5-vehicle fleet consisted of 2- and 4-passenger GEMs. The rental vehicles were used by tourists as a fun and colorful alternative form of transportation for recreational and sightseeing use. Although the concept was unique and applicable to the city, it did not result in a viable long-term business, and the vehicles were sold.

NEV use by five private citizens was monitored and included in the private citizen fleet data. These vehicles were used for a variety of purposes; one was used to assist with duties as a crossing guard at the school, another private citizen used the vehicle for use in a small pool maintenance and service business, and the remaining three NEVs were used for personal transportation.

Palm Valley Private Parties

Another private fleet included in the AVTA NEV data collection effort was in Palm Valley, Arizona, a suburb located 18 miles west of downtown Phoenix. Six of the GEM NEVs were converted to be able to use a fast charger, which was installed at the community golf club, and it was accessible to the public. These vehicles were typically used for personal transportation in the Palm Valley community and for golf. Overnight charge infrastructure was available at each NEV owner’s home.

In the government fleets, the fleet managers were allowed to develop the infrastructure necessary to support NEV operation, including charging, maintenance, mission selection, and operator training, and a fast charger was provided to the fleet manager to assist with charge infrastructure development. For private vehicles operated in Palm Valley and Palm Springs, a fast charger was installed at a location convenient to the NEV owners.

Results

A total of 168,419 miles (Table 1) were accumulated on the 101 NEVs. Various types of GEM models were included in the fleet. These included 2-passenger, 4-passenger, and long-bed and short-bed models. Some vehicles were modified with option packages to better accommodate functional use.

Although no formal mission criteria were identified to purchasers of NEVs participating in the testing, misapplication of vehicles was rarely a problem. Vehicles were typically applied into missions in which a daily reliable single-charge range was sufficient to support the mission. In a few circumstances, vehicles were placed in private applications into missions where daily range

requirements were beyond the reliable single-charge performance of the vehicle. For example, a swimming pool service in Palm Springs attempted to use a GEM for conducting its service route. Although a serious effort was made to adjust the route and opportunity charge using the Palm Springs fast charger, the effort was abandoned as the fast charger was not convenient to the pool service route. Rather than provide range extension, the fast chargers were used to replace overnight charge infrastructure. The fast charger could rapidly recover NEVs that were unable to charge overnight because of limited convenience outlet availability or because the NEV was not being plugged in.

Charge infrastructure was a serious problem at LAFB and, to a much lesser extent, in all other fleets. As NEVs charge from a Level 1 (120 V single phase) convenience outlet available in every electrified building, charging infrastructure was typically not an issue in the minds of NEV purchasers. When vehicles were aggregated in small numbers, sufficient convenience outlets were typically available to support charging. However, when large numbers of vehicles were aggregated, such as at LAFB, the available Level I 120 V convenience outlets were not sufficient to support charging needs. This resulted in overloading circuits by connecting multiple vehicles to a single circuit, vehicles not being charged, and extension cords stretching throughout NEV parking locations.

Vehicle maintenance was an issue in all fleets, becoming more critical in fleets such as LAFB where the NEVs were heavily used. Maintenance issues were both economic and logistic. Many NEV users had not anticipated the maintenance requirements of their vehicle and had no budget to maintain the vehicle. This resulted in vehicles being out of service for extended periods (often months) while waiting for repairs to be funded. When maintenance could be funded, it was necessary to use a GEM dealer or GEM mobile service (when available). Both sources required advanced scheduling and travel (either by the technician or the vehicle), which required several days to weeks to organize. Travel requirements also significantly impacted maintenance costs. Examples of maintenance costs for selected repairs are shown in Table 2. Some of the specific findings included:

- Mission selection can be done informally when the total daily operating range requirement is within the single-charge capability of the NEV, but it must be more formally conducted when opportunity charging is required to extend vehicle range beyond single-charge capability. Mission requirements must be coordinated with charging infrastructure and vehicle selection.
- Charge infrastructure for fleet vehicles must be formally provided. Where multiple vehicles congregate, convenience outlets provided for normal building services are not sufficient to provide charging power. Additional charging outlets must be provided, preferably in close proximity to NEV parking locations.
- Fast charging can provide a backup to overnight charging when NEVs do not receive an overnight charge. However, fast charging is not routinely used unless vehicle missions require opportunity fast charging.
- As a general rule of thumb, the following range extension can be expected: 120 V onboard charging can add 0.1 miles of range per minute of charging, and offboard Level 3 Fast Charging can add 1.0 miles of range per minute of charging.
- Preventative and corrective maintenance must be available promptly and at a reasonable cost to support NEV operations. Fleets of even moderate sizes should consider establishing contract or in-house maintenance capabilities to support their NEV operations. Preventative maintenance (including battery watering) should be the function of contract or in-house maintenance staff and not a function of the operator.
- Operators in all fleets must be made aware of vehicle range limitations, unique requirements (such as disconnect switches), and preventative maintenance requirements (such as battery watering).

Comparing NEV Fuel Costs per Mile

The efficiency at the charger, for the twelve NEVs baseline performance tested by the AVTA that used onboard chargers and conductive connectors, is used for the NEV propulsion efficiency. On average, the 12 NEVs required 152 watt-hours AC per mile traveled (Table 3). The efficiency at the charger measures the electrical energy for which the NEV

operator must pay the electric utility. It is measured offboard the vehicle, at the utility and NEV connection.

Because NEVs may be charged at many locations, NEV fuel cost per mile is calculated based on the average 2005 electricity rates for three sectors: residential rate—9.42 cents per kWh, commercial rate—8.68 cents per kWh, and industrial rate of 5.57 cents per kWh.

NEVs are often used in a fleet mission to replace an internal combustion engine vehicle. Many times they replace a pickup truck that may have an energy efficiency of less than 20 mpg. However, for the sake of argument, a fleet manager may also be considering using a hybrid electric vehicle instead of a NEV to replace an internal combustion engine vehicle. Therefore, in addition to assuming the internal combustion engine vehicle options get 20 and 30 mpg, a hybrid electric vehicle that is assumed to get 45 mpg (as do the Honda Insight and Toyota Prius in AVTA testing) is also included for comparison.

Recently, the cost for a gallon of gasoline has been highly volatile. Gasoline unit costs of \$2.50 per gallon and \$2.91 per gallon (a recent national high) were assumed.

As can be seen in Figure 3, the fuel cost per mile for NEVs is significantly lower than the other hybrid electric vehicle and internal combustion engine vehicle options. However, NEVs may provide less vehicle utility than hybrid electric vehicles and internal combustion engine vehicles. That is, the NEVs may not be able to perform some missions that require carrying greater payloads, traveling off-road, and providing more cabin environmental comforts such as air conditioning. However, if a NEV is capable of meeting mission needs, they can be a very viable economic option for a fleet.

Future Plans

The AVTA has been contacted by several new manufacturers of NEVs and is planning on conducting baseline performance testing on new NEV models.

Publications

1. Brayer, R., D. Karner, K. Morrow, and J. Francfort. *Guidelines for the Establishment of a Model Neighborhood Electric Vehicle (NEV) Fleet*. INL/EXT-06-11309. Idaho National Laboratory. Idaho Falls, ID.
2. Francfort, J.E. June 2006. *Hybrid Electric Vehicle and Lithium Polymer NEV Testing*. INL/CON-05-01003 42nd Power Sources Conference. Philadelphia, PA.



Figure 1. Luke Air Force Base SuperCharge Station



Figure 2. Luke Air Force Base NEVs Charging at 110 Volts

Table 1. NEV Fleet Mileage Accumulated

NEV Fleet	Number NEVs	Total Miles
United States Air Force—Luke Air Force Base	55	113,317
United States Marines—MCRDSD	10	11,858
City of Palm Springs—City Fleet	12	14,990
Palm Springs—Agua Caliente Band of Cahuilla Indians	6	11,349
City of Palm Springs—Public School District	3	4,915
Palm Springs—Private Vehicles	5	5,717
Palm Springs—GEM Rentals	5	5,276
Palm Valley—Private Vehicles	5	997
Totals	101	168,419

Table 2. Sample NEV Fleet Testing Maintenance Costs

Vehicle Fleet	Vehicle Type	Maintenance Required	Maintenance Cost
LAFB	GEM Long Bed	Battery Replacement	\$1,035
		Charger Replacement	\$1,015
		Controller Replacement	\$565
		Tire Replacement	\$465
City of Phoenix	GEM 4 passenger	DC-DC Converter Replacement	\$665

Table 3. NEV Energy Efficiency as Measured at the Charger During NEV America Baseline Performance Testing for the 12 NEVs Tested with Onboard Chargers and Conductive Connectors

NEV Model	Efficiency at Charger (Watt-hours per mile)	NEV Model	Efficiency at Charger (Watt-hours per mile)
GEM 2005 4 passenger	169	GEM 2002 4 passenger	141
GEM 2005 2 passenger	184	GEM 2002 2 passenger	125
GEM 2005 short bed	176	GEM 2002 long bed	131
GEM 2005 long bed	182	GEM 2002 short bed	109
Ford/Th!nk 4 passenger	168	ParCar 4 passenger	145
Ford/Th!nk 2 passenger	163	ParCar 2 passenger	133
Average NEV Energy Efficiency (for all 12 NEVs)			152

