Advanced Vehicle Technology Analysis and Evaluation Activities

2003 Annual Progress Report

FreedomCAR FUEL Partnership

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

freedomCAR & vehicle technologies program

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

U.S. Department of Energy
FreedomCAR & Vehicle Technologies Program
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FY 2003

Annual Progress Report for Advanced Vehicle Technology Analysis and Evaluation Activities

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

Lee Slezak, Technology Manager

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FOREWORD

On behalf of the U.S. Department of Energy's (DOE's) FreedomCAR and Vehicle Technologies (FCVT) Program, I am pleased to submit the Annual Progress Report for fiscal year 2003 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 automotive powertrain components and subsystems in a vehicle systems context. This includes improving the fuel economy of representative vehicle platforms while meeting future emissions regulations.

Objectives

The objectives of the AVTAE team activities are to provide performance targets and data that will enable the FCVT technology research and development (R&D) teams to focus research on areas that will maximize the potential for fuel efficiency improvements and emissions reduction. AVTAE also reviews and evaluates the integration of components developed by the FCVT technology R&D teams. The main challenge is to predict how individual technology components will perform in a vehicle environment through laboratory testing and computer simulation models.

As illustrated in Figure 1, AVTAE simulates and models advanced technologies, evaluates and recommends updates to the technical targets for technology R&D, and evaluates the hardware and validates the technologies for representative vehicle platforms in a simulated system environment and/or actual vehicle.

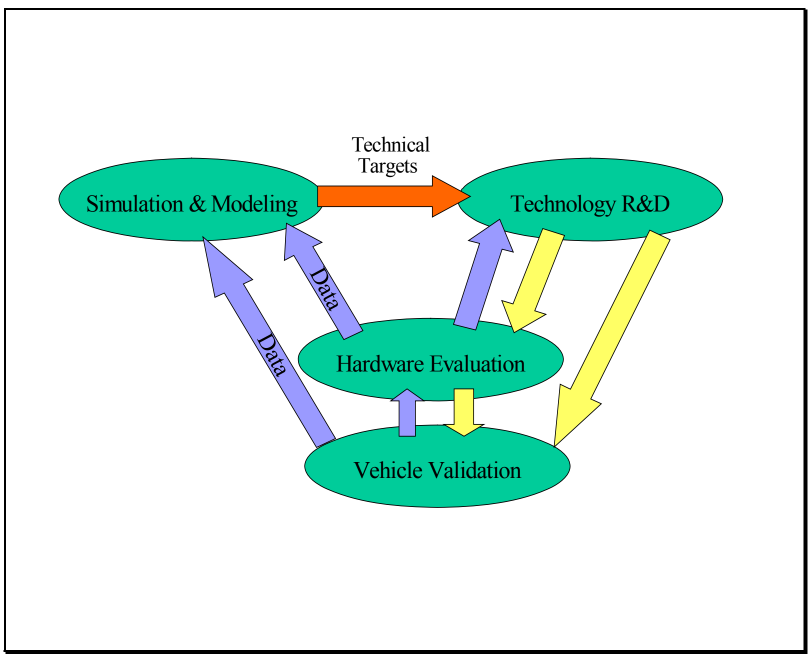

Figure 1. FCVT Technology Roadmap

FY 2003 AVTAE Activities

AVTAE provides an overarching vehicle systems perspective to the technology R&D activities of DOE's FCVT and Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Programs. It uses analytical and empirical tools to model and simulate potential vehicle systems, validate component performance in a systems context, 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 FCVT and HFCIT Programs is required for both analysis and testing. Analytical results of this sub-program are used to estimate national benefits and/or impacts of DOE-sponsored technology development, as illustrated in Figure 2.

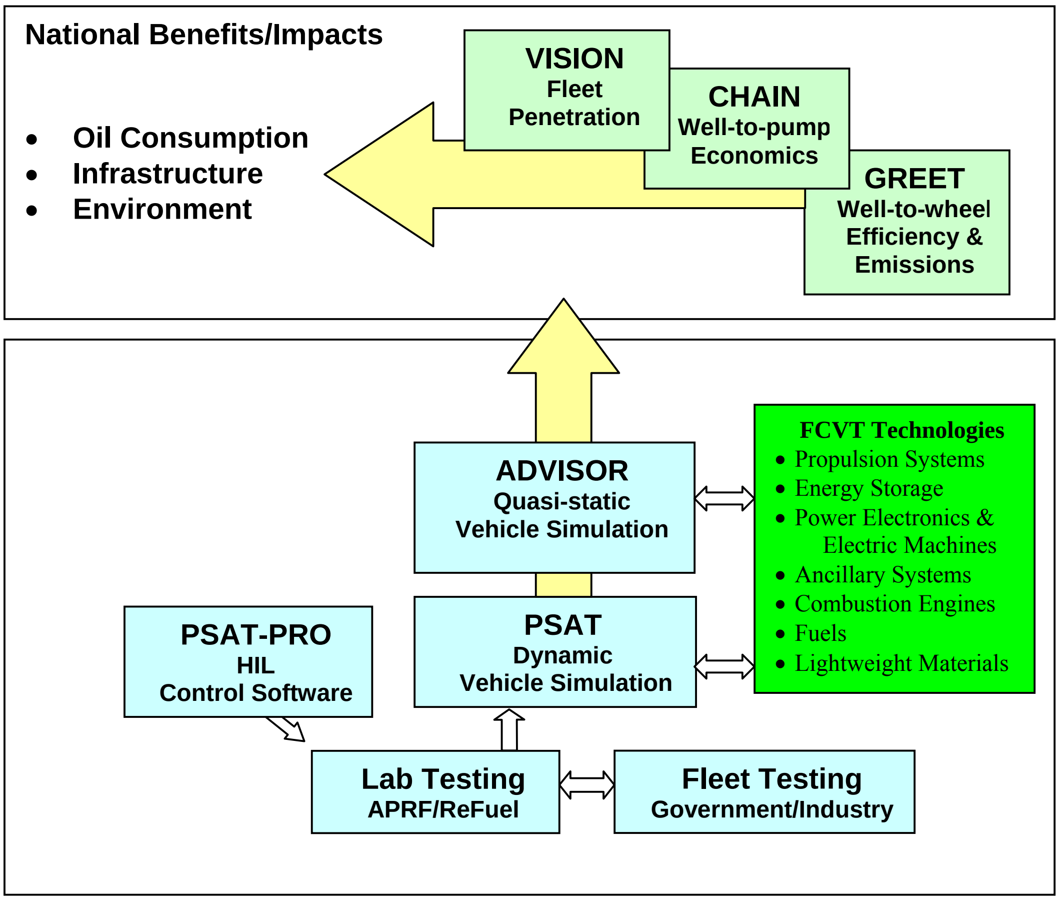

Figure 2. AVTAE activities providing estimates of national benefits and impacts of advanced technologies

Three main activity areas are described in this report:

I. Modeling and Simulation
- Development and validation of models and simulation programs to predict the fuel economy of and emissions from advanced vehicles; and
- Development of component and subsystem performance targets for a range of vehicle platforms.

II. Technology Benchmarking and Validation
- Benchmarking of commercially available vehicles and vehicle components to ensure that the FCVT technology targets represent significant advances over commercially available technologies; and
- Validation of advanced propulsion subsystem and auxiliary subsystem technologies, without building expensive test vehicles.

III. Advanced Vehicle Testing
- Track and field testing of advanced vehicles to validate models, collect data for model enhancement, and increase the awareness, deployment and use of hydrogen-fueled internal combustion engines, electric and hybrid vehicles (light, medium duty), and airport ground support equipment.

Major projects conducted by the national laboratories in support of these areas in FY 2003 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 Activity Manager 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 fuels and 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 2004, field and laboratory testing will be integrated with modeling/simulation tools. Test procedures will be finalized and models will be validated and enhanced to ensure their usefulness. In FY 2004 and 2005, 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. The development of vehicle simulation models will be essentially completed and commercialized to facilitate wider use in industry and universities.

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 for them, are scheduled for FY 2008.

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

Lee A. Slezak

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I. MODELING AND SIMULATION

Overview

Over the last decade, the U.S. Department of Energy's (DOE's) FreedomCAR & Vehicle Technologies (FCVT) Program has been evaluating the significance and relevance of its transportation technology development programs. Although many FCVT technology development programs and activities are component- or subsystem-focused (common in industry R&D), an overall systems perspective is essential for maintaining the context of these developments with the goal of reducing the nation's need for imported oil.

There are significant opportunities for reducing the fuel consumption of light- and heavy-duty vehicles through a systems approach. In addition, estimating the potential impact on the national fleet of vehicles and on the reduction in imported oil can help gauge the importance of new technology developments.

Advanced Vehicle Technology Analysis and Evaluation (AVTAE) activities employ digital modeling and simulation to perform trade-offs of alternate designs or builds of components (such as electric motors, batteries, or engines) in various vehicle system configurations. Simulated testing under different operating conditions and drive cycles can be used to optimize the system configuration. There is no need for building costly, time-consuming prototype vehicles.

Modeling and simulation can allow DOE to set targets and evaluate progress in a flexible environment applicable to a large number of vehicle platforms. DOE national laboratories have been developing the tools and expertise to address this need. A significant benefit of these tools is that it is possible to evaluate components that have not yet been built, or to visualize subsystems and vehicles that might result from introducing alternative technology development programs.

The national laboratories involved in this activity are the National Renewable Energy Laboratory (NREL), located in Golden, Colorado, the Argonne National Laboratory (ANL), located in Argonne, Illinois, and Oak Ridge National Laboratory (ORNL), located in Knoxville, Tennessee. The three laboratories have developed expertise in specific areas that together provide the necessary tools, data and analyses.

The laboratory scientists work with the automotive industry, including component and system suppliers, to identify unique opportunities for fuel consumption improvements enabled by vehicle systems.

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 the resulting characteristics each second (using component map data). These values are summed to produce overall results for a driving cycle, commonly referred to as backward-facing simulation. This architecture is suitable for quick evaluation of multiple scenarios. Capabilities include component selection and sizing (conventional, hybrid, and hybrid fuel cell vehicles), energy management strategies, optimization, and target development.

NREL has developed a three-pronged approach to help DOE reduce the fuel consumption of future vehicles:

1. Develop and apply tools, methods, and processes to create and evaluate technical targets for DOE's technology development programs.

2. Explore opportunities for DOE-developed technologies to enter the market in various vehicle configurations, once the technologies and targets are successfully modeled in a vehicle context. Apply optimization to explore new areas of technology development that could significantly improve the fuel economy of vehicles.

3. Develop and apply alternative integrated modeling methods to help remove technical barriers of new technology, and enable and accelerate the introduction of new fuel-efficient technologies in the marketplace.

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

GCTool was developed at 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.

At ORNL, highly accurate engine emission measurements are used to develop empirical models of aftertreatment methods. ORNL is also developing models for projecting cost benefits and/or penalties of advanced technologies at various production levels.

Major activities in modeling and simulation are described in the following sections. For further information, please contact the DOE Technology Manager named with each activity.

1.1. Technical Target Development

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Objective

- Analyze the impact of component and system technical targets on national oil use, for fuel cell hybrids competing with conventional vehicle technologies.

