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ADVANCED VEHICLE TECHNOLOGY ANALYSIS AND EVALUATION ACTIVITIES

Less dependence on foreign oil, and eventual transition to an emissions-free, petroleum-free vehicle

FreedomCAR and Vehicle Technologies Program

2004 ANNUAL PROGRESS REPORT

Acknowledgement

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In addition, we would like to thank all the participants for their contributions to the programs and all the authors who prepared the project abstracts that comprise this report.

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Office of FreedomCAR & Vehicle Technologies
1000 Independence Avenue, S.W.
Washington, DC 20585-0121

FY 2004

Annual Progress Report for
Advanced Vehicle Technology Analysis and Evaluation Activities

Energy Efficiency and Renewable Energy
Office of FreedomCAR and Vehicle Technologies

Lee Slezak, Technology Manager

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I. INTRODUCTION

On behalf of the U.S. Department of Energy's Office of FreedomCAR and Vehicle Technologies (FCVT), I am pleased to submit the Annual Progress Report for fiscal year 2004 for the Advanced Vehicle Technology Analysis and Evaluation (AVTAE) team activities. In prior years, these activities were reported in the Light Vehicle Propulsion and Ancillary Subsystems annual report.

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 towards evaluating and verifying the targets of the FCVT technology R&D teams and to provide guidance in establishing roadmaps for achievement of these goals.

Objective

The prime objective of the AVTAE team activities is to evaluate 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 Figure 1 below.

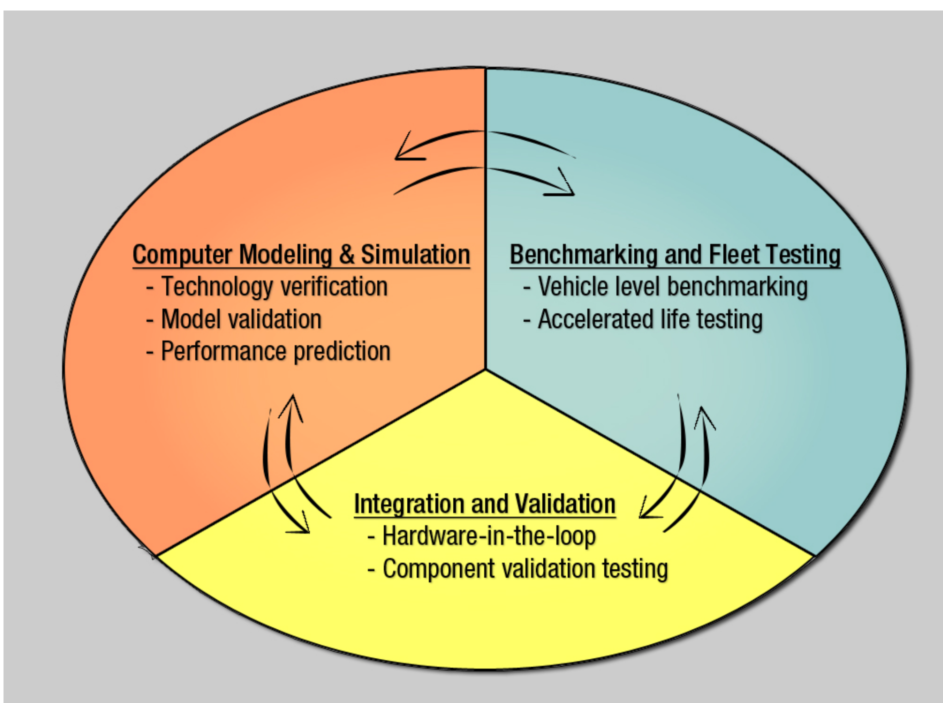

Figure 1. Integration of AVTAE computer modeling and testing activities.

FY 2004 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 in the Offices of FCVT and HFCIT is required for both analysis and testing. Analytical results of this sub-program are used to estimate national benefits and/or impacts of DOE-sponsored technology development, as illustrated in Figure 2 below.

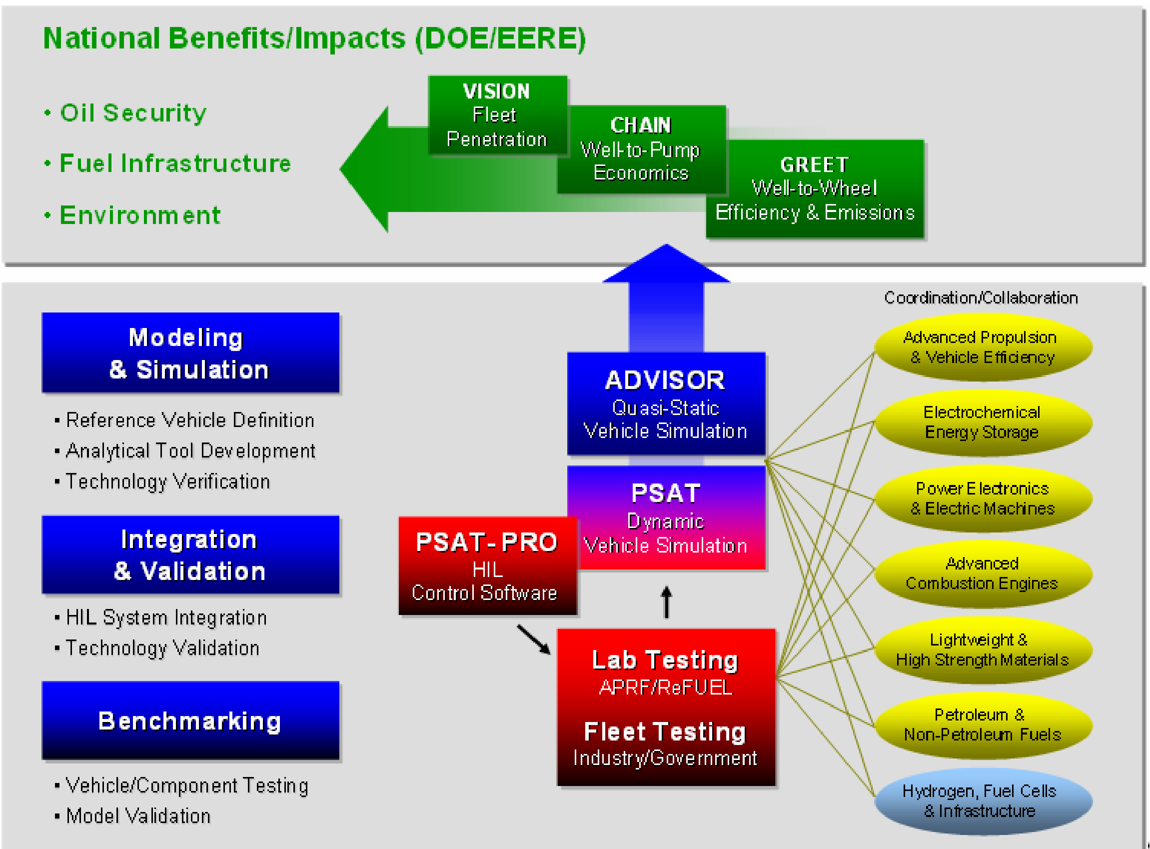

Figure 2. AVTAE activities providing estimates of national benefits and impacts of advanced technologies.

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 ADVISOR and PSAT modeling tools. 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). Laboratory testing is conducted at the Advanced Powertrain Research Facility (APRF) and the Renewable Fuels and Lubricants Facility (ReFUEL). Fleet tests are used to assess the functionality of technology in the less-predictable real-world 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.

ADVISOR (ADvanced VehIcle SimulatOR) is used to understand trends and preliminary vehicle design through quasi-static analysis of component performance and efficiency characteristics to estimate fuel economy. Vehicle power demand on the road is used to calculate the demand on propulsion system components and their resulting characteristics each second (using static component map data). These values are summed to produce overall results for a driving cycle (commonly referred to as "backward-facing" simulation). This approach to simulation is suitable for quick evaluation of multiple scenarios due to low execution times and reduced numerical processing. Capabilities include component selection and sizing (conventional, hybrid, and fuel cell vehicles), energy management strategies, optimization, and target development.

PSAT (Powertrain System 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, and 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.

PSAT-PRO (PSAT rapid control PROtotyping 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 (General Computational Toolkit) 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. During FY 2004 and continuing into FY 2005, hydrogen-fueled internal combustion engine hybrid configurations and control strategies are being explored using a mobile test platform/chassis on the 4WD dynamometer at APRF. This approach is consistent with program direction at DOE, utilizes techniques developed previously in the HIL powertrain test cell, capitalizes on the hydrogen fuel safeguards in the APRF and the 'transportable' test fixture (chassis) allows more flexibility in studying multiple configurations.

Different phases with associated research topics have been defined for this project:

- Model validation (Phase 1)
- Degree of hybridization for H2-ICE (Phase 2)
- Hybrid configuration for H2-ICE (Phase 2)
- Hybrid system control for H2-ICE (Phase 2)
- Impact of hybridization on H2-ICE calibration (Phase 3)

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 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. These, and other small facility upgrades, have made the APRF a world-class laboratory for data quality.

4. Operational and Fleet Testing

Operational and Fleet Testing evaluates vehicles in real-world applications to measure progress toward FCVT technical targets and disseminate accurate, unbiased information to potential vehicle users, DOE, and industry technology developers and vehicle modeling tasks. The scope includes vehicles that use DOE-sponsored technology or technologies of particular interest to FCVT (i.e., hybrids and internal combustion engine vehicles fueled with hydrogen and other gaseous/liquid fuels), as well as the related fueling infrastructure. Capabilities include measuring performance, costs, fuel consumption, in-use maintenance requirements, and operational characteristics including braking and handling. Operational and fleet testing develops test protocols and performance goals and collaborates with public and private entities to collect performance data and other relevant information. The execution of these tasks occurs under cost-shared agreements with industrial partners such as electric utilities and automotive companies. Test sites may include utility, government, or commercial locations where fleet vehicles are used and maintained. National laboratories provide data acquisition, analysis, reporting, and management support.

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.

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. The 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 the technical barriers, for using waste heat (coolant and exhaust for ICE) to provide cabin cooling and heating. The challenge is to incorporate this approach into hybrid electric vehicles (HEVs) which utilize engine off strategies as well as in fuel cell vehicles (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 2004 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

Transition to hydrogen vehicle technology will require the development of vehicle components, subsystems, and support systems, as well as the fueling infrastructure. The transition will require exploration of fuel and propulsion system combinations to get the most out of hybrid propulsion. It will require gaining experience with hydrogen technology while fuel cells are being developed into commercially viable products. 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 2005, field and laboratory testing will continue to be integrated with modeling/simulation tools. Test procedures will be finalized and models will be validated and enhanced to ensure their usefulness. In FY 2005 and 2006, AVTAE will complete the specification of representative vehicle platforms, complete baseline performance testing of hydrogen-fueled ICE vehicles, and validate simulation models on a fuel cell vehicle at the APRF. Although the development of vehicle simulation models will be essentially completed, the models 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, including advanced cabin climate control systems, 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. Technical Targets Evaluation, Analysis, and Tool Enhancement

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Objective

- Analyze the impact of component and system technical targets on national oil use for advanced technology vehicles including fuel cell hybrids, gasoline electric hybrids, and conventional vehicles.

Approach

- Define the light vehicle market in terms of EPA vehicle size classes;
- Program the Technical Targets Tool (T3) in MATLAB® and create easy-to-use Graphical User Interfaces (GUIs) that allow the user to easily modify the technical targets;
- Evaluate different component sizes in new technology vehicles (NTVs) based on technical targets to find the most competitive combination of vehicle characteristics, including fuel economy, cost, cargo volume, and performance;
- Use DOE's market penetration model to determine the penetration of the competing vehicle types and classes based on the vehicle characteristics;
- Compare oil use of a strictly conventional vehicle market with that of a market penetrated by new technology vehicles; and
- Quantify oil reduction impact by achieving research goals in each technical target area, such as fuel cells or energy storage systems.

Accomplishments

- Developed and compiled a simplified vehicle model to reduce computation time and utilize distributed computing resources;
- Incorporated time-varying technical targets as inputs;
- Revised market penetration modeling approach to estimate vehicle competitiveness based on vehicle attributes such as performance, cargo space, and cost; and
- Created the framework for an easy to use graphical user interface.

Future Directions

- Link to DOE's market penetration model;
- Run the tool to estimate component technical target impacts on national oil use;
- Run the tool to find the component sizing strategies that make advanced vehicles, such as fuel cell vehicles, most competitive with conventional vehicles; and
- Complete the graphical user interface to share modeling capabilities with DOE and others.

Introduction

In FY 2001, National Renewable Energy Laboratory (NREL) started working with the auto industry to determine a way to assess the potential impact of advanced light vehicle R&D technical targets on national oil use. The technical targets were originally formulated under the Partnership for Next Generation Vehicles (PNGV) program when the advanced vehicle R&D programs were focused on consolidating advanced technologies into a single light vehicle platform—a large car. As concepts were proven and progress was made towards this goal, it became more reasonable to think beyond a single vehicle platform and include all vehicle platforms that constitute the light vehicle market.

With the program's goals more market oriented, we needed a way to link the technical targets to this multi-platform environment. This link would then allow us to optimize the set of technical targets based on their potential impact on the entire light-vehicle market.

Approach

The process of creating the technical target-marketplace link began in FY 2001 as a joint effort between NREL and Teamworks, Inc. The concept was to create a tool, referred to as the Technical Targets Tool (T3), which would cascade the technical targets input by the user up to their potential to reduce national oil use. The pathway to get from technical targets to national oil use begins by finding the average non-powertrain vehicle characteristics for each class. Next, the powertrain component sizes are optimized for the most competitive combination of performance, cargo space and cost for each vehicle type in each class. The vehicle types are then compared to find their market share within the class. Finally, the resulting fuel economy, market penetration, and vehicle miles traveled is used to estimate the projected reduction in oil use.

Results

The first version of the T3 tool was spreadsheet-based and demonstrated the concept of cascading technical targets up to national oil use. This spreadsheet version was replaced by a more powerful version written in software called MATLAB®. The first MATLAB® version has been tested and completed. It includes graphical user interfaces (GUIs) for modifying targets, viewing and changing assumptions, determining target sensitivities and viewing results. Figure 1 shows a representative GUI for the Technical Targets Tool.

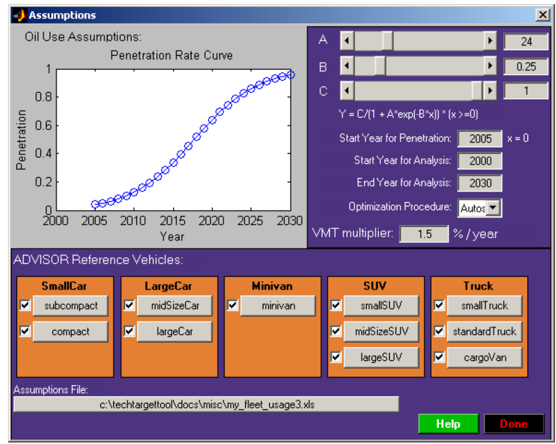

Figure 1. The graphical user interface for viewing and modifying assumptions.

In FY 2004, the first MATLAB® version was improved in several ways. The speed was improved by compiling code and expanding distributed computing. The scope was improved by expanding evaluations for one year to evaluating improvements in technical targets over time. Flexibility was added in defining vehicle classes. Now it can use anywhere from two vehicle classes up to 13 to represent the light duty fleet. The approach was improved by changing from sizing components for fuel economy to sizing components for competitiveness to better reflect reality.

Conclusions

The required framework of T3 is complete. DOE's market penetration model is the last component that still needs to be inserted into the framework. Once this last component is added, we will be able to estimate technical target impacts on oil use. We will also be able to find the component sizing strategies that make advanced vehicles, such as fuel cell vehicles, most competitive with conventional vehicles.

B. Vehicle Systems Optimization, Application, and Distributed Computing

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Objectives

- Develop specifications for an energy storage system for a fuel cell hybrid vehicle;
- Enhance and share distributed computing and optimization methods for vehicle systems research;
- Develop and validate detailed fuel cell system model for use with ADVISOR™.

Approach

- Define vehicle, model, and tool requirements;
- Collaborate with industry stakeholders to accurately define assumptions;
- Complete simulations that will shed light on design issues and potential solutions; and
- Present and publish study results.

Accomplishments

- Transferred the ADVISOR software to AVL Powertrain Engineering, Inc., for commercial distribution under exclusive licensing agreement;
- Completed study in collaboration with Energy Storage Technical Team to define power and energy requirements for a fuel cell hybrid vehicle;
- Published a paper discussing how fuel cell system attributes impact energy storage requirements;
- Developed a new version of DIRECT for optimization with built-in distributed computing functionality;
- Completed a report documenting distributed computing best practices for systems optimization studies; and
- Finalized a detailed fuel cell system model and generated vehicle level simulation results for a variety of environmental conditions to demonstrate model functionality.

Future Directions

- Evaluate dual-energy storage system technologies for hybrid electric vehicles;
- Quantify the sensitivity of energy storage system requirements to fuel cell system attributes for fuel cell hybrid vehicles;
- Develop a better understanding of grid-connected hybrid vehicle technology barriers and benefits in order to guide future research initiatives;
- Expand optimization applications to include multiple vehicle systems simulation codes; and
- Explore cylinder deactivation coupled with hybridization for fuel efficient vehicle design.

Introduction

In the past, the vehicle systems team at NREL was tasked with the development and application of vehicle systems modeling tools to address the needs of DOE and industry to understand hybrid vehicle architecture benefits and issues. Development efforts for ADVISOR™ software initiated in 1994 as part of DOE's HEV Program and accelerated well into 2002. As the tool matured and accumulated more than 8000 users world-wide, NREL's emphasis shifted from software development to application. In FY 2004, the ADVISOR™ software was successfully commercialized by our industry partner AVL. The primary application, in FY 2004 was in support of the Energy Storage Technical Team. The team is defining energy storage requirements for fuel cell hybrid vehicles. Additionally, a detailed fuel cell model was completed and used to quantify the sensitivity of a fuel cell hybrid vehicle operation under various environmental conditions. Distributed computing and optimization tools that wrap around ADVISOR™ and support detailed studies were further refined. NREL's vehicle systems team is building significant vehicle modeling capabilities in support of FreedomCAR goals.

Approach

The development of tools and analysis results in support of FreedomCAR requires a good understanding of the need. Working closely with industry partners and DOE clients, the analysis requirements are defined to provide project direction. Study parameters and assumptions are also jointly defined. Simulation results generated are shared with the partners. Ideally, the project findings are summarized and published in key technical conferences.

Results

The commercialization of the ADVISOR™ software in FY 2004 is considered a significant accomplishment. The software was licensed to AVL in 2003. NREL and AVL collaborated to finalize the software for official distribution in 2004. The software is currently being used by several companies, academic institutions, and even for an automotive powertrain training seminar organized by the Society of Automotive Engineers.

Collaboration with the Energy Storage Technical Team culminated in FY 2004 as we reached consensus on the power and energy requirements for fuel cell hybrid vehicles based on simulation results. For this study, a future Chevrolet Malibu-like vehicle was simulated and a range of fuel cell and energy storage system combinations were explored. Through an analysis of the power and energy events during typical driving profiles, it was determined that an energy storage system with 250Wh of usable energy and 20-25kW of peak power capability would be ideal for a fuel cell hybrid application. A sensitivity analysis of these results to key input assumptions is underway.

The results generated in support of the energy storage team were accomplished as the result of work in optimization and distributed computing methods. DIRECT is a derivative-free optimization algorithm that has been shown to be very effective for vehicle systems analysis studies. The DIRECT code was successfully restructured to take advantage of a distributed computing pool of more than 40 processors. This code development and successful expansion of the distributed computing pool has allowed us to complete more than 50,000 hours of vehicle systems simulations during the past year.

Finally, the analysis tools themselves were enhanced through the improvement of the fuel cell system model in the ADVISOR™ software. This was the last development completed prior to commercialization. The detailed fuel cell system model provides the ability to explore the system complexities of the fuel cell stack and its balance of plant. Specifically, we can explore the impacts of the fuel cell system attributes and operation on the vehicle. The fuel cell component model was used to quantify the impact of environmental conditions including altitude, humidity and temperature on both fuel cell and vehicle performance. It was found that due to reduced ambient pressure, the power output of the fuel cell degrades with increasing altitude and can significantly reduce vehicle fuel economy. The temperature and humidity levels were more influential on the overall design requirements and less so on the vehicle fuel economy.

Conclusions

FY 2004 marked the continuation of a shift from the development and validation of vehicle systems modeling tools to more intensive application of those tools. Specifically, we applied the existing tools to support the Energy Storage Systems Technical Team in their drive to define the power and energy requirements for fuel cell hybrid vehicles. The models were also used to uncover the detrimental impacts of environmental conditions on fuel cell hybrid vehicle performance and fuel economy. Finally, our cumulative experience in the development and application of distributed computing and optimization methods was applied to vehicle system simulation and this knowledge has been shared with DOE and our industry partners.

Publications / Presentations

1. Wipke, K., K. Haraldsson, and T. Markel, "Analysis of Fuel Cell Powertrain Implications Using ADVISOR," 2003 AVL International User Meeting. Graz, Austria, October 15, 2003.
2. Markel, T., K. Haraldsson, and K. Wipke, "Thermal Management Characteristics For A Fuel Cell Hybrid Vehicle Under Realistic Driving Demands," Fuel Cell Seminar 2003, Miami Beach, FL, November 3–7, 2003.
3. Haraldsson, K., T. Markel, and K. Wipke, "Ambient Conditions and Altitude Effects on PEMFC Hybrid Vehicle Performance," 20th International Electric Vehicle Symposium, Long Beach, CA, November 17–19, 2003.
4. Markel, T., K. Haraldsson, and K. Wipke, "Environmental Effects on Fuel Cell Hybrid Electric Vehicle Performance Understanding Relative Humidity, Temperature, and Elevation Impacts," FY04 Milestone Report, February 27, 2004.
5. Jeanneret, B. and T. Markel, "Adaptive Energy Management Strategy for Fuel Cell Hybrid Vehicles," 2004 SAE World Congress, SAE Publication 2004-01-1298.
6. Zolot, M., T. Markel, and A. Pesaran, "Analysis of Fuel Cell Vehicle Hybridization and Implications for Energy Storage Devices," 4th Advanced Automotive Battery Conference, San Francisco, CA, June 1–4, 2004.
7. Markel, T., A. Brooker, J. Lustbader, M. O'Keefe, and S. Sprik, "Distributed Computing Overview and Recommendations," FY04 Milestone Report, September, 2004.
8. Markel, T., "Fuel Cell Vehicle Systems Model Development, Validation, and Application," FY04 Milestone Report, September, 2004.

C. Well-to-Wheel Analysis of Current Engine and Fuel Cell Vehicle Technologies

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Objectives

- Quantify the impact of advanced powertrain technologies from a Well-to-Wheel (WTW) prospective using Powertrain System Analysis Toolkit (PSAT) for vehicle simulation, with GCtool-Eng for fuel cell system modeling and the Green house gases, Regulated Emissions and Energy use in Transportation (GREET) model for Well-to-Pump (WTP) emissions analysis.

Approach

- Eleven (11) vehicle configurations based on a representative sport utility vehicle (SUV) platform were developed, including conventional, parallel, fuel cell and fuel cell hybrids;
- Four (4) fuel converter technologies were selected (gasoline, diesel, hydrogen engine and hydrogen fuel cell);
- Five (5) driving cycles were simulated (UDDS, HWFET, US06, NEDC and Japan1015); and
- Vehicle acceleration performance (10 seconds), time period (2003) and glider mass were held constant to ensure a fair comparison.

Accomplishments

- Defined vehicle powertrains and performed simulations to evaluate performance;
- Short Term: Diesel engine and hybrid technology available today can offer dramatic benefits over conventional vehicles from a total cycle perspective;
- Near Term: Hydrogen engine hybrids can pave the way to a hydrogen economy; and
- Long Term: Fuel cell hybrids offer significant benefits on a well-to-wheel basis assuming hydrogen production from natural gas.

Future Directions

- Improve the linkage between PSAT, GREET and GCtool-Eng; and
- Compare advanced vehicle platforms for different timeframes.

Introduction

When considering the introduction of advanced vehicles, a complete well-to-wheel evaluation must be performed to determine the potential impact of a technology on carbon dioxide and Green House Gases (GHGs) emissions. Several modeling tools developed by Argonne National Laboratory (ANL) were used to evaluate the impact of advanced powertrain configurations. The Powertrain System Analysis Toolkit (PSAT) transient vehicle simulation software was used with a variety of fuel cell system models derived from the General Computational Toolkit (GCtool-Eng) for pump-to-wheel (PTW) analysis, and GREET (Green house gases, Regulated Emissions and Energy use in Transportation) was used for well-to-pump (WTP) analysis.

Approach

The reference vehicle is based upon an SUV (Sport Utility Vehicle) platform, and the vehicle's characteristics are listed in Table 1. An SUV was chosen since it represents the fastest growing segment in the United States. Fuel economy values mentioned in Table 1 are EPA unadjusted values. The combined fuel economy obtained with PSAT is higher than the reference value because the effect of cold start was not taken into account.

Table 1. Reference vehicle parameters and validation.

	Units	Test	PSAT
Vehicle Assumptions			
Vehicle Mass	kg	2104	
Glider Mass	kg	1290	
Engine		VL, V6, SOHC, 210hp	
Frontal Area	m^2	2.46	
Drag Coefficient		0.41	
Rolling Resistance		0.0084	
Wheel Radius	m	0.368	
Model Validation			
Acceleration (0-60 mph)	s	10.5	10.5
Fuel Economy	mpg	20	21

Eleven powertrain configurations have been simulated to evaluate the potential of fuel cell technologies:

1) Conventional vehicle (CONV) with gasoline engine (SI) and automatic transmission (reference).
2) Conventional vehicle (CONV) with diesel engine (CI) and automatic and manual transmissions.
3) Starter-alternator parallel hybrid (PAR ISG) with gasoline and diesel engines.
4) Pre-transmission parallel hybrid (PAR PRE-TX) with gasoline, diesel, and hydrogen engines (H_2 ICE).
5) Fuel cell vehicle (FC) with no energy storage.
6) Fuel cell hybrid (FC) with two hybridization degrees (small and large energy storage).

The simulations were performed on the standardized driving cycles for U.S., Europe, and Japan.

Results

Figure 1 details the fuel economies for the different configurations on the combined cycle (including UDDS and HWFET). Note that substantial gains can be achieved through dieselization or hybridization. The hybrid fuel cell configuration combines high fuel-cell system efficiency and regenerative braking to achieve the highest fuel economy. However, excessive hybridization diminishes the gain in fuel economy for two reasons: (1) the smaller battery configuration recovers most of the regenerative braking, and (2) decreasing the fuel cell system power leads to a decrease in the average efficiency of the fuel cell system.

The results are intuitive in that diesel hybrids are more fuel-efficient than gasoline hybrids. But the analysis also shows that fuel economy of hydrogen-fueled ICE hybrids could exceed that of conventional vehicles (gasoline or diesel) and is within 10% of the diesel hybrid. Note that the fuel economy of a conventional diesel with a manual transmission is comparable with that of a hybrid gasoline vehicle.