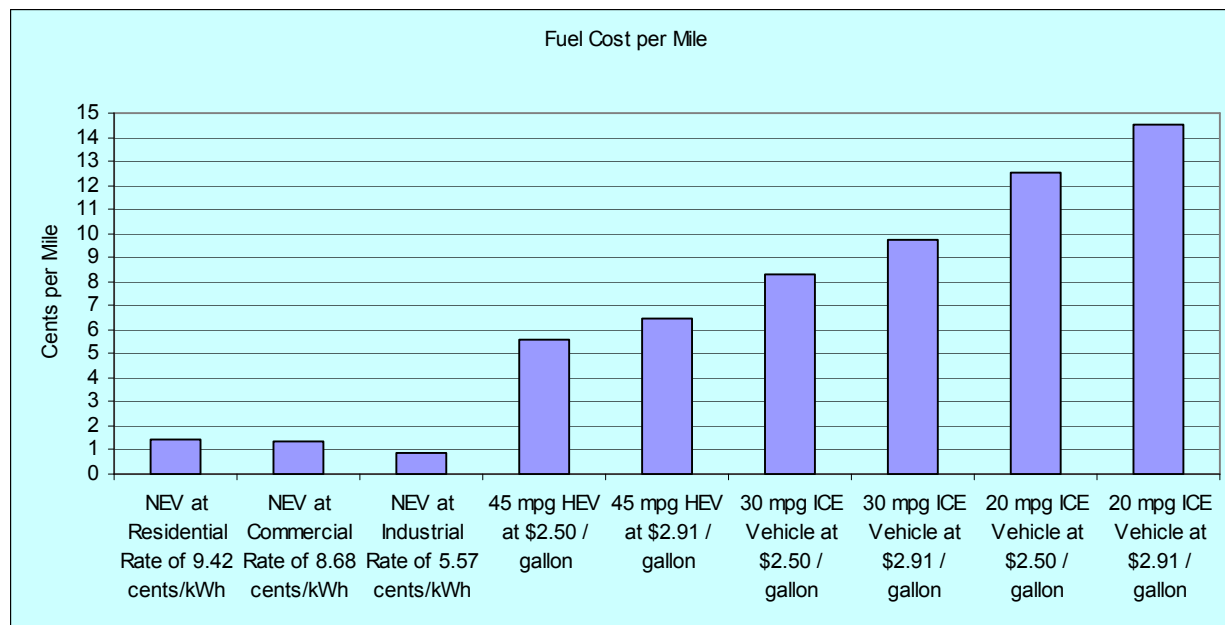


Figure 3. Fuel Cost Per Mile for NEVs, Hybrid Electric Vehicles (HEVs), and Internal Combustion Engine (ICE) Vehicles. Three NEV Electricity Costs are Used as are Two Gasoline Costs.

E. Urban Electric Vehicle Testing

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Objective

- Test and document the performance and reliability of urban electric vehicles (UEVs).

Approach

- Fleet test Nissan Hypermini UEVs.

Results

- Eleven Hyperminis were drive a total of 41,220 miles, over 439 months of use.
- Identified warranty needs, including 6 of the 11 vehicles required drive system repairs.
- Documents charging requirements.

Future Activities

- If recent product announcements come to fruition and additional urban electric vehicles are introduced, the AVTA will test them.

Introduction

Urban electric vehicles (UEVs) are pure electric passenger vehicles classified by NHTSA as regular passenger vehicles, and are subject to the same FMVSS requirements as full-size electric and gasoline-powered passenger vehicles. Unique benefits of UEVs include easier parking and better fuel economy under urban driving conditions due to their small size.

Approach

The AVTA, in partnership with the California cities of Vacaville and Palm Springs, collected mileage and maintenance and repairs data for a fleet of eleven Nissan Hypermini urban electric vehicles (UEVs). The eleven Hyperminis were deployed for various periods between January 2001 and June 2005.

The Nissan Hypermini Demonstration Program was an effort to determine whether the UEV concept was viable in the United States. The Hypermini HEVs were considered to have commercial potential because of emission cleanliness, reduced energy consumption, lower operating costs, and the convenience of home charging. Nissan leased 30 Hyperminis in California to state municipalities and utility companies. The vehicles and chargers were leased for a period of three years at a cost of \$99 per month, which included installation of the required charging unit. Under the program, Nissan hoped to obtain real-world data to assess the marketability of electric-drive vehicles in California.

The Hypermini (Figures 1 and 2), is 8.3 feet in length, 5 feet tall, and accommodates two passengers, with minimal cargo space. Locating the battery pack beneath the floor creates a low center of

gravity and high road stability. The Hypermini has a top speed of 60 mph and a marketed range 60 miles and are equipped with air conditioning, lithium-ion batteries, anti-lock braking, and dual air bags. The vehicles fully recharge in four hours using an inductive charger.

The AVTA obtained the final data during the fall of 2005, and the data was reported during early FY06.



Figure 1. Nissan Hypermini UEV Side View



Figure 2. Nissan Hypermini UEV Front View

Results

Nissan leased six Hyperminis to the City of Vacaville, a 27 square mile city of about 100,000 residents, located about 30 miles southwest of Sacramento in Northern California. The UEVs were assigned to various departments and services: one to the Police Department for parking enforcement, one to their recycling program (Public Works) for travel to promotional and educational events, one to their Central Garage, and three to Traffic and Engineering. The vehicles were used for a variety of work-related functions. This fleet was well-

established, and some operations data had been collected before the city joined the AVTA test. The Vacaville fleet was driven a total of 16,763 miles during a total of 204 months of use. Each Hypermini was driven an average of ~20 miles per week.

The City of Palm Springs also leased five Hyperminis. These vehicles were also used for city-based services, which included Parks and Recreation, Airport Services, City Hall, Planning and Code Enforcement, and Information Services/Print Shop. The Palm Springs fleet was driven a total of 24,457 miles during a total of 235 months of use, with each being driven an average of about 25 miles per week.

During the combined total of 439 months of use, the eleven Hyperminis were driven a total of 41,220 miles by staff from both cities. This equates to an average use of about 22 miles per week per vehicle.

Early in the program, the vehicles were repaired to correct a warranty-covered charging problem when the vehicles were recalled to upgrade the electrical system. Of the eleven Hyperminis, six required drive system repairs. One of the vehicles was involved in a collision, resulting in a significant out-of-service period. As the vehicles aged, it was reported that the auxiliary battery on the Hypermini would drain if the vehicle had not been driven for several days. This was a concern, because the vehicle could not be charged if the auxiliary battery was low. Frequently, the battery could be recovered with a charge or jump; however, two vehicles required replacement of the auxiliary batteries at no charge. In some cases, maintenance requiring replacement parts or specialty services resulted in the vehicle being placed out of service for significant periods of time. The delays prompted the City of Vacaville's central garage staff to initiate a preventative maintenance program. With the assistance of the local Nissan dealer, they were able to set up and conduct an effective program that involved such routine tasks as checking fluid levels and rotating tires. When replacement parts such as tires or batteries were required, Nissan would provide them to the garage, and the work would be done in the city's central garage, resulting in dramatic reductions in out-of-service time.

There were some early problems with the vehicles, including a charging problem and a need to upgrade the electrical system. In addition, six vehicles required drive system repairs. However, the repairs were all made under warranty.

The Hyperminis were generally well-liked and provided drivers with the ability to travel any of the local roads. Full charging of the Hypermini's lithium-ion battery pack required up to 4 hours, with about 8–10 miles of range available for each hour of battery charging. With its right-side steering wheel, some accommodation of customary driving methods was required to adapt for different blind spots and vehicle manipulation. For that reason, the drivers received orientation and training before using the vehicle. The Hypermini is instrumented in kilometers rather than in miles, which required an adjustment for the drivers to calculate speed and range. As the drivers gained familiarity with the vehicles, there was increased acceptance and a preference for using it over traditional city vehicles. In all cases, the Hyperminis attracted a great amount of attention and interest from the general public.

Future Plans

The AVTA does not currently have any UEV testing underway. However, given the potential of this niche market and various product announcements, the AVTA will test new entrants, especially if advanced batteries are used in the vehicles.

Publication

1. Brayer, R. and J.E. Francfort. January 2006. *Nissan Hypermini Urban Electric Vehicle Testing*. INL/EXT-06-01072. Idaho National Laboratory. Idaho Falls, ID

F. Oil Bypass Filter and Diesel Engine Idling Wear-rate Evaluation Testing

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Objective

- Test the concept of using oil bypass filters on diesel and gasoline engines to extend oil change intervals and reduce petroleum consumption.
- Support efforts to minimize diesel engine idling and reduce the annual consumption of millions of gallons of diesel fuel during heavy vehicle idling periods by conducting tests to characterize diesel engine wear rates during extended engine idling periods.

Approach

- Install PuraDYN and Refined Global Solutions (RGS) oil bypass filters on Idaho National Laboratory (INL) fleet vehicles, including 11 diesel buses and six gasoline Chevrolet Tahoes.
- Judiciously collect engine oil samples and perform oil analyses to determine the quality of the engine oils for continued use.
- Two INL fleet buses (equipped with Detroit Diesel Series 50 engines) were idled for 1,000 hours each. Engine wear metals were characterized from weekly oil analysis samples and destructive filter analyses. Engine oil full-flow and bypass filter cartridges were removed at four stages of the testing and sent to an oil analysis laboratory for destructive analysis to ascertain the metals captured in the filters and to establish wear-rate trends. Weekly oil samples were also sent to two independent oil analysis laboratories.

Results

- 1.3 million test miles were accumulated over the 3-year evaluation, with 982,548 test miles accumulated on the eleven buses and 303,172 test miles on the six Tahoes.
- PuraDYN oil bypass filter systems were tested onboard eight of the buses and six Chevrolet Tahoes for 1,173,552 miles. Refined Global Solutions (RGS) oil bypass filter systems were tested onboard three buses for 112,168 miles.
- Only 15 oil changes were required on the INL buses during the 3 year evaluation. Eight were required due to degraded oil quality, and seven for mechanical or human problems that included dipstick fitting failure, fuel dilution, mechanic error, injector failure, or intentional engine oil flushing.
- Low Total Base Numbers (TBN) alone, or in conjunction with high oxidation/nitration levels, necessitated seven of the eight bus oil changes. One oil change was required due to high oxidation/nitration levels alone. Seventy-two bus engine oil servicing events occurred during the evaluation, and with eight oil changes required because of degraded oil qualities, 64 oil changes were avoided by using the oil bypass filter systems. The 64 avoided oil changes means 2,164 quarts (541 gallons) of new oil was not consumed nor generated as waste oil. This equates to an 89% reduction in bus oil changes.
- The Tahoes were tested in several test periods. During the first period, the six Tahoes using bypass oil filters achieved a 75% reduction in oil changes and oil use from avoided oil changes. During a middle testing period, various problems, some caused by operations in subzero temperatures and some from human errors, resulted in

poor oil-use-avoidance rates. However, during the third testing period, the Tahoes had an 86% reduction in oil changes and oil-change-oil-use when a premium grade of oil was used during the third testing period.