Approach

- Define the light vehicle market in terms of U.S. Environmental Protection Agency (EPA) vehicle size classes;
- Program the Technical Targets Tool (T3) in Matrix Laboratory (MATLAB) and create easy-to-use Graphical User Interfaces (GUIs) that allow the user to easily modify the technical targets;
- Find vehicle characteristics, including fuel economy, cost, and performance, by simulating new technology vehicles (NTVs) based on the technical targets;
- Use the U.S. Department of Energy's (DOE's) Quality Metrics model to determine the penetration of the competing vehicle types and classes based on the vehicle characteristics;
- Find the best combination of vehicle efficiency and market penetration to maximize reduction in petroleum consumption; and
- Compare oil use of a strictly conventional vehicle market with that of a market penetrated by new technology vehicles.

Accomplishments

- Updated the market characterization study that defined the current performance and physical characteristics of each EPA vehicle size class;
- Investigated a more detailed method of determining if components fit in a vehicle; and
- Completed a version of the T3 in MATLAB:
  - Includes graphical user interfaces for program input and output,
  - Includes market characterization data and national oil use model,
  - Stores and tracks Research and Development (R&D) Plan technical targets,
  - Links to (Advanced Vehicle Simulator (ADVISOR) for vehicle systems analysis, and
  - Integrates design of experiments for quantifying sensitivities to technical target values.

Future Directions

- Compile simplified vehicle model to reduce computation times;
- Focus on technical targets trend with time (required for DOE's Quality Metrics Model);
- Couple market penetration and vehicle characteristics to optimize for minimum oil use;
- Link DOE's Quality Metrics Model for more accurate penetration estimates; and
- Revise the GUI to enhance functionality.

Introduction

In FY 2001, the National Renewable Energy Laboratory (NREL) started working with the auto industry on 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 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) that 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 starts by finding average vehicle characteristics for EPA's vehicle classes. Next, the non-powertrain attributes of each class, such as glider mass and drag coefficient, are used with new technology vehicle powertrains. All the different component size combinations for each powertrain are analyzed to find other vehicle characteristics, such as fuel economy, cost, and performance. These characteristics are then used to find out how well the vehicle would penetrate the market. Finally, the best combination of fuel economy, market penetration, and vehicle miles traveled is found to gauge the largest projected reduction in oil use resulting from the subject technology.

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 version of the tool, using graphical interface development software called MATLAB. The first MATLAB version has been tested and completed. It includes GUIs for modifying targets, viewing and changing assumptions, determining target sensitivities and viewing results. Figure 1-1 shows a typical GUI.

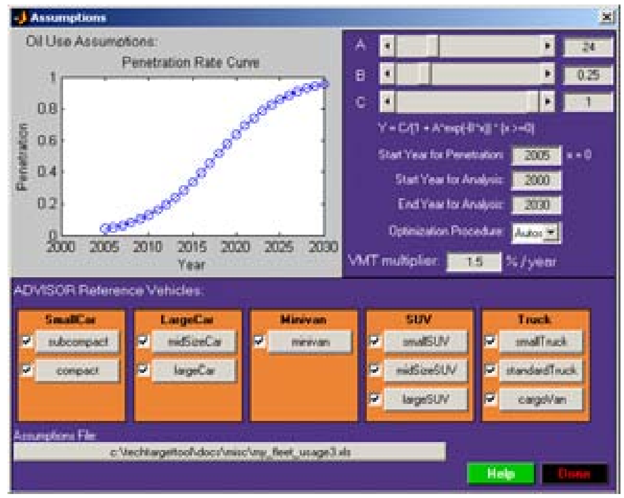

Figure 1-1. The graphical user interface for viewing and modifying assumptions

Conclusions

In FY 2003, NREL successfully completed the first MATLAB-based version of a software tool that cascades the potential impact of R&D vehicle component-level goals to future oil use in the United States. Work in FY 2004 will focus on improving the market characterization and linking to DOE's Quality Metrics model for a more accurate analysis. The improved version of T3 will consider vehicle characteristics such as fuel economy, cost, and performance, as trade-offs, rather than constraints, for finding the greatest reduction of petroleum consumption over time. It will explore the unique advantages of new technology vehicles that could help them get into the market place.

1.2. Advanced Applications of Digital Functional Vehicle (DFV) Process

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Objectives

- Investigate the technical barriers for new fuel-efficient automotive technologies (HEVs, fuel cells, and lightweight designs) through the application of advanced Computer-Aided Engineering (CAE) modeling techniques and innovative design processes;
- Develop processes and systems to analyze automotive energy savings and emissions, using math-based software that integrates CAE methods such as finite element modeling, probabilistic designs, optimization, design of experiments, and modeling of system dynamics.;
- Work directly with industry partners to include improved fuel economy and emissions considerations early in the design process of future production components and vehicles; and
- Demonstrate design techniques that account for manufacturing, material, and load variations to improve fuel efficiency and achieve six-sigma quality levels.

Approach

- Work with industry and software partners to identify key technical barriers to advanced automotive applications with energy savings potential;
- Work with technical contacts within industry to fully define the problem, specify the necessary engineering tools, and gather the necessary data to solve and validate the problem; and
- Develop integrated system of software tools and provide solutions to industry partner. Report results to industry and the U.S. Department of Energy (DOE), and transfer process to industry.

Accomplishments

- Integrated modeling methods were incorporated into other DOE activities for energy storage, fuel cells, heavy hybrid vehicle propulsion systems, and advanced power electronics;
- Published more than 20 conference papers, presentations, and trade articles; and
- Demonstrated that the integration of advanced CAE tools early in the design process can point to new innovative solutions while reducing development time and cost.

Future Directions

- Further quantify the energy savings associated with the application of integrated modeling methods;
- Identify new projects with automobile original equipment manufacturers (OEMs) to develop and apply the process further with even stronger ties to the impact on energy consumption;
- Investigate potential application of Digital Functional Vehicle (DFV) processes to remove technical barriers in fuel cell industry; and
- Formulate results in terms of energy sensitivity.

Introduction

The National Renewable Energy Laboratory (NREL) started working in 1998 with the U.S. auto industry, suppliers, and major engineering software companies to more fully realize the vision of the DFV process. The DFV process takes an integrated systems approach to analyze and make trade-offs of advanced vehicle concepts and designs, while pushing both energy efficiency and emissions to a higher level of visibility. This is accomplished through a seamless process involving an exchange of information between the engineering software tools already used by the auto industry and suppliers, and putting this integration to the test on real applications within industry.

This project was started with NREL, Parametric Technologies Corporation (PTC), and a few select suppliers in 1998. In FY 2000, Mechanical Dynamics Inc. (MDI) and new original equipment manufacturer (OEM) partners became active participants in the project. The process was applied to the Ford Th!nk neighborhood electric vehicle to realize savings in time, mass, and cost. In FY 2001, five separate projects were started and completed for the OEMs. All of these projects included using parametric models that are very flexible and are suitable for multi-disciplinary (such as structural and thermal, or thermal and fluids) and multi-platform analysis. In FY 2003, work continued with Advanced Engineering Solutions and focused on disseminating the DFV process to industry. New industry partnerships are being stressed to apply DFV to address key technical barriers in fuel cells and other advanced vehicle technologies.

Approach

The first step is to work directly with automotive industry partners to identify key technical barriers to fuel-efficient technologies. Next, the problem needs to be fully defined, appropriate engineering methods and processes identified, and the necessary data collected. This often includes Computer-Aided Drawing (CAD) designs and experimental data.

Integrated CAE methods are then developed for the analysis. The specific solution and design processes are reported to DOE and the industry partner. The models utilize automotive industry supported software tools, such as ANSYS, ADAMS, Saber, Fluent, iSIGHT, etc., integrated with modern design methods such as optimization techniques, design for six-sigma, and robust or probabilistic design methods. Using industry-supported software leverages the significant experience and data already existing in these tools, while focusing on the energy-saving aspects of design decisions.

Probabilistic modeling of material, loading and manufacturing variations can result in lightweight designs (for fuel efficiency) that also achieve the industry's desired quality level (i.e., six-sigma). Figure 1-2 provides an example of these parameter distributions for a battery thermal management system. Transfer of these processes to industry is a key goal of the project. This is reflected in the number of publications and presentations that have been co-authored with industry partners.

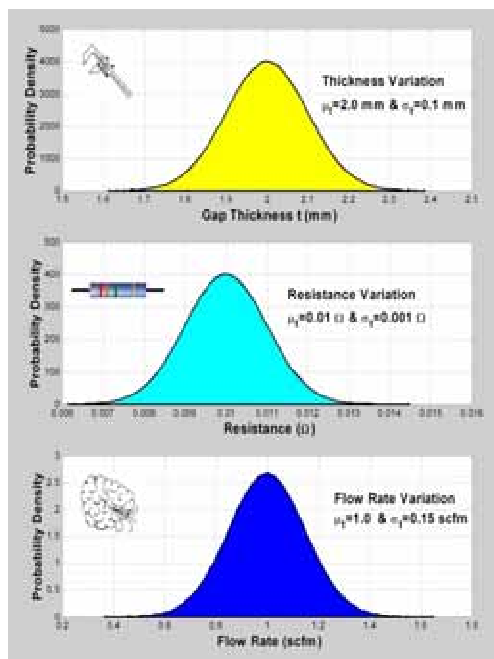

Figure 1-2. Example of Integrated DFV Process applied to Battery Thermal Management

Results

The DFV project has developed the capability to integrate existing analysis codes and automate design processes very quickly, thus allowing the selection of key design parameters that are most influential to the attributes of new fuel-efficient automotive technologies.
Figure 1-3 highlights a range of applications for these capabilities. The use of sensitivity and optimization algorithms examines the feasibility and allows the derivation of the best choice of the design parameters. Key results from FY 2003 are:

- Demonstrated and published the application of six-sigma design techniques to fuel cell industry in partnership with Plug Power;
- Conducted and published an optimization of pin-fin heat exchanger for vehicle power electronics cooling with Ballard Power Systems;
- Developed and published methodology for applying six-sigma probabilistic design techniques to battery thermal management in conjunction with Ford Motor Company and FreedomCAR Energy Storage Technical Team; and
- Demonstrated and published the application of Advanced Engineering Environment for packaging fuel cell components within a vehicle system.

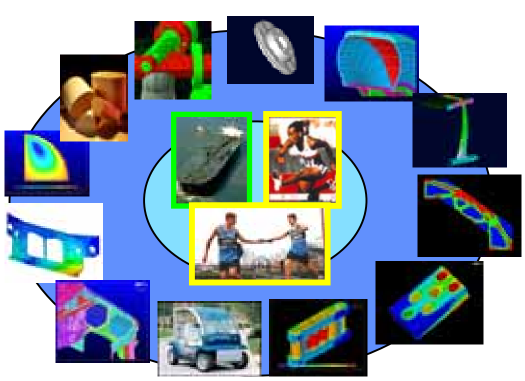

Figure 1-3. Digital Functional Vehicle Applications

Conclusions

In FY 2003, NREL was able to successfully partner with industry to focus the development and application of Integrated CAE Modeling tools at key vehicle technologies including: Energy Storage Systems, Fuel Cells, Advanced Heavy Hybrid Propulsion Systems, and Advanced Power Electronics. These applications have demonstrated how the integration of advanced CAE tools early in the design process can point to new innovative solutions and reduce development time and cost.