The results differ as a function of driving schedule. Figure 2 compares the efficiency results of the pre-transmission parallel hybrid and the reference vehicle for various cycles. The cycles with low power demand (low speed or steady-state

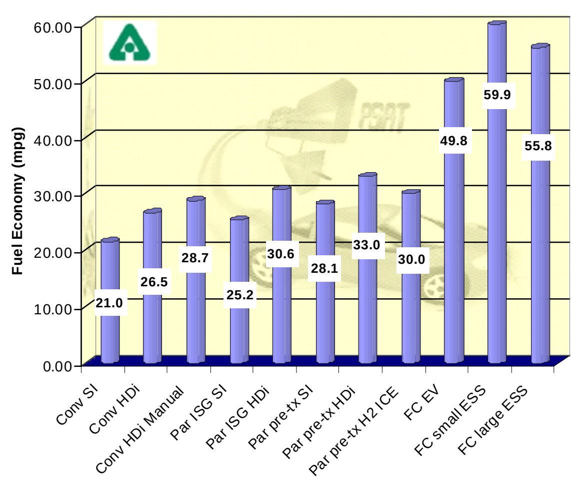

Figure 1. Fuel economy gasoline equivalent results for the combined metro-highway cycle.

operations) appear to be the best suited for hybrid operations. The US06 cycle, which is the most transient of the five, is consequently the least effective for HEV applications.

These results are logical considering the sources of savings for hybrid vehicles: regenerative braking, no engine idling, and better powertrain efficiency at low power demands. Transient drive cycles with low average vehicle speed are best suited for hybrid vehicles. As a consequence, the hybrid's fuel economy gains on the HWFET or US06 cycle are less than those for the UDDS or the Japan 1015.

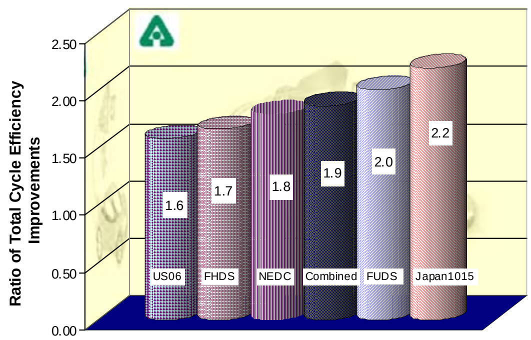

Figure 2. Driving cycle impact on powertrain efficiency improvements — example of the pre-transmission parallel HEV with diesel engine.

Previous studies pointed out that on a fixed time budget, vehicle miles traveled by vehicle vary inversely with the average driving speed. In other words, personal vehicles based in congested urban areas may accumulate fewer miles of driving per year than suburban-based vehicles. Thus, owners of hybrid vehicles living in congested areas may drive less than hybrid owners living in suburban area, nullifying the large fuel economy advantage they hold over comparable conventional vehicles on a per mile driven basis.

GHG emissions are an important consideration from a tailpipe emission perspective for most countries. A clean vehicle, such as a fuel cell vehicle, does not mean that there are no emissions from a well-to-wheel perspective. Figure 3 shows that fuel cell vehicles could contribute to a 60% decrease in GHG emissions, in comparison with the most advanced hybrid engine configuration. However, for current

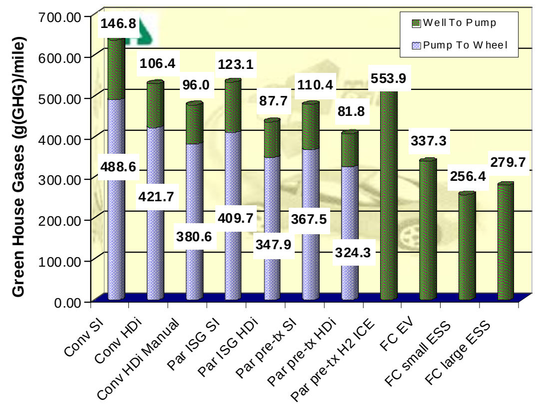

Figure 3. Greenhouse Gas Emissions (g/mi) – FUDS Cycle.

technologies, the pre-transmission diesel HEV appears the best option.

Conclusions

Current technology capabilities have been compared and their potential from a WTW perspective has been evaluated with a unique set of tools (GCTool-Eng, PSAT, and GREET). Hybrid electric vehicles with gasoline engines achieve performance comparable with that of conventional diesel vehicles. On the other hand, hybrid electric vehicles with a diesel engine appear to be competitive in terms of total energy cycle compared to FCHEV when hydrogen is produced from natural gas. The study also demonstrated that increasing the degree of hybridization for fuel cell vehicles does not always mean increased fuel economy. Despite the appearance that low-speed driving cycles would save more fuel than high-speed cycles, the study demonstrated that the potential savings for 10 hours of driving are similar from one cycle to another. One of the major issues with fuel cells is hydrogen production. So an intermediate step toward the hydrogen economy could involve using hydrogen ICEs to allow the development of the infrastructure. The results of this study are comparable with those from the 2001 Well-to-Wheel General Motors study, and yet they provide more information on the vehicle side. An additional study will be presented to compare future technologies and assess the benefits of potential 2010 fuel cell technology.

Publications / Presentations

Rousseau, A. and P. Sharer, "Comparing Apples to Apples: Well-to-Wheel Analysis of Current ICE and Fuel Cell Vehicle Technologies," SAE paper 2004-01-1015, SAE World Congress, Detroit, MI, March 2004.

D. Fuel Cell Vehicle Simulation and Control

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Objectives

- Assess the potential improvement in fuel economy of a fuel cell electric vehicle (FCEV) by hybridizing it with an energy storage system (ESS).

Approach

- Vehicles with several degrees of hybridization were defined;
- Direct hydrogen fuel cell systems were defined in the General Computational Toolkit (GCTool) and used in conjunction with the Powertrain System Analysis Toolkit (PSAT) using GCTool-Eng;
- Two driving cycles were simulated (UDDS, HWFET); and
- Vehicle acceleration performance (10 seconds) and glider mass were held constant to ensure a fair comparison.

Accomplishments

- Defined vehicle powertrains and performed simulations to evaluate performance;
- Developed several design-specific fuel cell system models;
- The fuel economy of hydrogen FCEV can be 2.5-2.6 times the fuel economy of conventional ICEV;
- Hybridization can lead to a fuel economy increase of more than 15%; and
- The potential gain in fuel economy using hybridization is greater for ICE vehicles than for fuel cell vehicles.

Future Directions

- Improve the linkage between PSAT and GCtool; and
- Look at different fuel cell system technologies.

Introduction

Automobile manufacturers are introducing gasoline-electric hybrids to overcome the drop off in the efficiency of the internal combustion engine (ICE) at part loads. According to different studies, hybridization has the potential to reduce the fuel consumption of gasoline ICE vehicles by 20-30% on standard U.S. drive cycles. In contrast to ICE, fuel cell systems (FCS) have the characteristic that the efficiency does not degrade at part load and in fact can be much higher. This is particularly advantageous in transport applications because the vehicles are mostly operated at part load conditions. A recent study concluded that the fuel economy of hydrogen fuel cell electric vehicles can be 2.5-3 times the fuel economy of the gasoline ICE vehicles.

The purpose of this study is to assess the potential improvement in fuel economy of a FCEV by hybridizing it with an energy storage system. The study is based on a mid-size family sedan as the vehicle platform, a direct-hydrogen pressurized FCS as the energy converter and a lithium-ion battery pack as the ESS. In comparing the fuel economies of fuel cell hybrid electric vehicles (FCHEV) with different degrees of hybridization we require that they have the same acceleration performance by holding the combined rated power of the FCS and ESS as constant. Consequently, the FCS is downsized as the degree of hybridization is increased by making the ESS larger.

Approach

The FCS analyzed in this study uses pressurized hydrogen as fuel. At the rated power point, the polymer electrolyte fuel cell (PEFC) stack operates at 2.5 atm and 80°C to yield an overall system efficiency of 50% (based on lower heating value of hydrogen). The system pressure is lower than 2.5 atm at part load and is determined by the operating map of the compressor-expander module. The nominal flow rate of cathode air is two times what is needed for complete oxidation of hydrogen (50% oxygen utilization).

Our interest is in a FCHEV in which the FCS is operated in a load-following mode and the ESS in a charge-sustaining mode. In this type of a hybrid system, the FCS provides the traction power under normal driving conditions and the ESS provides boost power under transient conditions. The ESS also stores part of the energy that must otherwise be dissipated during a vehicle braking event. To be competitive with the ICE propulsion system in terms of drivability and performance, the FCS in this type of a hybrid vehicle must satisfy the following requirements.

The FCS alone must be capable of meeting the vehicle power demands under all sustained driving conditions. These include a specified top sustained speed, taken as 100 miles/hour (mph) in this study, and ability to maintain the vehicle at 55-mph speed at 6.5% grade for 20 minutes.

With the assistance of the ESS, the FCS must have the response time to allow the vehicle to accelerate from 0 to 60 mph in a specified time, taken as 10 seconds in this study.

FCS must have 1-second transient response time for 10% to 90% power.

Figure 1 illustrates an example of the actual operating points of the developed fuel cell system during the FUDS.

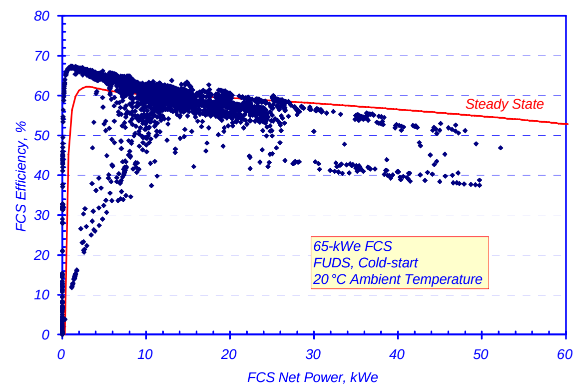

Figure 1. Example of fuel cell system performance.

The fuel cell non-hybrid configuration uses 120 kWe direct hydrogen fuel cell system. Based on this configuration, three design specific fuel cell systems of 100, 80 and 60 kWe were designed to be used with an energy storage system in a hybrid powertrain.

Results

Figure 2 compares the simulated fuel economy of the FCEV, including its hybridized counterparts, with the fuel economy of the ICEV on the highway (FHDS) and urban driving schedules (FUDS).

On the FHDS, the simulated fuel economy of the stand-alone FCEV after adjustment is 63.4 miles per gallon gasoline equivalent (mpgge) compared to 29 mpgge for the ICEV, and hybridization is seen to have a small effect (<3.2% improvement) on the fuel economy of the FCEV.

On the FUDS, the simulated fuel economy of the stand-alone FCEV after adjustment is 55 mpgge compared to 20 mpgge for the ICEV. The fuel economy of the FCEV on the FUDS improves to 67 mpgge with a small ESS (20 kWe) and to 65 mpgge with a larger ESS (40 kWe). Further increase in the size of the ESS to 65 kWe results in a marginal improvement in the fuel economy.

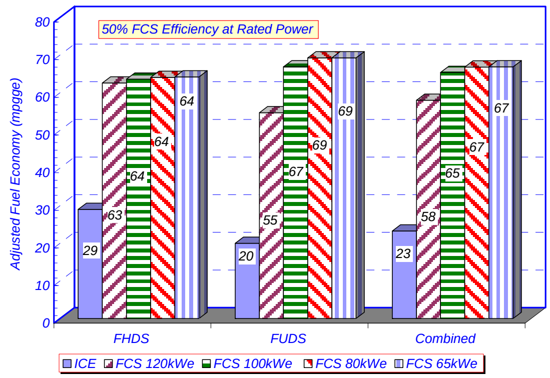

Figure 2. Fuel economy on different driving cycles.

On the combined FHDS and FUDS, the simulated fuel economy of the stand-alone FCEV is 2.5 times the fuel economy of the ICEV. With hybridization, the fuel economy multiplier for the combined schedules increases by about 17% to 2.9. The multiplier increases by about 3% on the highway portion and by about 29% on the urban portion of the combined cycle.

Figure 3 illustrates the effect of drive cycles on the simulated fuel economy of hybrid fuel-cell vehicles. The maximum increase in fuel economy with hybridization is about 3% on the FHDS, 29% on the FUDS, 7% on the aggressive US06 drive schedule, 17% on the New European Drive Cycle (NEDC), and 34% on the Japanese J1015 drive schedule.

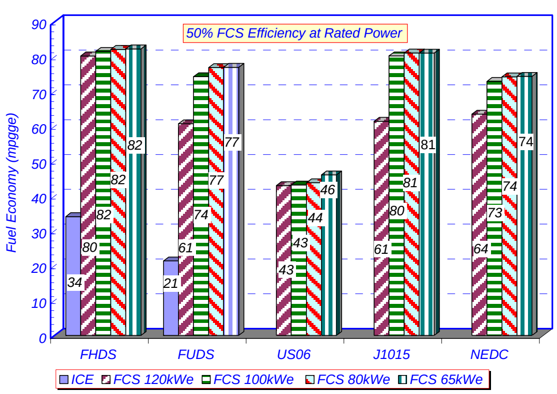

Figure 3. Effect of Drive Cycle on Fuel Economy.

Conclusions

The fuel economy of hydrogen FCEV can be 2.5-2.6 times the fuel economy of conventional ICEV. With a Li-ion battery pack, the fuel economy of a FCHEV on the combined cycle can be 17% higher than that of the FCEV. The extent of increase depends on the degree of hybridization. The increase in fuel economy with an ESS depends on the drive cycles: 3% on FHDS, 29% on stop-and-go FUDS, 7% on the aggressive US06 cycle, 34% on J1015, and 17% on NEDC. The potential gain in fuel economy with hybridization is greater for an ICEV than for a FCEV.

Publications / Presentations

1. Ahluwalia, R., X. Wang, A. Rousseau, and R. Kumar, "Fuel Economy of Hydrogen Fuel Cell Vehicles," Journal of Power Sources, February 2004.
2. Kumar, R., R. Ahluwalia, and A. Rousseau, "Fuel Economy of Hydrogen Fuel Cell Vehicles," 2003 Fuel Cell Seminar, November 2003.

E. High-Fidelity Component Model Integration into PSAT

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Objectives

- Integrate physics-based component models in Powertrain System Analysis Toolkit (PSAT) to be able to characterize advanced technologies without requiring extensive testing.

Approach

- Select the strategic advanced powertrain components;
- Review and inventory models that are currently available for each powertrain component and determine the feasibility of their respective integration into PSAT; and
- Integrate the representative high fidelity models into PSAT and validate.

Accomplishments

- Integrated a zero-dimensional high-fidelity turbocharged diesel engine model into PSAT; and
- Integrated nickel metal hydride (NiMH) and lithium ion (Li-ion) battery models into PSAT.

Future Directions

- Collaborate with the different FreedomCAR Technical Teams to use the models; and
- Continue to integrate detailed models for key components.

Introduction

Most of the component models used for fuel economy and performance prediction are based on look-up tables and are consequently dependant upon actual test data. To be able to evaluate the potential impact of a technology without building a prototype and testing it, physics-based transient component models must be used. Based on the complexity of these models, it was decided to implement existing state-of-the-art models rather than develop new ones internally.

The engine and battery were selected as critical components and candidates for implementation into PSAT.

Approach

Flexible, feed-forward vehicle system simulations, such as PSAT, require a transient engine simulation module capable of accepting a command from the driver or power controller and producing a realistic engine response in terms of torque and speed variation. Realistic engine response is a prerequisite for reliable predictions of the overall vehicle system response, and for high-fidelity study of complex interactions between the engine and other subsystems (driveline, electric components). Furthermore, a physically-based engine module is a critical link in the assessment of various control strategies and their impact on the fuel economy and emissions potential of the propulsion system, especially under transient conditions. Look-up table engine models based on steady-state dynamometer data, which are traditionally used in simulations such as PSAT, cannot satisfy the above requirements, especially if the user intends to assess new engine or engine component designs in order to improve the system performance. Hence the motivation arises to pursue development of a predictive, physically-based, crank-angle resolved engine system simulation suitable for integration with PSAT within the SIMULINK® programming environment.

At present ANL uses a lumped parameter equivalent circuit model to predict the battery's behavior. The actual potential of the cell is therefore the open circuit potential (OCP) corrected for the ohmic drop due to the internal resistance. Considerable improvements can be made to the prediction of the battery performance using a first-principles model. The battery model developed at the Penn State GATE Center is a thermal-electrochemical coupled model constructed on computational fluid dynamics, a computationally robust framework.

Results

Engine transient model. A transient, thermodynamic, physically-based, crank-angle resolved, turbocharged, intercooled diesel engine simulation was developed as a module that can be coupled to the rest of the vehicle propulsion system in SIMULINK®. The module is capable of accepting the driver command, external load and environmental conditions from the top system level and producing (1) torque at the flywheel, (2) realistic speed variations depending on active and resistive torque, and (3) a suite of other engine system variables that might be of interest to the system analysts.

Appreciating the need for maximum flexibility and the fact that the user might not be in a position to obtain all engine design data, automatic scaling routines are included in the code. This is illustrated in Figure 1. In other words, depending on specified new values for engine displacement and number of cylinders, the code automatically adjusts the sizes of engine parts, manifolds, valves and turbomachinery. The fuel injection controller and the engine friction model are offered as separate modules in a default

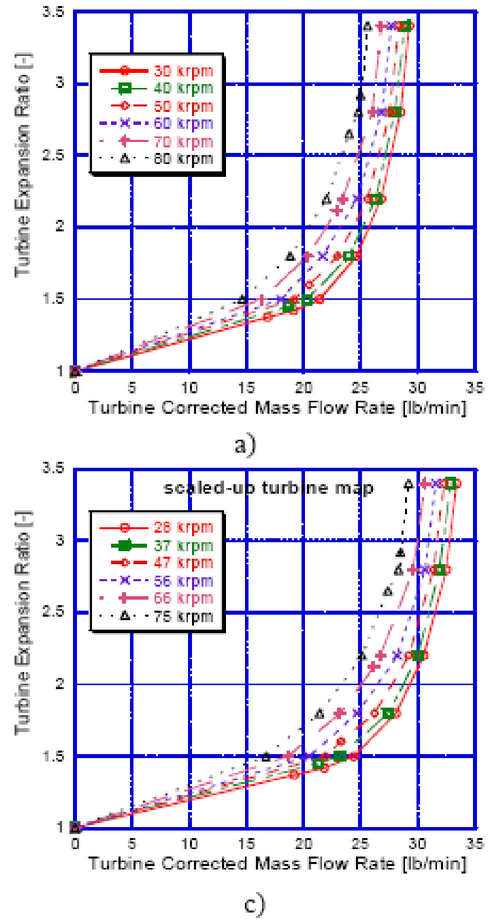

Figure 1. Example of Turbine Map Scaling.

configuration, developed to simulate a representative or "baseline" engine.

Hence, the user will be presented with options to (1) use the offered default calibration, (2) modify the default configuration according to the analysis needs, or (3) completely replace the default configuration with a proprietary module.

Battery transient model. The battery model developed at the Penn State GATE Center is a thermal-electrochemical coupled model constructed on computational fluid dynamics with a computationally robust framework. Validation against experimental data has demonstrated the robustness of this battery model in lead-acid, NiMH and Li-ion cell chemistries. Not only are the computation subroutines for the models faster than real time, they are also callable from SIMULINK® using MATLAB® MEX utilities. This makes the subroutines easily transportable into the PSAT environment without losing the modularity of PSAT.

The potential advantages of using this first principle approach instead of the lumped equivalent circuit approach lies in the ability of the first principle model to adapt to changes in design. For example, a change in the electrode structure (porosity, thickness), separator characteristics or particle size of the active material would change the internal resistance term, because of changes in the ohmic, kinetic or diffusion effects.

The battery models include multiple electrode reactions, charge transfer, multi-component species transport via diffusion, and convection and migration. They include solid state diffusion, gas generation and transport, and heat generation and transport. Hence, PSAT, integrated with the battery model, can be used to develop vehicle charging algorithms and thermal management systems for advanced batteries. Both the NiMH and the Li-ion models have been validated using test data. Figures 2 and 3 represent a portion of the model validation results compared against the Saft HP6 Li-ion battery.

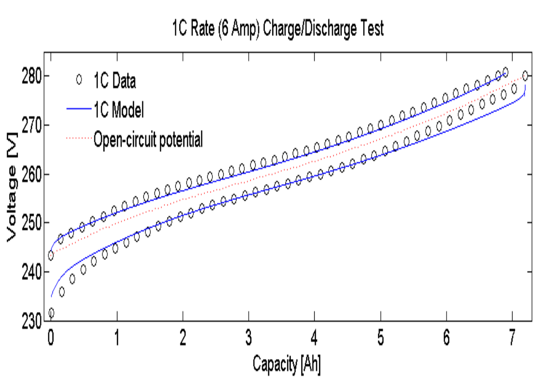

Figure 2. Validation of the Li-ion Model with Saft HP6 – 1C Charge / Discharge.

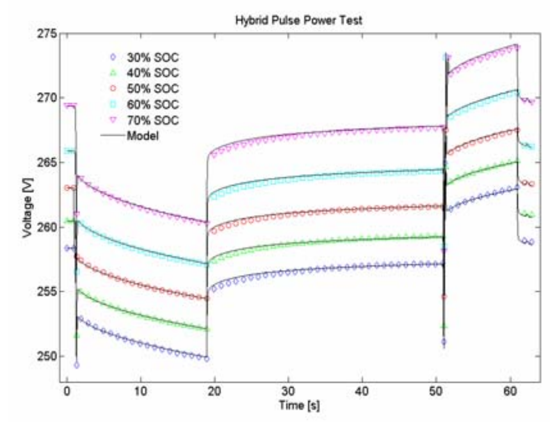

Figure 3. Validation of the Li-ion Model with Saft HP6 – Hybrid Pulse Power Test.

Conclusions

Several transient models, including a high fidelity turbocharged diesel engine as well as a NiMH and Li-ion battery, have been integrated into PSAT.

Publications / Presentations

1. Assanis, “DOE Report”, October 2003.
2. Smith, K., “PSAT Integration of the PSU Battery Model,” January 2005.
3. Smith, K., “A First Principles-Based Lithium Ion Battery Subcomponent Model for the PSAT Vehicle Simulator – Users Guide,” December 2004.
4. Smith, K., “A First Principles-Based NiMH Battery Subcomponent Model for the PSAT Vehicle Simulator – Users Guide,” December 2004.

F. Dual Source Energy Storage Potential for Fuel Cell Vehicle Applications

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Objectives

- Enhance Powertrain System Analysis Toolkit (PSAT) capabilities by implementing a dual energy storage option in existing powertrain configurations; and
- Evaluate the fuel economy potential of combining battery and ultracapacitor in a hybrid fuel cell application.

Approach

- Create and integrate ultra-capacitor and DC-to-DC converter models into PSAT;
- Compare existing battery chemistry designs and determine appropriate technology for use in conjunction with ultra-capacitors in a dual energy storage system;
- Simulate ultra-capacitor and appropriate battery technology in PSAT to determine benefits of dual storage energy system; and
- Validate results through hardware-in-the-loop (HIL) testing using PSAT-PRO.

Results

- Ultra-capacitor and power converter models have been successfully integrated into PSAT as standard components with the option of a dual energy storage system configuration; and
- Completed simulations that show lead acid battery technology offer the highest benefit from being associated with ultra-capacitors in a dual energy storage system configuration since the battery can operate in a wider state of charge range and the ultra-capacitors compensate for the low power density of the lead acid battery.

Future Plans

- Integrate fuel cell and ultra-capacitor hardware onto the HIL test rig for further validation work.

Introduction

A major objective of the FreedomCAR Partnership is to develop vehicles powered by hydrogen fuel cells. Fuel cell vehicles have high efficiency and low emission producing characteristics. Therefore, they are undergoing extensive research and development. Several studies demonstrated the benefits of hybridizing the fuel cell powertrain, mostly because of the potential to recover energy during braking.

Electrical energy storage is a very important element of hybrid vehicles. The technology choice and sizing of the energy storage system is a crucial part of the powertrain optimization process. They have to match both the energy and power requirements of the vehicle system.

Hybrid vehicles require a high power density device; batteries are, at present, the technology of choice. To allow the battery to operate at this power density requirement, both the original design of the battery and the manner in which it is used in the vehicle must be compromised. Specifically, the energy density and useful life of the battery are compromised by using very thin electrode plates to attain the very high power density required in the hybrid vehicle system.

The result is that the energy stored is higher than that needed to operate the vehicle because only a fraction of the stored energy is actually used during normal vehicle operation in order for the vehicle to meet the power requirements for both acceleration and braking. As a consequence, the battery could have been designed and operated at lower power levels over a wider state of charge range.

Several high power density devices have been developed, such as pulse batteries and ultra-capacitors, for use in hybrid electric powertrains. Until recently, batteries and ultra-capacitors were considered to be in competition. However, the benefits of using both technologies concurrently have become more evident; ultra-capacitors provide the major share of the power required in both acceleration and braking.

Combining an ultra-capacitor with a battery allows each of the energy storage technologies to be used for their most appropriate application, respectively. It is then possible to match all of the requirements and optimize the system by downsizing the battery, reducing the mass of the vehicle, and increasing battery life. Life-cycle considerations are important, but they are difficult to quantify without extensive testing.

This project focuses on determining the benefits of combining batteries and ultra-capacitors in a hybrid fuel cell powertrain configuration. Current battery technologies are evaluated in order to determine which is most benefited by the introduction of the ultra-capacitor arrangement. The most promising dual energy storage system is then modeled further, and validated through hard-in-the-loop testing.

Approach

In this study, the potential of associating high-power batteries with ultra-capacitors with a direct hydrogen fuel cell powertrain is investigated. Different battery technologies have been compared, such as lead-acid, nickel metal hydride, and lithium-ion, to evaluate the one that would benefit the most if combined with ultra-capacitors. An ultra-capacitor model was implemented into PSAT, and the fuel cell powertrain with dual energy storage technologies was simulated. Finally, these results have been compared with the results from tests undertaken at Argonne's Advanced Powertrain Research Facility (APRF) by using HIL.

Battery technology choice for use with ultra-capacitors. To determine the most suitable battery technology to be used with ultra-capacitors, a hybrid fuel cell vehicle, as outlined in Table 1, has been considered as the reference for comparison in this study. The hybrid powertrain includes a 100 kWe (electrical) traction motor, a 70 kWe fuel cell, and 30 kWe batteries.

Three different battery technologies were compared: lead-acid (Pb-A), nickel metal hydride (NiMH), and lithium-ion (Li-ion). The cell characteristics for these batteries are summarized in Table 2.

Table 1. Small passenger vehicle characteristics.

Parameter	Conventional Vehicle	Direct Hydrogen Fuel cell vehicle
Engine Power (kW)	85	0
Fuel cell Power (kW)	0	85
Motor Electric Power (kW)	0	100
Transmission	Auto 4 speeds	Single reduction
Final Drive ratio	4.07	
Wheels radius (m)	0.28	
Frontal Area (m^2)	1.72	
Coefficient Drag	0.38	
Vehicle mass (kg)	1233	1406
Acceleration: 0 to 60 mph (s)	11.5	10.9
FUDS Fuel economy (mpg)	35.7	62.1
FHDS Fuel economy (mpg)	49.8	80.9

Table 2. Battery cell characteristics.

	Units	Lead-Acid	Nickel Metal Hydride	Lithium-Ion
Nominal voltage	V	2	1.2	3.9
Capacity at C/3 rate	A.h	12	11	6
Specific energy	Wh/kg	30.1	41.2	61.6
Specific power	W/kg	226	343	2924
Mass	kg	0.8	0.32	0.38

Impacts of ultra-capacitors on fuel cell system. For this particular application, the Maxwell PC 2500 tested at INEEL was chosen, which has a rated capacitance of 2700 F.