- Depending on the assumptions employed, INL found that oil bypass filter systems for diesel engine equipped buses have a positive payback between 72,000 and 144,000 miles. The positive payback period for the gasoline engine Tahoes is between 66,000 and 69,000 miles.
- Concurrent with the filter analysis, a comprehensive array of other laboratory tests ascertained the condition of the oil, wear particle types, and ferrous particles during the idling test. Extensive ferrogram testing physically showed the concentration of iron particles and associated debris in the oil. The tests results did not show dramatic results during the extended idling periods, but did show wear trends.

Future Activities

- Both the oil bypass evaluation and the engine idling activities were completed during FY06.

Approach

Oil Bypass Filter Evaluation

Eleven INL four-cycle diesel-engine buses used to transport INL employees on various routes and six INEEL Chevrolet Tahoes with gasoline engines are equipped with oil bypass filter systems from the puraDYN Corporation and RGS, shown in Figure 1 and 2, respectively. Both filters are reported to have engine oil filtering capability of <1 micron and a heater component to evaporate undesirable fluids. PuraDYN also has an additive package to facilitate extended oil-drain intervals. The bypass filters are installed in the engine bays of the INL buses, shown in Figures 3 and 4. The condition of the engine oils was closely monitored by obtaining three oil samples every 12,000 miles in the buses and every

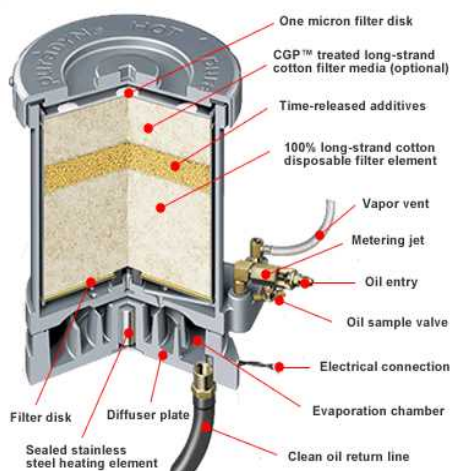


Figure 1. Cutaway View of a puraDYN Oil Bypass Filter

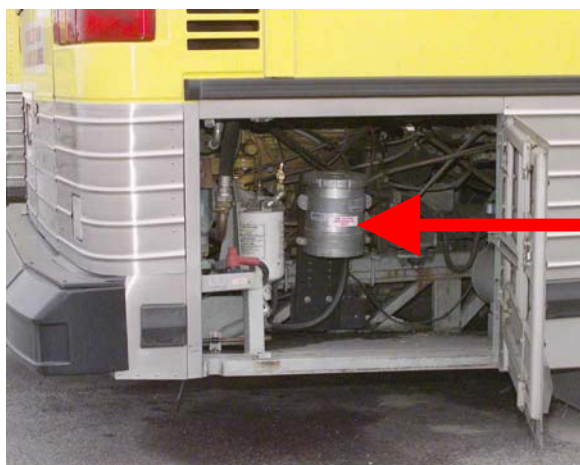


Figure 2. Engineering View of a RGS Oil Bypass Filter

3,000 miles in the Tahoes. Of the three samples, two were sent to two Tribology test labs and the third sample was archived. Based on the test results, the oil would either continue to be used or changed.

Diesel Engine Idling Wear-rate Evaluation Test

A diesel engine wear-rate evaluation was undertaken to support DOE's effort to minimize diesel engine idling in the United States and the annual consumption of over 850 million gallons of diesel fuel during periods of engine idling for heating, cooling, and auxiliary power generation purposes. In addition to the economic advantage of minimizing the use of fuel by avoiding engine idling, there is the



PuraDYN Oil Bypass Filter

Figure 3. PuraDYN Oil Bypass Filter Installed on an INL Bus

RGS Processor (Liquid Heating) Unit

RGS Filter Unit

Figure 4. RGS Oil Bypass Filter Installed on an INL Bus

possible economic advantage of extending engine life and maintenance intervals.

The INL characterized diesel engine wear and lubricating degradation due to extended periods of engine idling versus “normal” engine operations by idling two INL buses equipped with DD Series 50 engines for 1,000 hours each. The engine wear metals were characterized by analyzing the engine oil and by destructively analyzing the bypass and full flow oil filters to measure the engine wear metal particles captured.

The idle test began when the flushing oil was drained and new oil was again added to the bus engines. Both buses were then run on their respective routes for about 6,000 miles to age the test oil before the idling began.

To monitor the rates of engine wear metal, oil samples were taken each Monday and sent to two oil analysis laboratories for analysis. Also, at various intervals, the filters (one bypass and one full-flow filter) were removed and sent to National Tribology Services (NTS), Inc., of Minden, Nevada for destructive analysis. The filter test periods were (a) after the 6,000 miles of oil aging, (b) after 400 hours of engine idling, (c) after an additional 400 hours of idling (800 total hours), and (d) after 200 additional hours of idling (1,000 total hours of idling). The destructive filter analysis helped monitor the rates of engine metal wear and characterized what the filters captured, including qualitative evaluation of wear particle types (i.e., rubbing, fatigue and cutting) was captured and particle sizes. While the actual bus idling occurred during FY-2005, the data analysis and report

preparation occurred during FY06, so it is included in this annual report. New West Technology participated in the data reduction and analysis.

Results

Oil Bypass Filter Evaluation - Buses

The 11 diesel-powered buses traveled 982,548 miles during the entire evaluation. Figure 5 shows the quarterly and cumulative evaluation test miles for the buses. Figure 6 shows the total evaluation test miles by bus per test quarter. Figure 7 shows the total miles accumulated by bus, the miles achieved per oil change by each test bus, and the number of oil changes each bus would have experienced without the use of oil bypass systems.

Figure 7 does not show whether the 15 oil changes were due to poor oil quality or necessitated by human error or mechanical problems not part of the oil bypass evaluation. Buses 73416 and 73426 never did have an oil change during the test, but the other nine buses did have at least one oil change. Of the first nine oil changes (one per bus), four were the result of mechanical problems not due to poor oil quality issues. The two earliest oil changes (Figure 7) were early in the evaluation for bus 73413 due to a dipstick fitting failure, and for bus 73448 because of an inadvertent oil change. Each engine can be unique in its ability to extend the oil drain intervals. Extended oil drain intervals are also directly related to other intangibles such as operating environment, driver habits, engine age, oil usage, and mechanical problems. The total miles traveled by all the buses up to the first oil changes were 651,143 miles (considering all oil changes due to either mechanical problems or poor oil quality). Dividing 651,143 miles by 11 (the number of test buses) would be 59,195 miles per bus. This average is close to what three buses actually achieved. Two other buses had fewer miles, but these two buses had not yet had an oil change when the evaluation ended. Four more buses had much more miles on their first oil change, between 70,000 and 130,000 miles. Table 1 shows the complete history of oil changes and mileage accrued on the oil.

There were eight oil changes because of degraded oil quality and seven oil changes because of mechanical or human problems. The eight oil changes due to degraded oil quality were primarily

because of degraded TBN (total base number). The mechanical problems included injector failure and fuel dilution. Once, the oil was inadvertently changed by human error and it was also changed in two buses in preparation for the engine idling test.

Because there were 15 oil changes, 8 from degraded quality and 7 from mechanical or human reasons, there are some assumptions used to calculate the actual oil saved by using bypass filters for this evaluation. For this calculation, none of the mechanical or human problem oil changes were considered. Table 2 shows the calculated oil volume of 541 gallons saved during this evaluation.

Dividing the 982,548 total bus test miles by 12,000 miles (the “normal” INL bus oil change service interval) suggests that there would have been almost 82 service intervals, but in actuality the buses had 72 service intervals. The buses are typically called into service each time they reach 12,000 miles. The service “tickler” program used by the maintenance personnel is based on the mileage that is recorded by the bus drivers when the buses are fueled. Occasionally, the buses were operated farther than the 12,000 mile intervals, and this accounts for the difference between the actual service events (72) and the calculated events (82).

Another way to measure the success of bypass oil filtration is to look at the number of oil changes avoided and calculate the percentage of oil saved. In calculating the percentage of oil saved, the mechanical oil changes were not used, but the number of avoided oil changes was divided by the total service intervals. In the case of the INL buses used in this evaluation, there was an 89% reduction in oil-change oil use and a concurrent 89% avoidance of waste oil generation. Table 3 shows the number of serving intervals, oil changes, and avoided oil changes.