Publications / Presentations

1. "Design Space Exploration with Behavioral Modeling" 2003 PTC/User World Event, Orlando, FL, June 2003. (A. Vlahinos of AES and K. Kelly of NREL).

2. "Effect of Material And Manufacturing Variations on Membrane Electrode Assembly Pressure Distribution" ASME paper # FUELCELL2003-1707 First International Conference on Fuel Cell Science, Engineering and Technology, Rochester, NY, April 23, 2003. (A. Vlahinos of AES, K. Kelly of NREL, J. D'Aleo of Plug Power and J. Stathopoulos of Plug Power).

3. "Innovative Thermal Management of Fuel Cell Power Electronics" ASME paper # FUELCELL2003-1745 First International Conference on Fuel Cell Science, Engineering and Technology, Rochester, NY, April 23, 2003. (K. Kelly of NREL, A. Vlahinos of AES, P. Rodriguez of Ballard Power Systems and D. Bharathan of NREL).

4. "An Engineering System for Automated Design and Optimization of Fuel Cell Powered Vehicles" ASME paper # FUELCELL2003, First International Conference on Fuel Cell Science, Engineering and Technology, Rochester, NY, April 23, 2003. (G. Willis and R. Weller of Vulcanworks, K. Wipke of NREL).

5. "Robust Design of a Catalytic Converter with Material and Manufacturing Variations" SAE paper # 2002-01-2888, 2002 SAE Powertrain and Fluid Systems Conference San Diego, CA, October 22, 2002. (A. Vlahinos of AES, D. Suryatama, M. Ullahkhan, J. TenBrink and R. Baker of DaimlerChrysler Corporation).

1.3. Cost and Fuel Economy Trade-offs for Fuel Cell Hybrid Vehicles

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Objectives

- Develop specifications for an energy storage system for a fuel cell hybrid vehicle;
- Demonstrate multi-objective optimization methods applied to vehicle systems analysis;
- Assess the trade-offs between system cost, volume, and fuel economy for several fuel cell hybrid vehicle design scenarios; and
- Provide vehicle systems analysis support to the energy storage team.

Approach

- Identify potential roles for the energy storage system in a fuel cell hybrid vehicle;
- Quantify power and energy requirements of energy storage system for each role;
- Define energy storage system characteristics for scenarios with several combinations of roles;
- Apply optimization tools to find a solution that balances the cost, volume, and fuel economy trade-offs for fuel cell hybrid vehicles with energy storage; and
- Present and publish study results.

Accomplishments

- Provided a fuel cell hybrid vehicle design that optimizes both cost and fuel economy;
- Enhanced the knowledge base regarding the potential roles and benefits of energy storage for fuel cell hybrid vehicles; and
- Laid the groundwork to develop optimum energy storage specifications for a fuel cell hybrid vehicle.

Future Directions

- Quantify the sensitivity of optimal vehicle design attributes to fuel cell efficiency characteristics;
- Provide a complete set of energy storage system performance specifications specifically for fuel cell hybrid vehicles; and
- Apply optimization methods and design of experiments to understand the relative influences of component characteristics and energy management strategy parameters on fuel cell hybrid vehicles.

Introduction

The energy storage system is a critical component of a hybrid electric vehicle. Past energy storage system research focused on batteries to satisfy the requirements of battery/combustion engine hybrid vehicles. With the current emphasis toward fuel cell technology, there evolved the need to define energy storage systems that meet the specific needs of fuel cell hybrid vehicles. This project develops a better understanding of the energy storage requirements for fuel cell hybrid vehicles, using vehicle simulation and optimization tools.

The energy storage system can potentially have multiple roles in a fuel cell hybrid vehicle, including capturing regenerative braking energy, assisting traction power, and providing auxiliary and traction power during fuel cell system start-up and shut-down. It is important to find characteristics of the energy storage system that complement the fuel cell by improving its performance and fuel economy.

Industry representatives from FreedomCAR Energy Storage, Systems Engineering and Analysis, Hydrogen Storage, and Fuel Cells technical teams reviewed the input assumptions and directed these analyses to explore areas of interest. Both the National Renewable Energy Laboratory (NREL) and Argonne National Laboratory (ANL) provided systems analysis support. The goal of the analyses was to provide a set of battery characteristics that are most suitable for a fuel cell hybrid vehicle system. Specifically, it is important to quantify the desired power, energy and transient operating capabilities that provide the best complete system design.

Approach

The energy storage system requirements for fuel cell hybrid vehicles can be defined by first determining the specific benefits that the energy storage system may provide. Figure 1-4 summarizes some of the potential beneficial roles the energy storage system may provide.

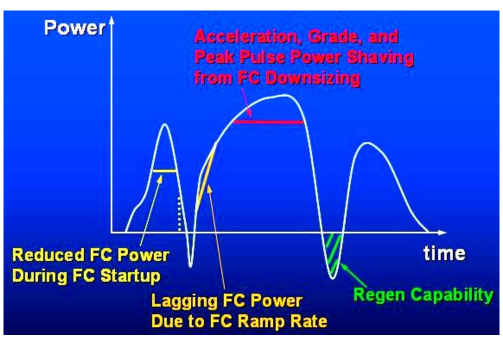

Figure 1-4. Potential beneficial roles of energy storage in a fuel cell hybrid vehicle

Vehicle system simulation tools were used to predict the traction power profile for a set of vehicle and drive cycle assumptions. The power and energy requirements for each of the specific roles were quantified for the entire driving profile. These requirements were then compared and combined to estimate the energy storage system requirements as a function of other vehicle system assumptions for fuel cell size, fuel cell operating characteristics, and energy management strategy choices. Since the ranges of possible variations in the system are quite extensive, the parametric design of experiments analysis outlined above was extended with multi-objective optimization to highlight the best solution.

Results

In order to size a vehicle's primary and secondary power sources, in this case the fuel cell power plant and electrochemical energy storage unit, the roles of the secondary power system should first be established. The following roles have been considered for the electrochemical energy storage system:

- Traction power during fuel cell start-up;
- Power-assist during drive cycles;
- Regenerative braking energy recapture;
- Gradeability performance;
- Acceleration performance;
- Electrical accessory loads; and
- Fuel cell startup and shutdown.

Each role has an associated energy and power requirement. As an example, the energy storage system power and energy required to satisfy the traction demands over the US06 cycle for a mid-size car and a mid-size sport-utility vehicle (SUV) for the range of fuel cell sizes are shown in Figures 1-5 and 1-6, respectively. The energy requirement grows exponentially as the fuel cell is downsized. Figure 1-7 provides a summary of the energy loss due to friction braking over three different drive cycles for the mid-size SUV. If the energy storage system is sized appropriately to capture as much regenerative braking energy as possible, overall vehicle fuel economy can be improved.

Energy storage system requirements can be defined when all of the power and energy requirements for the individual roles are combined. Figure 1-8 is one set of energy storage system requirements for the SUV case as a function of fuel cell size. Many other alternative scenarios can be developed and compared on a fuel economy, cost, and volume basis. The fuel economy impact of fuel cell shut-down for the SUV design scenario was also studied. The baseline (always on) and two alternatives a) fuel cell off at 0 mph and b) fuel cell off at below 0 kW traction power were analyzed. For the composite of city and highway driving, both levels increase fuel economy by reducing idle fuel consumption. For the US06 cycle (high speed and high acceleration) the 0 mph case has very little impact. In general the impact is between 3% and 15% depending on the drive cycle and control choices. This fuel savings benefit may be offset, however, by the electrical loads associated with fuel cell start-up.

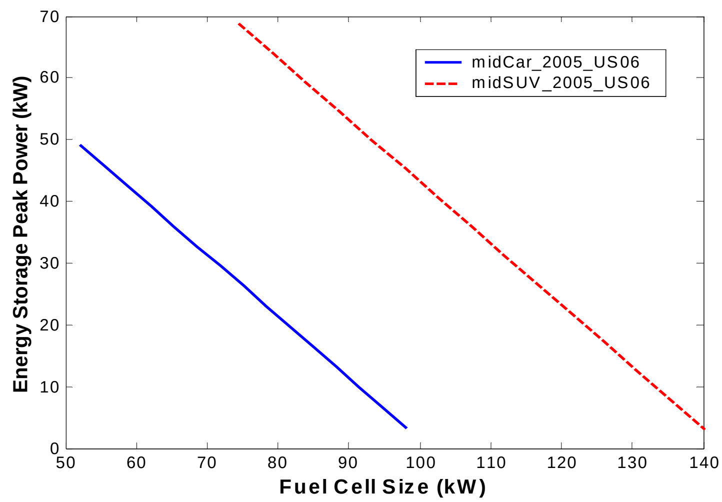

Figure 1-5. Energy storage system power to satisfy traction power demands for the US06 Drive Cycle

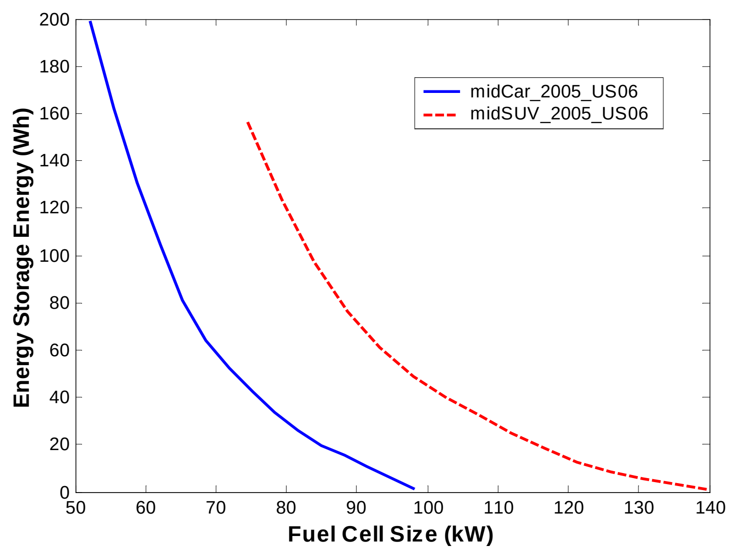

Figure 1-6. Energy storage system energy requirements to satisfy traction power demands for the US06 Drive Cycle