The system considered is similar to the previous outlined in Table 1, with batteries and ultra-capacitors providing the remaining 30 kWe. Power conditioners have been integrated into PSAT to provide a more realistic and more stable system, allowing different voltages within the system.

Results

Battery technology choice for use with ultra-capacitors. Upon defining the vehicle parameters, the next step consists of sizing the components. To study the impact of an energy storage system sizing and to highlight the characteristics of each technology, the batteries have been sized by using both power and density considerations.

Figure 1 shows the fuel economy improvement due to the fuel cell vehicle hybridization. As one can expect, fuel economy gains are greater for driving cycles that have a high level of regenerative braking energy available (the Federal Urban Driving Schedule, or FUDS) and marginal for high-speed cycles (the Federal Highway Driving Schedule, or FHDS). Moreover, independent of the methodology used, the lead acid battery technology has the lowest fuel economy, mostly because of its high power density. Finally, the Li-ion offers the best fuel economy out of the group studied.

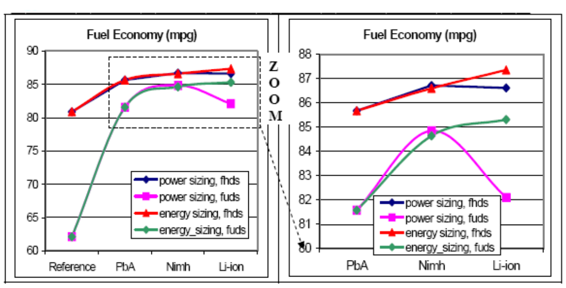

Figure 1. Influence of component sizing for several battery technologies.

When sizing the batteries on the basis of power, the NiMH battery achieves higher fuel economy than does the Li-ion battery. The reason is that, even if the Li-ion has better specific energy and specific power than any of the other technologies studied, few cells are needed to achieve the required power (30 kW). As a consequence, there is less energy storage capability with the Li-ion battery (632 Wh versus 3604 Wh).

Figure 2 emphasizes this point by showing the mechanical brake power when the vehicle decelerates. The mechanical brake needs to be used more for the vehicle configured with the lithium-ion batteries than for the nickel metal hydride batteries. All of the gain from the lithium-ion technology is nullified because of a lack of energy during regenerative braking because the Li-ion battery ratio of power to energy is too large (47.5 for Li-ion versus 8.3 for NiMH).

One of the key issues in hybrid vehicles is battery life. Indeed, to extend the battery life, optimize the system, and have near maximum power capability for both vehicle acceleration and regenerative braking, the battery state of charge has to be maintained in a narrow range. Test data demonstrates that lead-acid battery life is shorter than expected when used in this mode, because of irreversible sulfation, which is the result of using the battery without periodically fully charging it. Other battery technologies, such as NiMH or Li-ion batteries, appear to respond better to shallow cycling and do not have a decrease in expected life when used under these conditions.

Therefore, ultra-capacitors appear well matched with state-of-the-art, inexpensive, and robust lead acid batteries.

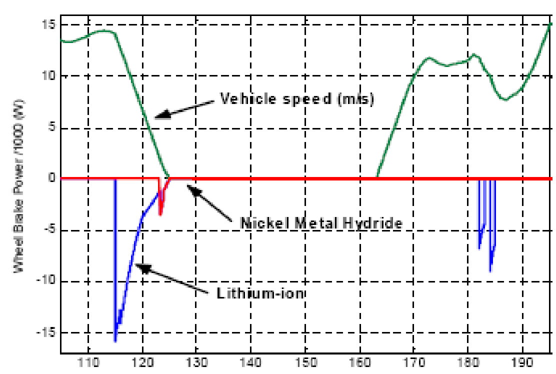

Figure 2. Mechanical brake power comparison for Li-ion and NiMH when sizing based on power.

Conclusions

An ultra-capacitor model was developed and integrated in PSAT. Several battery technologies were compared for use with ultra-capacitor in a fuel cell vehicle. In general, only small fuel economy improvements were noticed when adding ultra-capacitors. Lead-acid technology benefits the most as they can be used in a wider state-of-charge range with the ultra-capacitors compensating for its lack of power density. Finally, battery life is expected to be increased with ultra-capacitors being used for transient purposes.

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 production-cost estimation via a uniform estimation methodology, allowing a comparison of alternative technologies under consideration by the FreedomCAR community to facilitate component technical target setting and research focus; and
- Develop a repository of cost data about various component-level technologies being developed today for new generation vehicles.

Approach

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

Accomplishments

- Developed baseline mass and cost estimates for thirteen EPA light-duty vehicle classes considered by the Technical Targets Tool under development by National Renewable Energy Laboratory (NREL), for the estimation of potential oil savings from a particular vehicle class; and
- Initiated the documentation of automotive system cost model (ASCM) and extension of the cost modeling framework’s capability for the life cycle cost estimation.

Future Directions

- Integrate ASCM into the performance model PSAT;
- Develop “Cost Roll-Ups” of advanced vehicle designs covering all three light-duty vehicle platforms; and
- Enhance the cost modeling capability to include both medium- and heavy-duty trucks.

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 past collaboration among the vehicle engineering technical team (VETT), Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), and support from IBIS Associates, Inc., has resulted in a modular automotive system cost model (ASCM) by incorporating a new definition of vehicle subsystems, employing the sizing routines of ANL powertrain and chassis developed by ORNL, covering three major light-duty vehicle types (i.e., passenger car, pick up truck, and sport-utility vehicle [SUV]) and limiting cost estimation to vehicle production only. The focus of this year's work has been to develop mass and cost relationships for thirteen EPA light-duty vehicle classes considered by the Technical Targets Tool currently under development by NREL, and to enhance the modeling framework capability in terms of vehicle life cycle cost estimation. This tool considers a change in the vehicle cost as one of the factors in the penetration of different vehicle classes of advanced technologies to estimate potential oil savings. ASCM continues to be enhanced by incorporating advanced technology data as they become available and including a range of baseline light-duty vehicles which can then be used as the starting point for any cost analysis.

Approach

Cost assessment of advanced vehicle designs need to be performed at the vehicle system/subsystem level. 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 was selected for each 13 EPA vehicle classes to reflect major technical differences in 35+ vehicle components considered in ASCM. Baseline cost estimates were made for both 2004 and 2010, by taking into account likely technology improvements occurring mainly in powertrain-related components for the latter case.

Results

A representative vehicle considered under each 13 EPA light-duty vehicle classes for Technical Targets Tool is as follows:

- Two-seater passenger car: GM Corvette
- Minicompact passenger car: BMW Mini
- Subcompact passenger car: BMW 3 series
- Compact passenger car: Honda Civic
- Midsize passenger car: Honda Accord
- Large passenger car: Ford Taurus
- Small pick up truck: GM S10
- Standard pick up truck: Ford F150
- Full cargo van: GM Express/G van
- Minivan: DaimlerChrysler Caravan
- Small SUV: Honda CR-V
- Midsize SUV: Ford Explorer
- Large SUV: GM Tahoe

Figure 1 shows the relative baseline 2010 production cost distribution estimates, disaggregated total vehicle cost into powertrain and glider vehicle subsystems components for 13 light-duty EPA vehicle class considered here. All production cost ratio estimates shown in this figure are relative to two-seater passenger car (i.e., GM Corvette) considered here. Baseline mass and cost estimates were calibrated and based on the data obtained from various sources including published literature and direct interviews with OEM and supplier engineers and designers. Although relative vehicle production cost estimates of some light-duty trucks (as shown in Figure 1) are lower than other vehicle types, but due to higher profit margin in the former causes their retail price to be higher. Interrelationships between powertrain and non-powertrain components considered in ASCM for chassis component sizing and thereby its cost were also developed and calibrated for each EPA vehicle class case. Glider mass and cost relationships as a function of powertrain mass required as the input for Technical Target Tool were derived based on the regression analysis of results obtained from iterations in increments of 100 kg between 200 and 1300 kg of powertrain mass for both 2004 and 2010 baseline cases.

The development of mass and cost relationships for Technical Target Tool has now provided a library of thirteen baseline light-duty vehicle classes which an ASCM user can use this as the starting point for any advanced technology vehicle case cost analysis. An enhancement of ASCM capability for the life cycle vehicle cost estimation was also initiated including model documentation. Additional data beyond the vehicle manufacturing step (i.e., corporate overhead, dealer cost, financing, insurance, maintenance & repair, fuel, local fees, and disposal) were being collected, where field data collected by the Advanced Vehicle Testing Analysis and Evaluation activity at Idaho National Laboratory could be used for maintenance and repair costs.

Future Directions

During the coming year, with the completion of life cycle cost estimation capability, model integration into the performance model Powertrain System Analysis Toolkit, and documentation, model should distributed to a wide range of users and validation activity be initiated. Data on advanced technologies should be collected for various vehicle subsystems as they become available. In addition, a limited number of "Cost Roll-Ups" will be developed for several generic vehicle configurations covering some of the 13 available EPA light-duty vehicle classes to demonstrate the relative cost sensitivity of the model due to a change in technology for motors, batteries, engines, or body materials.

It is proposed that the framework be enhanced to include multiple heavy-duty vehicle classes drawing from some similarities that may exist between light- and heavy-duty vehicles. 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. Only hybrid propulsion systems will be considered for heavy-duty vehicles; fuel cells will only be considered as auxiliary power units (APUs). The initial focus of enhancements may be on Class 4, Class 6, and Class 8 heavy-duty vehicles, consistent with the Advanced Heavy Hybrid Propulsion Systems program.

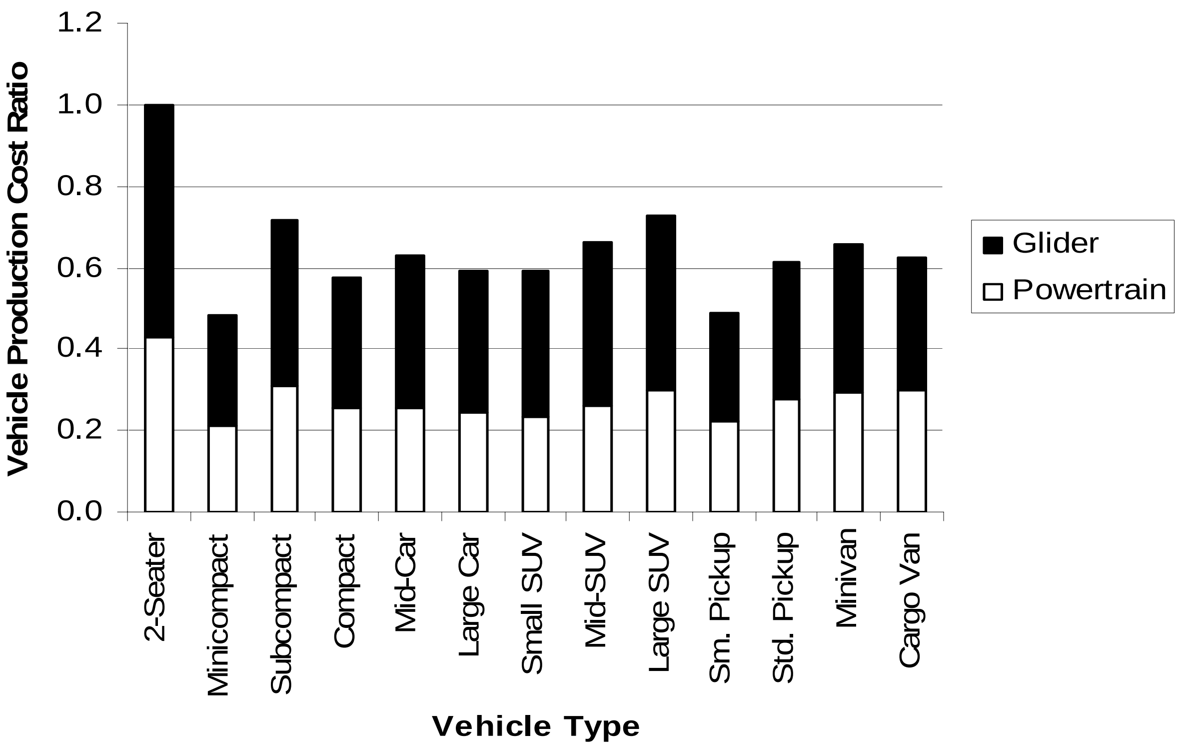

Figure 1. Projected relative production cost of 2010 baseline 13 light-duty EPA vehicle classes.

H. Model Validation Procedure Improvements in PSAT

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Objectives

- Validate vehicles in Powertrain System Analysis Toolkit (PSAT) using test data from Argonne National Laboratory's (ANL's) Advanced Powertrain Research Facility (APRF); and
- Enhance the data Quality Check (QC) and validation process.

Approach

- Develop a new graphical user interface for PSAT to facilitate data transfer;
- Automate the data QC process to evaluate the uncertainty of the sensors;
- Facilitate the control strategy understanding using pre-defined functions; and
- Facilitate the comparison between test and simulation.

Accomplishments

- Designed a new Graphical User Interface (GUI);
- Added the ability to rename and rescale sensor parameters using templates;
- Modified the post-processing functions used for simulation so that they can also be used for test; and
- Defined several levels of plots to perform data QC.

Future Directions

- Continue to improve and automate the data QC process; and
- Use ANL APRF vehicle data to validate PSAT when available.

Introduction

One of the unique capabilities at ANL is the combination of state-of-the-art test facilities with unique modeling and simulation tools. To maximize this potential, it is crucial to have a seamless path for data from test to simulation. ANL has been working for the past several years on the development of a generic validation process for advanced vehicles. Developing tools to facilitate the application of this process will further enhance the overall capabilities at ANL.

Approach

A new graphical user interface has been developed to facilitate the transfer, validation, and analysis of data from APRF to PSAT. Its main goal is to rename and scale the data to follow PSAT nomenclature and allow an easy and semi-automated way to analyze and compare them with simulation results.

In addition, PSAT post-processing routines have been modified so that they can be used for both simulated and test data. For example, engine efficiency will be automatically calculated from the engine speed and torque sensors.

Finally, the data analysis features (such as pre-defined plots) will also be shared between test and simulation to allow for an easy comparison.

Results

An interactive GUI has been developed. The different steps to implement test data into the PSAT environment are described in Figures 1 through 5 below.

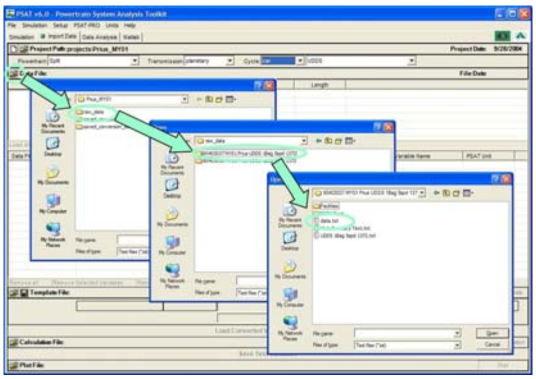

Figure 1. Step 1: The user loads the raw data from the tests. It should be noted that a specific format was developed to recognize the units of each sensor.

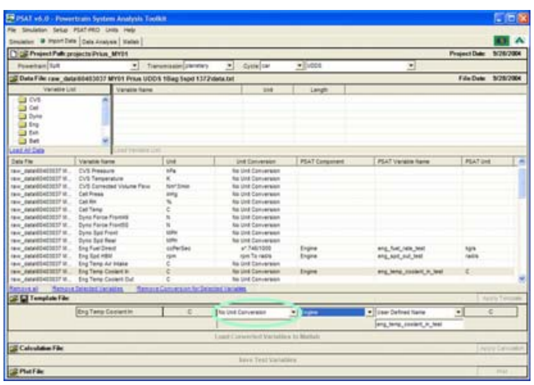

Figure 2. Step 2: The user renames and rescales the parameters to follow PSAT nomenclature.

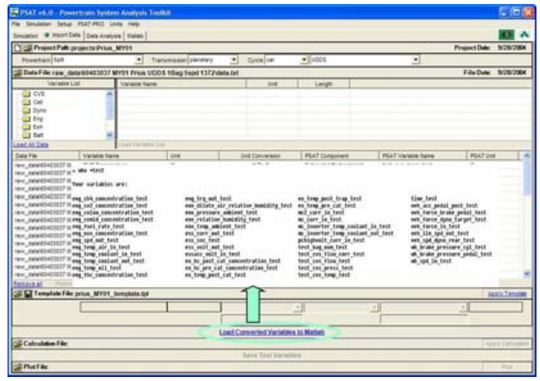

Figure 3. Step 3: The renamed variables are loaded into MATLAB®.

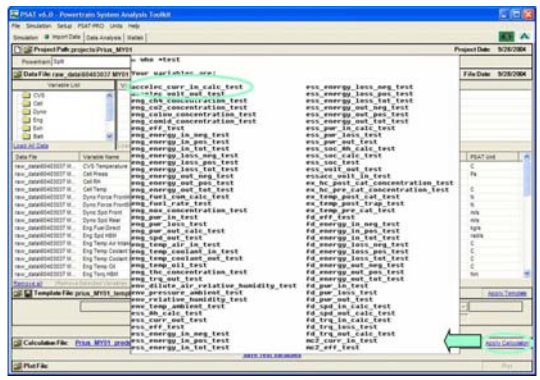

Figure 4. Step 4: Based on the sensor information, effort and flow of the components are calculated. Using these values, power, energy and efficiencies are automatically computed. All the new parameter names end by *_calc_test versus *_test for the sensors.

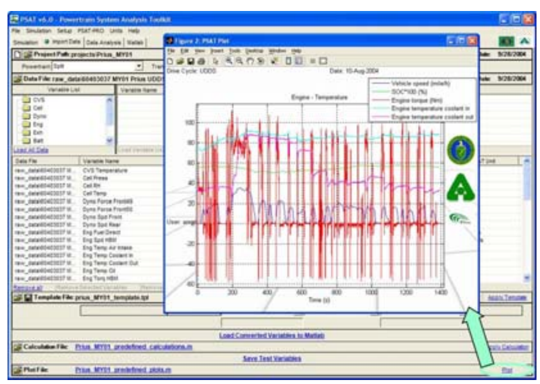

Figure 5. Step 5: Several lists of predefined plots are created to allow a quick QC of the test data as well as first analysis of the control strategies.

Conclusions

An innovative process has been developed to easily import, rescale and rename data from ANL's test facility. An interactive GUI is used to define specific post-processing (calculations and plots) for a defined vehicle. Once the process is in place, any additional test data from the vehicle can be analyzed within minutes. Modifications were performed in PSAT as well as in the APRF to enhance the synergy between both capabilities. This process allows a quicker test data quality analysis as well as comparison between simulation and test data, thus accelerating the validation.

I. PSAT and PSAT-PRO Maintenance

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Objectives

- Enhance Powertrain System Analysis Toolkit (PSAT) capabilities to better support DOE's activities; and
- Ensure PSAT compatibility with latest MathWorks MATLAB® and SIMULINK® versions.

Approach

- Prioritize software enhancement based on DOE support and users' feedback.

Accomplishments

- Implemented additional initialization files and pre-defined vehicles;
- Enhanced post-processing calculations;
- Added an ultra-capacitor component model;
- Added flexible saving options; and
- Released PSAT V5.2.

Future Directions

- Continue to enhance PSAT capabilities based upon DOE and users needs.

Introduction

To better support DOE and its PSAT user community, it is important to review and enhance the capabilities and content of PSAT to remain current on new and emerging technologies. Therefore, several new features have been identified and implemented into PSAT. Some of the most significant accomplishments are described below.

Results

Argonne National Laboratory's (ANL's) vehicle systems analysis team released the newest version of its vehicle simulation modeling software in November 2003. The latest Powertrain System Analysis Toolkit (PSAT V5.2) includes many new features and improvements, some of which are highlighted below. These changes were based on feedback from industry and universities that use the software, as well as the needs expressed by staff at DOE and ANL. PSAT V5.2 runs with MATLAB® R13 & R13 SP1. A 30-day demonstration version can be downloaded at http://psat.anl.gov.

Enhanced post-processing capabilities. The first enhancement concerns the post-processing. A significant amount of post-processing calculations were already performed in previous versions. The new release focused on highlighting the most important ones, such as the average energy losses per component, the percentage of regenerative braking energy recovered during the cycle or the average powertrain efficiency.

Additional component models. In order to compare the energy storage technologies, it was necessary to integrate an ultra-capacitor model into PSAT. Using test data from Idaho National Engineering and Environmental Laboratory (INEEL), a model based on a representative R-C circuit was developed as illustrated in Figure 1.

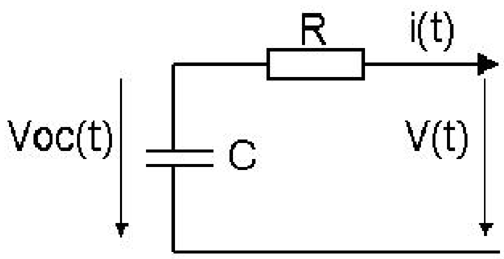

Figure 1. Ultracapacitor RC Model developed by ANL for PSAT implementation.

If the current and voltage equations are solved for a constant current discharge and we consider an infinitely slow discharge, the maximum energy deliverable can be expressed as:

$$(1) \quad E = \frac{1}{2} C V_{OC}^2$$

The ultra-capacitor model is implemented in MATLAB®/SIMULINK® blocks. The model limits power to keep the ultra-capacitor within operating limits, and calculates *SOC* and heat generation from the ultra-capacitor. The set of parameters (V_{oc}, R, and power), are the variables of a quadratic equation to solve for the equivalent circuit's current. The total current that the ultra-capacitor can deliver is limited to an allowable range. The ultra-capacitor current is then used to update the effective SOC. The thermal model of the ultra-capacitor calculates the module temperature, which is fed back to be used in determining the performance parameters.

The main equations used in this model in addition to Equation (1) above are:

(2) Voltage:

$$V = V_{OC} - R \times I$$

(3) Open circuit voltage:

$$V_{OC} = SOC \times (V_{\max} - V_{\min}) + V_{\min}$$

(4) Maximum discharge current:

$$I_{\max\_dis} = \frac{(V_{OC} - V_{\min})}{R_{\text{int}}}$$

(5) Maximum charge current:

$$I_{\max\_chg} = \frac{(V_{OC} - V_{\max})}{R_{\text{int}}}$$

(6) Maximum discharge power:

$$P_{\max\_dis} = V \times I_{\max\_dis}$$

(7) Maximum charge power:

$$P_{\max\_chg} = V \times I_{\max\_chg}$$

(8) State Of Charge:

$$SOC = \frac{(V_{OC} - V_{\min})}{(V_{\max} - V_{\min})}$$

Flexible Saving Options. After each simulation, PSAT is used to save several files to:

- Store the initial conditions and the main results;
- Store the simulation parameters for later analysis; and
- Rerun the simulation.

As this process was time-consuming and not always required, it was decided to let the user decide whether or not the simulations should be saved. As a default, the simulation will NOT be saved anymore. However, when several simulations are involved (e.g., "multicycle," "conso & perfo", "parametric study"...), the simulations will be automatically saved. Users now have the ability to save the simulation from the beginning as shown in Figure 2 below or at the end of the simulation.

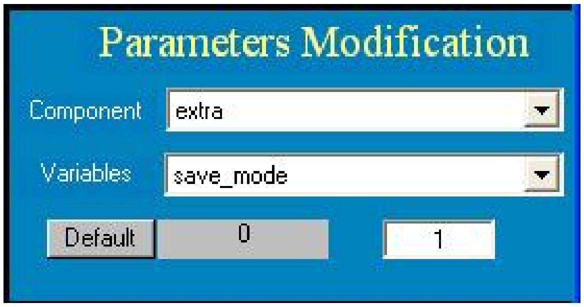

Figure 2. Process to save the simulation data from the beginning in PSAT.

Conclusions

PSAT V5.2 has been released with many new features based on DOE and user's feedbacks. New capabilities include advanced calculations for post-processing simulation data, additional component models and data sets as well as flexible saving options. In addition to the release of VPSAT V5.2, a 30-day demo version was made available for download through the ANL website.

III. INTEGRATION AND VALIDATION

A. Hydrogen ICE Hybrid Powertrain Configuration Development

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Objectives

- Quantify the potential and identify the technical barriers of hydrogen use for internal combustion engine hybrid electric vehicle (HEV) applications through an integrated vehicle systems approach.

Approach

- Perform research and development in partnership with one or more FreedomCAR industrial partners;
- Validate the Ford Focus Powertrain System Analysis Toolkit (PSAT) model using test data collected at the Advanced Powertrain Research Facility (APRF);
- Evaluate baseline performance of this conventional compact car in simulation;
- Use PSAT to select the most suitable hybrid powertrain configuration for hydrogen internal combustion engines (H_2-ICE) with the objective to maintain the same level of performance;
- Develop the corresponding hybrid control strategies to reach performance, fuel economy and emissions targets; and
- Investigate varying degrees of hybridization with respect to the H2-ICE and associated hybrid powertrain configuration.

Accomplishments

- Validated the baseline conventional compact car model;
- Performed multiple PSAT simulations to evaluate baseline performance information;
- Decided appropriate sizing of powertrain components through simulation using PSAT with the objective to maintain performance levels equivalent to the established baseline conventional vehicle;
- Determined appropriate traction motor size and technology, energy storage system size and chemistry, and motor coupling for the compact car segment;
- Identified powertrain component hardware based on parametric simulation study; and
- Investigated emulation techniques to vary the degree of hybridization for the selected hybrid powertrain configuration.

Future Directions

- Complete the dynamic virtual inertia emulation needed to vary the degree of hybridization.

Introduction

In order to validate the performance of DOE-sponsored technologies in the context of complete vehicle systems, dynamic simulation models (PSAT) are combined with DOE's specialized equipment and facilities (APRF). This integrated process, called Hardware-In-the-Loop (HIL), assesses real component technologies and control strategies in an emulated vehicle test environment quickly and cost-efficiently. In this initiative, Argonne National Laboratory (ANL) has embarked on a challenging project aimed at demonstrating the potential and identifying the technical barriers of hydrogen use for internal combustion engine hybrid electric vehicle applications. Hydrogen-fueled engines offer a near-term alternative to gasoline ICE and a step towards hydrogen economy. However, hydrogen with its low density and low ignition energy poses some new challenges to retain the functional characteristics of current vehicles. Turbocharging has the potential to compensate H_2 engine low power density but what are the impacts on the engine torque response? Hybridization and integrated control offer new perspectives to the vehicle system complementing H_2 engine technology and improving vehicle performances, while reducing fuel consumption and NO_x emissions. In support of FreedomCAR goals to develop a hydrogen ICE powertrain system with a cost target of $45/kW by 2010, a peak engine efficiency of 45% while meeting or exceeding emission standards, an H_2-ICE hybrid propulsion development project was proposed to DOE and USCAR. Ford Motor Company provided support to the project by donating two engines, which were a production gasoline-fueled 2.3-L 16 valve inline four cylinder engine and a comparable hydrogen-fueled engine.

Approach

The first step in this project was to validate the Ford Focus PSAT model. In order to complete this first objective, ANL staff utilized an available Ford Focus test vehicle. This vehicle is normally used as a correlation vehicle to compare the data collected at ANL's Advanced Powertrain Research Facility (APRF) with various testing facilities. The vehicle has been performance tested for 0 to 60 mph acceleration and fuel economy on the highway and urban driving cycles. The data collected were then compared with the simulation results of the Ford Focus model performing the same testing procedures. Analysis of the simulation and test data showed that the vehicle model can predict accurately the Ford Focus fuel economy within 5% as shown in Table 1.