Three scenarios were considered for the economic analysis of installing bypass filter systems on the diesel-engine-equipped INL buses. The costs were computed over 504,000 miles for each of the three bus scenarios (assumes the approximate life of a bus diesel engine at 500,000 miles, and an equal number of 12,000-mile oil service segments). This analysis assumes that a bypass filter system would operate for all 504,000 miles on a diesel bus engine and that

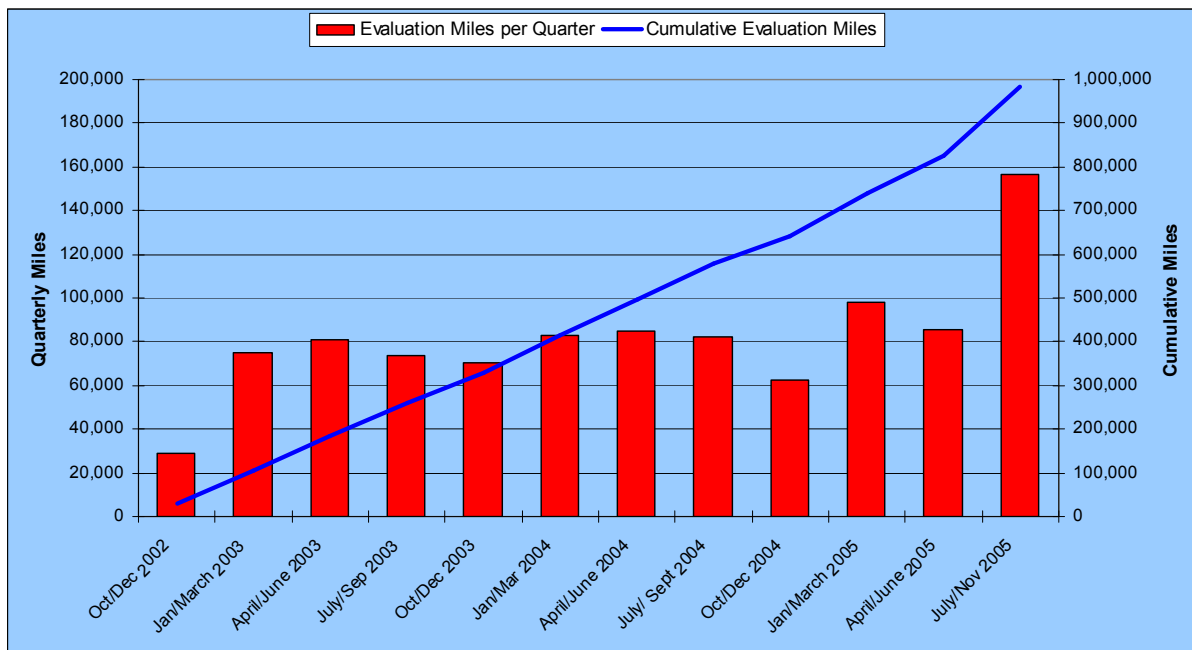


Figure 5. Quarterly and Cumulative Miles Traveled by the Test Buses

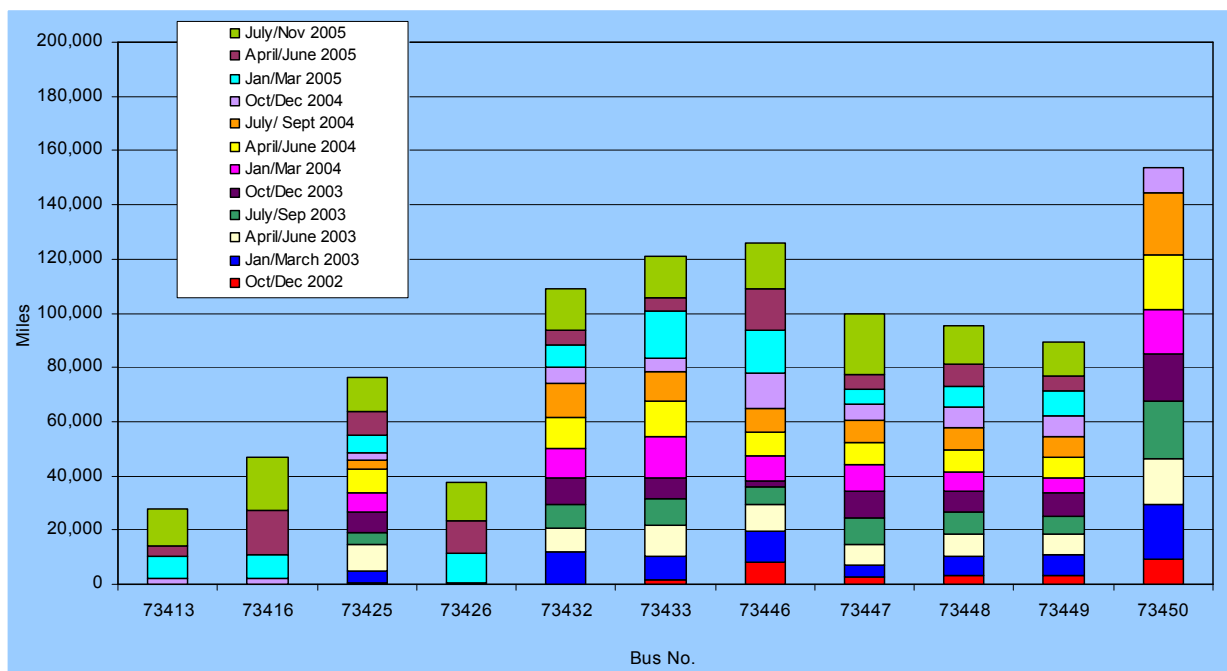


Figure 6. Total Evaluation Miles by Bus and Per Quarter

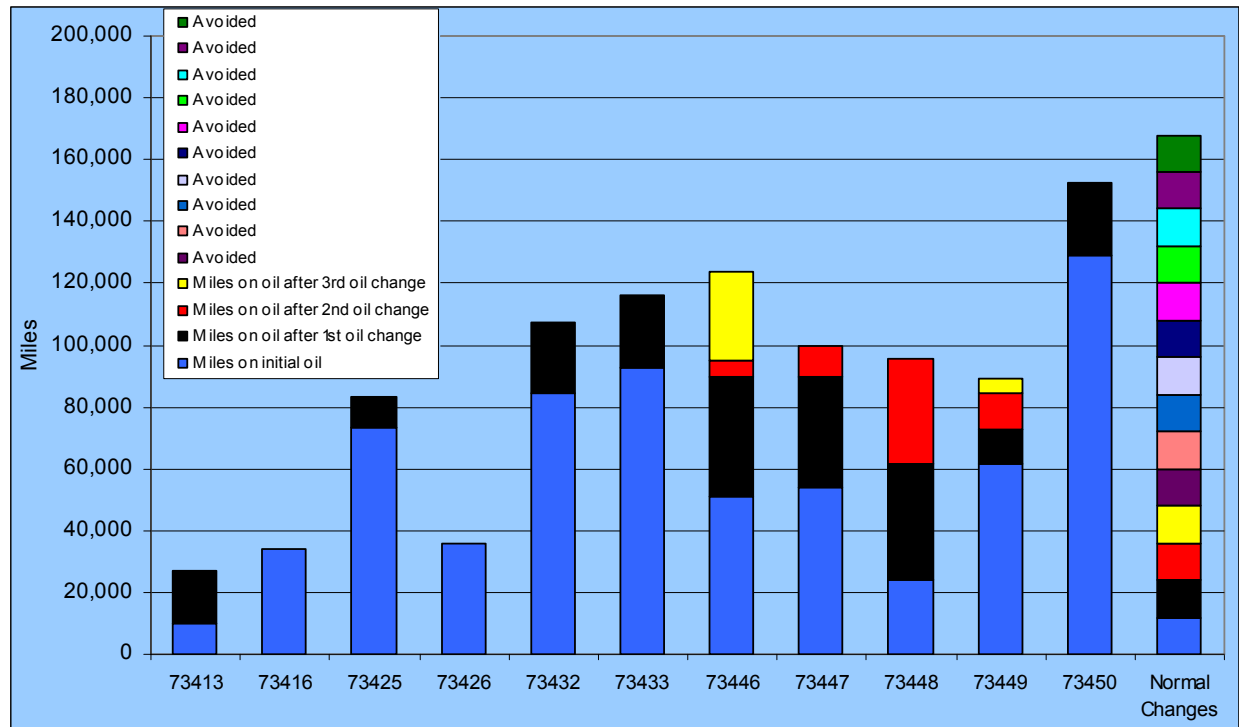


Figure 7. Test Miles Per Oil Change by Individual Bus. The “Normal Changes” Bar Shows the Number of Oil Changes That Would Have Occurred if the Engine Oils were Changed Every 12,000 Miles

Table 1. History of Oil Changes, Miles On Oil, and the Reasons For the Oil Change

Bus	1st change date & miles on oil	Reason	2nd change date & miles on oil	Reason	3rd oil change date & miles on oil	Reason	Total test miles
73413	4/13/05 10,250	Dipstick fitting failure					27,856
73416	Not changed						46,796
73425	8/16/2005 73,351	Low TBN					76,487
73426	Not changed						37,516
73432	2/22/2005 84,601	Idling Test					108,907
73433	2/22/2005 92,335	Idling Test					121,125
73446	6/2/2004 51,233	Low TBN	3/22/2005 38,690	Low TBN, high nitration	4/20/2005 5,022	Injector failure	125,870
73447	8/3/2004 54,201	Low TBN	9/21/2005 35,336	High oxidation, high nitration			99,928
73448	9/16/2003 24,258	Inadvertent change	11/17/2004 37,582	Low TBN, high oxidation			95,477
73449	12/20/2004 61,312	Low TBN, high oxidation and nitration	5/17/2005 11,640	Inadvertent change	10/3/2005 11,594	fuel dilution	89,158
73450	8/3/2004 129,140	Low TBN					153,428
Total Miles							982,548

Table 2. Oil Savings

Bus Number	Actual Oil Changes Avoided ^a	Quarts oil per change	Quarts of Oil Avoided	Gallons of Oil Avoided
73413	1	28	28	7
73416	3	28	84	21
73425	4	28	112	28
73426	3	28	84	21
73432	8	28	224	56
73433	9	28	252	63
73446	8	40	320	80
73447	5	40	200	50
73448	6	40	240	60
73449	6	40	240	60
73450	10	38	380	95
Total Gallons				541

^a A calculated value would be to take the total test miles and divide by 12,000 miles, but the actual value would be to count the number of service events and subtract 1 (one) for any change due to oil quality to get the actual oil changes avoided.

Table 3. Avoided Oil Changes

Bus Number	Test Miles	Actual Service Intervals	Total Oil Changes	Changes for Oil Quality	Changes for Mechanical/Human Reasons ^a	Avoided Changes	Percent Saving
73413	27,856	2	1		1	2	100
73416	46,796	3				3	100
73425	76,487	5	1	1		4	80
73426	37,516	3				3	100
73432	108,907	8	1		1	8	100
73433	121,125	9	1		1	9	100
73446	125,870	10	3	2	1	8	80
73447	99,928	7	2	2		5	71
73448	95,477	7	2	1	1	6	86
73449	89,158	7	3	1	2	6	86
73450	153,428	11	1	1		10	91
Totals	982,548	72	15	8	7	64	89%

^a Oil changes for mechanical reasons were not included in the calculation for the avoided changes and percent savings.