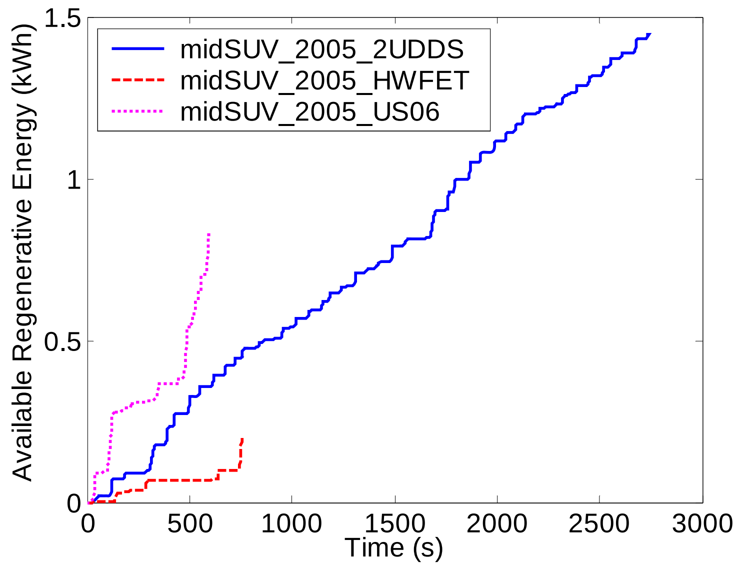

Figure 1-7. Energy dissipated in friction brakes for three drive cycles

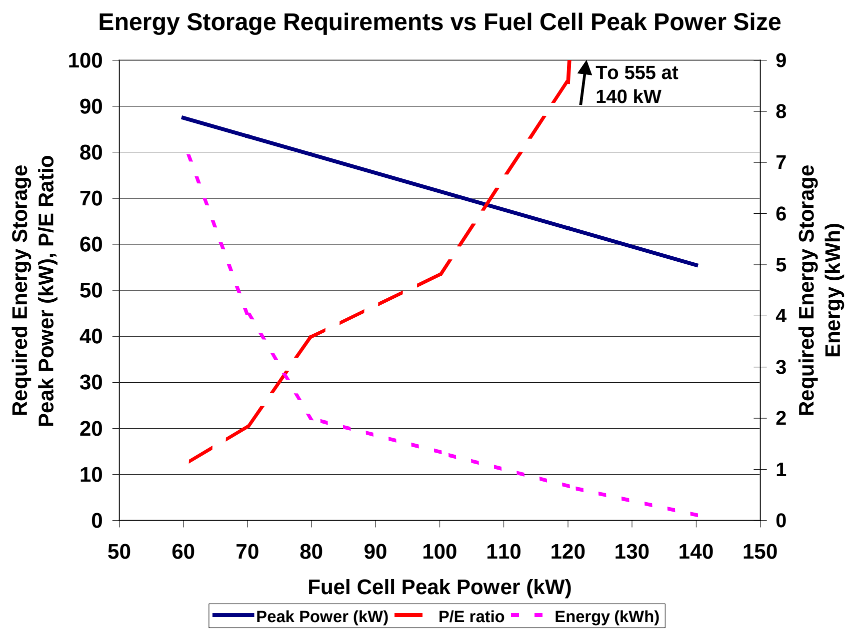

Figure 1-8. Energy storage system characteristics for SUV scenario

Because there are a multitude of options to choose from, optimization tools have been applied to quantify the trade-offs between high fuel economy and minimal incremental cost with respect to the energy storage and fuel cell sizing and usage. When cost is included in the optimization equation, the fuel economy decreased by less than 0.5% while the cost decreased by more than 4%. It is very important that the FreedomCAR program leads to systems that are both fuel-efficient *and* cost competitive.

Conclusions
The project findings have expanded the understanding of the energy storage requirements for fuel cell hybrid vehicles. The energy storage system can provide substantial fuel economy improvement via fuel cell downsizing and regenerative braking energy capture. However, the best storage technology (NiMH, Li-ion, Ultracapacitor, etc.) and its specific characteristics will depend on the roles that the energy storage system will be expected to satisfy. It is important to consider cost, volume, and fuel economy when considering the value of any specific design scenario. Using a fuel cell system shut-down strategy during idle periods can provide a fuel economy benefit of 3–15% depending on drive cycle. In general the benefit is greater on urban driving and minimal on high acceleration rate and highway drive cycles.

Publications / Presentations
1. Markel, T.; Wipke, K.; Pesaran, A.; Zolot, M. "Energy Storage System Requirements for Hybrid Fuel Cell Vehicles" Advanced Automotive Battery Conference. Nice, France. June 10-13, 2003.

2. Markel, Tony. "Multi-Objective Fuel Cell Hybrid Vehicle Design Studies" FY03 Milestone Report. August 1, 2003.

3. Markel, Tony. "Energy Storage Requirements for Fuel Cell Hybrid Vehicles." FY03 Milestone Report. September 11, 2003.

1.4. Effect of Hybridization and Controls on Diesel Emissions

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Objective
- Determine the impact of the degree of hybridization and powertrain system control on diesel engine emissions and efficiency.

Approach
- Obtain reference data for a baseline diesel vehicle by disabling the electric motor and operating the continuously variable transmission (CVT) in a manual gearbox mode;
- Develop and test different hybrid control strategies using the hardware-in-the-loop (HIL) facility; and
- Compare strategies with the baseline reference.

Results
- CVT and electric motor provide great flexibility for the control of engine torque and speed, thereby allowing the diesel engine to operate on its best efficiency curve; and
- A trade-off control strategy is needed to ensure reduced NO_x emissions while maintaining the efficiency improvements.

Introduction

Argonne National Laboratory (ANL) completed the design and installation of a hybrid electric powertrain in the Advanced Propulsion Research Facility (APRF) in FY02. The powertrain consisted of a compression-ignition direct-injection (CIDI) engine and electric motor in parallel driving through a CVT. The components and the hybrid powertrain system were simulated in the Powertrain Systems Analysis Toolkit (PSAT), which was translated to PSAT-PRO (PSAT's prototyping extension) to control the components individually and as a system in the hardware-in-the-loop (HIL) mode. Several control strategies were developed, fine tuned and tested in simulation and hardware.

Approach

Testing of the conventional CVT diesel vehicle configuration (with electric drive disabled) was completed first. The CVT was controlled to act as a manual transmission. During each gearshift, the clutch was disengaged and reengaged to mimic the behavior of a conventional powertrain.

PSAT simulation was used to develop the control approach and test data were correlated with simulation to validate experimental assumptions. The study of the conventional operation of the powertrain provided new insights that enhanced CVT utilization in its hybrid context.

A Critical Flow Venturi (CFV) was used to make direct mass measurements of the exhaust gases. A sample probe was added to obtain particulate matter (PM) mass readings. Figure 1-9 shows the CFV design.

A Li-ion battery was selected and the battery model was verified. The control strategy was refined to accommodate the battery characteristics.

While production versions of CVTs use an internal engine shaft-driven hydraulic pump, the CVT mounted on the powertrain was fitted with an auxiliary hydraulic pump to allow accurate measurements of CVT losses. The pump supplied clamping pressure needed for proper operation of the CVT push belt and pulley assembly. Ideally, the pressure should always be minimized to allow efficient torque transmission while avoiding belt slipping (if pressure is too low) or overheating and abnormal wear (if pressure is too high).

A control algorithm was developed to maintain the engine on its best efficiency curve using CVT ratio control. The control parameters were fine tuned before data were collected over a Federal Urban Driving Schedule (FUDS) cycle. Recalculating the fuel consumption from emissions measurements validated the emissions data.

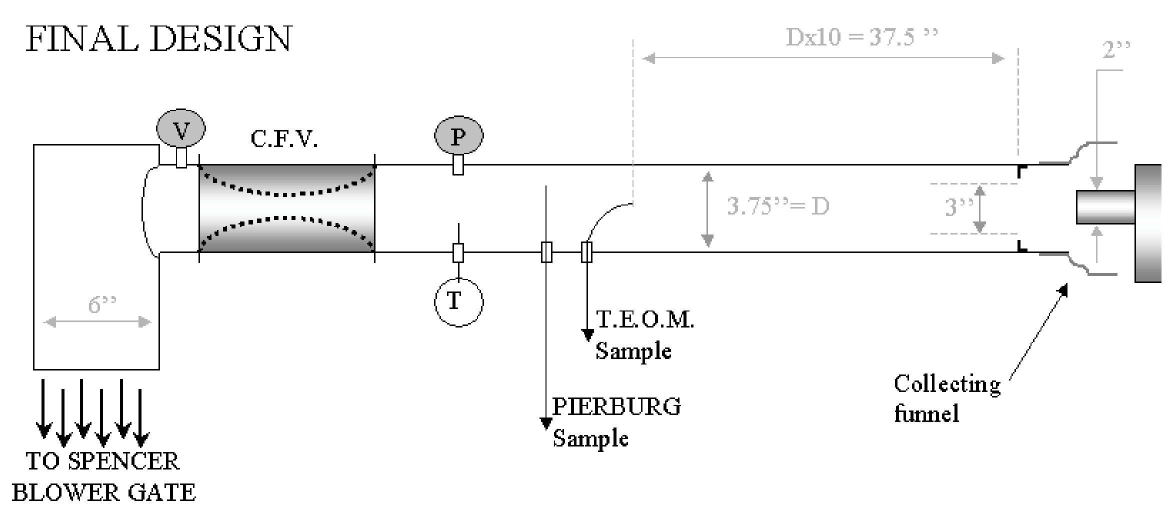

Figure 1-9. Critical Flow Venturi design for direct mass measurements of emissions

Results

Different hybrid control strategies were developed in simulation, implemented in HIL and compared to the reference. For increased fuel economy, the control strategy requires operation on its best efficiency curve. To address the emission reduction issues, the control strategy should allow trade-offs between fuel economy and emissions.

Operating the engine with the best efficiency approach increases fuel economy by 57% compared to the reference. However, operating the engine on its best efficiency curves increases NO_x emissions by 37% because of the high load on the engine. The trade-off control strategy seems more suitable for diesel hybrid application. Fuel economy improvement of 41% and NO_x reduction of 43% was demonstrated (Figure 1-10), but this was accompanied by an increase in PM mass emissions. Therefore, after-treatment technology may need to be integrated to the vehicle control strategy to ensure that the diesel hybrid will meet future PM standards.

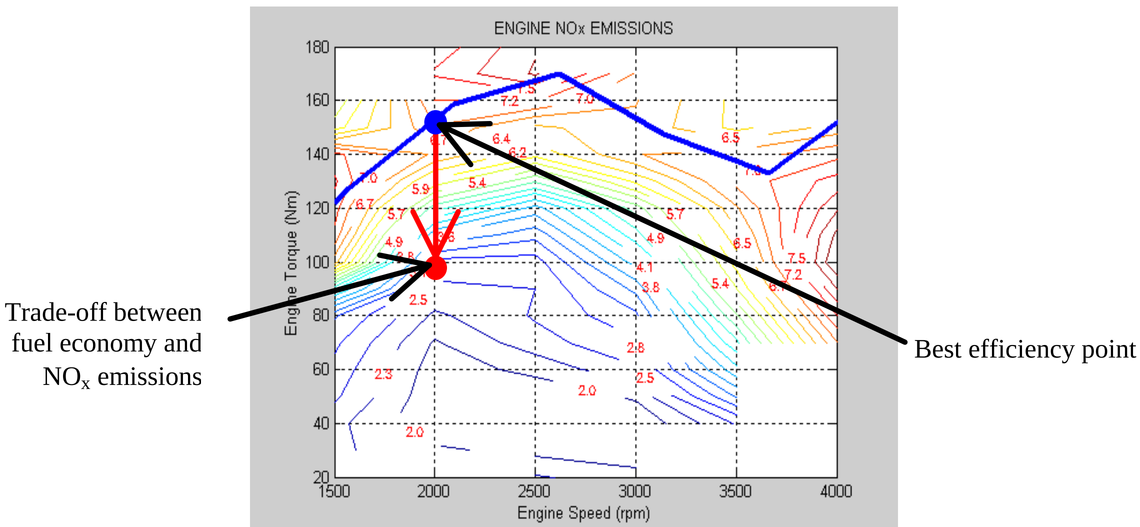

Figure 1-10. Engine set points for efficiency and NO_x emission trade-offs

1.5. Downstream Emissions Control (Aftertreatment) Modeling

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Objective

- Provide simplified models of advanced emissions control technologies to facilitate inclusion of the benefits of these technologies in vehicle-systems level models.