Once the accuracy of the vehicle was demonstrated, further simulation studies could be performed. Using simulation, our team defined the baseline performance targets of the conventional compact car. Those targets were used throughout the study as a baseline for evaluation of the hydrogen-fueled engine vehicle performances. The baseline performance targets are summarized in Table 2.

Table 1. Validation results.

2004 Ford Focus – ZETEC	HWFET (mpg)	UDDS (mpg)
PSAT simulation results	37.36	27.95
Actual Test Results	37.83	27.92

Table 2. Baseline performance targets.

Vehicle Test and Simulation mass	3125 lb
0-60 mph PSAT simulation results	11.6 s
0-60 mph test data	11.0 s

Using PSAT capabilities, our team replaced the gasoline engine existing in the conventional vehicle model by a hydrogen-fueled engine. As part of our collaboration with industry on this project, Ford Motor Company supplied a hydrogen engine dedicated to this project. In order to perform the required simulation tasks, Ford also provided a proprietary performance map of the donated hydrogen engine. Using this engine map and the previously validated Ford Focus model, simulation was used to predict the vehicle performance of our baseline vehicle with a hydrogen engine. This step allowed us to quantify the impact of using a hydrogen engine on vehicle performance and fuel consumption. Specifically, the lack of power density – characteristic of a hydrogen engine if no supercharging devices are being used – has been quantified.

In order to compensate for this lack of power density, various engine calibration techniques can be used. During the course of this study, ANL took the approach to determine hybridization impact on hydrogen engine vehicle performance. This is shown graphically in Figure 1. Using simulation, our team selected the most suitable hybrid powertrain configuration for hydrogen internal combustion engines with the objective to maintain the same level of performance. Furthermore, the corresponding hybrid control strategies were developed to reach performance, fuel economy and emissions targets.

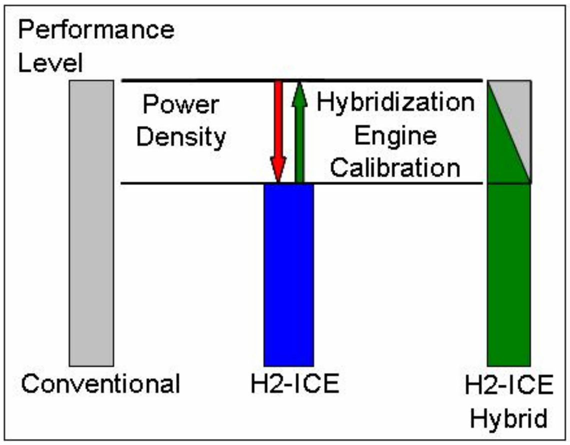

Figure 1. Hybridization impact on H2-ICE vehicle.

The performance based control strategy operates the engine at its maximum available torque for a given rotational speed. The fuel economy based control strategy operates the engine at its best efficiency while meeting requirements of the driver to follow the prescribed vehicle speed profile. Finally, the emissions based control strategy has been developed from the steady state NO_x emissions data of the engine. NO_x emissions are particularly critical for a hydrogen fueled engine. In addition, NO_x emissions are directly correlated with engine air/fuel ratio. Therefore, a hybrid control strategy focused on NO_x emissions reduction is promising as it could also allow operating the engine at a higher air/fuel ratio benefiting the vehicle fuel economy. An algorithm was developed to determine a range of engine torque and speed operating points where the lowest amount of NO_x emissions would be produced for a given engine power requirement. For this same power output, within the previously determined range of low NO_x operating points, the algorithm then found the most efficient point to operate the engine. A trade-off between NO_x emissions and engine efficiency was assigned for each power. The NO_x emissions reduction control strategy was designed to operate the engine on this point to produce the demanded power.

Once the hybrid configuration was selected and the control strategies were developed, the next step of the simulation task was to investigate varying degrees of hybridization with respect to the H_2-ICE and associated hybrid powertrain configuration.

Results

Simulation results showed that a hybrid configuration comprised of only a starter-alternator did not improve the overall power density enough to meet the performance criteria. Even with a higher voltage/power integrated starter alternator (ISA), the power density did not meet the criteria. By varying the degree of hybridization in simulation and observing the vehicle performance, our team was able to determine the minimal battery power required to meet the performances target, as shown in Figure 2.

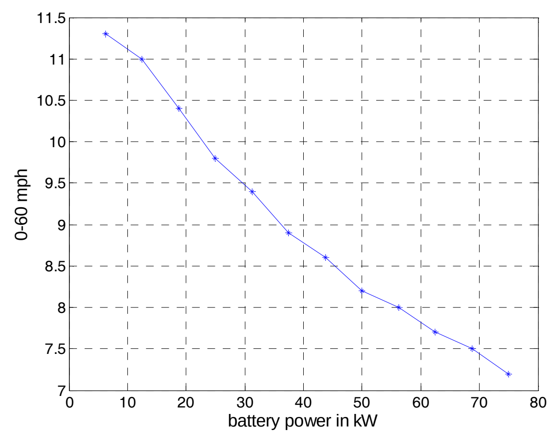

Figure 2. Performance (0–60 mph) vs. battery power.

Considering this minimal degree of hybridization, the hybrid powertrain configuration selected includes two electric machines: an ISA and a pre-transmission traction motor. An ISA powertrain facilitates idle engine stop and thus increases fuel economy. The use of a pre-transmission traction motor eliminates the need for a higher power ISA.

Using the flexibility afforded by PSAT, our team searched for an ideal transmission candidate for our application. Despite its good drivability, we eliminated the automatic transmission because of the inefficiency of its torque converter (not required in a hybrid pre-transmission vehicle). A six-speed manual transmission presents the advantages of higher mechanical efficiency and allows greater flexibility for engine speed control, but manual gear shifting was viewed as a disadvantage. Because of the hydrogen engine power density, our team pursued advanced transmissions providing no torque interruption at the wheels. A continuously variable transmission (CVT) was considered because it provides a wide range of options to control the engine speed and it continuously transmits torque at the wheels. However, our team selected a more efficient transmission design that provided the same benefit. ANL investigated the benefits of a Dual Clutch Transmission (DCT) for use in H_2-ICE hybrid vehicle. One of the main challenges of the project is to use a vehicle system approach to compensate for the low power density of the H_2-ICE. The selection of the most suitable transmission for application in the H_2-ICE hybrid vehicle should therefore depend on transmission performance and efficiency. A DCT offers better acceleration than a manual transmission and provides more engine speed control potential to improve fuel economy with an optimized shift pattern. Besides eliminating the torque converter, the fuel efficiency and performance advantages of a DCT over a CVT and automatic transmission are a higher mechanical efficiency, a reduced number of clutches and related losses, minimized applied clutch actuation pressures, and optimized gear ratios. A DCT can provide the full shift comfort of traditional automatics but offer significantly improved fuel efficiency and performance. A DCT has been selected for its compatibility with H_2-ICE characteristics. A mechanical diagram of the DCT chosen for this project is shown in Figure 3.

A parametric PSAT study determined the appropriate powertrain component sizes with the constraint of maintaining performance levels equivalent to the baseline vehicle. Motors sizes and technology, battery size and technology, and motor coupling have been selected for the compact car segment. The results of this study are summarized in Table 3. Additional simulations were performed using the same approach for a representative SUV.

Hardware-in-the-loop powertrain component hardware has been selected based on the simulation results. In order to emulate various power output traction motors, the electric machine and drive

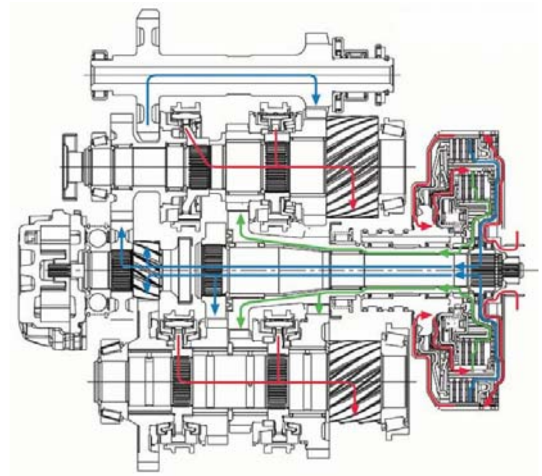

Figure 3. Mechanical diagram of a DCT.

Table 3. Hybrid Components Sized to Exceed Performance Targets.

Battery Size	31 kW	Battery power density – 865 W/kg
Motor Size	25 kW	Motor efficiency for sizing assumed to be 80%, Motor/drive power density – 667 W/kg
Hydrogen Engine Peak Power	84 kW	Actual 0-60 mph performance – 9.8 s

system have to be scalable. Different options have been investigated and a through-shaft motor with input and output torque sensors has been selected.

Industry representatives were consulted to provide a solution satisfying the requirements in terms of dynamics for virtual inertia emulation, and a suitable drive, motor and user interface have been selected. Work is currently in progress to satisfy the requirements of dynamic virtual inertia emulation for the scalable electric drive system.

The battery model was modified to allow hardware emulation using a controllable DC power source. Definition of the battery characteristics is critical as the battery will impact electric motor use, resulting in varied engine utilization and affecting vehicle fuel economy and associated exhaust emissions. The battery model must match the vehicle electrical power requirement and to belong to commercially available technology in order to support realistic results. PSAT was used to design two battery packs matching our power requirement. These are:

- Pack A: Li-ion from Panasonic; 3.6V / 5Ah / 230g / 437 W For each cell; 72 Cells.

- Pack B: Cylindrical Ni-Mh from Panasonic; 1.2V / 6Ah / 200g / 150W for each cell; 240 Cells.

The following plots show voltage, current, and state of charge (SOC) variation of the batteries simulated. Figure 4 shows the results for battery pack A, while Figure 5 represents battery pack B.

Battery pack B was selected based on a PSAT optimization study using the complete vehicle model. The control strategy has been modified to fit the new constraints imposed by this battery. The choice of the battery has an impact on the utilization potential of the motor. To avoid reaching the maximum discharge power of the battery, the decision to start the engine has been modified to use the electric motor less. Figures 6 and 7 show the impact of the battery selection on behavior of the system and subsequent traction motor use.

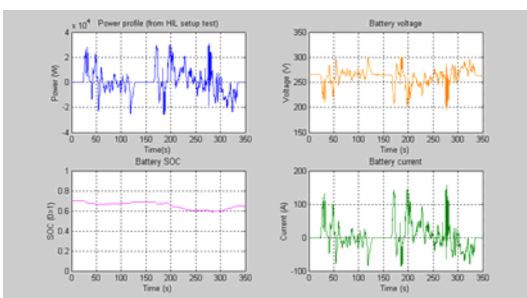

Figure 4. Simulation results of battery pack A.

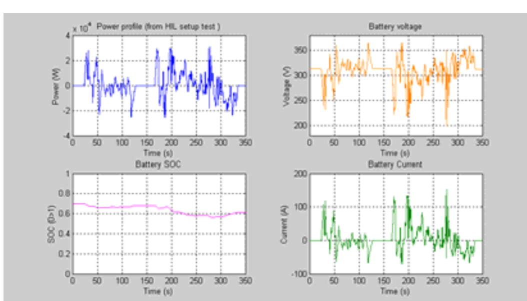

Figure 5. Simulation results of battery pack B.

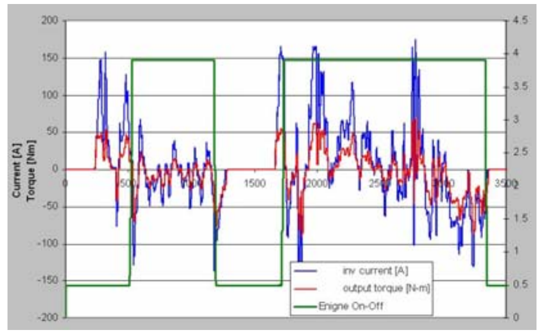

Figure 6. Impact of battery and control on motor and engine utilization – pack A.

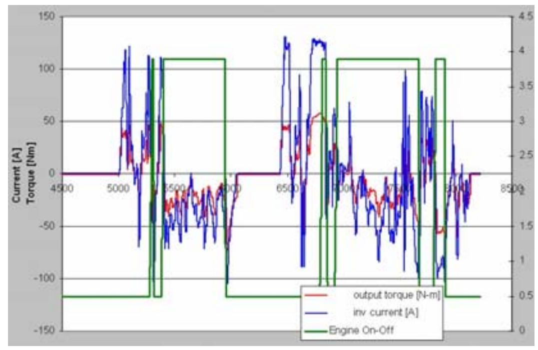

Figure 7. Impact of battery and control on motor and engine utilization – pack B.

An initial vehicle control strategy was developed using PSAT. The design philosophy of this control strategy is to have the engine operating on its best efficiency curve. The surplus power of the engine operating in this manner will be used to charge the battery, depending on the SOC. It was observed that the engine, while trying to maintain operation at the best efficiency region, would provide much more charging energy to the battery than the battery would get from regenerative braking.

Oxides of nitrogen (NO_x) are a serious concern with hydrogen engines, especially when the combustion is close to stoichiometric. The second control strategy focuses on engine control in an effort to reduce NO_x emissions from the engine. NO_x emissions data allow definition of a minimal NO_x curve that can be used to determine the lowest NO_x production for a given engine power. For each engine iso-power curve, if several NO_x minimal exist for a particular engine power, the controller selects the most efficient operating point. The engine torque and the dual clutch transmission gears are controlled to operate the engine on this "NO_x curve" while satisfying engine power demand. With this "NO_x curve," the engine is operating at lower load and higher speed. Consequently, the motor is able to absorb the excess power generated by the engine and is not limited by its negative torque. The engine operates on the specified "NO_x curve" for most of the simulation. To maintain the engine on this operating curve, the engine power might have to be slightly higher or lower than the actual commanded power. This difference between the engine power command and engine power delivered is compensated by the electric motor.

Conclusions

Researchers at ANL have embarked on an ambitious program to quantitatively demonstrate the potential of hydrogen as a fuel for ICEs in hybrid-electric vehicle applications. In this initiative, ANL researchers need to investigate different hybrid configurations, different levels of hybridization, and different control strategies to evaluate their impacts on the potential of hydrogen ICEs in a hybrid system.

This task utilizes the PSAT, a simulation tool developed by Argonne National Laboratory, to select the most suitable hybrid powertrain configuration for the H_2-ICE.

Since the motor and the battery are simulated, PSAT makes it possible to resize the battery and the motor for every change in control strategy, thus enabling an iterative loop between control strategy and component sizing. This iterative sizing process would then result in components optimized for a control strategy. The ultimate aim of this iterative process is to identify the optimal control strategy and component sizing for a particular specifications set (performance and fuel economy).

As a first step, this interdependent sizing process will be studied in simulation only. The next stage will be to validate the simulation results with the test data collected for different degrees of hybridization and different control strategies.

Publications / Presentations

1. Pasquier, M., "Continuously Variable Transmission Modifications and Control for a Diesel Hybrid Electric Powertrain," 2004 International Continuously Variable and Hybrid Transmission SAE Congress, Sacramento, CA, September 2004.
2. Pasquier, M., "Diesel Hybridization and Emissions," DOE Report.
3. Pasquier, M., "Status of Hardware-In-the-Loop Activities," Argonne National Laboratory, IL, February 2004.
4. Pasquier, M., "Diesel CVT Hybrid Electric Vehicle Study Results," Argonne National Laboratory, IL, October 2003.
5. Pasquier, M., "Status of Diesel Hybrid Project," Argonne National Laboratory, IL, March 2004.

B. Hydrogen ICE Hybrid Test Setup Instrumentation and Implementation

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Objectives

- Build a portable test fixture with the flexibility to demonstrate the potential of hydrogen fueled internal combustion engines (H_2-ICE) combined with various hybrid powertrain technology; and
- Take advantage of a portable test fixture environment to instrument a Hydrogen ICE hybrid powertrain in order to support hardware-in-the-loop (HIL) research experiments.

Approach

- Design and fabricate a research platform with custom measurement instrumentation and "virtual inertia" scalable electric machine providing the flexibility to test an H_2 engine in varied degrees of hybridization;
- Develop a comprehensive list of sensor and actuator needs for component control and systems analysis;
- Integrate a supervisory control system, both in hardware and software, and the data acquisition system into a tight package in support of HIL activities; and
- Validate instrumentation, data acquisition and control systems.

Accomplishments

- Designed the Mobile Automotive Technology Testbed (MATT), a research platform providing the flexibility to integrate and test DOE-sponsored subsystem hardware in an emulated environment;
- Constructed the research platform with the flexibility to easily swap components under test enabling HIL system integration and technology validation;
- Developed the concept of a "virtual inertia" scalable electric machine providing the flexibility to vary the degree of hybridization;
- Consulted hydrogen engine experts to determine appropriate engine instrumentation needs;
- Evaluated different data acquisition options to interface with the control hardware; and
- Implemented complete instrumentation, data acquisition system, and controlled component hardware into MATT system to support HIL testing.

Future Directions

- Complete the development phase of the H_2-ICE and hybridized powertrain implementation; and
- Test and analyze the results provided by the MATT HIL system for the H_2-ICE hybrid powertrain study.

Introduction

In order to validate the performance of DOE-sponsored technologies in the context of complete vehicle systems, dynamic simulation models (Powertrain System Analysis Toolkit - PSAT) are combined with DOE's specialized equipment (Mobile Automotive Technology Testbed - MATT) and facilities (Advanced Powertrain Research Facility - APRF). This integrated process, called hardware-in-the-loop (HIL), assesses actual hardware component technologies and control strategies in an emulated vehicle test environment quickly and cost-efficiently. This process requires subsystem integration in the HIL environment before being able to validate its technological potential. The hydrogen engine hybrid test setup instrumentation and implementation task consists of integrating DOE-sponsored experimental component/ subsystem hardware in an emulated vehicle environment with realistic control system interfaces and interactions. Different approaches were considered to best demonstrate the potential efficiency gains that are achievable through the application of H_2-ICE hybrid technology. The flexibility of a portable test fixture capable of emulating a variety of hybrid powertrain configurations becomes apparent. Different possibilities were evaluated in order to provide maximum flexibility and reusability of the portable test fixture. The MATT provides the solution for powertrain testing and integrated control strategy development without the need for building costly prototype vehicles.

Approach

In order to support the H_2-ICE hybrid powertrain technology studies it became necessary to develop and fabricate a portable test facility designed such that a host of different powertrain configurations can be emulated.

MATT is a mobile testbed comprised of a ladder frame mounted onto four wheels where powertrain components can be easily configured and then evaluated on a chassis dynamometer through driving wheels just as a production vehicle would eb tested. MATT is currently configured with a new parallel hybrid prototype powertrain. Initially, a four-cylinder gasoline engine with a dry clutch, an Emerson 100-kW AC induction traction motor and an Audi TT dual-clutch Direct-Shift Gearbox will be controlled and tested in order to verify the experimental setup. The next step will be to replace the gasoline engine with a hydrogen-fueled internal combustion engine. Using the PSAT control strategy code, we will control the hardware implementation of this hybrid electric vehicle (HEV) powertrain on the 4WD chassis dynamometer located at the Argonne National Laboratory's (ANL's) APRF. The powertrain will be commanded by PSAT-PRO©, the control software developed by researchers at ANL. PSAT-PRO is a MATLAB® based program using dSPACE© hardware to make the link between PSAT control strategy and real-time hardware controllers.

The HIL platform, MATT, is a flexible chassis testbed that allows researchers to easily replace components or change the architecture of the powertrain. A pre-transmission parallel architecture has been chosen for this study.

A layout of the major powertrain components is shown below in Figure 1.

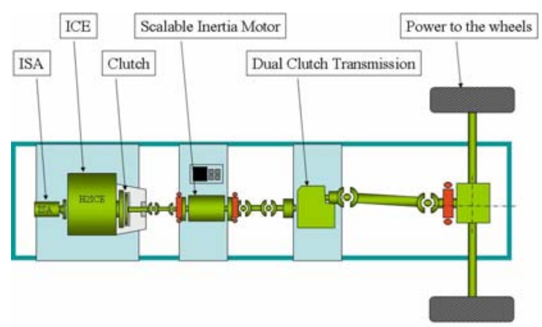

Figure 1. MATT powertrain major components.

The unique characteristic of MATT is the "scalable inertia motor." The "scalable inertia" motor is a 100-kW induction motor-drive, which can emulate any motor smaller than 100 kW by emulating the torque and the rotational inertia of the smaller motor. A photograph of the actual hardware used for the "scalable inertia motor" is shown in Figure 2.

A simulation model of the motor to be emulated ("emulated motor") by the scalable inertia motor runs in real time with the vehicle controller. The vehicle controller sends to the "scalable inertia" motor the torque command that it would actually send to the "emulated motor."

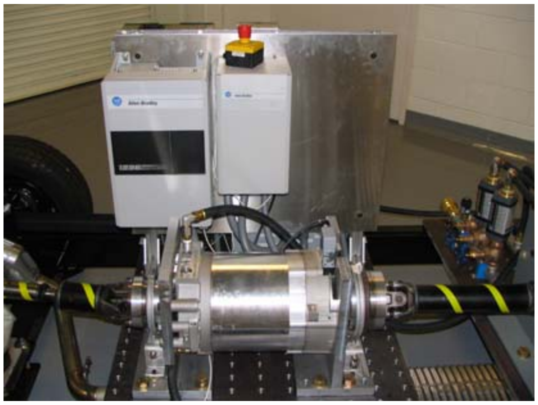

Figure 2. Scalable inertia motor and controller.

The controller also sends the inertia of the "emulated motor" to the controller of the 100-kW "scalable inertia" motor controller. With this information, the "scalable inertia" motor emulates the torque dynamics of the "emulated motor" on its output shaft. The "scalable inertia" motor uses torque sensor inputs from both sides of the rotor shaft (engine side and transmission side). It also receives speed feedback from the two ends of the motor shaft. These inputs enable the motor controller to calculate the actual electromagnetic torque, which would result in the torque dynamic of the smaller, "emulated" motor. The simulation model of the "emulated motor" is used to calculate losses, efficiency, and other parameters.

The "scalable inertia motor" gives the necessary flexibility to emulate various degrees of hybridization.

Results

The ladder frame shown in Figure 3 was designed and fabricated by ANL Central Shops based upon a previous design review and subsequent engineering calculations and drawings. The ladder frame was designed to accommodate a maximum total component load of 2000 lb (2 X 1000 lb) at any two points on the frame with a safety factor exceeding 3.0. Three drilled and tapped base plates with which to mount test equipment are positioned and clamped to the longitudinal rails of the ladder frame from the under side. These systems include; engine accessories such as the integrated starter-alternator motor, the AC electric traction motor, and the transmission. The custom built rear axle and suspension components were assembled within the APRF and function as they would in a vehicle on the road. The complete MATT system with DC power supply, "scalable inertia motor," and respective drivetrain components in shown in Figure 4.

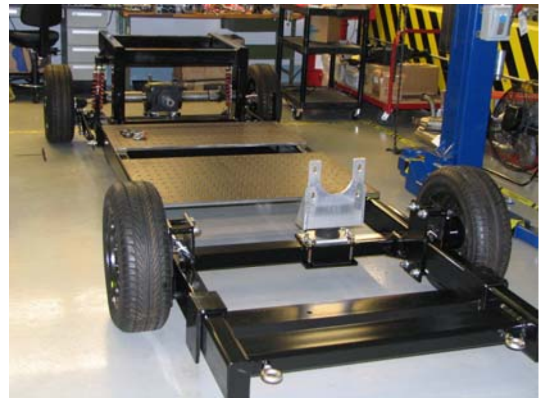

Figure 3. Rolling ladder frame.

Figure 4. Mobile Advanced Technology Testbed (MATT).

The design of test platform needed to possess the capability to test transverse and longitudinally mounted transmissions. A 1:1 ratio 90° angle bevel gearbox has been integrated into the MATT in order to achieve this design objective. The rear frame has been designed and constructed to accommodate this.

The rear axle assembly was designed by our engineers and then fabricated by ANL Central Shops. The rear axle consists of many components, the first of which is a center mounted gearbox with one input and two output shafts. The gearbox specified for this application is an optimal design because of its high efficiency due to low bearing losses and gear design. The gearbox input/output ratio is 1:1. Power is transmitted to the wheels through conventional half-shafts and hubs. Central Shops fabricated the clam-shell clamping type adapters which connect the gearbox output shafts to the half-shafts. All of these components are securely mounted on a tubular frame section which was designed and fabricated by ANL Central Shops. This frame member is connected to the ladder frame by a four-link style rear suspension. The suspension components, shown in Figure 5, consist of two ladder bars, two coil over spring/shock absorbers, and a track link. These components were specified by our engineers with support from ANL Central Shops and are all designed specifically for this type of application.

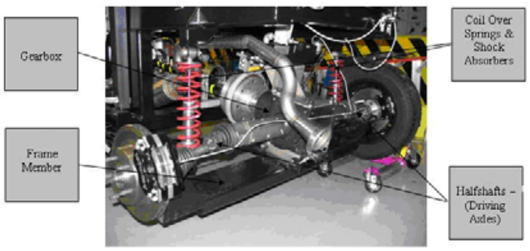

Figure 5. Rear axle and suspension.

Control of the HEV powertrain resides in one supervisory controller, which executes PSAT-PRO. Specifically, the computer based PSAT-PRO vehicle controller controls the torque of the powertrain at the wheels to track a standard dynamometer driving cycle. The speed of the transmission output shaft, corresponding to the wheels, and the dynamometer rolls speed are measured. The measured dyno speed feeds back into PSAT-PRO for speed regulation. The vehicle torque losses that would be produced in reality by the vehicle are emulated by the dynamometer.

PSAT-PRO provides the capability to use and enhance the modeling work for control system development purposes. The power management system can be readily exercised in a real environment or HIL. PSAT-PRO software has been developed in order to facilitate HEV control development. The software has been designed in order to optimize the link between modeling and prototyping, especially for the use and transfer of work from modeling to real world applications. It uses PSAT modeling software as a base and cannot be used independently. Figure 6 illustrates the role of PSAT-PRO in the experimental setup. HIL can be used to test HEV components when they cannot be tested or instrumented easily in their operational environments.

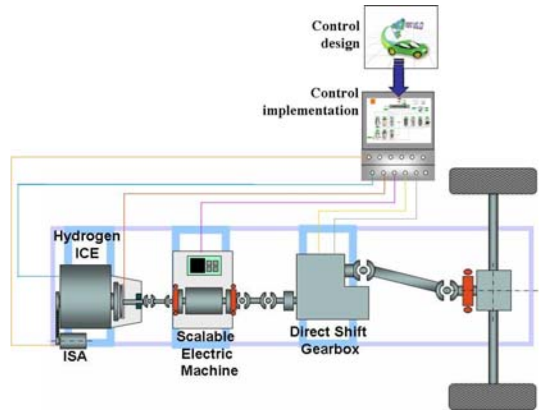

Figure 6. PSAT-PRO integration.

In PSAT-PRO, each measured signal is compared to the limitations of the associated component. In case of the detection of an abnormal condition (motor over-speed, coupling or shaft failure, etc.), the PSAT-PRO emergency stop function will reset the torque and speed command to 0 stopping powertrain components and aborting the current test. Moreover, for safety purposes, all output signals of the PSAT-PRO controller are saturated and inhibited by the emergency watch system. This will avoid sending the wrong command to the components.