Figure 8. INL Personnel Viewing the Location of the Oil Bypass Filter Installation in the Engine Compartment of an INL Chevrolet Tahoe

90% of the oil changes would be avoided. This is based on INL being able to avoid on average, 89% of the oil changes in the test buses.

Comparing the traditional 12,000-mile oil change method and the way INL operated the oil bypass filter systems (the bypass filters and full flow filters were changed every 12,000 miles), oil bypass filter systems have a positive payback between 132,000 and 144,000 miles for the buses.

Comparing the traditional 12,000-mile oil change method and if INL had operated the oil bypass filter systems as directed by the manufacturer (only changing the full flow filters every 48,000 miles), oil bypass filter systems would have a positive payback between 72,000 and 84,000 miles for the buses.

Oil Bypass Filter Evaluation -Tahoes

Six INL Chevrolet Tahoe sport utility vehicles were used as light-duty test vehicles for evaluating oil bypass filter systems. The vehicles were part of the security force fleet at INL, and they traveled a total of 303,172 miles during the evaluation. The test vehicles were 2002 models, and when the test began at the end of 2003, the engines already had between 35,000 and 45,000-miles each. To establish a historical baseline of the engine wear metals, before the oil bypass filters were installed, several oil analysis samples were taken prior to the start of testing. This baseline provided a benchmark for each

vehicle against which to compare future test results, plus it would not be prudent to start a test on an engine that was failing.

The baseline samples showed that the Tahoe engines tend to generate high copper wear metals. In ten oil analysis reports, the copper values ranged between 10 and 242 ppm, with 30 or less parts per million considered more normal. Part of an oil analysis report is a subjective observation germane to the condition of the oil by the test laboratory personnel (based on established values). If the values were within the established range, then the disposition is “normal”; if the values are out of an established range, they are “abnormal,” and if the values are much out of the range, they are “severe or critical.” An interesting observation was made at the end of the light vehicle evaluation when it was noticed that the copper values had dropped about 2.6 times with the use of the puraDYN oil bypass filters.

In the first test period, the six Tahoes traveled 98,266 miles. They avoided 18 oil changes and the use of 90 quarts of oil; an oil change avoidance rate of 75%.

During the second test period, it appeared that there were oil condition trends in some vehicles but not in others. As a result, it was decided to change to a premium grade oil in the Tahoes. It was hoped that by restarting with a new oil, the light-duty phase of the project could be brought under control. The new

oil was actually changed a second time to ensure the detergent chemistry of the new oil had time to dissolve any sludge deposits left when using the previous oil.

During this time, a review of the oil analysis reports showed that sometimes the oil values improved and sometimes they declined even with the new oil. The directions in the electronic work orders were changed, and a regular full-time service mechanic took over. However, the TBN values on the vehicles were still lower than what was hoped for. The puraDYN service representative visited INL and reviewed the oil analysis reports and thought that he had a solution for enhancing the longevity of the oil.

When the puraDYN bypass filter systems were originally installed in the Tahoes, the standard 1/32-inch orifice (0.0313 inch) was used. However, because of the cold weather in Idaho (-20°F to -40°F is not infrequent), this orifice allowed too much oil into the filter housing early in the mornings when the engines and engine oils were cold. The cold oil was too thick to flow through the dense filter media, and as designed, the oil would back up and overflow through a release valve on the filter housing, resulting in puddles of oil underneath some of the Tahoes. After researching this problem with puraDYN's help, replacement cold weather 1/64-inch (0.0156-inch) orifices were installed on all the Tahoes. This change was made only a couple of weeks into the testing during the first test period. There were no more overflows, and it was with this smaller orifice that the first two phases of the evaluation occurred.

Towards the end of the middle testing period, it was thought that the low TBN values might be caused by insufficient oil flows to the bypass filters due to the use of the small 1/64-inch orifices. Therefore, puraDYN provided new valve assemblies with a 1/40-inch (0.025 inch) orifice in order to increase the oil flow to the bypass filters. The 1/40-inch orifices were installed in hopes of reducing the rapid decline of TBN values. The 1/40-inch orifices were installed prior to the start of the last test period. This second orifice change occurred at the same time that there were inconsistencies with record keeping and other previously discussed evaluation problems during the middle test period, that were not to be blamed on the puraDYN systems.

In the third test period, the six Tahoes traveled 99,123 miles. They avoided 25 oil changes and the use of 125 quarts of oil; an oil change avoidance rate of 86%.

Two scenarios were considered for the economic analysis of installing bypass filter systems on the gasoline engine Tahoes. The costs were computed over 150,000 miles (assumes a life of 150,000 miles for the Tahoes and an equal number of 3,000-mile oil service segments).

This analysis assumes that a bypass filter system would operate for 150,000 miles on a Tahoe and that 80% of the oil changes would be avoided. This is based on INL being able to avoid 75% of the oil changes in the Tahoes during the first testing period and 86% during the third testing period. It was decided not to penalize the economics of oil bypass systems on light-duty vehicles because of the difficulties encountered by INL during the middle testing period.

Comparing the traditional oil change method and the way INL operated the oil bypass filter systems on the Tahoes, the oil bypass filter systems have a positive payback between 66,000 and 69,000 miles on the Tahoes.

Diesel Engine Idling Wear-rate Evaluation Test

The primary role of INL in this project was to ensure the buses were each safely idled for 1,000 hours and to collect oil samples and operation parameters, including idling times, engine speeds, and oil use.

As measured by the condition of the oils, the idling of the two bus engines appear to have been easier on the engines than during normal operations. Equating the 400 hours of idling to 12,000 miles of normal operations may not be accurate, based simply on engine revolutions, especially given that the 12,000 miles included what were likely to be heavier engine loads. Filter additives likely affected the results of the oil condition, but to what level is not known. Longer idling test hours may have provided better results, but funding did not make this possible.

Future Activities

The oil bypass evaluation and the engine idling projects were completed during FY06. Final reports were written and published during FY06.

Publications

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2. Zirker, L.R., J.E. Francfort, and J. Fielding.
February 2006. *Diesel Engine Idling Test*.
INL/EXT-05-00888. Idaho National Laboratory.
Idaho Falls, ID.

G. Advanced Technology Medium and Heavy Vehicles Testing

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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.
- 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.
- Provide updates on current applications to DOE and other interested organizations, as needed.

Results

- Published final results on Ebus Hybrid Electric Buses and Trolleys operating in Indianapolis and Knoxville.
- Analyzed 12 months of in-service data, published a 6-month interim report and also prepared a draft final report on all 12 months from an evaluation of hybrid electric articulated buses in Seattle, WA.
- Analyzed 12 months of in-service data, published a 6-month interim report and also prepared a draft final report on all 12 months from an evaluation of hybrid and CNG buses at New York City Transit.
- Initiated a project with Wal-Mart and International Truck to evaluate an advanced battery powered HVAC/idle reduction system and drafted fact sheet.
- Updated information on hybrid vehicle activity via the EERE website – HD HEV spreadsheet.

Future Activities

- Complete evaluations on current fleet vehicles, initiate new evaluations.
 - Coordinate modeling and testing activities with other DOE projects such as 21CT and Vehicle Systems Analysis.
 - 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 2006 included:

- Fleet evaluations
- Short term technology reports

Fleet Evaluations

In FY 2006, AVTA worked with 3 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 made a commitment to the technology by purchasing 325 of these hybrids in two orders: the first order of 125 is an upgrade from the fleet's prototype Orion VI hybrids. The second order of 200 have several additional modifications to further improve the system performance (including EGR). A selection of each order are the subject of this ongoing evaluation.

In addition to the hybrid buses, NYCT is also operating Orion VII CNG buses. These natural gas buses are included in the evaluation. In FY2006, AVTA finished the data collection on the fleet of CNG and Hybrid (125 order) buses. Interim results for the evaluation were presented to the industry at the APTA Bus Conference in May 2006 and also published in the interim report which covered eight months of maintenance data and 12 months of fuel

economy data. In June of 2006, the final draft report was submitted to DOE which covers all 12 months of maintenance and fuel economy data. Highlights of this report are as follows:

- NYCT quickly integrated the CNG and hybrid buses into the fleet, achieving a similar usage rate of approximately 2,300 monthly miles per bus.
- Both the CNG and 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 hybrid).
- The CNG buses had an average fuel economy that was 25% lower than the diesel baseline buses, which is typical for low-average-speed operation of the spark-ignited natural gas engines (Figure 1).
- The hybrid buses had an average fuel economy that was 34-40% higher than the diesel baseline buses (Figure 1).

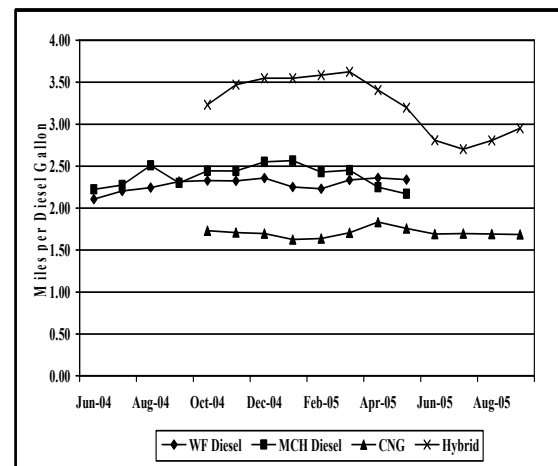


Figure 1. Fuel Economy Summary of Bus Groups

- The CNG buses had an average total maintenance cost higher than that of the hybrid buses: CNG buses cost 5% more than the hybrid buses. For the propulsion system only maintenance costs, the CNG buses were 5% lower than the hybrids (Figure 2).
- 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.