Approach

- Develop simplified physics-based models of emissions control devices; and
- Use industry-developed prototype emissions control devices in a laboratory to generate calibration and verification data for the models.

Accomplishments

- An existing urea selective catalytic reduction model was improved in FY 2003.

Future Directions

- No additional work is planned for FY 2004 due to budget constraints. The aftertreatment models will be incorporated into the Advanced Vehicle Simulator (ADVISOR) and Powertrain Systems Analysis Toolkit (PSAT) simulation programs.

Introduction

Achieving ultra-low emissions levels from lean-burn engines remains as perhaps the most difficult technical barrier to be overcome before these fuel-efficient engines can be incorporated into advanced vehicles for public use. Although hybridization can provide benefits in terms of decreased pollutant emissions, and fuel efficiency gains, it is unlikely that advanced, highly efficient vehicles can meet the stringent U.S. Environmental Protection Agency (EPA) Tier 2 emissions requirements without using one or more advanced emissions control technologies.

These technologies (NO_X adsorbers, Urea-selective catalytic reduction systems, diesel particle filters, plasma-assisted catalysis, and perhaps others) are presently emerging and improving, but do show the potential to allow lean-burn engines to achieve emissions levels consistent with the Tier 2 rule. Although technical issues remain that currently prevent these technologies from commercialization, they are of critical importance to the future of fuel-efficient powertrains. Hence, it is important to include the potential benefits and drawbacks of these technologies in models aimed at investigating advanced vehicle designs.

Approach

Although these technologies are still maturing for vehicle usage, prototype devices are in use for research and development. While a thermo-chemically exhaustive model of one of these devices remains a computationally intensive activity, simplified, low-order models can now be developed to operate using a desktop PC. These simplified models must, necessarily, not include exhaustive treatment of the complex chemistry involved, but can provide estimates of the potential benefits and limitations of advanced emissions control technologies. This activity focuses on developing low-order physically based models of emissions control devices, followed by laboratory characterization of prototype devices provided by industry partners. The laboratory characterization provides performance data to calibrate and "anchor" the physical models.

Results

A series of experiments were run to study the catalytic performance of a commercially available zeolyte catalyst for selective catalytic reduction of nitric oxide by ammonia. Tests were conducted on a bench-flow reactor setup simulating exhaust gas containing 5% H_2O, 5% CO_2, 12% O_2, and various levels of NO and NH_3, and results obtained via Fourier Transform Infrared (FT-IR) spectroscopy.

Adsorption isotherms were first developed for temperature ranges from 150–450°C for NO, NO_2, and NH_3. From literature reviews, the generally accepted behavior for the Selective Catalytic Reduction (SCR) reaction is that of an Eley-Rideal mechanism, where strongly adsorbed NH_3 reacts with weakly adsorbed or gas phase NO to form N_2 and water. The experimental catalyst tested showed much more capacity for the storage of NH_3 than for either NO or NO_2, which would tend to agree with an Eley-Rideal-type mechanism. Steady state data at SV = 25,000/hr, $\frac{NH_3}{NO} = \alpha = 1.2$ was collected for a range of NO inlet concentrations through the same temperature range. The catalyst achieved 100% conversion of NO for temperatures above 250°C. Above 280°C, a competing ammonia oxidation reaction was also observed from flowing a constant stream of 500 ppm NH_3 in N_2 while increasing the catalyst temperature at 5°C/min from 150°C to well over 500°C. To be able to extract relevant kinetic data, the scope of the current study was limited to temperatures below 250°C where it was thought partial conversion of NO would be observed. Figure 1-11 presents NO conversion data for a temperature range of 150–200°C. While the catalyst shows increased catalytic activity at higher temperatures for all concentration levels, the NO conversion appears to decrease as a function of increasing NO inlet level. This could suggest a non-first order reaction rate with respect to NO, and a kinetic study of the data revealed a reaction rate approximately equal to $k_{NO}C_{NO}^{0.9}$. An NO_2 study comprising of the same basic experimental matrix is currently being performed. Interestingly, NO_2 activity appears to be higher than that of NO. At 150°C, over 80% NO_2 conversion is achieved.

Conclusions

Highly efficient vehicle designs are likely to require the use of advanced emissions control technologies in order to meet the EPA's future emissions requirements. With this in mind, it is obvious that these technologies should be included in vehicle models aimed at discovering avenues for improvement in vehicle efficiency.

Significant progress has been made in developing physically based, low-order models to simulate the dynamic performance of diesel oxidation catalysts, lean NO_x adsorbers, diesel particulate filters, and urea selective catalytic reduction.

Although these low-order models are not replacements for more computationally intensive models aimed at device design, they are important for screening the performance parameters and expected beneficial effects of these technologies in vehicle-systems modeling and planning.

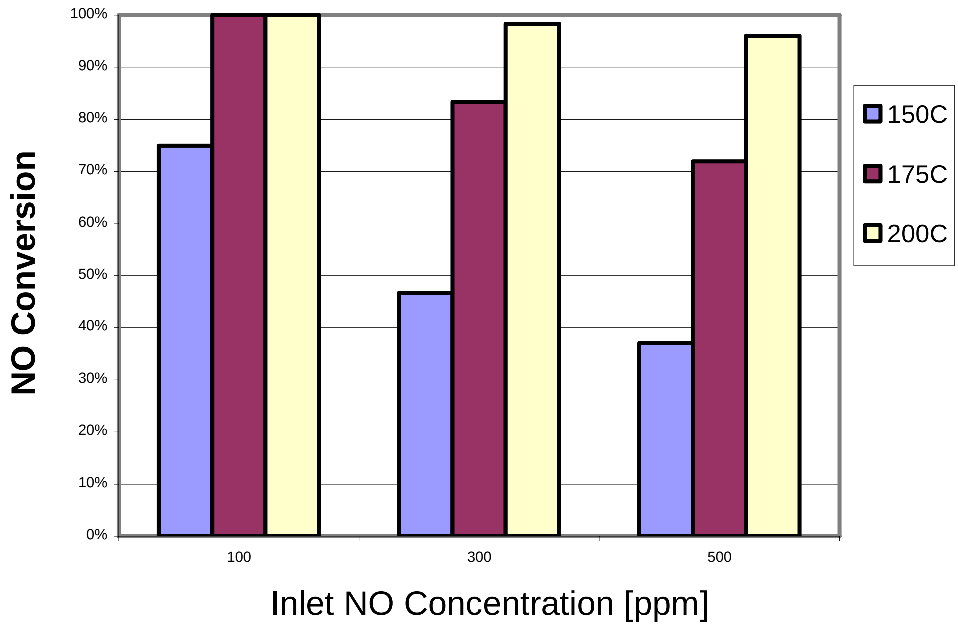

Figure 1-11. NO conversion from ammonia SCR reaction. Experimental Conditions: 5% CO_2, 5% H_2O, 12% O_2, $\alpha = 1.2$

1.6. Transient Fuel Cell Model Development

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Objectives

- Develop a polymer electrolyte membrane (PEM) fuel cell (PEFC) subsystem model in the Powertrain Systems Analysis Toolkit (PSAT);
- Provide capabilities to realistically estimate the potential benefits (fuel economy and emissions); and
- Quantify technical requirements of fuel cells in vehicles by taking into account transients, temperature, and altitude.

Approach

- Translate the General Computational Toolkit (GCTool) fuel cell design and analysis model into a form appropriate for vehicle simulation;
- Integrate a transient model of a PEFC system in PSAT; and
- Verify the methodology.

Accomplishments

- Created PSAT executable for gasoline reformed ambient pressure PEFC system; and
- Created PSAT executable for ambient pressure direct hydrogen PEFC system.

Future Directions

- Develop and verify kinetic models for auto-thermal reformers for PSAT.

Introduction

Argonne National Laboratory (ANL) has been modeling fuel cells as well as developing and testing hardware for over 20 years. The General Computational Toolkit (GCTool) was developed for steady state and dynamic analysis of fuel cell systems. GCTool is focused on design and searches for optimum configurations. ANL has also developed the Powertrain Systems Analysis Toolkit (PSAT), a transient vehicle simulation software that allows users to evaluate fuel consumption, exhaust emissions and vehicle driving performance.

If the capabilities of GCTool and PSAT can be combined, various fuel cell configurations can be examined for their suitability in vehicle applications.

Approach

The detailed thermodynamic and chemical transport algorithms in GCTool are generally inappropriate for use in vehicle studies because of greatly increased computer run time. The overall approach is to build engineering models of fuel cell components and systems using the GCTool architecture and link them to PSAT.

To automate the linkage process, a translator was written to produce a Matrix Laboratory (MATLAB)/Simulink executable from the GCTool driver. The executable becomes a member of the drivetrain library in PSAT. For fast computational speed, special models have been developed that rely on performance maps that are generated either from experimental data or from detailed component models in GCTool.

A PSAT executable for ambient pressure direct hydrogen PEFC system was developed first. Version 6 of the direct pressurized hydrogen fuel cell was created. As part of the enhancement of the fuel cell system thermal management model, the compressor expander module tables and the radiator, condenser, and pump parameters were modified so that the size of the thermal management system could be easily modified. Consequently, the S-Function was modified with the addition of "vehicle velocity," "power demand," and "power loss" as input parameters. In an effort to parameterize the S-Function and be able to later rerun the same simulation, the name of the compressor expander and fuel cell system file are now parameters of the S-Function.

After the multistage preferential oxidation (PROX) selectivity work, the development of a PROX kinetic model based on Los Alamos National Laboratory's (LANL's) experimental data was initiated. This involves determining reaction rates and estimating kinetic parameters (i.e., activation energies, reaction orders and pre-frequency factors). The model results appear to agree with the latest experiments.

Several design-specific fuel cell system models were developed/enhanced to support the joint fuel cell-battery-vehicle systems tech team activities.

Work was initiated on a PROX reformer model in GCTool based on LANL experimental data. We simulated the multistage PROX process to investigate the relationships between CO oxidation selectivity and CO inlet/outlet concentration and compared the simulation results of one-, two- and three-stage cases (i.e., each PROX reactor is called a stage). In a two-stage case for example, the outlet of the first stage is connected to the inlet of the second stage and the overall selectivity is calculated. The (physical design) goal is to get as much O_2 out of air to react with CO (not H_2) to produce CO_2 so that the CO concentration can be lowered efficiently. The more stages used, the higher the selectivity (or the less air needed). But more stages mean more controls and equipment cost, so three stages were set as the limit for analysis. The results have been shared with ANL's Chemical Engineering Division and LANL to assist faster warm-up design.

Work focused on the modeling analysis of CO adsorption/desorption/oxidation on Pt catalyst. Experimental data were obtained from published papers and adsorption/desorption equilibrium models derived. When the literature data were compared with the models, large deviations were noticed between the model results and the literature. The authors were contacted and the problem was resolved. Now the equilibrium model works consistently with the literature results.

Results

A draft report was completed describing the development of the design-specific pressurized direct hydrogen fuel cell system model from GCtool used for the Joint Technical Team study.

The adsorption/desorption of carbon monoxide on platinum while oxygen is present has been studied to develop a model of temperature dependency for GCTool. To date, several standard adsorption/desorption/reaction schemes could not reproduce the literature data.