Initially, a 2.3L four-cylinder Duratec spark-ignition gasoline-fueled engine was provided to ANL by Ford Motor Company. The engine has been tested at Ford to verify calibration for dyno use. Later, a gaseous hydrogen fueled engine of the same physical dimensions will be provided by Ford. This engine series is found in both the Ford Escape and the Focus vehicle platforms. The engine has been mounted onto the MATT system using three resilient motor mounts which help to isolate vibration transfer to other components. ANL Central Shops fabricated these mounts. All of the electronics required to support engine operation, the conventional radiator type cooling system and the integrated starter-alternator are all mounted onto a plate located just forward of the engine on the ladder frame, as shown in Figure 7.

Figure 7. SI 2.3L engine & support systems.

A conventional automotive dry clutch with ANL designed and built pneumatic/hydraulic controls afford the ability to engage/disengage the engine from the other powertrain components as needed during testing. This is shown in Figure 8. A shaft which engages into the clutch disc is mounted on a sealed bearing within the bell housing. The output side of this shaft is a flange which connects to a driveshaft.

Figure 8. Bell housing with internal clutch assembly.

A pneumatic cylinder will actuate the clutch. The pneumatic cylinder pushes on the input of a vehicle hydraulic slave clutch cylinder, which in turn operates the throw-out bearing in the bell housing thus disengaging the clutch. The ANL HIL computer located in the control room can remotely actuate this system. The clutch actuator system is shown in Figure 9.

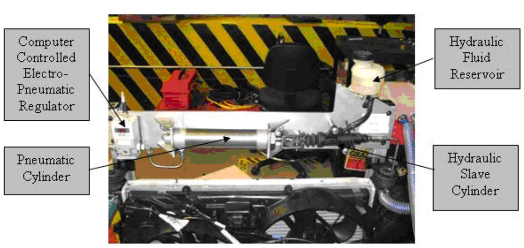

Figure 9. Clutch actuator system.

An ANL-designed and built starter/alternator has been coupled to the front of the engine crankshaft. This motor or an auxiliary starter mounted onto the clutch bell housing will start the engine when needed for testing. In the first phases of the project, the standard 12V starter will be used to start the engine. Engine starting torque will be defined and the integrated starter/alternator will be sized accordingly. In order to refine the level of sophistication, the integrated starter/alternator will then be used to reflect realistic engine operation for a hybrid system.

A dual-clutch transmission (DCT) has been selected for this project. DCTs are providing the full shift comfort of traditional automatics but offer significantly improved fuel efficiency and performance. A DCT has been selected based on preliminary modeling studies and is apparent compatibility with H_2-ICE characteristics.

The transmission used in this powertrain is a modified dual-clutch direct shift gearbox from a 2004 Audi TT automobile. This transmission is commercially available in the U.S. and Europe. The modifications made to this transmission are mechanical and electrical and both internal and external to the transmission.

In stock trim, an original equipment manufacturer (OEM) off-board transmission control unit controls the transmission clutches and the shift requests. This transmission no longer utilizes that controller. Now, all transmission control is done with the HIL computer. Additional hardware has been added to support this approach, as shown in Figure 10.

Figure 10. Modified DSG transmission.

The other main modification to the transmission was removal of the internal high-pressure hydraulic pump drive shaft. As received, the hydraulic pump had been driven by the input shaft of the transmission. This shaft was removed, modified, mounted externally to the transmission, and is driven by an electric motor.

A cradle has been designed for the transmission. Component mounting cradles need to slide on a horizontal plane to allow for shaft alignment adjustments. A transmission adapter plate has been built for implementation of the transmission onto the chassis. The plate has been designed to allow for maximum flexibility and adjustment for shaft alignment. The transmission has been opened and the differential welded to send torque out to only one shaft.

A comprehensive instrumentation list was generated to evaluate project needs. In addition, different data acquisition options have been evaluated. The APRF has been experimenting with a CAN-based communications system. This option was looked at for integrating it into a tight package with the current control system using dSpace/PSAT-PRO tools.

HBM T10-F non-contact type torque sensors, shown in Figure 11, are used in three locations in the driveline to measure speed and torque. This style of torque sensor was designed specifically for this purpose and has been in use at ANL for several years. These torque sensors consist of two main components: a rotor that contains a strain gauge and mounts in-line with the driveline and a non-contacting signal conditioner base with an antenna.

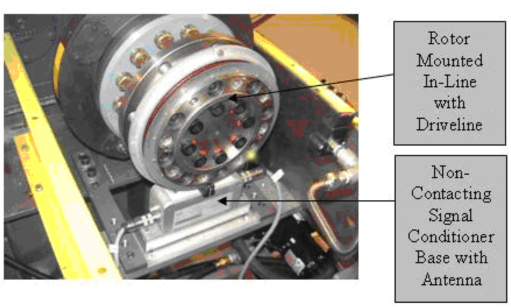

Figure 11. Non-contact torque sensors.

One sub-system of particular interest was the DCT. The control of the DCT in the context of a hybrid powertrain represented a challenge. As a first step, investigation into hydraulic control concepts has been initiated. In addition, control hardware options were also being investigated. The existing DCT transmission controller block — including two (2) clutch solenoids, four (4) actuator solenoids and 1 sequencing solenoid — was studied to overcome the challenge. Three (3) control hardware options were selected and investigated in parallel. The control hardware for the DCT is shown in Figure 12. The final control hardware option was selected based on cost, lead time and reliability.

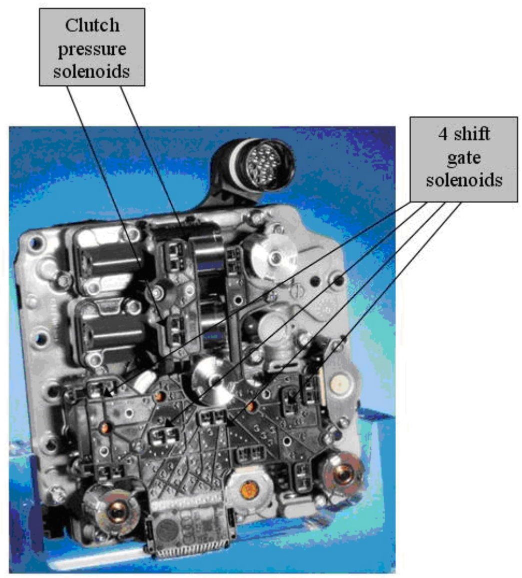

Figure 12. Transmission controller and instrumentation.

In order to provide braking control of MATT during dynamometer driving cycles, a set of hydraulic, automotive style friction disc brakes were added to the rear axle. This brake system was designed to provide the stopping power required for most any standard or custom dynamometer driving cycle. One caliper and disk are used at each rear driving wheel so that no radial force is applied to the rotating shaft and the calipers act as a couple. The calipers, rotor disks, and master cylinder are automotive aftermarket typically used in racing applications. The control of the system is provided from the ANL HIL computer as an analog signal. The brake control hardware is shown in Figure 13.

Figure 13. Brake controller.

Conclusions

With the completion of the MATT platform, DOE will have the ability to integrate and test subsystem hardware in an emulated environment. This capability provides a cost effective solution to subsystem and component technology validation at a vehicle systems level.

The implementation and validation of the "virtual inertia" scalable electric machine provide the flexibility to test advanced components in various degrees of hybridization.

As an example of MATT emulation and the "virtual inertia" scalable electric machine capability utilization, ANL will provide an independent evaluation of hybridization potential for overcoming the technical challenges related to H_2-ICE vehicle. Degrees of hybridization impact will be assessed in terms of fuel economy, performances, and level of emissions improvement.

Publications / Presentations

1. Pasquier, M., "Continuously Variable Transmission Modifications and Control for a Diesel Hybrid Electric Powertrain," 2004 International Continuously Variable and Hybrid Transmission SAE Congress, Sacramento, CA, September 2004.
2. Pasquier, M., "Diesel Hybridization and Emissions," DOE Report.
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5. Pasquier, M., "Status of Diesel Hybrid Project," Argonne National Laboratory, IL, March 2004.

C. Mobile Automotive Technology Testbed (MATT) Functional Validation

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Objectives

- Test a gasoline engine in a conventional powertrain and in a hybrid electric vehicle application using the Mobile Automotive Technology Testbed (MATT) in order to provide baseline and recommendations for the hydrogen-fueled engine implementation and testing.

Approach

- Characterize a production gasoline-fueled engine on a dynamometer to establish a baseline;
- Test and validate conventional and hybrid operating modes utilizing the baseline engine in conjunction with the MATT platform; and
- Make recommendations for hydrogen fueled engine (H_2-ICE) testing in a hybrid powertrain configuration.

Accomplishments

- Determined operating envelope of a baseline gasoline-fueled engine through extensive dynamometer testing;
- Successfully implemented gasoline engine into MATT platform including development of a custom engine cradle which allows for a variety of engine locations in the powertrain;
- Integrated production engine controller unit into overall hardware-in-the-loop (HIL) control system;
- Established baseline results for gasoline engine operating in a hybrid mode of operation on the MATT platform; and
- Formulated recommendations for testing H_2-ICE in a hybrid configuration based on observations made from the baseline results.

Future Directions

- Test hydrogen fueled engine in the simulation-recommended hybrid vehicle application using MATT.

Introduction

Argonne National Laboratory (ANL) researchers have embarked on an ambitious program to quantitatively demonstrate the potential of hydrogen as a fuel for internal combustion engines (ICEs) in hybrid-electric vehicle applications. Ford Motor Co. is helping by donating two engines, a stock gasoline-fueled 2.3-L four cylinder engine and a comparable hydrogen-fueled engine. The testing of the gasoline engine in a conventional and in the simulation-recommended hybrid vehicle application using the MATT provides a baseline for the entire study. The supplied H_2 engine can then be implemented on MATT to validate simulation results and identify additional technical barriers.

Approach

The approach consists of characterizing a production gasoline-fueled engine on a dynamometer to establish a baseline. The gasoline engine is first tested in order to determine the basic engine operating characteristics. The test data is then utilized to develop an engine efficiency map and the torque envelope that is then used to populate the engine component model into Powertrain System Analysis Toolkit (PSAT). The combination of the engine dynamometer testing and the Ford Focus vehicle testing provides a strong data base to validate our baseline vehicle model. Model validation is critical to the accuracy of our analysis.

The second step includes the integration of the gasoline baseline engine on the MATT. The implementation of the gasoline engine into the MATT platform includes development of a custom engine cradle which allows for a variety of engine locations in the powertrain. The task consists also in integrating the production engine controller unit into the overall HIL control system.

The third step in this process is the testing and validation of the baseline engine in the MATT platform environment in conventional and hybrid operating modes. The transition between electric-only and hybrid mode requires particular attention. The control algorithm developed for the gasoline engine will be reused for the H_2-ICE.

Finally, the objective of this task is to make recommendations for H_2-ICE testing in a hybrid powertrain configuration. The idea is to not only used for the gasoline engine to develop our baseline, but also to validate all aspects of the emulated environment and gain experience that will be beneficial for the H_2-ICE implementation on the MATT platform.

Results

The engine has been tested at Ford to verify calibration for dynamometer use. The operating envelope of the baseline gasoline-fueled engine has been determined and implemented in the PSAT engine model. Specifically, the engine model has been modified to represent the exact engine efficiency map and the maximum torque curve of the gasoline engine under test.

The engine accessories have been removed. An engine cradle has been designed and built to comply with MATT's components flexibility principle, and the engine has been mounted. The cooling system and clutch assembly have been adapted to match MATT requirements. The original equipment manufacturer's (OEM's) engine wiring harness has been studied for proper connection. The main challenge was the interaction of the production engine controller and the HIL system controller, in particular the integration of the gasoline engine controller harness in the MATT controller environment where part of the component is emulated.

In order to couple an ANL designed and built starter/alternator to the front of the engine crankshaft, our team had to take off the harmonic balancer and then re-time the engine. Our team did a compression check and used an advanced system for visualization of the combustion and injection processes (VisoScope) to ensure adequate operation of the cylinder valves. An example of this visualization is shown in Figure 1.

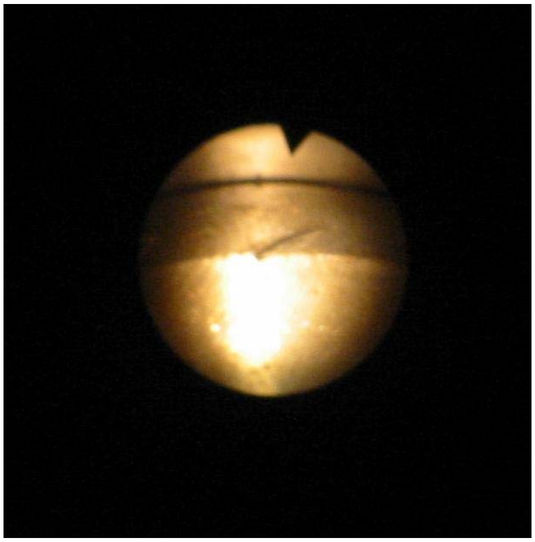

Figure 1. Picture of a cylinder valve using the VisioScope.

One of the challenges that our team experienced to implement the gasoline engine into the MATT platform was the actuation of the engine clutch. As the gasoline engine has been only tested on a dynamometer setup, the clutch system was not working. Therefore, our team had to integrate a hydraulic actuator into the clutch housing and modify the clutch plates assembly in order to have an operational clutch system remotely controllable from the HIL computer.

Similarly, no electronic throttle body was present on the engine so our team implemented a linear actuator acting directly on the engine throttle and remotely controlled from our HIL controller, as shown in Figure 2. To complete the interaction between the engine control module and the HIL controller, the throttle position feedback information is sent in real-time as it is required by the closed loop throttle position control developed in PSAT-PRO©.

Figure 2. Linear actuator acting directly on the engine throttle.

The engine has been tested in the MATT environment in conventional mode. Once that was completed, the switch from electric only to hybrid mode using a sophisticated control algorithm was successfully demonstrated. When the power required by the drive cycle reaches a certain point and/or when the battery state of charge becomes too low, the hybrid system control strategy decide to use the engine to propel the vehicle. On this decision, the engine is automatically started and the speed is regulated to match the electric motor speed. Once the two speeds are close enough, the clutch engages in three distinctive phases to ensure smooth engine engagement and the engine is then able to provide power.

Conclusion

A Ford-donated gasoline engine has been tested on a dynamometer to provide operational characteristics that were necessary for accurate engine model development in PSAT. The collected data has also been used to validate the model.

The gasoline engine has been implemented in the MATT emulated environment. The engine has been mounted on the testing platform (Figure 3) and the control interactions in between the engine control module and the HIL controller has been developed and validated.

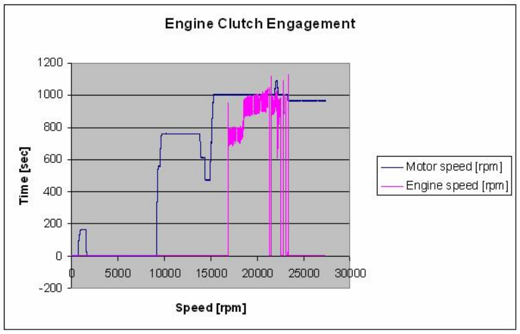

Figure 3. Gasoline engine clutch engagement on the MATT platform.

Publications / Presentations

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IV. LABORATORY TESTING AND BENCHMARKING

A. MY04 Prius Benchmarking

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Objectives

- Provide operational data during chassis dynamometer testing of the Model Year (MY) 2004 Toyota Prius for the purposes of technology evaluation of the major subsystems and the overall hybrid control strategy.

Approach

- Procure a representative vehicle with associated manufacturer's service manuals and diagnostic's tool;
- Accumulate mileage on the test vehicle for break-in of powertrain components;
- Instrument vehicle with necessary wiring and data acquisition equipment and design new engine torque sensor configuration; and
- Plan and execute extensive test schedule that includes standard cycles and various "off-cycle" tests that reveal powertrain behavior and performance.

Accomplishments

- Developed a new "unobtrusive" engine torque sensor design that allowed installation without adding extra spacer hardware;
- Ran over 100 tests that included steady-state speeds, standard drive cycles, performance, and high temperature (95°F) battery performance; and
- Conducted three weeks of testing with Ford engineers on-site for guidance and assistance.

Future Directions

- Argonne National Laboratory (ANL) has become a leader in measuring torque in the vehicle and will further expand on the design to collaborate with Teledyne to make a 2-channel unit for measuring engine and motor torque separately in an integrated starter alternator (ISG) hybrid.

Introduction

Vehicle benchmarking combines testing and data analysis to characterize powertrain efficiency, performance and emissions as a function of duty cycle as well as to deduce control strategy functions under a variety of operating conditions. Characterizing the MY 2004 Toyota Prius has become a high priority due to its reported improvements in fuel economy and acceleration in a larger vehicle.

Approach

The MY 2004 Toyota Prius was first driven for mileage accumulation then instrumented using the latest techniques developed by ANL and with the most state-of-the-art data acquisition equipment. The Advanced Powertrain Research Facility (APRF) chassis dynamometer facility with enhanced data acquisition was utilized. A photograph of the Prius test vehicle secured to the four wheel-drive (4WD) chassis dynamometer at the APRF is shown in Figure 1. Investigating the new split electrical power bus and measuring engine torque without vehicle chassis modification were the primary objectives. Benchmark data was generated for the purposes of model validation, component technology benchmarking, and comparison to other hybrid electric vehicle (HEV) powertrain designs and control strategies.

Figure 1. MY 2004 Prius on the APRF 4-wheel chassis dynamometer.

A new method of measuring engine torque was developed with an industry partner. The collaboration with Teledyne Instruments resulted in a non-invasive device that did not require vehicle modifications for installation, as shown in Figure 2.

Figure 2. ANL-designed engine torque sensor for 2004 Prius.

In the previous designs, coupling flanges and a rather large spacer, as shown in Figure 3, was required to hold the assembly together, this required vehicle frame modification before final installation.

Over 100 data signals were collected from the MY 2004 Toyota Prius. Due to the complexity of the energy storage system, extensive data collection was necessary to track energy flows to and from the various high voltage components.

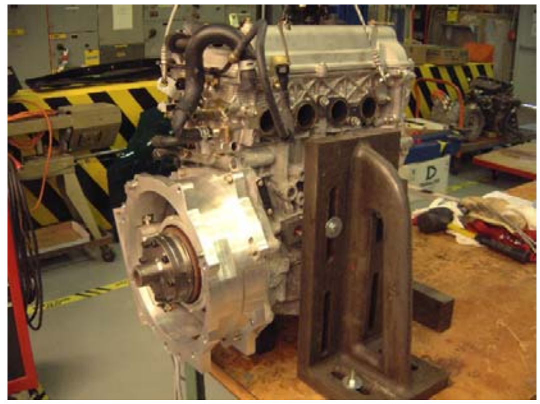

Figure 3. Previous torque sensor design for 2001 Prius included a 5-inch spacer.

In addition to the raw data collected, ANL developed a system to continuously stream vehicle information from any of the on-board vehicle control computers directly to data logging equipment. The diagnostic tool used by most automobile dealer service departments normally can only take short snapshots of vehicle data. The low-level communication between the laptop computer and the scan tool was deciphered allowing limitless logging of vehicle information from the vehicle.

This information proved valuable to understanding vehicle operation. A list of the vehicle computers polled and some sample information given by each is shown below:

<u>Hybrid Engine Control Unit (ECU)</u>
- Battery state of charge (SOC)
- MG1 torque and speed
- MG2 torque and speed
- MG1 & MG2 temperature
- Inverter temperature
- MG1 & MG2 carrier frequency

Engine ECU
- Ignition advance
- A/F ratio
- Evaporative emissions system status
- Throttle position
- Estimated intake port temperature
- Requested and estimated engine torque

Battery ECU
- Battery SOC
- Voltage and current
- Module voltage and resistance
- Battery cooling fan speed
- Battery temperature (3 places)

Braking ECU
- Brake stroke level
- Master cylinder pressure
- Caliper pressure
- Regen torque request

Results

Test data showed where energy was flowing and where efficiency gains were achieved. For example, a simple comparison between the steady-state fuel consumption of the MY 2001 and MY 2004 Toyota Prius show the gains in fuel economy at various speeds from the previous generation to the current vehicle, as shown in Figure 4. Analysis of the various data streams show the MY 2004 Toyota Prius made the most gains in lower speeds due to the fact that more electric operation was used. Improved efficiency was also observed at higher speeds due to lower driving losses and better utilization of the engine with improved control strategies.

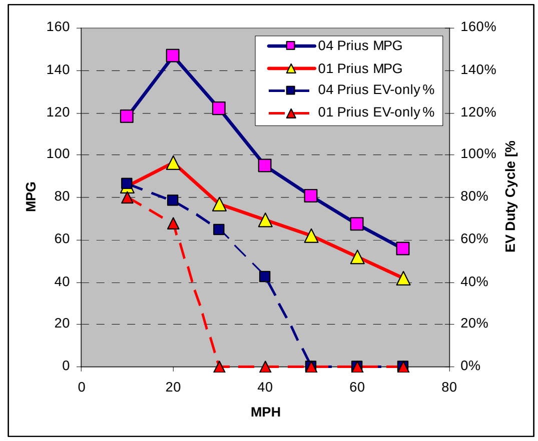

Figure 4. Steady-state speed comparison of MY 2001 Prius with MY 2004 Prius

Figure 5. Two engineers from Ford at the APRF analyzing data with ANL engineers.

During the benchmarking testing, ANL worked closely with Ford and General Motors. Ford visited ANL for a total of three separate visits totaling nearly three weeks of on-site collaboration, an example of which is shown in Figure 5. The APRF design with useful tools for data collection and analysis made these visits very productive. Feedback from the original equipment manufacturers (OEMs) has been extremely positive.

In summary, over 100 tests were conducted based upon a comprehensive test plan. The tests were tailored to focus on the many technology interests at FreedomCAR and at Ford and General Motors. Special focus areas were the energy storage system, the engine and emissions control, and the overall hybrid control behavior.

Power Electronics Component Testing: Collaboration between ORNL and ANL.

The TTRDC/ Power Electronics group of Oak Ridge National Laboratory (ORNL) contacted ANL-APRF for in-vehicle Prius component test data. Extra instrumentation was added to the MY 2004 Prius to measure electric powertrain component efficiency. A Yokogawa PZ4000 power analyzer was used for more precise inverter power measurements. This work was completed in May 2004 and presented at the 2004 ORNL Annual Merit Review program held at ORNL, June 2004. This test data is presented in the ORNL “Evaluation of 2004 Toyota Prius Hybrid

Electric Drive System Interim Report," which can be found at http://www.ornl.gov/~webworks/cppr/y2001/rpt/121813.pdf.

Conclusions

ANL has furthered the state-of-the-art in advanced vehicle instrumentation by adapting torque sensing technology into the MY 2004 Toyota Prius without requiring vehicle modification. Many data streams were collected including reading the stock computers for a comprehensive set of benchmark data.

The results have shown that the second generation MY 2004 Toyota Prius represents a substantial improvement compared to the "Gen I" Prius. ANL's data and analysis of the MY 2004 Toyota Prius allows engineers from all across the vehicle technology spectrum to understand why the vehicle achieves higher fuel efficiency as well as higher performance. Numerous advancements in the technology as seen by inspection are supported with extensive data in an integrated effort supporting DOE's mission to stay focused on pushing the next generation technology to market sooner.

B. Hydrogen-Fueled Vehicles

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Objectives

- Provide performance and emission data during chassis dynamometer testing of the hydrogen-fueled vehicle for the purposes of technology evaluation of the total vehicle system.

Approach

- Conventional gasoline vehicle was modified for hydrogen/natural gas operation and loaned to Argonne National Laboratory (ANL);
- Accumulate mileage on the test vehicle for break-in of powertrain, using hydrogen and natural gas mixture; and
- Reveal powertrain behavior and performance characteristics through execution of standard test cycles.

Accomplishments

- Vehicle tests were completed successfully using fuel blends of 0%, 15%, 30% and 50% hydrogen, the remainder being compressed natural gas;
- Key emission and fuel economy data were collected for statistical analysis; and
- A student master thesis was also written.

Future Directions

- ANL has become a pioneer in testing of hydrogen-fueled vehicles and a new hydrogen delivery and real-time flow measurement system will be built to further facilitate vehicle testing.

<u>Introduction</u>

An investigation was conducted on the emissions and thermal efficiency obtained from combustion of hydrogen blended compressed natural gas (CNG) fuels in a prototype light duty vehicles. The different blends used in this investigation were 0%, 15%, 30% and 50% hydrogen, the remainder being compressed natural gas. The blends were tested using a Ford F-150 truck supplied by Arizona Public Service.

A previous investigation by Don Karner and James Francfort of Idaho National Engineering and Environmental Laboratory (INEEL) on a similar Ford F-150 using 30% hydrogen blend showed that there was substantial reduction when compared to gasoline in carbon monoxide, oxides of nitrogen and carbon dioxide emissions while the reduction in hydrocarbon emissions was minimal.

<u>Approach</u>

This investigation was performed using different blends of CNG and hydrogen to evaluate the emission reducing capabilities associated with the use of the different fuel blends. The results were then tested statistically to confirm or reject the hypotheses on the emission reduction capabilities.

A statistical analysis was performed on the test results to determine whether hydrogen concentration in the hydrogen/natural gas (HCNG) blends had any effect on the emissions, or the efficiency. It was found that emissions from hydrogen blended compressed natural gas were a function of driving condition employed. Also, emissions were found to be dependent on the concentration of hydrogen in the compressed natural gas fuel blend.

The hydrogen/natural gas ready F150 truck was tested thoroughly and driven for mileage accumulation before testing at ANL. The vehicle will be tested without modifications at ANL using cylinders containing mixtures of hydrogen and natural gas. All the fuel composition data will be obtained from Air Gas for further analysis. The new APRF chassis dynamometer facility with state-of-the-art emission benches will be utilized for testing.

Results

Relation between hydrogen concentration in CNG and emission

From the testing data, a plot of emissions versus driving cycle was made for the different fuel blends. We wanted to determine if there was a relationship between the concentration of hydrogen in the HCNG and the resultant emissions and efficiency.

From Figure 1, it was seen that 30% hydrogen blend (85% CNG) was shown to have the lowest total hydrocarbon emissions compared to the other blends for the New European Driving Cycle (NEDC). However, for other cycles the total hydrocarbon emissions were nearly the same for all the blends except for the 50% HCNG fuel blend in the Highway Fuel Economy Test (HWFET) cycle.

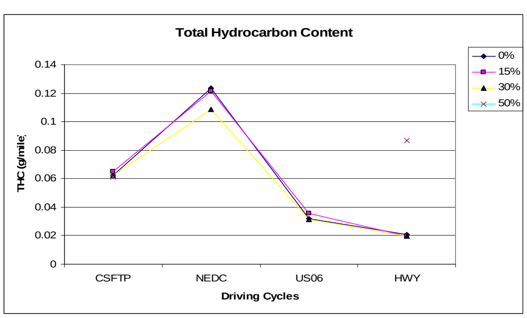

Figure 1. Total hydrocarbon emissions from different blends for different driving cycles.

From Figure 2, the carbon monoxide emissions are observed to decrease as the concentration of hydrogen increases in the HCNG fuel blend for the US06 Supplemental Federal Test Procedure and the HWFET cycle, except for the 50% for which we do not have enough data points. However, this trend was not observed for the Cold-Start Federal Test Procedure (CSFTP) and NEDC cycles.