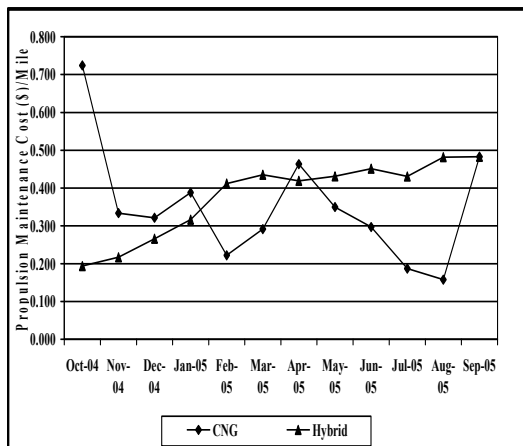


Figure 2. Propulsion System Maintenance Costs

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 FY06 to evaluate this new hybrid system in comparison to conventional diesel buses from the same order. The diesel buses use the same platform and engine, making this a good “apples-to-apples” comparison for AVTA.

In May 2006, AVTA published an interim project report for 6 months of data on the buses in service. These results for the evaluation were presented to the industry at the APTA Bus Conference in May 2006. In September of 2006, the final draft report was submitted to DOE which covers all 12 months of maintenance and fuel economy data. Highlights of this report are as follows:

- Figure 3 shows the fuel economy comparison between the hybrid and diesel buses. These preliminary results show an overall increase of 26% in fuel economy for the hybrid buses when compared to the diesel buses in a similar service.
- Figure 4 shows the total maintenance cost for both types of buses. The hybrids averaged \$0.44/mile while 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.

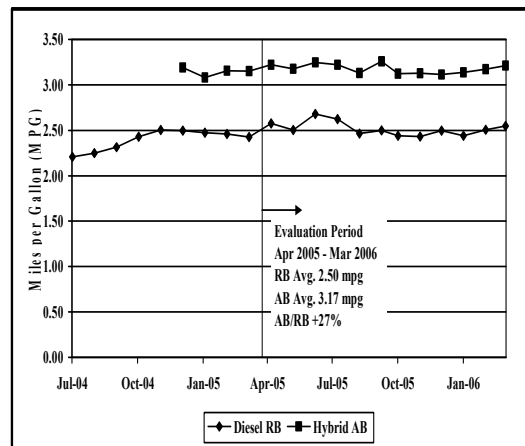


Figure 3. Fuel Economy for Hybrid and Diesel Buses at KC Metro in Similar Duty Cycle

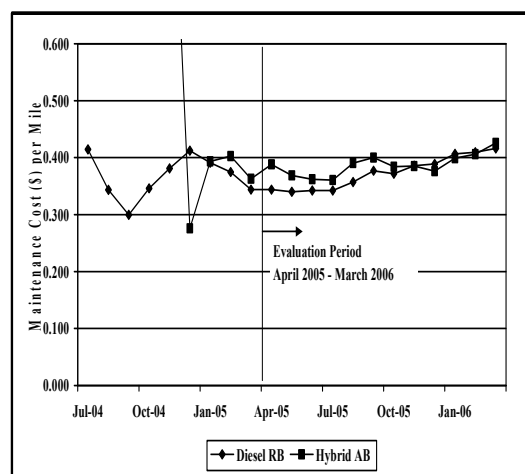


Figure 4. Total Maintenance Costs/Mile

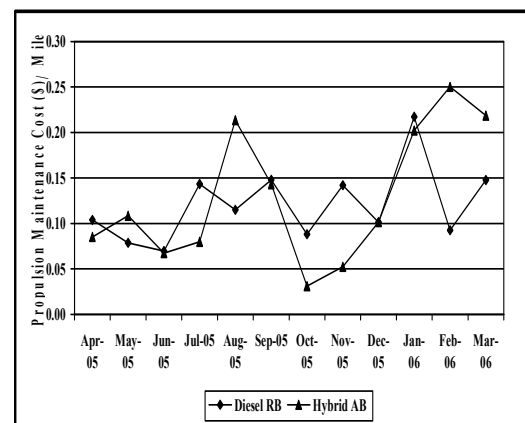


Figure 5. Propulsion Only Maintenance Costs/Mile

- Warranty costs for both vehicles were calculated but do include 6 failed Dual Power Inverter Modules (DPIM's) for the 20 hybrid buses. As the replacement cost 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 20 buses during the evaluation period.
- 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).
- 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.

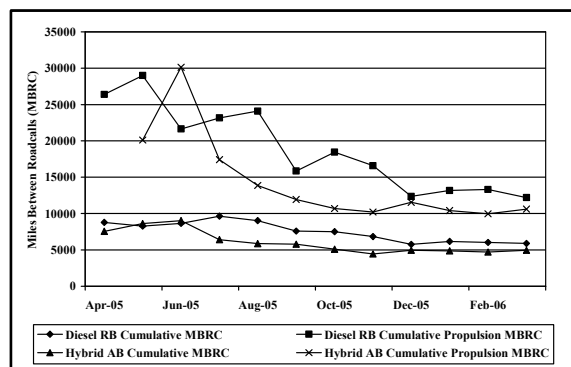


Figure 6. MBRC for Both Bus Groups

3) Wal-Mart Fleet in Southern CA.

A new fleet evaluation was initiated in FY2006. AVTA will be evaluating trucks in a Wal-Mart fleet in Southern California (SCAQMD) to evaluate the performance of Class 8 sleeper cab trucks equipped with advanced battery powered HVAC systems. The intent of the project is to compare these battery powered HVAC trucks with diesel APU HVAC equipped trucks. Current lead acid battery systems are not adequate for extended idle times and diesel equipped APU HVAC systems which will require advanced pollution control devices in 2008. An evaluation to assess the performance and feasibility of this technology was initiated. A draft fact sheet was produced and testing should begin in mid-CY2007.

Short-Term Technology Reports

HD HEV Implementation Data

The AVTA team completed an update to the HD HEV tracking spreadsheet which tracks all recent implementations of HD HEV's in North America. Currently, there are 153 HD hybrid fleets that AVTA is tracking.

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.

Publications

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- Chandler, K., Eudy, L., January 2006, *New York City Transit Hybrid and CNG Transit Buses: Interim Evaluation Results*, Technical Report NREL/TP-540-38843, National Renewable Energy Laboratory, Golden, CO.
- Chandler, K., Walkowicz, K., April 2006, *King County Metro Transit Hybrid Articulated Buses: Interim Evaluation Results*, Technical Report NREL/TP-540-39742, National Renewable Energy Laboratory, Golden, CO.
- Barnitt, R., *Evaluation Results on Orion CNG and Orion BAE Hybrid Buses at New York City Transit*, Presentation for the APTA Bus and Paratransit Conference, May 2006.

5. Walkowicz, K., *Testing and Evaluation of the GM/Allison Hybrid System in the King County Metro Transit Fleet - Seattle, WA*, Presentation for the APTA Bus and Paratransit Conference, May 2006.
6. Barnitt, R., Chandler, K., June 2006, *New York City Transit (NYCT) Hybrid (125 Order) and CNG Transit Buses: Final Evaluation Results (Final Draft)*, Technical Report, NREL/TP-540-40125, National Renewable Energy Laboratory, Golden, CO.
7. Chandler, K., Walkowicz, K., September 2006, *King County Metro Transit Hybrid Articulated Buses: Final Evaluation Results (Final Draft)*, Technical Report, Technical Report.
8. NREL/TP-540-40585, National Renewable Energy Laboratory, Golden, CO.

VI. LIGHT VEHICLE ANCILLARY SYSTEMS

A. Light Vehicle Ancillary Systems

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Objectives

- Research and develop innovative techniques and technologies that will reduce the fuel used for vehicle ancillary loads by 75% and increase national security by reducing imported crude oil.
- Assess the climate control system impact on thermal comfort, fuel economy, and emissions using an integrated modeling approach.
- Investigate turning low-grade waste heat into useful energy.

Approach

- With industry cooperation, develop and test ancillary load solutions to reduce fuel use while maintaining occupant comfort.
- Develop a passenger compartment cooling system using waste heat as an energy source.

Accomplishments

- Completed testing of technologies to reduce the thermal load on a Cadillac STS as part of the Improved Mobile Air Conditioning (I-MAC) Cooperative Research Program.
 - PPG Sungate EP solar reflective glass
 - PPG prototype solar reflective paint
 - Webasto solar powered parked car ventilation system
- A combination of these technologies reduced breath air temperature by 12°C (22°F), seat temperatures by 11°C (20°F), windshield temperature by 20.5°C (37°F) and the instrument panel surface temperature by 17°C (30°F).
- Completed an analysis to estimate the impact of reducing the thermal load on A/C system capacity of a Cadillac STS.
- Results show that the AC load can be reduced by over 30%. Vehicle simulations show that the 30% reduction in thermal load results in a 26% reduction in fuel used for AC.
- Completed the building and testing of a traveling wave thermoacoustic prototype.

Future Directions

- Despite the near term potential to significantly reduce fuel use, the OFCVT Multiyear Program Plan calls for the phase out of the Light Vehicle Ancillary Systems task in 2007.

- In FY07, write an Ancillary Load Reduction Task closeout report and technical papers that document analysis and test results of efforts to reduce A/C fuel use through reducing the passenger compartment thermal load, using efficient delivery techniques of conditioned air focusing on occupant comfort, and heat generated cooling.

Introduction

Fuel used for vehicle climate control significantly affects our nation's energy security by decreasing the fuel economy of the 222 million light-duty conventional vehicles in the United States. Air conditioning (A/C) can also reduce the fuel economy of advanced vehicles by as much as 35%. To address these issues, NREL works closely with industry to develop techniques to reduce the ancillary loads, such as climate control, in vehicles. We are conducting research to improve vehicle efficiency and fuel economy by controlling the climate in the vehicle, while still keeping the passengers comfortable. As part of this effort, we are conducting research in integrated modeling, optimized techniques to deliver conditioned air to the vehicle occupants, thermophysiological modeling, and waste-heat cooling and heating opportunities.