Work has focused on fuel processing-reaction kinetic modeling for autothermal reforming of isooctane. Kinetic analysis has been performed based on the experimental data of autothermal reforming of isooctane. Different reaction mechanisms have been hypothesized and tested by the data. Appropriate kinetic models for GCTool to simulate the fuel processing within a fuel cell system will be developed in 2004.

1.7. Fuel Cell Vehicle System Simulation for Fuel Economy Analysis

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Objectives

- Combine Argonne National Laboratory's (ANL's) fuel cell and vehicle simulation capability ("tank-to-wheels") with the energy pathways assessment capability ("well-to-tank") to provide a global picture of the consequences of vehicle technology and fuel pathways; and
- Compare advanced propulsion technologies for conventional, hybrid and fuel cell vehicles on a well-to-wheel energy basis.

Approach

- Use Powertrain Systems Analysis Toolkit (PSAT) to design, simulate and realistically compare advanced drivetrain configurations; and
- Use the Greenhouse Gases, Regulated Emissions and Energy use in Transportation (GREET) model to translate the vehicle fuel economy and emissions characteristics to provide an overall impact assessment.

Results

- Substantial gains in fuel economy can be achieved through dieselization and hybridization. For fuel cell vehicles, degree of hybridization should be chosen to optimize the regenerative braking and yet minimize the hybrid fuel cell system's losses;
- Hybrid fuel cell powertrain consumes less energy than a system containing only a fuel cell; and

- For current technologies, the pre-transmission diesel hybrid electric vehicle (HEV) appears to be the best option.

Future Directions

- Compare future technologies and assess the benefits of potential 2010 fuel cell technology.

Introduction

This project encompasses a wide range of expertise and tools developed by ANL for vehicle modeling, fuel cell modeling and greenhouse gas emissions estimation. The modeling tools used for this analysis included the General Computational Toolkit (GCTool), PSAT and GREET.

GCTool was developed at ANL for steady state and dynamic analysis of fuel cell systems. It allows users to establish realistic system constraints and conduct optimization studies. GCTool has an extensive library of model classes for components and devices that appear in practical energy conversion systems. In particular, the library includes various fuel cell types, hydrogen storage devices, reformers, and heat exchangers. Engineering models of fuel cell systems and components using GCTool architecture were developed and linked to Matrix Laboratory (MATLAB)-based vehicle codes used in PSAT. The MATLAB-linked model is called GCTool-Eng.

PSAT provides realistic estimates of the wheel torque needed to achieve a desired speed by sending commands for engine throttle, clutch, transmission, and brake positions. PSAT allows the virtual vehicle (with advanced components with known or projected performance characteristics) to be 'driven' over predefined drive cycles.

GREET is an analytical tool for estimating well-to-wheel (WTW) energy use and emissions associated with transportation fuels and advanced technology vehicles. Only the well-to-pump or "upstream" values are used from GREET. Pump-to-wheel (PTW) or "downstream" values are obtained from PSAT and GCTool-Eng, as shown in Figure 1-12.

Technical Approach

Different vehicle powertrains (conventional, hybrid, and fuel cell) were evaluated for overall efficiency and greenhouse gas emissions (GHGs). For fuel cell vehicles, the impact of different fueling scenarios was also examined. Since the goal of this study was to evaluate drivetrain configurations rather than fuel production, only the reforming at a station was first considered.

The study focused on comparison of several current technologies (conventional, internal combustion engine [ICE] HEVs, and fuel cell) from a well-to-wheel prospective. Vehicle assumptions were modified according to input from the FreedomCAR vehicle systems technical team. Design-specific fuel cell models were developed for the study to represent current technologies.

A reference vehicle based upon a sport-utility vehicle (SUV) platform, gasoline engine and automatic transmission was selected and its U.S. Environmental Protection Agency (EPA)-tested fuel economy was verified using PSAT. The combined fuel economy obtained with PSAT is slightly higher (21 mpg) than the reference value (20 mpg) because the effect of cold start was not taken into account.

Eleven powertrain configurations that were simulated to evaluate the potential of fuel cell technologies included:

- Conventional vehicle (CONV) with gasoline engine and automatic transmission (the reference vehicle).
- CONV with diesel engine and automatic and manual transmissions.
- Starter-alternator parallel hybrid (PAR ISG) with gasoline and diesel engines).

- Pre-transmission parallel hybrid (PAR PRE-TX) with gasoline, diesel, and hydrogen engines.
- Fuel cell vehicle with no energy storage.
- Fuel cell vehicle with two hybridization degrees (small and large energy storage).

A defined set of rules was adopted to ensure fair and consistent comparison between the vehicles. These included:

- The components of each configuration were sized to achieve performance similar to that of the reference vehicle (0–60 mph in 10.5s; maximum speed >100 mph).
- All components were based on current technology. A pressurized direct hydrogen fuel cell system based on available data was used. NiMH batteries were employed.
- All powertrain configurations were simulated on the Federal Urban Driving Schedule (FUDS), Federal Highway Driving Schedule (FHDS), US06, Normalized European Driving Cycle (NEDC), and Japan 1015 mode. This will allow easy evaluation of each powertrain anywhere in the world.
- Vehicle aerodynamic drag, tire rolling resistance, and glider mass were kept constant for all vehicles. The differences between the vehicles are only due to their powertrain configurations and control strategies.
- Cold start was not taken into account for the engines or the fuel cell.

Results

Table 1-1 shows the fuel economies of all configurations for the Combined Cycle (FUDS and FHDS). Substantial gains can be realized from dieselization and hybridization. The hybrid fuel cell configuration combines high fuel cell system efficiency and regenerative braking to achieve the highest fuel economy. However, the fuel cell hybrid system efficiency decreases somewhat with the larger energy storage system. For optimum efficiency, the energy storage systems should not be larger than necessary for storage of the regenerative energy.

From the WTW perspective, conventional gasoline and hydrogen ICE vehicles are rather inefficient (~14% and 15.7% respectively). The conventional diesel with manual transmission is as efficient as the hybrid spark ignition (SI) engine. The fuel cell hybrid vehicle with a small energy storage system is the most efficient configuration. However, it should be noted that the large PTW efficiency advantage of a hydrogen fuel cell vehicle is significantly diminished when WTW efficiencies are considered. Also, the hybrid fuel cell consumes less energy than a system containing only the fuel cell. The weight advantage of the fuel cell is insufficient to compensate for the loss in regenerative energy.

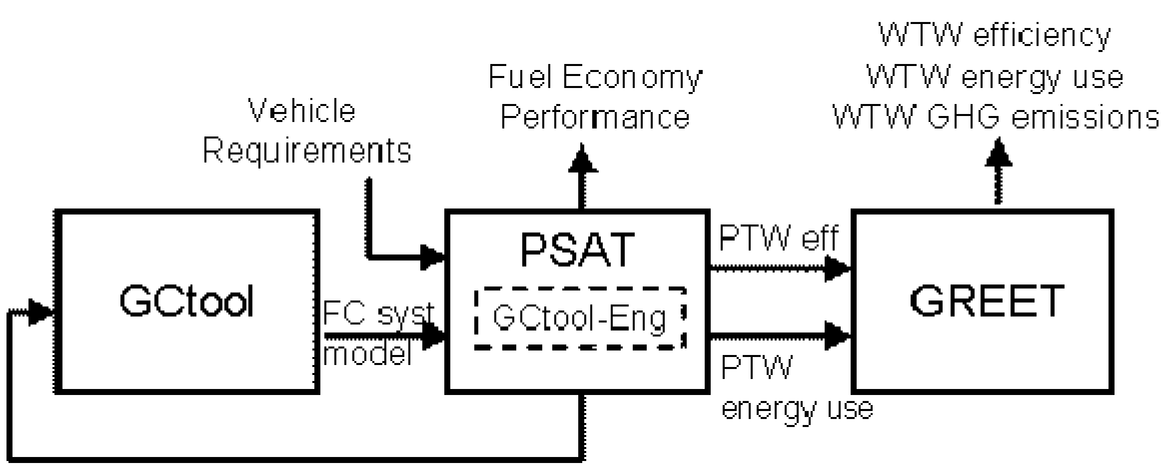

Figure 1-12. Well-to-wheel simulation process

Table 1-1. Comparison of Fuel Economy of Vehicle Configurations (Combined Cycle)

Vehicle Configuration	Fuel Economy* (mpg)	Efficiency (%)	
		Pump to Wheel	Well to Wheel
Conventional SI	21.4	16.8	13.2
Conv. Hdi**, auto	26.5	21.1	17.4
Conv. Hdi**, manual	28.7	23.0	18.9
Starter-alternator Hyb, SI	25.2	21.3	16.9
Starter-alternator Hyb, Hdi	30.6	24.8	20.4
Pre-transm. Hybrid, SI	28.1	27.1	21.4
Pre-transm. Hybrid, Hdi	33.0	30.0	24.7
Pre-transm. Hybrid, H2 ICE	30.0	28.1	15.7***
Fuel Cell EV	49.8	42.4	23.6***
Fuel Cell Hyb, small ESS	59.9	49.4	27.6***
Fuel Cell Hyb, large ESS	55.8	47.9	26.7***

* gasoline-equivalent SI- spark ignition
** diesel engine
*** hydrogen reformed at pumping station

GHG emissions are an important consideration from a tailpipe emission perspective. Table 1-2 shows a comparison of emissions from the different vehicle configurations. GHG emissions of a clean vehicle, such as a fuel cell vehicle, will be entirely due to the production of hydrogen. In the case of on-site reforming at the pump, GHG emissions on an equivalent energy basis can be substantial. But in spite of this, fuel cell vehicles offer a 60% decrease in GHG emissions when compared with the most advanced hybrid engine configuration. For current technologies, the pre-transmission diesel HEV appears to be the best option.

Conclusions

PSAT, GCTool-Eng, and GREET were successfully used to analyze the fuel economy and GHG emission from several conventional and hybrid vehicle configurations operating with gasoline engines, diesel engines and fuel cells. Hybrid electric vehicles with gasoline engines achieve fuel economy comparable with that of conventional diesel engine vehicles.

Table 1-2. Projected Greenhouse Gas Emissions

Vehicle Configuration	WTP GHG Emission (g/MJ)	PTW GHG Emission (g/MJ)	WTW GHG Emission (g/mi)
Conv. SI	22.2	73.9	544.7
Conv. Hdi**, auto	19.7	78.1	448.6
Conv. Hdi**, manual	19.7	78.1	414.6
Starter-alternator Hyb, SI	22.2	73.9	461.3
Starter-alternator Hyb, Hdi	19.7	78.1	387.2
Pre-transm. Hybrid, SI	22.2	73.9	426.2
Pre-transm. Hybrid, Hdi	19.7	78.1	369.2
Pre-transm. Hybrid, H2 ICE	119.8	0	498.0
Fuel Cell EV	119.8	0	293.0
Fuel Cell Hyb, small ESS	119.8	0	250.3
Fuel Cell Hyb, large ESS	119.8	0	268.8

Hybrid electric vehicles with a diesel engine appear to be competitive with hydrogen ICE vehicles on a total energy basis when hydrogen is produced by reforming natural gas at the pump.

The results of this study are comparable with those from an earlier General Motors study.