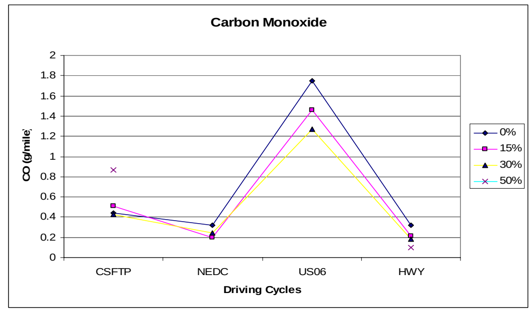

Figure 2. Carbon monoxide emissions from different blends for different driving cycles.

From Figure 3, that the carbon dioxide emissions are observed to decrease as the hydrogen concentration in the HCNG fuel blend increases. This trend was seen across all the driving cycles.

The total hydrocarbon, carbon monoxide, and carbon dioxide emissions decreases with the increase in the hydrogen concentration in the HCNG blend as the corresponding carbon concentration decreases.

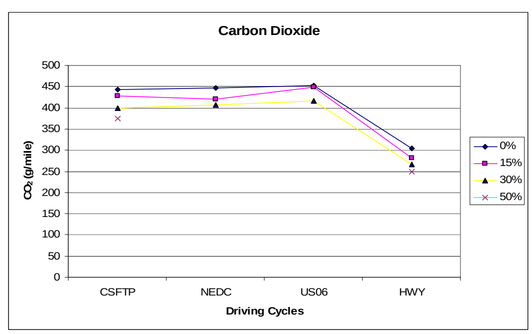

Figure 3. Carbon dioxide emissions from different blends for different driving cycles.

In Figure 4, the nitrogen oxide emissions increased with an increase in hydrogen concentration in the HCNG for the CSFTP, US06 and the HWFET cycles. However, this trend is not seen for the NEDC cycle. The nitrogen oxide emissions for 50%

HCNG blend did not follow the trend of other blends. A possible explanation could be that the vehicle used for the 50% blend had a different catalytic converter. Another possible explanation could be that there may be an experimental error involved in the testing of 50% HCNG blend. The nitrogen oxide emission for the CSFTP was higher as a cold engine tends to produce more nitrogen oxide emission than a hot engine.

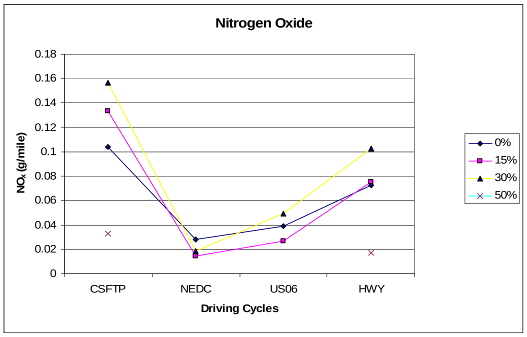

Figure 4. Nitrogen oxide emissions for different blends for different driving cycles.

From Figure 5, it was seen that the efficiency (equivalent miles/gallon) is nearly the same for all the cycles. The concentration of hydrogen in HCNG seems to have no effect on the efficiency (equivalent miles/gallon).

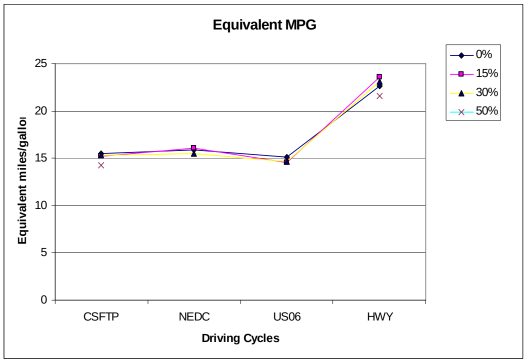

Figure 5. Efficiency (miles/gallon) for different blends for different driving cycles.

From the graphs above, it was not very clear if the trace lines were overlapping each other or not. T-tests were performed to determine whether they were statistically different. From the t-test results, it can be seen that in most cases the value of α was greater than 0.1. In these cases, trace lines cannot be considered to be statistically different and hence the emissions were function of the driving conditions. For the cases where the value of α was less than 0.1, the trace lines were statistically not different, and hence the emissions were not a function of the driving conditions.

Conclusions

The purpose of this project was to study the effects of hydrogen concentration in the HCNG fuel blend. The conclusions from this study are summarized below.

1) Total Hydrocarbon Content
   - CSFTP: 50%<30%<0%<15%
   - HWFET: 30%<15%<0%<50%
   - NEDC: 30%<15%<0%
   - US06: 30%<0%<15%
2) Carbon Monoxide
   - CSFTP: 30%<0%<15%<50%
   - HWFET: 50%<30%<15%<0%
   - NEDC: 15%<30%<0%
   - US06: 0%<15%<30%
3) Carbon Dioxide
   - CSFTP: 50%<30%<15%<0%
   - HWFET: 50%<30%<15%<0%
   - NEDC: 30%<15%<0%
   - US06: 30%<15%<0%
4) Nitrogen Oxide
   - CSFTP: 50%<0%<15%<30%
   - HWFET: 50%<0%<15%<30%
   - NEDC: 15%<30%<0%
   - US06: 30%<0%<15%
5) Equivalent mpg
   - CSFTP: 50%<15%<30%<0%
   - HWFET: 50%<30%<0%<30%
   - NEDC: 30%<0%<15%
   - US06: 15%<30%<0%

As observed above, there is no consistent trend in emissions or efficiency with respect to either the hydrogen concentration or the driving cycles. However, there are some significant results which are discussed below.

The carbon dioxide emissions decrease with an increase in hydrogen concentration in the CNG. This trend was consistent across all the driving cycles. For example, for the CSFTP cycle, the CO_2 emissions from the 50% blend were about 15.65% less than the 0% blend.

The nitrogen oxide emissions increased by 51% when the hydrogen concentration in the CNG blend increased from 0% to 30%. However, the nitrogen oxide emission for the HWFET and CSFTP cycle for 50% hydrogen blend shows some inconsistencies.

The hydrogen concentration in the CNG blend did not have a substantial effect on the fuel efficiency (EQMPG) and the total hydrocarbon emission for all the driving cycles.

In summary, emissions and efficiency were a function of driving conditions and the concentration of hydrogen in the compressed natural gas fuel blends.

Presentations

1. Samrat D., R.W. Peters, F.H. Fouad, H. Ng, and M. Duoba, "Performance on a Ford F-150 Using Various Blends of Compressed Natural Gas and Hydrogen," AIChE 2004 Annual Meeting Proceedings, Austin, November 2004.

C. HEV Test Methods and Procedure Analysis

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Objectives

- Answer the testing community's concern over the accuracy of testing a hybrid electric vehicle with regenerative braking on a single-axle dynamometer.

Approach

- Use existing Argonne National Laboratory (ANL) hybrids and test on four wheel-drive (4WD) chassis dynamometer;
- Investigate underlying regenerative braking strategies and how they may interact with operating on the dynamometer in its various mode;
- Use various cycles including those with high rate braking events;
- Observe final results and analyze regenerative braking through use of data acquisition; and
- Report results and make recommendations for testing hybrids.

Accomplishments

- The Model Year (MY) 2000 Honda Insight, MY 2001 and MY 2004 Toyota Prius were tested in 2WD and 4WD chassis dynamometer modes over various driving cycles;
- Analysis of braking strategy showed that all three vehicles have a "series" regenerative braking design such that recovered braking energy was not effected by additional braking on the rear axle;
- Discovered that attention to detail in the coast down procedures were important in achieving compatible results when changing from 2WD to 4WD; and
- Alleviating concerns in the testing community, demonstrated that no evidence exists to support that testing on a 2WD chassis dynamometer will bias fuel economy results for the types of hybrids tested.

Future Directions

- The conclusion was that current technology 2WD hybrids do not require testing on a 4WD chassis dynamometer, however future hybrids will employ 4WD systems and there is no guarantee that future control strategies may require 4WD testing capabilities so ANL must revisit the issue periodically; and
- Statistical significance was not found because the normal variations in test-to-test results are high in a hybrid. Future use of a robotic driver will allow much tighter control of test variations and the issue will be visited one more time for a very precise answer to the 2WD vs. 4WD testing question.

Introduction

Argonne National Laboratory (ANL) addressed the difficult task of making an assessment of the differences in testing hybrid electric vehicles (HEVs) in single axle (2WD) compared to running the same vehicle on both axles (4WD) on ANL's Advanced Powertrain Research Facility (APRF) 4WD chassis dynamometer.

Virtually any modern HEV design will capture deceleration energy though the drive motor, termed "regenerative braking" (regen). The maximum amount of regen is a consequence of the system architecture, the component operational limits, the control strategies employed, and how the other subsystems interact (namely, the friction brakes).

HEV fuel economy is sensitive to the amounts of regenerative braking energy put into the energy storage system during braking events. Nearly all vehicles are certified on dynamometers that only engage one axle of the vehicle. Whereas the braking dynamics in a conventional vehicle will not affect the fuel economy results, the concern is that any differences in regenerative braking operation on the dynamometer versus on-road operation could bring HEV fuel economy results measured on a 2WD chassis dynamometer into question.

Approach

Three ANL HEVs were used to investigate regenerative braking and fuel economy differences in 2WD versus 4WD dynamometer operation. ANL test vehicles feature extensive instrumentation revealing electrical energy flows (including current and voltage) and mechanical power flows (including axle torque and wheel speed). First, the study looked closely at braking operation to identify the possible interaction between fuel economy and regenerative braking. Then, cycle fuel economy results obtained from a 2WD chassis dynamometer are compared to repeat tests taken from a 4WD chassis dynamometer. Special attention was given to the procedures that match the dynamometer loads with coast down data to ensure that fuel economy results are not biased due to small differences in dynamometer settings.

Results

The test data shows that at any rate of deceleration, the friction braking system will be blended as the vehicle comes to rest. If the rear brakes are making a significant contribution when stopping the vehicle only in 4WD operation, it will be seen in the dynamometer tractive force measurements. Measurements taken from the dynamometer on a federal urban driving (UDDS) cycle illustrate the small significance the rear braking provides during the UDDS cycle, as shown in Figure 1. In the portion shown, the rear braking power trace is clear in the graphs only after the traces are enlarged to see the rear braking power "bump" as the vehicle nears zero speed (see insets of Figure 1).

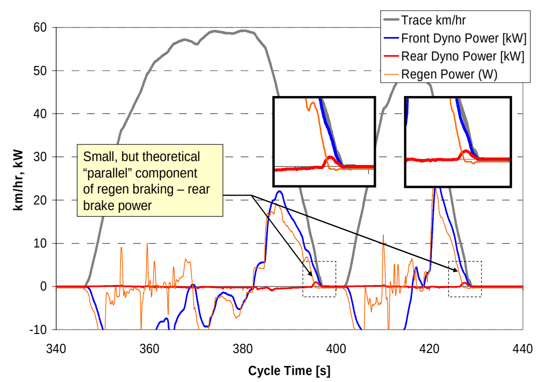

Figure 1. Front and rear axle braking power during urban driving cycle.

Although this data supports the notion that regenerative braking should be relatively unaffected, testing was conducted to make solid conclusions.

Results of 2WD and 4WD regenerative braking energies of a single braking event during a particular portion of a standard cycle (in this case a long deceleration from roughly 70 mph to zero) were analyzed for differences. This is shown graphically in Figure 2. Test-to-test variation is present, however, on average there is no observed difference in the recaptured DC electrical energy at the battery terminals.

In the next phase, the UDDS cycle was examined for the 2004 Toyota Prius. If there is an issue testing the certification cycle in the USA, it is most certainly a cause for concern. Once again care was taken to make sure the coast down results were equal and the non-driven axle inertia settings were correct (1.5%

non-driven axle inertia for the 2WD case). The fuel economy results are shown in Figure 3 and Figure 4. Again we find that there is no significant difference in fuel economy. Certainly a much larger data set would be necessary to show that a 0.1 mpg difference is due to dynamometer operation, and, this level of precision is not expected in chassis dynamometer testing.

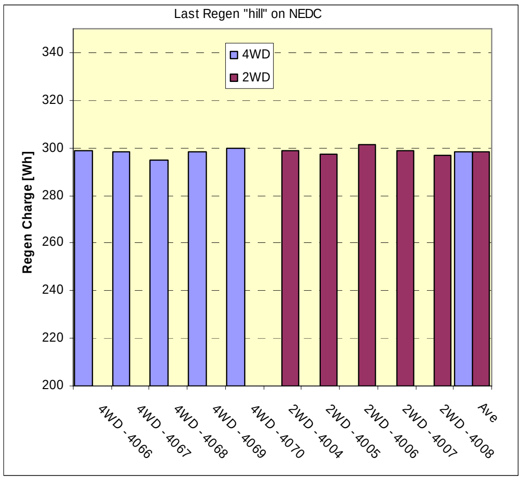

Figure 2. Equal amounts of electrical energy captured during last decel in the NEDC Cycle for 2WD and 4WD dyno operation.

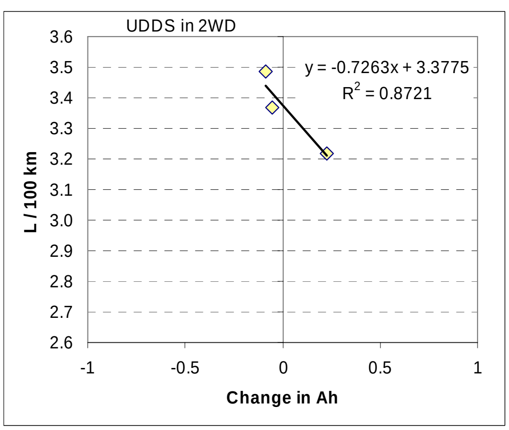

Figure 3. HEV correction graph of the 2004 Prius 2WD UDDS Cycle, fuel consumption is 3.378 L/100km.

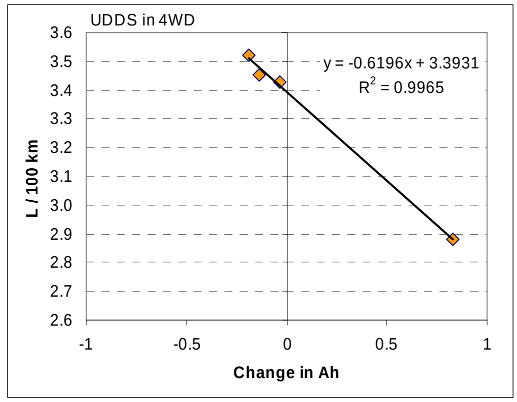

Figure 4. HEV correction graph of the 2004 Prius 4WD UDDS Cycle, fuel consumption is 3.393 L/100km.

Conclusions

The final conclusion (now being sited by EPA and others) is that the mechanism for regenerative braking found in the current production HEVs (Insight, MY 2001 and MY 2004 Toyota Prius) should not make a difference in fuel economy. The results showed no statistically significant difference however it may be required to do as many as 10 to 20 tests in each mode in order to rule out test-to-test-variations and other biases.

Current technology hybrids utilize their regenerative capacity to the maximum, thus the rear brakes are not in competition with the front brakes in absorbing the vehicle kinetic energy during cycle braking events. Under hard and light braking, the regenerative braking energies are equal for 2WD and 4WD dynamometer operation. In conclusion, for the designs currently sold, the vehicle test engineer should not be concerned over accuracy of testing hybrids on a 2WD dynamometer. However, with the release of 4WD hybrid systems (such as the Lexus 400h) the issue must be revisited.

Publications / Presentations

1. 2005-01-0685, “Investigating Possible Fuel Economy Bias Due To Regenerative Braking in Testing HEVs on 2WD and 4WD Chassis Dynamometers.”

V. OPERATIONAL AND FLEET TESTING

A. Arizona Public Service (APS) Alternative Fuel (Hydrogen) Pilot Plant Monitoring, Hydrogen and Compressed Natural Gas (CNG) Dispenser Testing (real-time fuel blending), and Hydrogen 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; and
- Assess the safety and reliability of using hydrogen/CNG (HCNG) blends for fueling ICE-powered vehicles.

Approach

- Use the Arizona Public Service Hydrogen/CNG Pilot Plant in Phoenix to fuel two 100% hydrogen ICE Ford pickups converted by Electric Transportation Engineering Corporation (ETEC) and two ICE Ford F150 pickups operating on HCNG blends;
- Fleet test 18 additional HCNG-powered ICE test vehicles to provide HCNG ICE vehicle operating knowledge in a government fleet and a utility fleet in the greater Phoenix area;
- Operate and test a 100% hydrogen and HCNG fuel dispenser that blends hydrogen and CNG in real-time instead of in batches; and
- Install monitoring sensors in order to measure energy and water use within the Pilot Plant, subsystems and components to measure plant capacities and energy efficiencies.

Results

- The Pilot Plant has operated since June 2002 with no unusual events, having fueled 100% hydrogen and HCNG vehicles approximately 3,000 times with 250,000 miles accumulated;
- No safety problems were encountered with fueling or operating the ICE vehicles with 100% hydrogen and various blends of HCNG;
- The vehicles demonstrated consistent, reliable behavior;
- Hydrocarbon and carbon monoxide emission levels were reduced below levels observed with pure CNG vehicles;
- Hydrogen production costs at the Pilot Plant have been documented; and
- Vehicles equipped with ICEs can safely operate on 100% hydrogen and HCNG fuels.

Future Directions

- Consider testing additional hydrogen and HCNG vehicles that become available; and
- Continue to monitor the Pilot Plant efficiencies as an aid to setting DOE hydrogen goals.

Introduction

Federal regulation requires energy companies and government entities to use alternative fuels in their vehicle fleets. As a result, several automobile manufacturers are producing compressed natural gas (CNG)-fueled vehicles. Several converters are modifying gasoline-fueled vehicles to operate on both gasoline and CNG (Bifuel). Because of the availability of CNG vehicles, many energy company and government fleets have adopted CNG as their principle alternative fuel for transportation. Meanwhile, recent research has shown that blending hydrogen with CNG (HCNG) can reduce emissions from CNG vehicles.

However, due to the lower volumetric energy density of hydrogen in relation to CNG, blending hydrogen with CNG without any engine modifications reduces engine power output. Therefore, several different hydrogen/CNG blend ratios and test methods were employed on test vehicles to obtain an overall picture of the effects and viability of using HCNG blends in existing CNG vehicles.

Approach and Results

Alternative Fuel (Hydrogen) Pilot Plant

The APS Alternative Fuel Pilot Plant, shown in Figure 1, is a model hydrogen, compressed natural gas (CNG), and HCNG blends refueling system. The plant distinctly separates the hydrogen system from the natural gas system, but can blend the two fuels at the stationary filling system.

Hydrogen is produced though electrolysis of purified water during off-peak hours and it can produce up to 18 kilograms (kg) of hydrogen per day by electrolysis. The hydrogen is compressed to 6,400 psi and stored in a high-pressure storage tank. It can store up to 155 kg of hydrogen. In addition to producing hydrogen, the plant also compresses natural gas to 5,000 psi. The hydrogen production, compression and storage equipment are physically located in a large open-air building (Figure 1); and

Figure 1. APS Alternative Fuel (Hydrogen) Pilot Plant, with fuel dispensing island in the foreground.

the water purification, nitrogen, and helium equipment are located in an adjacent building.

The fueling station is located outside the buildings. Hydrogen, CNG, and HCNG 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 hydrogen-enriched CNG and 100% CNG at a vehicle pressure rating of up to 3,600 psi.

APS Pilot Plant Monitoring

The U.S. Department of Energy's (DOE's) Advanced Vehicle Testing Activity (AVTA), along with Electric Transportation Applications (ETA) and Arizona Pubic 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 hydrogen and HCNG 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.

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 the electrolysis process is monitored to allow calculation of the total cost of plant operations and plant efficiencies. The monitoring system at the Pilot Plant will include about 100 sensors when complete (50 are installed to date), allowing for analysis of component, subsystems, and plant-level costs.

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

Using the APS general service plan E32 electric rate of 2.105 cents per kWh, during a recent eight-month period when 1,200 kg of hydrogen was produced and the plant capacity factor was 26%, the electricity cost to produce one kg of hydrogen was $3.43. If a plant capacity factor of 70% can be achieved with the present equipment, the cost of electricity would drop to $2.39 per kg of hydrogen. Power conversion (76.7%), cell stack (53.1%), and reverse osmosis system (7.14%) efficiencies are also calculated, as is the water cost per kg of hydrogen produced ($0.10 per kg).

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.

100% Hydrogen and HCNG Dispenser Testing

The AVTA is currently testing a prototype gaseous fuel dispenser developed by the Electric Transportation Engineering Corporation (ETEC). The dispenser, shown in Figure 2, delivers three types of fuels: 100% hydrogen, 100% compressed natural gas (CNG), and blends of HCNG 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 HCNG fuels. This nozzle connects to both a CNG supply line and hydrogen supply line and blends the hydrogen and CNG to supply HCNG levels of 15, 20, 30, and 50% hydrogen by volume.

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.

Figure 2. 100% hydrogen, CNG, and 15, 20, 30, and 50% blended HCNG (by volume) prototype dispenser brassboard design.

100% Hydrogen Vehicle Testing Procedures

As is true of all of the vehicle technology classes, the first step in baseline performance testing of hydrogen and HCNG ICE vehicles is to develop the vehicle technical specifications and test procedures. During FY 2004, the following specifications and test procedures were completed and published for testing 100% hydrogen and HCNG fueled internal combustion engine vehicles:

HICEV America Hydrogen Internal Combustion Engine Vehicle (HICEV) Technical Specifications

HICEV America Test Procedures

- HICEV America Test Sequence
- ETA-HITP01 Implementation of SAE Standard J1263 - Road Load Measurements and Dynamometer Simulation Using Coast Down Techniques

- ETA-HITP02 Implementation of SAE Standard J1666 May93 - HICE Vehicle Acceleration, Gradeability, and Deceleration Test Procedure
- ETA-HITP03 Implementation of SAE J1634 May93 - Fuel Economy Testing
- ETA-HITP04 HICE Vehicle Constant Speed Fuel Economy Tests
- ETA-HITP05 HICE Vehicle Rough Road Course Test
- ETA-HITP06 Braking Test
- ETA-HITP07 Road Course Handling Test
- ETA-HITP11 Vehicle Verification
- ETA-HIAC01 Control, Close-out and Storage of Documentation
- ETA-HIAC02 Control of Test Conduct
- ETA-HIAC03 Preparation of Issuance of Test Reports
- ETA-HIAC04 Review of Test Results
- ETA-HIAC05 Training and Certification Requirements for Personnel Utilizing ETA Procedures
- ETA-HIAC06 Receipt Inspection
- ETA-HIAC07 Control of Measuring and Test Equipment (M&TE)
- ETA-HIQA01 Audit of the Quality Assurance Program for the Control and use of Measuring and Test Equipment
- ETA-HIQP01 Quality Program

Hydrogen and HCNG Vehicle Testing

Eighteen HCNG blended fuel vehicles have been operating in two fleets and fueling at the Pilot Plant. This provides knowledge of and experience with handling and fueling HCNG fuels. In addition, two 100% hydrogen ICE pickups were built during FY 2004. However, testing on these vehicles did not commence until FY 2005. 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 40% on the engine dynamometer while the 16-valve engine was designed as a low-cost option. Both engines were installed in Ford pickups and commenced testing. The engine conversions were performed by ETEC.

<u>Publications</u>

1. Francfort, J.E., and D. Karner, “Hydrogen Fuel Pilot Plant and Hydrogen ICE Vehicle Testing,” INEEL/CON-04-02198, 2004 Fuel Cell Seminar. San Antonio, TX, August 2004.
2. Karner, D. and J.E. Francfort, “Arizona Public Service – Alternative Fuel (Hydrogen) Pilot Plant Design Report,” INEEL-03-00976, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID, December 2003.
3. Karner, D. and J.E. Francfort, “Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150,” INEEL-03-01313, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID, November 2003.

B. Hybrid Electric Vehicles (HEVs) Testing

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Objective

- Benchmark commercially available hybrid electric vehicles (HEVs); and
- Reduce the uncertainties about HEV battery and vehicle life.

Approach

- Perform baseline performance and accelerated reliability tests on HEV; and
- Put selected HEVs in fleets to obtain fuel economy and other life-cycle related vehicle data under actual road conditions.

Results

- The 20 HEVs tested exhibited varying fuel economies: 37.6 mpg for the 4 Honda Civics, 40.9 mpg for the 6 first generation (Gen I) MY 2002 Toyota Prius, 45.6 mpg for the 6 Honda Insights, 45.1 mpg for the 2 Gen II Prius, and 17.7 mpg for the 2 Chevrolet Silverado HEVs; and
- Fleet tests showed that fuel economy is significantly reduced during the summer months due to the use of air-conditioning.

Future Activities

- Benchmark new HEVs available during FY 2005; and
- Ascertain HEV battery life by accelerated reliability testing at the end of 160,000 miles.

Introduction

Today’s light-duty hybrid electric vehicles (HEVs) use a gasoline internal combustion engine (ICE) and electric traction motor with traction batteries for onboard energy storage. The batteries are charged by the onboard ICE and the regenerative braking system. Future HEV onboard storage systems may include combinations of multiple battery technologies employing different charge/discharge methods, ultracapacitors, and flywheels. The future HEV ICEs may run on alternative fuels such as hydrogen, methane, HCNG, propane, or natural gas. The DOE’s Advanced Vehicle Testing Analysis and Evaluation (AVTAE) program benchmarks and tests HEVs to compare the advantages and disadvantages of each technology.

Approach

During FY 2004, the AVTA performed accelerated reliability and fleet testing on 20 HEV models: the Gen I Toyota Prius, Honda Insight, Gen II Toyota Prius, Chevrolet Silverado, and Honda Civic.

Results

As of the end of September 2004, the 20 HEVs accelerated reliability testing had total 1.2 million test miles, shown in Figure 1, and the fuel economies ranged from 17.7 to 45.6 mpg, shown in

Table 1. All of the HEVs accelerated reliability tested to date exhibit seasonal variations in fuel economy, illustrated in Figure 2, with highest mpg during the cooler months and lowest mpg during the hotter months.

In addition to the HEV fuel economy and total test miles data being collected, all maintenance events, including the costs, dates and vehicle miles when a maintenance event occurred is collected and disseminated as an aid to compiling life-cycle costs. This data is also presented on the AVTA's web pages as both a maintenance fact sheet, as shown in Figure 3, and a HEV fact sheet , shown in Figure 4, with includes miles driven, fuel economy, mission, and life-cycle cost based on either the estimated value or real selling price if the vehicle was been sold.

The Environmental Protection Agency (EPA) tests HEVs during separate city and highway dynamometer drive cycles, while the AVTA also uses two dynamometer drive cycles to test fuel economy. However, the two AVTA drive cycles combine city and highway driving patterns into a single identical test cycle, but one AVTA test is performed with the air conditioning on maximum and the other AVTA test is performed with the air conditioning 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, shown in Figure 5, and below the EPA results.