Approach

NREL uses a variety of tools to research and develop innovative techniques and technologies that will reduce the fuel used for vehicle auxiliary loads. Specifically, NREL has led efforts to:

- Develop and test ancillary load solutions to reduce fuel use while maintaining occupant comfort.
- Develop a passenger compartment cooling system using waste heat as an energy source.

Results

Testing Thermal Load Reduction Technologies on a Cadillac STS. From July 23, 2006 to September 7, 2006, outdoor thermal soak tests were performed on a pair of Cadillac STSs loaned to NREL by GM. One vehicle was modified with the load reduction technologies while the other vehicle was not modified except for the control paint that color matched the solar reflective paint. The advantage of using two vehicles is that the impact of day-to-day environmental differences is minimized, although we still needed a high solar load and light winds. We

measured the temperature difference at various locations between the vehicles. Table 1 outlines the 4 configurations we tested.

Table 1. 2006 I-MAC Team 3 Cadillac STS Test Matrix

Config.	1	2	3	4
Ventilation	X			
Solar Ref. Windshield	X	X	X	X
Solar Ref. Backlite	X	X	X	
Solar Ref. Sidelites	X	X		
Solar Ref. Paint	X	X	X	X

The tests were performed in Golden Colorado at the NREL's South Table Mesa site (Figure 1). The ground surface was a mixture of crushed rock and dirt. The vehicles were oriented to 160° and were leveled to approximately the same tilt angle. The seats were adjusted to the same position. Since the Sungate EP windshield did not have a shade band, the shade band region on both vehicles was covered with an opaque material. The windows were cleaned frequently to eliminate dust accumulation.



Figure 1. Cadillac STSs at NREL Test Site

GM provided the data acquisition system in both vehicles and Nissan instrumented the vehicles. For the soak test, 41 type K thermocouples were used to measure surface and air temperatures. NREL radiation shield were added to the breath air temperature thermocouples. Adhesive thermocouples reinforced with metallic tape were used on most surfaces. The exterior roof surface thermocouple was secured using thermally conductive Omega epoxy.

Environmental conditions were measured by a weather station at a nearby building. The parameters of interest were ambient temperature, global horizontal solar radiation, and wind speed/direction. The test day was determined to be good if the average wind speed was less than 2.5 m/s and there were no significant clouds between 10:00 and 13:30.

The data system was typically started around 8:00 am and data were recorded every minute throughout the day. The reduction in temperature (Team 2 – Team 3) was then computed for each location. The time period 12:30 to 13:30 was determined to be the critical period because the temperature differences between the vehicles were fairly constant during this time. The average reduction in temperature for a given day is the time average from 12:30-13:30. For most of the configurations, we had multiple good test days and these data were averaged. Only configuration 3 had a single day of good data, but it was a optimum day.

Figure 2 shows the reduction in temperature for the four configurations.

Configuration 1 – Solar Reflective Glass (All Locations), Solar Powered Ventilation, Solar Reflective Paint

The combination of solar reflective glass (all locations), solar powered ventilation, and solar reflective paint resulted in significant temperature reductions. Upon entering a vehicle, an occupant first contacts the air and seat. The breath air temperature was reduced 12.0°C and seats 10-12°C. Thermal radiation from the dashboard and windshield is also impacts thermal comfort. The dashboard temperature was reduced 16.8°C and the windshield was reduced 20.4°C.

During the solar soak tests, the difference in windshield temperature was easy to detect by touch. While the control windshield felt very hot, the Sungate EP windshield felt cool. While the lower paint temperature was noticeable, it was not as easy to detect by touching the surface.

We found that the operation of the solar powered ventilation affected the roof skin temperature. The flow exiting the vehicle entrained cool ambient air and caused increased heat loss from the roof skin. The temperature reductions from the non-ventilation configurations were within $\pm 0.5^\circ\text{C}$, therefore the 6.0°C temperature reduction reported for the configuration 1 is the average of the 3 non-ventilation configurations.

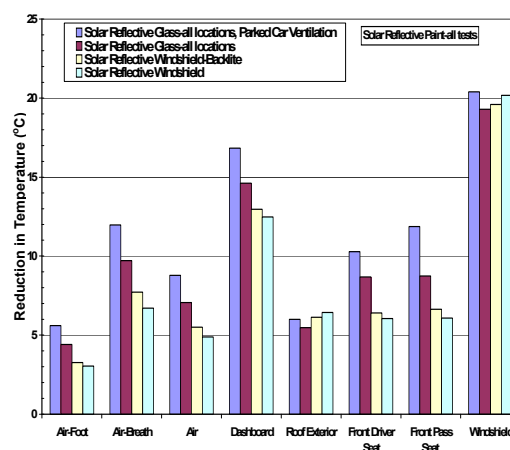


Figure 2. Reductions in Temperature ($^\circ\text{C}$)

Configuration 2 - Solar Reflective Glass (All Locations), Solar Reflective Paint

Without the solar powered ventilation, the vehicle interior temperatures still were dramatically cooler. The average air temperature and seat temperature were reduced 9.7°C and 8.7°C respectively. The windshield was 19.7°C cooler and the dashboard was 14.6°C cooler.

Configurations 3 & 4 - Solar Reflective Glass (Windshield & Backlite and Windshield Only), Solar Reflective Paint

Reductions in temperature with the windshield/backlight and windshield-only were similar. This is because the vehicles were oriented towards the sun and the solar load on the backlight was small. If the vehicles had been oriented away from the sun, the modified vehicle air temperatures would have been essentially the same as the control vehicle since the solar load on the north-facing windshields would have been lower. The windshield/IP/seats would have been cooler in both vehicles since there would have been shading from the roof and less direct sun load.

Develop, validate, and use an integrated cabin thermal fluid – thermal comfort model to evaluate technologies to reduce vehicle thermal loads by 30% for the DOE/EPA/SAE/Industry Improved Mobile Air Conditioning Project. A numerical model of the STS test vehicle was developed using AVL's FIRE CFD software and RadTherm thermal analysis software. The CAD files of the vehicle interior geometry were obtained from GM. The CAD was imported into ANSA software where it was cleaned up, details were removed, and surface meshed. The model volume mesh was created using AVL's FAME hybrid mesh tool. The resulting volume mesh was approximately 900,000 cells; the surface mesh in RadTherm was approximately 136,000 elements. RadTherm models the solar load on the vehicle, convection losses on the interior and exterior surfaces and conduction through the surfaces. AVL's FIRE CFD software was used to model the convective heat transfer and fluid flow in the cabin. During the analysis RadTherm and FIRE interact in the following way. RadTherm provides surface temperature boundary conditions to FIRE and FIRE provides heat transfer coefficients and fluid temperatures to RadTherm. Several exchanges between RadTherm and FIRE were needed to achieve a consistent solution.

The model was first validated against a quasi steady state soak data from the Cadillac STS test. Figure 3 shows the air temperatures in a plane through the drivers seat. Figure 4 compares the model prediction to test data for the baseline vehicle. The results show excellent agreement. The results for the reduced load

vehicle also show good agreement. The validated model was then used to simulate the vehicle cool down.

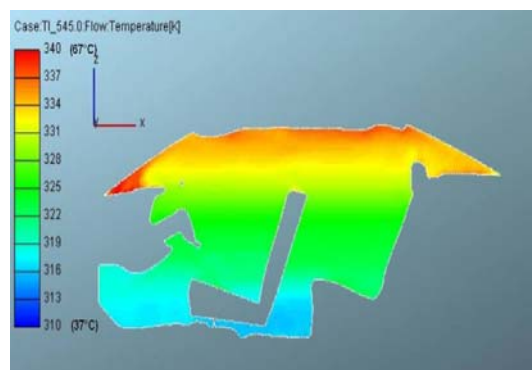


Figure 3. Cadillac STS Baseline Soak Temperature Contours

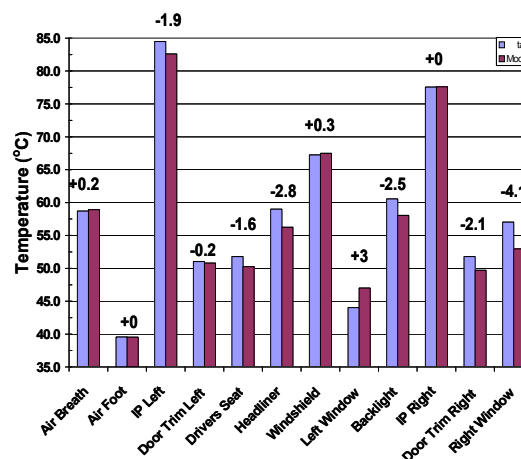


Figure 4. Baseline Soak Results Comparison to Test Data

It was found that excessive run times were needed to achieve a cool down simulation using the full FIRE/RadTherm model. Therefore, a simplified model was created for the cool down simulations which used only RadTherm. In the full FIRE/RadTherm simulation, the heat transfer coefficients and fluid temperatures are mapped to the RadTherm mesh. In the simplified model, the heat transfer coefficients are mapped to the RadTherm mesh and held constant during the cool down. The fluid temperatures are now simulated by eight fluid nodes, making use of the advection capabilities in RadTherm. In essence the model was bisected in each plane into eight fluid volumes, in contrast to the 900,000 fluid volumes in the FIRE

model. This simplified model was validated to vehicle cool down data. A typical baseline cool down comparison is shown in Figure 5.