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1.8. Energy Storage Requirements of Fuel Cell Vehicles

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Objectives

- Combine Argonne National Laboratory's (ANL's) fuel cell and vehicle simulation capabilities to define the energy storage requirements of fuel cell vehicles; and
- Analytically determine the battery energy storage requirements for fuel cell vehicles (FCVs) and verify the results with hardware-in-the-loop (HIL) testing.

Approach

- Use the Powertrain Systems Analysis Toolkit (PSAT) with a transient fuel cell model derived from the General Computational Toolkit (GCTool) to define fuel cell system characteristics representative of mid-term technologies; and
- Compare advanced drivetrain configurations with a standard sport-utility vehicle (SUV) platform to define impact of hybridization degree, control strategy and energy storage technology on fuel economy.

Results

- Degree of hybridization should be chosen to optimize the regenerative braking and yet minimize the fuel cell system's losses; and
- Selecting a lower battery state-of-charge (SOC) target allows an increase in regenerative braking, which can contribute to further reduction in degree of hybridization.

Future Directions

- Define energy storage requirements of different vehicle platforms and component technologies, based on the findings of this study.

Introduction

ANL has developed unique integrated capabilities in modeling, HIL, and vehicle testing, which are being utilized to analyze fuel cell-powered vehicles. Several FreedomCAR technical teams worked to define future electrochemical energy storage requirements for fuel cell vehicles by using advanced simulation tools.

Approach

Simulation Tools Development

GCTool was developed to conduct fuel cell system optimization studies. GCTool has an extensive library of models for components and devices that appear in practical energy conversion systems. In particular, the library includes various types of fuel cells (polymer electrolyte, solid oxide, phosphoric acid, and molten carbonate), hydrogen storage devices (compressed gas, liquid hydrogen, metal hydrides, glass microspheres, etc.), catalytic reactors (such as for auto-thermal reforming, steam reforming, water-gas shift, preferential oxidation, and sulfur removal), and heat exchangers (counterflow, air-cooled condenser, finned radiator, etc.). Several thermodynamic codes are available in GCTool for equations of state of mixtures of gases, liquids, and condensables, which can be used for gaseous (e.g., hydrogen and methane), liquid (methanol, ethanol, octane, etc.), and synthetic fuels (gasoline and diesel).

The detailed algorithms in GCTool (thermodynamic and chemical transport) are generally inappropriate for use in vehicle studies because of the greatly increased computer run time. For this reason, engineering models of fuel cell systems and components using the GCTool architecture have been developed for vehicle analyses, as has a procedure to automate the linkage to Matrix Laboratory (MATLAB)-based vehicle codes (such as PSAT).

PSAT was developed to allow users to evaluate fuel consumption, exhaust emissions, and vehicle driving performance. PSAT estimates the wheel torque needed to achieve a desired speed by sending commands to the different components, such as the engine throttle, clutch, transmission, or mechanical brakes. The model can be used to 'drive' the vehicle to follow a predefined speed cycle. Since components react to commands as in reality, transient effects (such as engine starting, clutch engagement/disengagement or shifting), can be studied to develop realistic control strategies. PSAT has been validated by using several vehicles.

To automate the GCTool link with PSAT, a translator was developed to produce a MATLAB/Simulink executable from the GCTool model. The executable then becomes a member of the drivetrain library in PSAT, which can be used for analyzing transient fuel cell system responses during drive-cycle simulations of hybrid vehicles. The executable is specific to the fuel and the system configuration setup in the GCTool model, and a new one must be produced if there is any change in system attributes. The methodology has been demonstrated by using direct hydrogen fuel cell systems.

Vehicle Definition

Three different vehicle platforms were selected for this study: compact, midsize, and sport-utility vehicle (SUV).

The fuel cell system powertrain, shown in Figure 1-13, includes a fixed ratio in addition to the final drive, as well as DC/DC converters for the high-voltage battery and the 12-V accessories.

The fuel cell vehicle must be designed to provide performance similar to that of the reference vehicle, including 0–60mph acceleration (10.5 s), sustained grade of 6.5% at 55 mph, and maximum speed above 100 mph. The fuel cell system must provide power for top speed and grade performance and to have a 1-second transient response time for a power request change of 10–90% of the maximum power. Moreover, it should reach maximum power in 15 seconds for cold start from 20°C ambient temperature and in 30 seconds for cold start from −20°C ambient temperature.

The fuel cell systems defined with GCTool were based upon mid-term technology (2005). The Saft Li-ion HP6 battery was selected as the reference energy storage technology as it was recently tested at ANL, and industry considers it to be current state-of-the-art.

Control Strategy

Because of the high efficiency of fuel cell systems (see Figure 1-14), there is no benefit in using the energy storage system to provide the total traction power at any time. For a fuel cell vehicle, the main function of the storage system should be to store the regenerative braking energy from the wheels for use by the vehicle system at appropriate times. The control strategy selected uses battery energy when the vehicle is operating at low power demand (low vehicle speed) and provides instantaneous power during transient peaks whenever the fuel cell is unable to meet driver demand.

The three controller outputs are fuel cell ON/OFF, fuel cell power, and motor torque. Battery state-of-charge (SOC) is maintained within a defined operating range. To minimize the impact of SOC variation, the same values were selected for both the initial conditions and the SOC goal. As shown in Figure 1-15, the consequence is that the battery will supply the system with the energy that it had just recovered from regenerative braking. For instance, the SOC will go up after regenerative braking, and this recovered energy will be returned to the vehicle during the next acceleration, thus returning the SOC back to its goal value. In other words, to maintain the SOC goal, the battery does not store any net energy over the cycle.

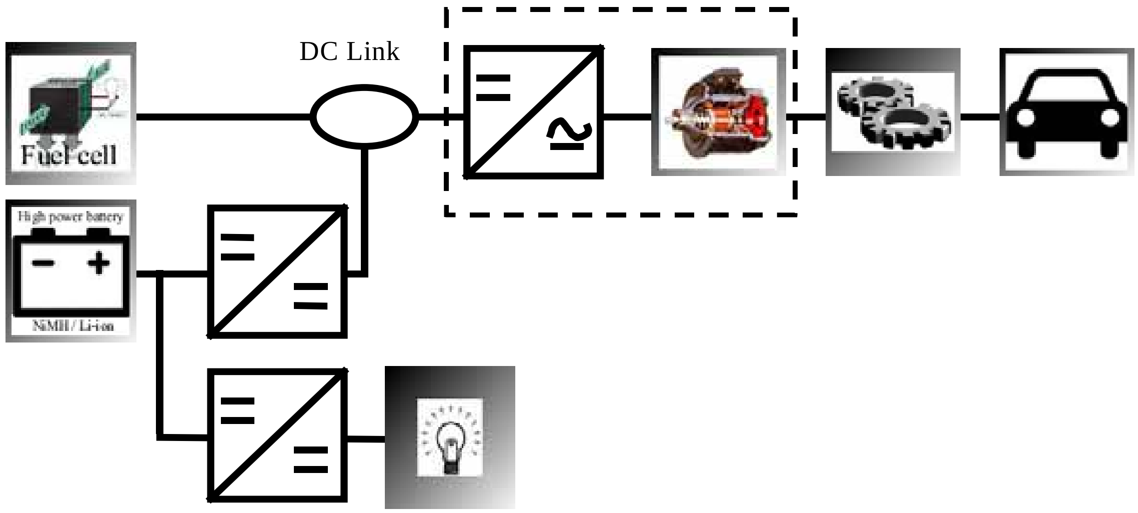

Figure 1-13. Fuel cell system powertrain

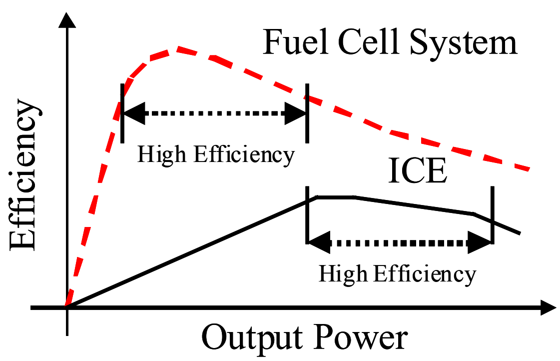

Figure 1-14. Fuel cell system efficiency vs. internal combustion engine efficiency

To implement this aspect of the control strategy, the total power required by the vehicle is compared to a threshold: the minimum power demand needed to use the fuel cell. This control strategy parameter is set by using the PSAT graphic user interface (GUI). More specifically, this control parameter is defined as the sum of the wheel power demand from the driver model (set to zero in the default control strategy) plus an additional power, depending upon the SOC value. If the SOC is above its goal, the additional power will be negative, and the fuel cell will be used later. For example, if the SOC is 70%, the value will be zero, but with a higher SOC (71%), the minimum power might be 3 kW, allowing the energy storage to be discharged and return to the SOC goal.

<u>Hybridization Degree</u>

The first step in defining the energy storage requirements consists of selecting the proper hybridization degree. The electric motor needs 160 kW peak electrical power to provide performance characteristics similar to those of the reference vehicle. In addition to the "fuel cell only" case, four options were selected: from 20 kW energy storage and 140-kW fuel cell (on the left) to 80 kW energy storage and 80-kW fuel cell. Fuel cell systems with a lower power than 80 kW were not considered because it is the minimum power necessary to sustain a 6.5% grade at 55 mph—one of the vehicle performance requirements.

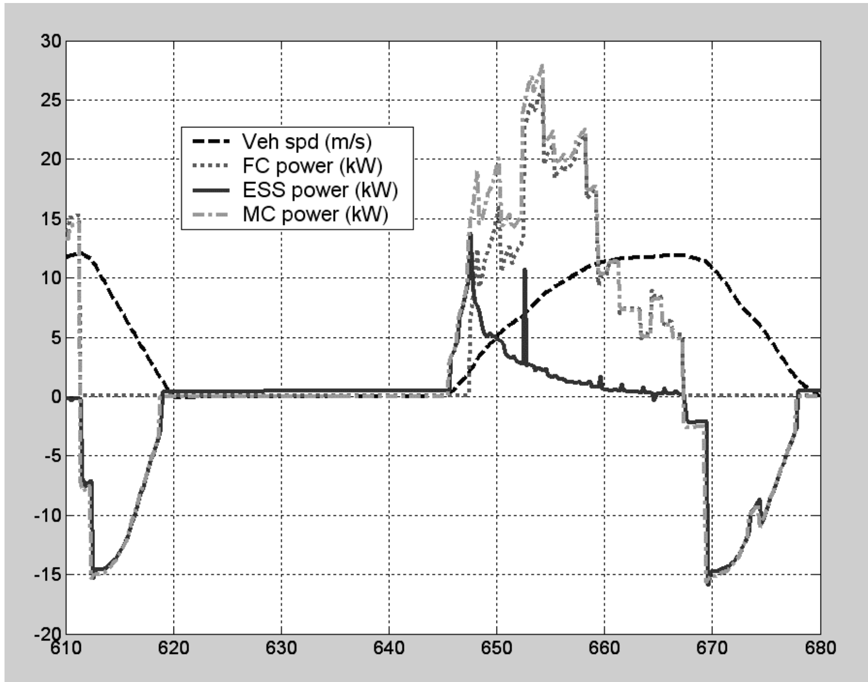

Figure 1-15. Default control strategy—part of the Federal Urban Driving Schedule (FUDS) cycle—100-kW fuel cell, hot start

For the Li-ion battery technology and the default control strategy used, the most significant increase in fuel economy is obtained at the lowest hybridization degree (140-kW fuel cell), as shown in Figure 1-16. This large fuel economy increase is mostly due to regenerative braking energy. A further increase in the degree of hybridization still provides some improvements in fuel economy until we reach the optimum of a 100-kW fuel cell. Fuel economy then starts to decrease. At this point, the decrease in fuel cell system efficiency on the driving cycle is greater than the gain due to regenerative braking.