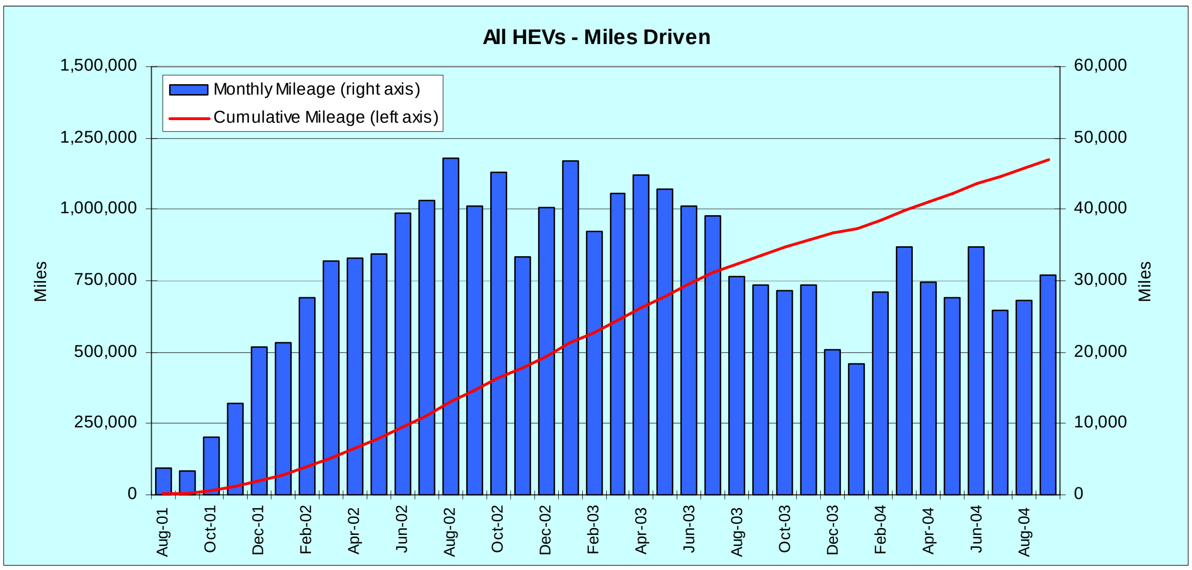


Figure 1. Total and monthly accelerated reliability testing mileage accumulation.

Table 1. HEV total accelerated reliability testing miles and total HEV model testing miles, as well as HEV fuel economy results (as of September 2004).

Number of models in testing	Total test miles	Miles per gallon
6 Honda Insights	381,000	45.6
4 Honda Civics	337,000	37.6
6 Gen I Toyota Prius	419,000	40.9
2 Gen II Toyota Prius	35,000	45.1
2 GM Silverado	1,000	17.7

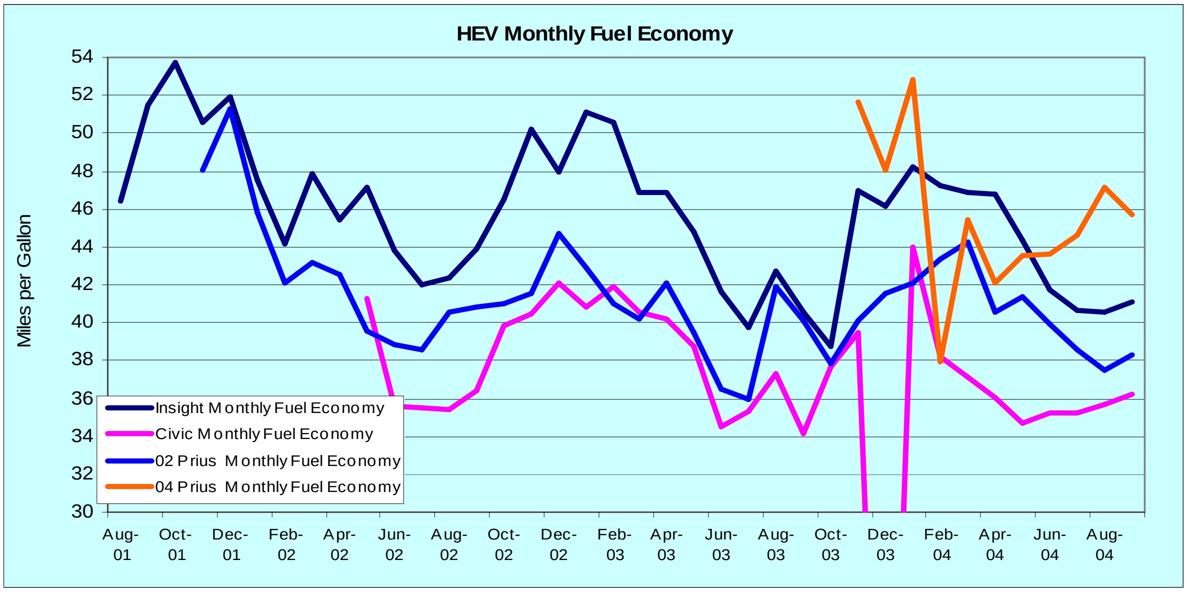


Figure 2. Monthly fuel economy testing results by HEV model.

HEV Fleet Testing - Maintenance Sheet
2001 – Honda Insight Hybrid

U.S. Department of Energy Energy Efficiency and Renewable Energy

FreedomCAR

Advanced Vehicle Testing Activity

VIN #JHMZE14701T002688

Date	Mileage	Description	Cost
2/7/2002	7,473	Change oil and rotate tires	$ 27.00
4/12/2002	14,946	Change oil and rotate tires	$ 27.00
6/4/2002	20,165	Change oil and rotate tires	$ 27.00
4/17/2002	14,952	15,000 mile service	$ 154.76
7/25/2002	28,213	Change oil and rotate tires	$ 34.08
8/26/2002	32,172	30,000 mile service	$ 420.98
9/20/2002	36,096	Change oil and rotate tires	$ 31.59
10/16/2002	40,170	Change oil and rotate tires	$ 30.87
12/9/2002	48,082	Change oil and rotate tires	$ 30.99
1/30/2003	55,856	50,000 mile service	$ 324.33
3/10/2003	61,577	Transmission shifting erratically. Change engine oil, flush transmission and replace front brake pads	$ 399.34
4/28/2003	69,098	Change oil and replace two tires	$ 187.64
6/3/2003	74,410	Change oil and rotate tires	$ 30.86
6/26/2003	76,977	Transmission still shifting erratically. 15,000 mile service and transmission flush.	$ 314.01
7/10/2003	77,054	Transmission still shifting erratically. Replace transmission, sparkplugs and fuel injectors.	warranty
7/15/2003	69,098	Replace accessory 12 volt battery	$ 65.92
7/24/2003	78,700	Replace headlight	$ 15.80
8/11/2003	80,871	Change oil and rotate tires	$ 31.63
9/3/2003	84,003	Change oil and rotate tires. Two tires replaced under warranty	$ 61.42
9/29/2003	86,290	Replace front wheel bearings	$ 50.00
10/14/2003	88,438	Change oil and replace hatch lifts	$ 172.02
11/18/2003	92,050	90,000 mile service	$ 182.33
12/15/2003	96,092	Change oil and rotate tires	$ 31.17
2/17/2004	103,963	15,000 mile service	$ 250.29
4/5/2004	111,714	Change oil and rotate tires	$ 30.63
4/27/2004	115,473	Change oil and rotate tires	$ 30.63
5/24/2004	119,800	30k miles interval service, replace front brakes pads and rotors, replaced lower transmission mount	$ 1,087.74
6/4/2004	120,817	Recall headlight wire harness replacement	NC
6/23/2004	123,564	Oil change and 2 tires replacement	$ 174.94
8/11/2004	124,904	Repair collision damage	$ 1,277.17
8/11/2004	124,904	Repair collision damage	$12,272.00
9/3/2004	124,904	Engine mounts and fuel sending units replacement	$1,296.76

Figure 3. Example of HEV maintenance records for a Honda Insight HEV.

freedomCAR & vehicle technologies program

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy

HEV Fleet Testing

Advanced Vehicle Testing Activities

2003
Civic Hybrid

VIN #
JHMES96653S001603

FreedomCAR

Less dependence on Foreign oil, and eventual transition to an emissions-free, petroleum-free vehicle

Fleet Performance

Description:
This vehicle was operated throughout the State of Arizona by Bank One of Arizona's courier pool. It was operated 24 hours a day, six days a week, transferring documents between branches and a central processing center located in Phoenix on city streets and urban freeways as well in intrastate courier routes, with typical high-speed round trips of 100 to 300 miles.

Major Operations & Maintenance Events:
CVT transmission failed @ 99,102 miles
Cost: $3,500
Catalytic converter failed @ 100,715 miles
Cost: $1,164

Operating Cost:
Purchase Cost: $23,174 (5/02)*
NADA Used Vehicle Price: $12,350 (4/04)
Sale Price: In operation
Maintenance Cost: $0.07/mile
Operating Cost: $0.07/mile
Total Ownership Cost: $0.24/mile

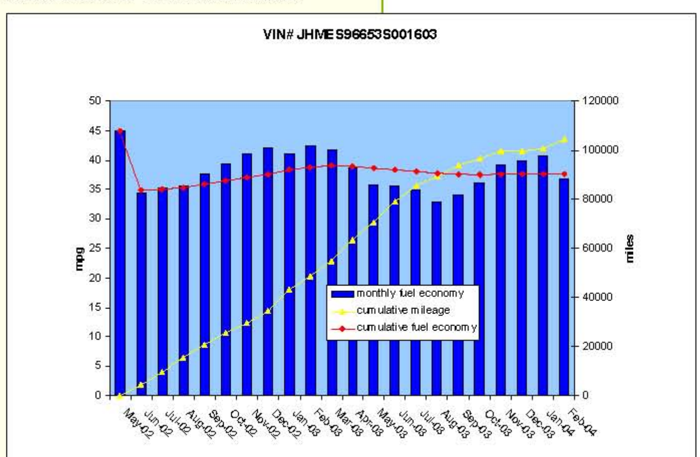
Operating Performance:
Total miles driven: 104,381
Cumulative MPG: 37.6

** Purchase includes dealer price with options plus taxes. It does not include title, license, registration, extended warranty or delivery fee costs.*

Vehicle Specifications

Engine: 4-cylinder, 70 kW @ 5700 rpm
Electric Motor: 10 kW
Battery: Nickel Metal Hydride
Seatbelt Positions: Five
Payload: 882 lbs
Features: Regenerative Braking
CVT Transmission

See HEVAmerica Baseline Performance Fact Sheet for more information.



U.S. Department of Energy
Energy Efficiency and Renewable Energy

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Figure 4. Example of HEV testing fact sheet.

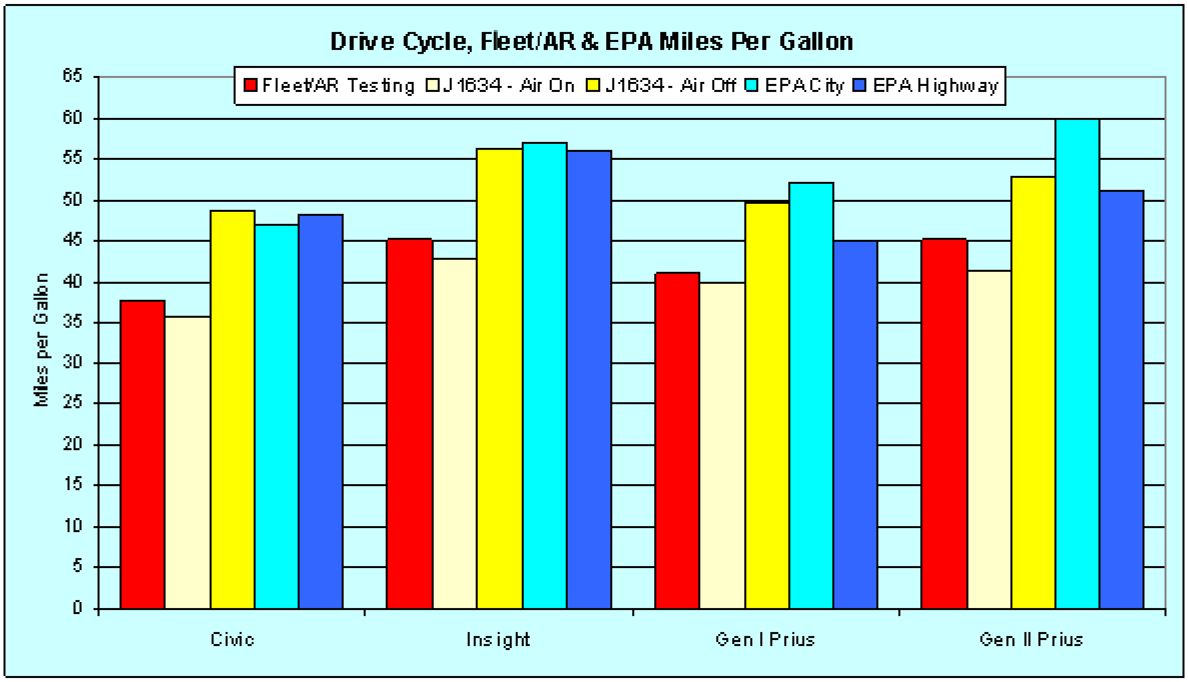


Figure 5. EPA and AVTA fuel economy testing results for the Civic, Insight, Gen I Prius, and Gen II Prius HEVs.

Conclusions

The largest impact on fuel economy is from the use of the air conditioning with these early HEV models during the summer months. The HEV battery packs appear to be robust, as of the end of FY 2004 and 1.2 million test miles, there was only one traction battery failure.

Future Activities

New HEVs available from U.S., Japanese and European manufacturers will be benchmarked during FY 2005. Most new HEVs will be tested to reduce uncertainties about HEV technologies, especially the life of their batteries and other onboard energy storage systems.

Publications

There were approximately 30 HEV fact and maintenance sheets presented on the web site. The HEV baseline performance testing procedures and vehicle specifications were also updated and republished on the web. All of these documents can be found at http://avt.inl.gov/hev.shtml.

1. Francfort, J.E., Advanced Technology Vehicle Testing, INEEL/CON-04-01691, 41st Power Sources Conference, Philadelphia, PA, May 2004.
2. Francfort, J.E., Hybrid Electric Vehicle and Idle Reduction Technology Activities, INEEL/CON-04-01859, Energy Smart America 2004, Minneapolis, MN, May 2004.
3. Francfort, J.E., Advanced Technology Vehicle Testing, INEEL/CON-03-00780, The 20th Electric Vehicle Symposium and Exposition, Long Beach, CA, October 2003.

C. Testing of Neighborhood Electric Vehicles (NEVs)

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Objective

- Conduct baseline performance testing and fleet testing to reduce the uncertainties about the performance and reliability of neighborhood electric vehicles (NEVs).

Approach

- Initiate baseline performance testing of 4 NEVs during FY 2004; and
- Fleet test 100 NEVs, with some using fast chargers.

Future Activities

- Up to a half dozen new models of NEVs will be available for testing in the near future; and
- Future testing will continue to be limited to baseline performance testing and fleet testing.

Introduction

A neighborhood electric vehicle (NEV) is a 4-wheeled vehicle, operating on batteries charged from the electricity grid system. NEVs are generally larger than golf carts but smaller than normal light-duty passenger vehicles. They are usually configured to carry two or four passengers, two passengers and a pickup type bed, or two passengers with various maintenance support equipment. The National Highway Traffic Safety Administration (NHTSA) defines NEVs as subject to Federal Motor Vehicle Safety Standard (FMVSS) No. 500 (49 CFR 571.500). Per FMVSS 500, NEVs have top speeds between 20 and 25 mph, and are defined as "Low Speed Vehicles" (LSVs). While "Low Speed Vehicle" is technically the correct term, *NEV* has become the term used by industry and fleets to refer to passenger vehicles subject to FMVSS 500. About 35 states have passed legislation or regulations allowing NEVs to be licensed and driven on roads that are generally posted at 35 mph or less.

The NEV market has relatively low entry barriers for manufacturers, and several possible new manufacturers include Liddo, Western Car, Giliberti, *feel good cars*, and Lamborghini, as well as Chinese manufacturers.

Approach

With more than 20,000 NEVs on the road in the United States, more NEVs have been deployed domestically than any other class of pure electric vehicle. However, significant numbers of the individual NEV deployments occurred when the public took advantage of tax incentives. Fleet managers have been slower to embrace NEVs due to uncertainty about performance and reliability. It is for this reason that the AVTA baseline performance tested four NEVs during FY 2004 from Global Electric Motors (GEM), a Daimler Chrysler company, shown in Figure 1. In addition, 100 NEVs are being fleet tested, with some fast charged, in fleets such as Luke Air Force Base, Camp Pendleton, and the cities of Palm Springs and Palm Valley. The operating characteristics of NEVs do not make them good candidates for accelerated reliability testing.

Results

The 14 NEVs tested as of the end of FY 2004 all have ranges of 31 to 51 miles per charge, with an average range of 39 miles per full charge. The energy efficiencies for the four NEVs testing during FY 2004 are all greater than 9 miles per kilowatt-hour, shown graphically in Figure 2. The NEVs are becoming popular as community vehicles in warmer states, and with some private and government fleets in specific applications that are looking to reduce their petroleum consumption. Federal fleets use NEVs to comply with fuel-use reduction directives such as Executive Order 13149 (*Greening the Government Through Federal Fleet and Transportation Efficiency; Section 6*).

Publications

1. Kirkpatrick, M. and J.E. Francfort, "Federal Fleet Use of Electric Vehicles," INEEL-03-01287, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID, November 2003.

NEV baseline performance testing fact sheets were also published and they are available at http://avt.inl.gov/nev.shtml.

Figure 1. Four GEM NEVs at the test track.

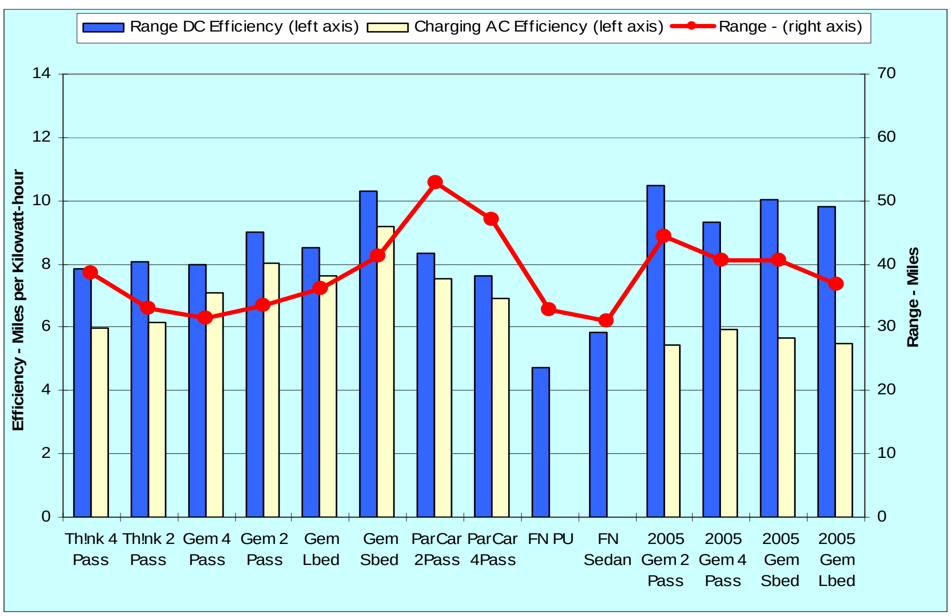

Figure 2. Range testing results for 14 NEVs baseline performance tested through the end of FY 2004. The four model year 2005 Gems were tested during FY 2004 (right 4 test results).

D. Urban Electric Vehicles Testing

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Objective

- Gain fleet test experience to reduce the uncertainties about the performance and reliability of urban electric vehicles (UEVs).

Approach

- Perform accelerated reliability and fleet testing of TH!NK city UEVs;
- Fleet test Nissan Hyperminis and Toyota eComs;
- Collect demographics data from TH!NK city participants via the Internet; and
- Support Ford's 250 TH!NK city deployments in California, Michigan and Georgia.

Results

- The range of UEVs in fleet applications is as high as 50 miles and their top speeds about as high as 50 mph;
- Range is over 60 miles per charge at a constant 35 mph on a test track; and
- UEVs are very popular with participants and replace a high percentage of gasoline vehicle trips.

Future Activities

- Given the potential of this niche market and the potential use of UEVs to obtain California credits, additional UEVs may be introduced, and the DOE's Advanced Vehicle Testing Analysis (AVTA) will continue to test new entrants.

Introduction

Urban electric vehicles (UEVs) are pure electric passenger vehicles with top speeds of about 60 mph and a per-charge range of about 50 miles. They are classified by the National Highway Traffic Safety Administration (NHTSA) as regular passenger vehicles, and are subject to the same Federal Motor Vehicle Safety Standard (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 TH!NK *city*, made by Ford Motor Co., is the UEV most in use. It previously completed baseline performance testing, and is undergoing accelerated reliability and fleet testing. The AVTA is fleet testing 100 TH!NK *cities* in suburban New York State, just outside New York City. The 100 *citie*s are being used as commuter vehicles from commuters' homes to train stations, as shown in Figure 1. The AVTA is collecting energy use data, both at the train stations and commuters' homes. The 100 commuters are also being surveyed monthly to collect qualitative data, such as participant demographics via the Internet. The AVTA is also supporting

Figure 1. TH!NK city urban electric vehicles parked and charging at the Brewster, New York, Metropolitan Train Station.

Ford's 250 TH!NK *city* deployments in California and Atlanta, with Ford supplying qualitative reports.

Results

The one AVTA TH!NK *city* in accelerated reliability testing has been driven over 12,000 miles and its fuel economy has been 3 miles per kWh of electricity. The ownership cost is $1.15 per mile, shown in Figure 2.

The TH!NK *city* Electric Vehicle (EV) Program is in its second full year in the United States and the partners include Federal, state, and municipal agencies and commercial partners. Phase I, placing the vehicles in test programs, was completed in 2002. Phase II, ongoing monitoring of these programs, is underway. The Program has successfully placed 195 EVs with customers (including Hertz) in California, 108 in New York (including loaner and demonstration vehicles), 15 in Georgia, 8 to customers outside of the United States, and 36 in Ford's internal operations in Dearborn, Michigan—362 vehicles total. The Program is the largest operating urban EV test program in the United States.

Phase II, ongoing monitoring of an operational field fleet, has now been underway for approximately one year. The AVTA is highly involved with the monitoring of the TH!NK *city* vehicles in the New York Power Authority / TH!NK Clean Commute Program through the AVTA's partnership with ETA, which provides separate reports to DOE. The remainder of the TH!NK *city* fleet is monitored through Ford's internal operations. The TH!NK testing activity's goals and objectives include:

- Enhancing public awareness of urban EVs;
- Defining the unique urban EV market and niche applications;
- Enhancing EV infrastructure; and
- Investigating the economic sustainability of urban EVs.

The TH!NK *city* testing programs have achieved a high level of public acceptance now that targeted customers have had the vehicles for a period of time. Some of the participate demographics include:

- 52% of the participants have a combined annual income of $150,000 or greater
- 79% are age 41 or older
- 86% are male
- 48% have two or three vehicles in the family
- 35% travel between 20 to 90 miles each week, both commuting and running errands
- 45% rated the program highly satisfactory
- 57% have previously leased a vehicle
- 43% were introduced to leasing versus purchasing through the Clean Commute Program.

Future Plans

Both Toyota (e-com) and Nissan (Hypermini) have a limited number of UEVs in use in California. The AVTA is collecting fleet data, such as miles driven and the energy used during charging. Given the poor success of full-size pure EVs, companies are cautious to commit to this market segment. However, the initial results from the New York State TH!NK *city* program suggests consumers like the vehicles. The AVTA will continue to baseline performance test new entrants and, depending on capabilities, also perform either accelerated reliability or fleet tests.

Publications

1. Francfort, J.E. and V. Northrup, "TH!NK city – Electric Vehicle Demonstration Program: Second Annual Report 2002–2003, July 2004," INEEL-04/02133, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID, November 2004.

freedomCAR & vehicle technologies program

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy

UEV America

Advanced Vehicle Testing Activities

1999
Ford
TH!NK *city*

VIN #
YYCDA11AOYAAA14161416

FreedomCAR

Less dependence on Foreign oil, and eventual transition to an emissions-free, petroleum-free vehicle

Fleet Performance

Description:
This vehicle was operated by Electric Transportation Applications in Phoenix, Arizona. It was assigned to an individual responsible for mileage accumulation. It was driven in a planned urban route as necessary to achieve monthly mileage objectives and occasionally for business travel and from home to work. The vehicle was rarely operated on highways with speed limits of 55 mph or greater.

Major Operations & Maintenance Events:
Battery servicing at 6,319, 10,754, and 11,890 miles. Cost: Ave. of $200 each time
Vehicle ran out of energy at ~30% SOC at 1,250 miles, battery replaced under warranty.
Radiator fan failed at 4,347 miles. Cost: $237
Charger brought inside, too hot to charge outside. Cost: none

Operating Cost:
Leasing Cost: $ 6,381 for 30 months
Maintenance Cost: $0.07/mile
Operating Cost: $0.56/mile
Total Ownership Cost: $1.15/mile

Operating Performance:
Total miles driven: 12,132
Cumulative miles per kWh: 2.98

Vehicle Specifications

Electric Motor: 27 kW, AC Induction
Battery: Nickel Cadmium (NiCd)
Seatbelt Positions: Two
Payload: 451lbs
Features: Regenerative Braking
Single Speed Transmission

See UEVAmerica Baseline Performance Fact Sheet for more information.

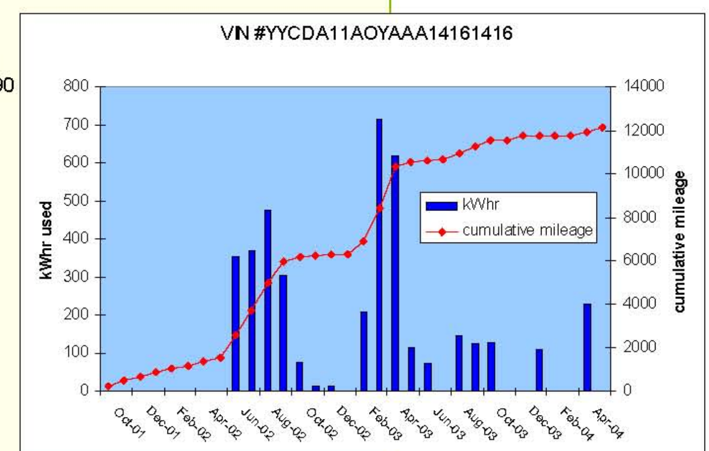

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Figure 2. TH!NK city testing fact sheet.

E. Oil Bypass Filter 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.

Approach

- Install puraDYN oil bypass filters on INL fleet vehicles, including diesel buses and gasoline Chevrolet Tahoes;
- Judiciously collect engine oil samples and perform oil analyses to determine the quality of the engine oils for continued use; and
- Collect oil use and oil change data.

Results

- The oil bypass filters eliminate up to 90% of the normal diesel engine oil changes in the buses;
- The oil bypass filters eliminate oil changes in the gasoline Chevrolet Tahoes, but not as many as in the diesel buses; and
- The addition of makeup oil appears to help extend oil change intervals.

Future Activities

- Add additional test buses with 4-stroke diesels engine as they are added to the INL fleet and test additional oil bypass filters from other manufacturers.

Approach

Eight Idaho National Laboratory (INL) four-cycle diesel-engine buses used to transport INL employees on various routes and six INL Chevrolet Tahoes with gasoline engines are equipped with oil bypass filter systems from the puraDYN Corporation. The bypass filters are reported to have engine oil filtering capability of <1 micron and a built-in additive package to facilitate extended oil-drain intervals. The bypass filters are installed in the engine bays of the INL buses.

Results

As of the end of September 2004, the eight buses had accumulated 580,848 test miles, as shown in Table 1, since the beginning of the test and 516,401 miles without an engine oil change. This represents an avoidance of 43 oil changes, which equates to 1,505 quarts (376 gallons) of new oil not consumed and 1,505 quarts of waste oil not generated.