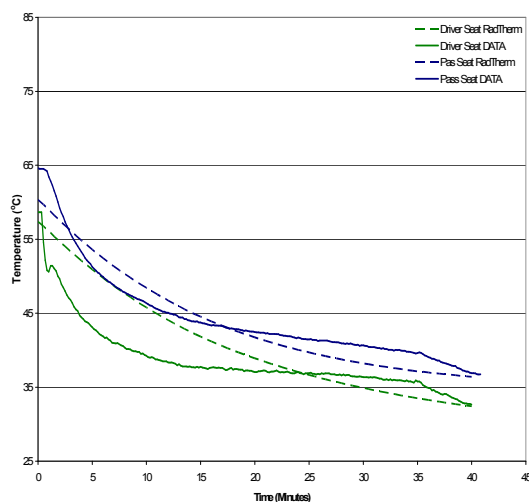


Figure 5. Baseline Cool Down Comparison

A cool down time of 30 min was chosen. That is the vehicle cabin was assumed to be at a comfortable temperature in 30 min. The approach that was used was to fix the cooling load in the baseline vehicle at 4 kW, which matched the vehicle data. The cooling load in the reduced thermal load vehicle was then reduced until the vehicles had an equal cool down, which was determined in two ways. The first method was to use a mass average temperature, and then determine at what cooling load the two vehicles achieved an equal mass average temperature in 30 minutes. The second method calculated a heat balance for each vehicle.

The mass average temperature calculation shows an equal cool down time with approximately 35% lower AC load, as is shown in Figure 6. The heat balance calculation shows equal time to comfort with a 30% lower AC load. To be conservative the 30% lower load, 2.8 kW was used in the fuel use calculations.

The ADVISOR vehicle simulator was used to determine the effect of the reduced AC load on fuel use. The vehicle was simulated on standard city and highway drive cycles and the results compared to published window sticker values. The AC load on the vehicle was modeled by using a curve of

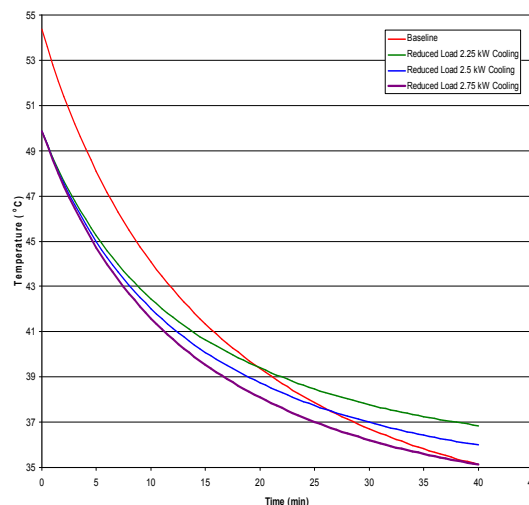


Figure 6. Mass Average Temperature

compressor power as a function of compressor rpm obtained from the OEM. The vehicle fuel economy was then calculated in the simulator over the FTP cycle for the vehicle without AC, baseline AC, and 30% reduced AC. The Vehicle Miles Traveled with AC on (VMTAC) is the average miles traveled by a passenger car in the US (11,998 miles⁵) multiplied by the average percent of AC use in the US (32.6%¹). VMTAC is 3,911 miles. Fuel used per vehicle is calculated by dividing the miles traveled by the fuel economy (miles per gallon). Fuel used for AC is then the difference between fuel used with AC on and fuel used with AC off. This calculation showed that reducing the AC load by 30% resulted in reducing fuel used for AC by 26%.

Design, build, and test a traveling wave thermoacoustic engine capable of delivering 1kW of acoustic power to cool vehicle interiors. A counterintuitive but promising path to reducing the loads imposed by automotive air conditioning systems is to use heat—specifically the waste heat generated by engines. This is an abundant source of energy, since light-duty vehicles with combustion engines have a cycle efficiency of 20% over the FTP cycle. With that degree of thermal efficiency, an engine releases 80% of its fuel energy as waste heat through the coolant, exhaust gases, and engine compartment warm-up.

NREL is exploring several technologies that could be developed to yield heat-generated cooling systems for future vehicles. Each has unique

advantages, and some are accompanied by substantial engineering challenges. Thermoacoustics is an innovative technology that uses sound to cool the interior of the vehicle. Thermoacoustic effects, which convert heat energy to sound, have been understood for over a hundred years. However, only over the past two decades has substantial improvements been made to the design of thermoacoustic engines and refrigeration cycles. Recent thermoacoustic refrigerators have flown on the space shuttle and cooled electronics in a Navy destroyer. The idea is simple... The waste heat from your vehicle can be used to set up a temperature difference across a pile of plates or “stack”. During periodic fluctuations in gas pressure, the gas passing through the stack is heated at the proper phase in the acoustic cycle to amplify the oscillations – much like the light waves in an optical laser. The imperfect thermal contact in the stack's pores provides the phasing between the compressions, expansions and acoustic displacements necessary to lead the gas through the desired thermoacoustic cycle.

Thermoacoustics has many potential advantages over a conventional A/C system. It uses waste heat, is reliable and inexpensive, does not entail the use of an extra energy load on the engine, relies on gases that are environmentally benign, has no moving parts (and thus should have a long lifetime), and requires no lubrication. The down side is, because of its low energy density, the device could take up a lot of volume. If we can overcome that barrier it could be one of the cool technologies in your next-generation car.

During FY04, NREL designed and developed a standing wave thermoacoustic device that pumps heat using a standing sound wave to take the working fluid (helium) through a thermodynamic cycle. We rely on the heating and cooling that accompany the compression and expansion of a gas in a sound wave to produce the cooling for the interior of a vehicle. The device is modular and allows for different stack designs and heat exchangers to be used in order to assess the most cost efficient and best performing components. Modeling efforts show that a thermoacoustic standing wave engine/heat pump has a heat efficiency of approximately 15% and a heat pump COP of approximately 1. The VALR team

completed testing of the standing wave thermoacoustic engine and heat pump during FY05. The thermoacoustic engine performed within 10% of modeled results. However, the heat pump only provided 20 watts of cooling. The poor performance of the heat pump was attributed to combining the room temperature heat exchanger for both the engine and heat pump into a single unit. It was determined that the pressure wave from the engine needs to be fully developed before it can be utilized for cooling. This problem can be easily rectified by separating the heat engine from the heat pump and utilizing two ambient heat exchangers. Although the standing wave thermoacoustic system works, the size necessary to generate sufficient cooling power for a light duty vehicle precludes its use. In FY06, NREL researchers concentrated their efforts on developing a smaller traveling wave thermoacoustic system.

During FY06, the VALR team assembled and tested a traveling wave thermoacoustic engine (Figure 7). Like the standing wave prototype, the traveling wave system was modular and allowed for different components (heat exchangers, regenerators, etc...) to be tested.



Figure 7. Traveling Wave Prototype

In particular, we tested a micro-channel regenerator and a copper foam heat exchanger. Our modeling indicated that the micro-channel regenerator would approximately double the total acoustic power output and increase the conversion efficiency of heat to acoustic power by 15% as compared to traditional wire mesh regenerators. However, the micro-channel regenerator (Figure 8) did not perform to expectations. Rather than decreasing the viscous losses, the soldering technique as well as the method used to trim the shims increased the viscous losses

in the regenerator. Furthermore, the spacing between plates within the regenerator was uneven which led to further efficiency losses.



Figure 8. Micro-Channel Regenerator

The copper foam heat exchanger (Figure 9) was utilized in the hopes of eliminating hundreds of welds used in traditional shell and tube heat exchangers for thermoacoustic systems. The copper foam heat exchanger design also eliminated the need for penetrations into the pressure vessel thus relying on heat conduction through the pressure vessel walls and the copper foam to exchange the hot vehicle exhaust gas with the thermoacoustic working fluid. Unfortunately, the copper foam heat exchanger had a very large temperature difference across its surface. The large temperature difference resulted in a non-uniform amplification of the incoming sound and further has the potential to cause jet or convective streaming reducing the overall efficiency of the thermoacoustic device.



Figure 9. Proposed Metal Foam Heat Exchanger

From NREL's modeling and test results, a traveling wave thermoacoustic system for direct vehicle cooling will not be viable for light duty vehicles - the resonant cavity will be too large. In order to decrease the size of the resonant cavity, a new combination of gases, working fluid, will need to be found that will lower the resonant frequency of the device without lowering the power per unit volume. One way to decrease the length of the resonant cavity is to combine a heavier gas with a lighter gas. Unfortunately, combining gases precipitously reduces the power per unit volume resulting in an unrealistically large diameter for the device in order to provide the necessary cooling for the vehicle. However, it was determined that a traveling wave thermoacoustic system could still be used in light duty vehicles for electricity generation. Electrical power could be produced through the use of a flexible membrane, which would also determine the resonant frequency of the thermoacoustic system and therefore its size. Future work should be concentrated on reducing the cyclical fatigue of such a membrane for eventual integration into light duty vehicles.

Conclusions

NREL is pursuing a variety of avenues in its efforts to improve vehicle efficiency and fuel economy by controlling the climate in the vehicle, while still keeping the passengers "comfortable." Because climate control loads significantly affect our national energy security, as well as the fuel economy and tailpipe emissions of conventional and hybrid electric automobiles, NREL is working closely with industry to develop techniques to reduce the auxiliary loads, such as climate control, in a vehicle. The load reduction technologies tested on the Cadillac STS as well as climate control seating are available for today's vehicles. If incorporated in conjunction with a smaller A/C system or the A/C is used less often, the reduced A/C fuel use will save drivers money at the pump and the reduced temperatures will improve thermal comfort immediately after a hot soak. The reduced fuel use translates directly to reduced CO₂ emissions which is good for the environment.

One way to reduce near term vehicle fuel use is to increase the efficiency of vehicles. There is great potential to reduce AC fuel use because AC systems

have been designed to maximize capacity, not efficiency. The technologies discussed in this report have the potential to significantly reduce AC fuel use. Despite the phase out of the Light Vehicle Ancillary Systems task in 2007, the authors feel strongly research in this area should continue to reduce the fuel use and improve the energy security of the United States.

Publication

1. Rugh, J.; King, C.; Paul, H.; Bue, G.; and Trevino, L. (2006) "Phase II Testing of Liquid Cooling Garments Using a Sweating Manikin, Controlled by a Human Physiological Model," Proceedings of the 36th International Conference on Environmental Systems, Paper # 2006-01-2239, July 17-20, 2006, Norfolk, VA, Society of Automotive Engineers.

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