Table 1. Test buses and test mileage on the bus engine oil as of September 30, 2004.

Bus Number	Test Start Date	Bus Mileage at Start Date	Current Mileage (Sept. 30)	Total Test Mileage	Mileage on Initial Oil (Sept. 30)	Miles on Current Oil (Sept. 30)
73425	Dec 18, 2002	41,969	89,203	47,234	47,234	47,234
3432	Feb 11, 2003	47,612	121,605	73,993	73,993	73,993
73433	Dec 4, 2002	198,582	277,036	78,365	78,365	78,454
73446[1]	Oct 23, 2002	117,668	182,432	64,764	53,194	11,570
73447[1]	Nov 14, 2002	98,069	158,588	60,519	54,201	6,318
73448[2]	Nov 14, 2002	150,600	208,247	57,647	25,572	32,075
73449	Nov 13, 2002	110,572	165,274	54,702	54,702	54,702
73450[1]	Nov 20, 2002	113,502	257,126	143,624	129,140	14,484
				580,848[3]	516,401[4]	318,741[3]

[1] The oil bus was intentionally changed due to degraded oil quality, determined by low total base numbers.
[2] The oil on bus 73448 was inadvertently changed on September 16, 2003.
[3] The total bus test miles are 580,848 miles.
[4] The total bus test miles without an oil change.

As of the end of September 2004, the six Tahoes had accumulated 150,205 total test miles. The Tahoe filter test is in transition, however, because the engine oils are being cleaned and flushed, and the recycled oil used from the outset of testing is being replaced with virgin 10W-30 Castrol oil. Three Tahoes have been flushed to date and testing restarted.

Oil Use In INL Buses With Bypass Filters

The oil use for each bus has been tracked since the oil bypass filter technology evaluation began. Oil use consists of (1) oil that is added periodically to a bus engine when the oil is checked daily and the oil level is low, and (2) oil that is added to the bus engine to replenish the oil lost when the full-flow or bypass oil filter is changed. A log sheet is kept onboard each bus, attached to the inner wall of the cargo bay near the containers of Shell Rotella-T, 15W-40 oil used for this evaluation. The bus drivers (who fuel the buses and check the engine oil levels daily) and the service mechanic were asked to update the log sheet when oil is added to the bus engines. Table 2 shows the total oil consumption for each bus since the oil bypass filter evaluation began.

Discussion

During the oil bypass filter evaluation, oil analysis reports document the oil quality as the oil ages. However, the quality (such as the Total Base Number - TBN) of the engine oil in the buses can be enhanced by regular multi-quart infusions of fresh oil to the oil supply system. The oil quality of a leaking engine with a premium oil bypass filter system may not degrade because the regularly added oil bolsters the oil values. However, if an engine is new or otherwise does not consume oil, the oil values may degrade faster, not being replenished. The INL buses used in this evaluation are equipped with the newest engines in the fleet and were the only four-cycle diesel engines at the time the puraDYN oil bypass filters were installed.

Some interesting facts are evident in Table 2. Buses 73425, 73432 and 73433 have four-cylinder Detroit Diesel (DD) engines, whereas the other buses have six-cylinder engines. Looking at the oil use as measured by the oil replacement ratio, these four-cylinder DD engines have greater oil use than the six-cylinder DD engines. The volume replacement in respect to the oil pan volume capacity varies between 2.0 and 4.5 times for the four-cylinder DD engines, whereas the six-cylinder DD engine oil volume replacement in respect to the oil pan volume capacity varies between 1.0 and 1.3 times.

The oil use per 1,000 miles driven for the three four-cylinder engines ranged between 1.2 and 1.6 quarts per 1,000 miles driven. For the five six-cylinder engines, oil use per 1,000 miles varied between 0.7 and 1.0 quarts per thousand miles. The two buses with the highest oil use, 73432 (104 quarts) and 73433 (127 quarts), also have the two highest TBN

Table 2. Engine oil use as of September 30, 2004.

Bus Number	73425	73432	73433	73446	73447	73448[9]	73449	73450[10]
Test start date[1]	12/18/02	2/11/03	12/4/02	10/23/02	11/14/02	11/14/02	11/13/02	11/20/02
Volume of oil pan[2]	28	28	28	40	40	40	40	38
Miles on oil[3]	47,234	73,993	78,365	53,194	54,201	57,942	54,995	129,140
Status of test[4]	Ongoing	Ongoing	Ongoing	6/2/04	8/3/04	9/16/03	Ongoing	8/31/04
Daily oil check top-off[5]	27	60	80	13	20	13	13	63
Filter service makeup oil[6]	29	44	47	38	32	28	27	40
Total oil added[7]	56	104	127	51	52	41	40	103
Oil replacement ratio[8]	2.0	3.7	4.5	1.3	1.3	1.0	1.0	2.7
Oil use per 1,000 miles	1.2	1.4	1.6	1.0	1.0	0.7	0.7	0.8

1 Date the bypass filter system and the new 15W-40 Shell Rotella-T oil were installed in each bus.
2 Total volume capacity, in quarts, of the diesel engine oil pan.
3 The miles traveled since the initial charge of oil at the beginning of the test (if the bus is still traveling on the initial charge of oil), or the miles since the initial charge to when the initial oil was changed.
4 The status of the test is either “ongoing” (if the bus is still traveling on the initial charge of oil), or the date the initial test oil was changed.
5 Volume of oil, in quarts, added during the daily oil check up or to the date the initial oil was changed.
6 Volume of oil, in quarts, added to provide the make-up oil when the filters are changed during servicing up to 9/30/04 or to the date that the initial oil was changed. On some buses, the volume added during the filter servicing was not recorded on the oil use log; therefore, an average volume of seven quarts was substituted for the missed servicing. Seven quarts is used as the volume added for the filters varied between 4 and 10 quarts
7 Total quarts of oil added to the system since the start of the test activity or to the date the initial oil was changed (sum of the above two lines).
8 The oil replacement ratio is the amount (in quarts) of oil added during the filter evaluation project divided by the size of the engine oil pan.
9 The oil on bus 73448 was inadvertently changed on 9/16/03Since this chart tracks daily and filter service oil use, Bus 73448 values include all the miles traveled and oil used to date, but do not include the oil change on 9/16/03.
10 The oil-use log for bus 73450 is incomplete. Only data for 9 months of 2004 are available. The daily top-off and filter make-up oil for the 9 months of 2004 were used to extrapolate the volume of oil used for 2003.

values (high is good), 7.1 and 8.3. Of the six-cylinder engines, only one is still operating on its initial charge of oil—bus 73449. All of the other engine oils have been changed due to a drop in TBN below 3.0.

Future Activities

Diesel Engine Idling Wear-Rate Evaluation Test

A diesel engine wear-rate evaluation will be undertaken to support DOE’s effort to minimize diesel engine idling in the United States and the associated 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 are other possible economic advantages if engine life can be extended and maintenance intervals lengthened.

The INL plans to characterize diesel engine wear and any 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 will be 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 two INL fleet buses were selected because:

The two buses are part of the Oil Bypass Filter Evaluation

Their engine wear patterns have been monitored for 20+ months

The two buses are equipped with four-cycle engines

The two buses have a documented history of maintenance and fuel usage

INL Fleet Operations provides consistent and scheduled maintenance of these buses.

Refined Global Solutions Filter Evaluation

The ongoing oil bypass filter technology evaluation is being expanded to include oil bypass filters from Refined Global Solution (RGS), Inc., of Bluffdale, Utah. It is proposed during the next fiscal year to install RGS FP-1000 bypass filter systems on three INL fleet buses with recently refurbished four-cylinder, four-cycle diesel engines. This will expand the bypass filter evaluation from eight to eleven buses.

Publications

1. Francfort, J.E., "Demonstrated Petroleum Reduction Using Oil Bypass Filter Technology on Heavy and Light Vehicles," INEEL/CON-04-02260, Diesel Engine Emissions Reduction Conference, San Diego, CA, August 2004.
2. Zirker, L.R., J.E. Francfort, and J. Fielding, "Oil Bypass Filter Technology Evaluation, Seventh Quarterly Report April - June 2004," INEEL-04-02194, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID, August 2004.
3. Zirker, L.R. and J.E. Francfort, "Oil Bypass Filter Technology Evaluation, Sixth Quarterly Report January - March 2004," INEEL-04-02004, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID, June 2004.
4. Zirker, L.R. and J.E. Francfort, "Oil Bypass Filter Technology Evaluation, Fifth Quarterly Report October - December 2003," INEEL-04-01618, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID, February 2004.
5. Zirker, L.R. and J.E. Francfort, "Oil Bypass Filter Technology Evaluation, Fourth Quarterly Report July - October 2003," INEEL-03-01314, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID, November 2003.

F. 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 further optimize and improve the systems; and
- Facilitate purchase decisions of fleet managers by providing needed information.

Approach

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

Results

- Produced final report on liquefied natural gas (LNG) refuse haulers, using an advanced compression ignition cycle engine;
- Drafted status report on idle reduction technology demonstrations; and
- Kicked-off evaluations of 3 fleets using various hybrid-electric buses.

Future Activities

- Complete evaluations on current fleet vehicles; and
- Monitor and evaluate promising new technologies and work with additional fleets to test the next-generation of advanced vehicles.

Introduction

Understanding how advanced technology vehicles perform in real-world service, and the associated costs, is important to enable full commercialization and acceptance in the market. DOE's Advanced Vehicle Testing Analysis (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 2004 included:

- Fleet evaluations
- Idle reduction technology demonstrations, and
- Short term technology reports.

Fleet Evaluations

In FY 2004, AVTA worked with five fleets to evaluate the performance of advanced technologies in service.

In 2001, *Norcal Waste* began operating a fleet of 14 LNG refuse haulers equipped with prototype Cummins-Westport (CWI) ISXG engines, an example of which is shown in Figure 1. The ISXG engine, which was specifically designed for use with LNG, uses the Westport-cycle™ high-pressure direct injection fuel system. By injecting a small amount of diesel fuel into the engine cylinder, this system enables the ISXG engine to operate on the more efficient compression ignition cycle while using natural gas as the main fuel. In early FY 2004, AVTA completed data collection and produced a final report outlining the costs and operating experience of the fleet. In general, the fleet had a very good experience with the LNG trucks.

Figure 1. Norcal's LNG Refuse Hauler uses a Cummins-Westport HPDI system.

Some results are as follows:

Drivers reported that the performance of the LNG trucks was as good as, or better than, that of the diesel trucks.

The LNG trucks were operated more than 1.8 million miles through July 2003 and were projected to operate 2.3 million miles through December 2003. The LNG trucks have been used at a rate of 100,000 miles per month. This high use rate for the LNG trucks indicates improving reliability.

The LNG trucks were used nearly as much as the diesel trucks in the same operation, with average monthly mileage 9% lower during the evaluation period. This is much better than previous results from other LNG truck operations, in which other LNG trucks typically were used 25% less than diesel trucks.

The energy equivalent fuel economy was 10.5% lower for the prototype LNG trucks compared with the newest diesel trucks. This is much better than results from previous studies of spark-ignition, heavy-duty natural gas trucks, which had equivalent fuel economies 27%–37% lower than diesel trucks over the same duty cycle.

Maintenance costs for the prototype LNG trucks were 2.3 times higher per mile than for the newest commercial diesel trucks, as shown in Figure 2. This was expected because the LNG engine technology is in the prototype stage. For CWI, one objective of this project was to study ways to enhance reliability of this new potential product. The components and systems with maintenance issues were the LNG pump, high-pressure diesel fuel system, and High-Pressure Direct Injection (HPDI) injectors. CWI continues to plan better integration strategies for these and other related components.

New York City Transit (NYCT) has been investigating clean fuel technologies for several years. AVTA is continuing to work with the fleet to evaluate the next-generation Orion VII/BAE hybrid bus. NYCT has made a commitment to the

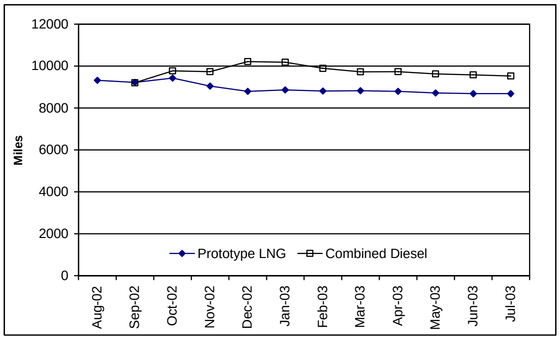

Figure 2. Running monthly average mileage per LNG truck.

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. A selection of each order are the subject of this evaluation In addition to the hybrid buses, NYCT is also receiving Orion VII CNG buses, an example of which is shown in Figure 3. These natural gas buses will be included in the evaluation. In FY 2004, AVTA continued the data collection on the fleet. The interim report on early results will be completed in the next year.

Figure 3. NYCT operates a fleet of Orion VII transit buses with BAE SYSTEMS' HybriDriveTM Propulsion.

Ebus hybrid electric shuttle bus evaluations: Ebus manufactures and assembles 22-foot bus and trolley platforms, powered by a series hybrid electric powertrain using a Capstone microturbine as a powerplant. The Ebus series hybrid system is charge sustaining, meaning that the batteries will have power as long as the microturbine has fuel, which can be either diesel or propane. The bus design incorporates regenerative braking, which provides additional energy to recharge the NiCd battery pack. When the bus is not in operation, it can be plugged into a fast charging station to "top off" the batteries in approximately 1 hour. In FY 2004, AVTA began working with two fleets implementing this hybrid electric bus technology from Ebus:

Indianapolis Public Transportation Corporation (IndyGo) is using five Ebus hybrid electric buses to serve the Blue Line, which is a 4.3-mile route to cultural and commercial attractions in downtown Indianapolis. An example of the IndyGo hybrid shuttle bus is shown in Figure 4. The microturbines on these buses are being fueled with diesel. National Renewable Energy Laboratory's (NREL's) evaluation of the buses began in mid-2004, and will continue for approximately six months. During the FY 2004, NREL established a relationship with IndyGo personnel by conducting a visit to the fleet, and began collecting performance and operational data. A 2-page fact sheet and a final report will be produced in FY 2005.

Figure 4. IndyGo hybrid shuttle bus.

Knoxville Area Transit (KAT) is using four Ebus hybrid electric trolleys on its new Red Line Trolley Route, shown in Figure 5. Designed to reduce downtown congestion, the Red Line is intended primarily for downtown employees who park remotely and use public transit to get to work. The microturbines on these buses are being fueled with propane. NREL'S evaluation of the buses began in early 2004, and will continue for approximately six months. During 2004, NREL established a relationship with KAT personnel by conducting a visit to the fleet, and began collecting performance and operational data. A 2-page fact sheet and a final report will be produced in FY 2005.

Figure 5. KAT Ebus hybrid trolley.

King County Metro in Seattle, Washington (KC Metro) has begun replacing a large fleet of older technology buses with New Flyer articulated (60-ft) buses using the GM-Allison parallel hybrid system, an example of which is shown in Figure 6. At 235 buses, this is the large order of these buses to date. AVTA is working with the fleet 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 the closest "apples-to-apples" comparison that AVTA has conducted. In 2004, AVTA kicked-off the data collection with a fleet visit. The evaluation will continue into the next two years, with a 2-page fact sheet and interim report completed for 2005.

Figure 6. KC Metro operates 213 New Flyer articulated buses with the GM-Allison hybrid system.

Idle Reduction Technology Demonstration

The common practice of idling truck engines to provide auxiliary power for drivers wastes millions of gallons of fuel and produces tons of pollutants each year. In FY 2002, AVTA established a new project to investigate technologies that have the most potential to reduce excess idling of heavy truck engines. In FY 2003, a demonstration plan was developed to gather in-use information on the performance of available idle reduction technologies. In FY 2004, three projects were awarded to characterize the cost, fuel savings, payback, and user impressions of various systems and techniques. These project teams consist of a truck fleet, truck manufacturer, and idle reduction technology manufacturer. The three awards are described as follows:

Schneider National Inc., in a project titled "Cab Heating and Cooling," is demonstrating the Webasto Cab Cooler, which uses a phase change cooling storage technology to cool the truck cab when the engine is off. Nineteen Freightliner trucks are equipped with the Cab Cooler, and 100 trucks are equipped with a self-contained diesel-fueled air heater to demonstrate engine-off cab heating.

Caterpillar Inc., in a project titled "Demonstration of the New MorElectric Technology as an Idle Reduction Solution," is applying electrically driven accessories for cab comfort during engine-off stops and for reducing fuel consumption during on-highway operation. International Truck equipped five new trucks with the technology for operation by Cox Transfer.

The third award, to Espar Heater Systems, for a project titled "Idle Reduction Technology Demonstration and Information Dissemination," is demonstrating a combined heating and cooling system. Twenty International trucks are equipped with the system for operation by Wal-Mart Transportation, LLC. Espar engine pre-heaters also are installed to reduce idling done to avoid cold-start problems.

Early results from the Schneider project indicate some reduction in idle times. These results and the status of all the idle reduction technology demonstrations are summarized in a status report produced in FY 2004. The report also identifies potential next steps based on early results.

Short Term Technology Reports

The AVTA team completed several short-term reports during FY 2004.

Annual Market Overview Update. Since FY 2000, AVTA has produced an annual overview of the transportation market. The document, which covers energy use, vehicle sales, emissions, potential partners, advanced technology vehicle availability, and other factors, offers a "snapshot" of current vehicle technologies and trends. DOE program managers use this document to plan test and evaluation activities that focus resources where they will have the greatest impact. In FY 2004, AVTA produced an update of this document to include the most recent technology advancements in transportation.

Electric Propulsion in Transit Study. The AVTA team conducted a study on recent experiences with electric propulsion buses. Using a focus group made up of professionals from transit agencies across the country that have experience with electric propulsion vehicles, the team compiled information for other transit agencies interested in the technology. The results of the study, which was conducted in 2003, was published in early 2004.

Results

Results from AVTA fleet evaluations have been 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

1. Eudy, L. and M. Gifford, "Challenges and Experiences with Electric Propulsion Transit Buses in the United States," DOE/GO-102003-1791, National Renewable Energy Laboratory, Golden, CO, November 2003.
2. Chandler, K. and K. Proc, "Norcal Prototype LNG Truck Fleet – Final Result," DOE/GO-102004-1920, National Renewable Energy Laboratory, Golden, CO, July 2004.
3. Eudy, L. and J. Zuboy, "Overview of Advanced Technology Transportation, 2004 Update," DOE/GO-102004-1849, National Renewable Energy Laboratory, Golden, CO, July 2004.

VI. LIGHT VEHICLE ANCILLARY SYSTEMS

A. Light Vehicle Ancillary Load Reduction

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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; and
- Investigate turning low grade waste heat into useful energy.

Approach

- Develop a validated and industry accepted measurement tool to assess human comfort;
- Develop a passenger compartment cooling system using waste heat as an energy source; and
- With industry cooperation, develop and test ancillary load solutions to reduce fuel use while maintaining occupant comfort.

Accomplishments

- Completed fabrication of the thermal manikin (ADAM) and used the improved human thermal physiological model to simulate skin temperatures within approximately +3/- 1°C of literature;
- Designed and developed a standing wave thermoacoustic device that is capable of using waste heat to generate cooling; and
- A combination of modeling and experimental testing showed a 2.8 % - 4.5% reduction in automotive air-conditioning fuel use by improving thermal comfort with a ventilated seat prototype. The Vehicle Climate Control Laboratory (VCCL) was developed to enable this and future testing.

Future Directions

- Investigate thermal load reduction techniques as part of the vehicle integration team for the industry/government/SAE I-MAC Cooperative Research Project;
- Investigate and research new heat exchangers and regenerators for a traveling wave thermoacoustic system to be placed in a SUV or light truck;
- Simulate all climate control and ancillary systems to determine their impacts on fuel economy, tailpipe emissions, and the occupants' response to the thermal environment;
- Determine potential for further reducing A/C fuel use by optimizing ventilated seat design with an industry partner using the VCCL and ADAM; and

- Demonstrate the manikin to original equipment manufacturers (OEMs) and suppliers through collaborative projects.

Introduction

Fuel used for vehicle climate control affects our nation's energy security significantly by deceasing the fuel economy of the 222 million light-duty conventional vehicles in the United States. A/C can also reduce the fuel economy of advanced vehicles by as much as 35%. To address these issues, the National Renewable Energy Laboratory (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 into 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 a validated and industry accepted measurement tool to assess human comfort;
- Develop a passenger compartment cooling system using waste heat as an energy source; and
- Develop and test ancillary load solutions to reduce fuel use while maintaining occupant comfort.

Results

Demonstrate the manikin/physiological model can predict human skin temperatures within ± 0.5°C. In order for automotive OEMs to reduce the size and fuel use of air conditioning (A/C) systems, they need to be able to show comfort will be enhanced or at the very least maintained. A barrier to the adoption of reduced fuel use A/C systems is that OEMs and suppliers do not have the measurement tools to assess human thermal comfort in a transient non-homogeneous environment. To overcome this barrier, NREL has developed a portfolio of thermal comfort tools including an ADvanced Automotive Manikin (ADAM), Human Thermal Physiological Model, and Human Thermal Comfort Empirical Model, as demonstrated in Figure 1.

NREL completed fabrication of the thermal manikin (ADAM) with the installation of the breathing, battery charging, and communication systems. The manikin is now fully functional and is the most advanced thermal comfort manikin in the world. The ability to simulate vasoconstriction/dilation of the blood vessels was added to the Human Thermal Physiological Model. In addition, the Human Thermal Comfort Empirical model was integrated into the physiological model. Now the local and global sensation and comfort can be predicted using the model skin temperatures.

Calibration testing of NREL's thermal manikin was conducted in a Manikin Climate Control Chamber and validation testing of the manikin/model was initiated. Initial results indicate the manikin with physiological model control yields human-like skin temperature distribution. Compared to data from literature, the skin temperatures were within approximately +3/- 1°C. Although this is greater than our goal, the variability in testing with nude

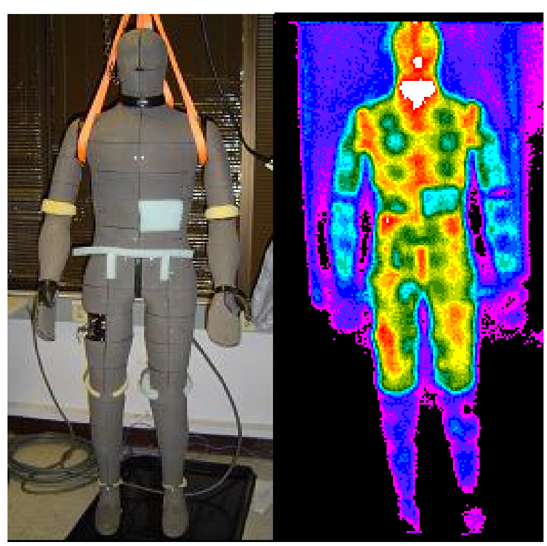

Figure 1. Photo and IR image of ADAM during validation testing.

manikins and measuring skin temperatures on human subjects means our original goal of +/-0.5°C may have been too aggressive.

Understanding thermal comfort is critical to our efforts to reduce the national fuel used for climate control. One way to reduce climate control fuel use is to use smaller A/C systems in vehicles. These systems have to maintain or enhance occupant comfort; otherwise auto manufactures will not implement them. Using the thermal comfort tools we have developed, we can help automobile manufactures and suppliers develop more fuel-efficient A/C systems to enhance our nation's energy security.

Demonstrate a heat generated cooling system with a COP of 0.45. 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 are only about 30% efficient at best. With that degree of thermal efficiency, an engine releases 70% of its fuel energy as waste heat through the coolant, exhaust gases, and engine compartment warm-up. During much of a typical drive cycle, the engine efficiency is lower than the maximum. As efficiency decreases, the amount of waste heat increases, representing a larger potential energy source.

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. 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, however, is that 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 FY 2004, 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, shown in Figure 2, is modular and allows for different frequencies, 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% with an engine coefficient of performance (COP) of 0.1 and a heat pump COP of greater than 1.

The VALR team completed testing of the standing wave thermoacoustic engine and heat pump during FY 2005. 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

Figure 2. Standing Wave Thermoacoustic Refrigerator.

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 preludes its use. In the future, NREL researchers are concentrating their efforts on developing a smaller traveling wave thermoacoustic system.

Determine the potential reduction in fuel use for mobile air-conditioning due to efficient delivery of climate control: NREL has developed a Vehicle Climate Control Laboratory (VCCL) to allow rapid and repeatable evaluation of occupant thermal comfort response to advanced climate control systems in a controlled, asymmetrical, thermal environment; enabling the estimation of impacts on thermal comfort and fuel economy. The major components of the VCCL test cell are shown in Figure 3.

Using a combination of experimental testing and modeling, researchers quantified improved thermal comfort and potential fuel savings due to ventilated seats. The ventilated seat decreased steady-state seat contact temperature by 3.5°C ± 0.9°C and increased back thermal comfort. A low mass mesh back seat was also shown to reduce back temperature by approximately 4°C. Subjective jury data has been used to show trends. These trends show that the cooling capacity of the air-conditioning system can be reduced by 4% while maintaining thermal comfort through the use of a ventilated seat. Using ADVISOR© software, the reduction in A/C cooling capacity can be translated into a reduction of compact car A/C fuel use by 2.8% on an EPA highway cycle and 4.5% on an EPA city cycle. While this reduction is modest for an individual car, the potential fuel savings is significant on a national level.

This project demonstrates the potential of ventilated seats for improving delivery of conditioned air, increasing thermal comfort, and reducing air-conditioning loads. Optimizing ventilated seat design and integrating these seats with other advanced delivery methods shows promise to further reduce national A/C fuel use.

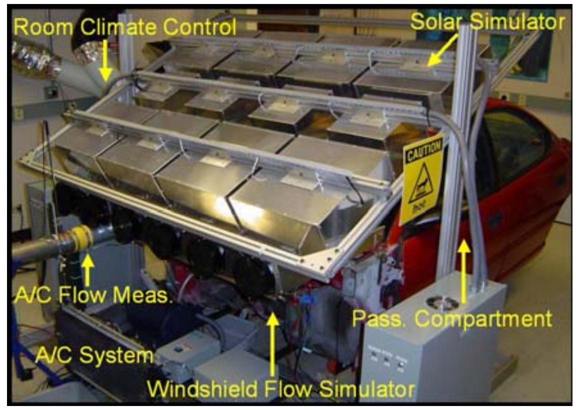

Figure 3. Vehicle Climate Control Laboratory.

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 and 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.

Publications

1. Farrington, R; J. Rugh, and D. Bharathan, "Use of a Thermal Manikin to Evaluate Human Thermoregulatory Responses in Transient, Non-Uniform, Thermal Environments," Proceedings of the 2004 International Conference on Environmental Systems, Paper # 2004-01-2345, Colorado Springs, CO, July 19-22, 2004, Society of Automotive Engineers, 2004.
2. Rugh, J. and V. Malaney, "Comparison of Indoor Vehicle Thermal Soak Tests to Outdoor Tests," Proceedings of 2004 SAE Congress, Paper # 2004-01-1376, Society of Automotive Engineers, Detroit, MI, 2004.
3. Rugh, J., V. Hovland, and S. Andersen, "Significant Fuel Savings and Emission Reductions by Improving Vehicle Air Conditioning," Mobile Air Conditioning Summit, Washington, D.C., April 14-15, 2004.

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