Referring back to Figure 1-16 and the efficiency curve of the fuel cell system, this result is in agreement with expectations. The fuel cell has a “sweet spot” at relatively low power. If the average operating point of the cycle falls in this “sweet spot,” maximum fuel economy is attained. Downsizing the fuel cell will cause the average operating point to shift to the right. If the initial operating point is before the “sweet spot,” downsizing will be advantageous. The operating point will move to the right and enter the “sweet spot.” (The fuel economy trend in Figure 1-16 is positive from 140 kW to 100 kW.) However, additional downsizing of the fuel cell below 100 kW will push the operating point farther to the right and out of the optimal efficiency region. At 80 kW, the fuel cell is over-downsized—or, to state it another way, the fuel cell vehicle is over-hybridized. For the component technologies considered, a low degree of hybridization is the most suitable solution to optimize the regenerative braking gains while maintaining a high fuel-cell-system efficiency. The degree of hybridization has a significant impact on component behavior and, consequently, will be a determining factor of the energy storage requirements.

Temperature Impact

GCTool allows users to evaluate the influence of temperature. Cold (−20°C), ambient (20°C) and hot (80°C) starts were studied. It was found that initial temperature mostly affects the energy storage requirements during the first 200 s of the cycle. Moreover, because of lower efficiencies, and consequently a higher amount of heat rejected, the temperature of the fuel cell increases faster after a cold start than that for the ambient condition.

Control Strategy Impact

As previously mentioned, the battery SOC and the minimum fuel cell power demand threshold are key parameters of the control strategy. These parameters were modified to evaluate the impact of control strategy options on the energy storage requirements.

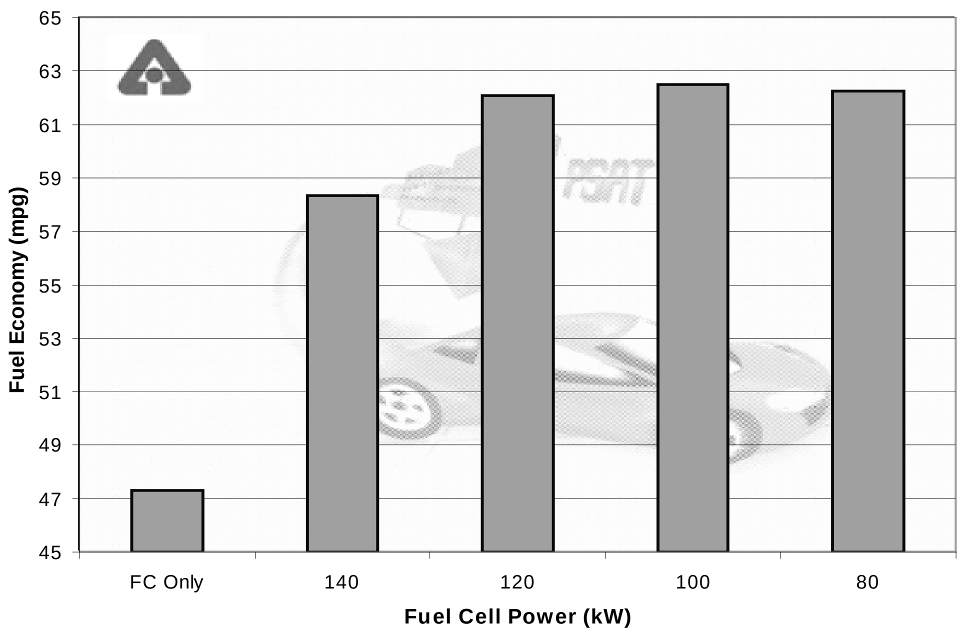

Figure 1-16. Impact of degree of hybridization on vehicle fuel economy—FUDS cycle

Table 1-3 compares fuel economy results when the SOC is 0.7 and 0.5 (both for the initial conditions and goal). Note that an increase in fuel economy of up to 4% can be achieved just by selecting a lower energy-storage SOC. The main reason for this improvement in fuel economy is an increase in regenerative braking energy combined with a small increase in fuel cell system efficiency.

On the other hand, increasing the minimum fuel cell power demand threshold (and consequently increasing energy storage) leads to a decrease in fuel economy as a result of an increase in powertrain losses—even though the amount of regenerative braking increases. As previously discussed, regenerative braking energy and fuel cell system efficiencies are key to the system optimization. In this case, an increase in regenerative braking energy does not lead to an increase in fuel economy because a larger increase in fuel cell system energy loss nullifies the benefit associated with regenerative braking.

A different control strategy, where the energy storage is used as the main energy source rather than the fuel cell (“large ess” case), was also explored. For both the FUDS and Federal Highway Driving Schedule (FHDS) cycles, the fuel cell system efficiency significantly decreases when the use of the energy storage increases. However, for the US06 cycle, a larger SOC window may be desirable because by allowing the battery to be discharged more during acceleration, more regenerative braking energy can be recovered during deceleration.

In summary, control strategy philosophies and their parameters have a significant impact on energy storage requirements. Several options to increase the energy storage usage were investigated by increasing the minimum wheel power demand to use the fuel cell and by changing the control strategy philosophy by using energy storage as the first choice. The results demonstrated increasing energy storage usage resulting in a decrease in fuel economy. A better option to increase regenerative braking would be to decrease the SOC goal. A value of 50% was chosen because there is still enough available energy to start the vehicle at very low temperatures.

Energy Storage Technology Impact

In the previous example, the Saft Li-ion HP6 battery has been used. To properly define the energy storage requirements for fuel cell vehicles, NiMH and ultracapacitor technologies were investigated. The NiMH battery used had a capacity of 28 Amp-h and was manufactured by Ovonic. The ultracapacitor had a capacitance of 2,700 microfarads and was manufactured by Maxwell. As shown in Figure 1-17, the best fuel economy is obtained for different hybridization degrees for each technology. In this example, the Li-ion is optimum with a 100-kW fuel cell and a 60-kW battery. Both NiMH battery and ultracapacitors achieve best performance at low hybridization degrees.

These differences are explained both by the difference in power density and in physical characteristics. At a low degree of hybridization (i.e., a 140-kW fuel cell), the regenerative energy potential is the main reason for achieving better fuel economy At a high degree of hybridization, the mass increase from NiMH and ultracapacitor technologies becomes a significant factor, as shown in Figure 1-18.

Table 1-3. Impact of SOC target and fuel cell power demand threshold on fuel economy

SOC Target	Min Fuel Cell Power Demand	Percentage Regen Braking	Fuel Economy (mpg)
0.7	0 kW	84.5	62.2
0.5	0 kW	97.1	62.5
0.7	15 kW	88.1	60.2
0.5	15 kW	97.15	61

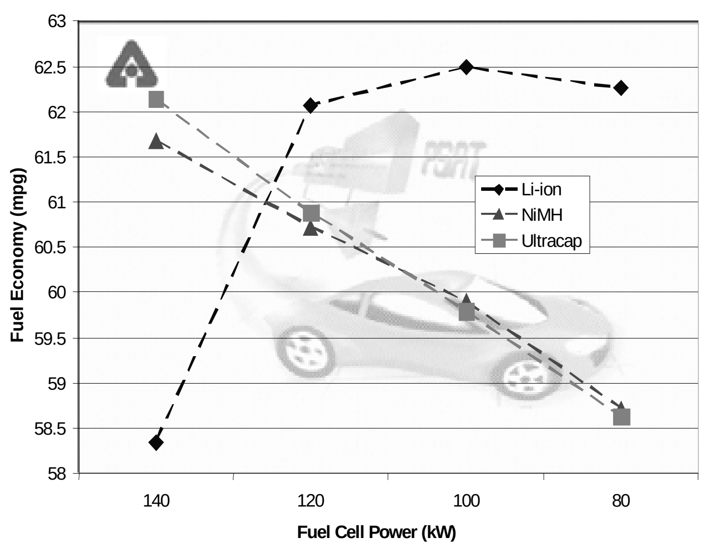

Figure 1-17. Relationship between degree of hybridization and energy storage technology–FUDS Cycle

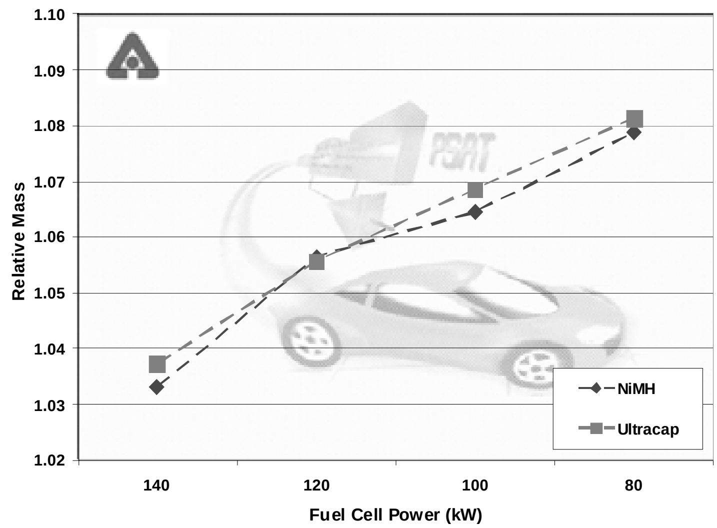

Figure 1-18. Vehicle test mass for each energy storage technology relative to Li-ion battery

Conclusions

By using GCTool and PSAT, specific direct hydrogen fuel cell systems and powertrains were developed to achieve performance characteristics similar to conventional vehicles. For a specific vehicle platform, a systems approach is needed to define the energy storage requirements of fuel cell vehicles. On the basis of mid-term component technologies, the degree of hybridization should be chosen to optimize the regenerative braking, while minimizing the fuel cell system's losses. Moreover, selecting a lower battery-SOC target allows an increase in regenerative braking energy stored, which can contribute to further lowering of the degree of hybridization. The control strategy should be oriented toward optimizing regenerative braking energy by using a narrow SOC range for low transient cycles (FUDS and FHDS) and a large one for high transient cycles (US06). This study allowed us to narrow the scope of the study for the other vehicle platforms and component technologies. The results will be used to define the energy storage requirements for each case.

Publications

1. A. Rousseau ; Sharer, P. ; Besnier, F. 2004. *"Feasibility of Reusable Vehicle Modeling: Application to Hybrid Vehicles,"* SAE04-454, SAE World Congress, Detroit.

2. B. Deville and Rousseau, A. 2001. "*Validation of the Honda Insight Using PSAT"*, DOE report, September.

3. A. Rousseau and Pasquier, M. 2001. *"Validation Process of a System Analysis Model: PSAT,"* SAE paper 01P-183, SAE World Congress, Detroit, March 4–8.

4. P. Sharer and Rousseau, A. 2001. *"Validation of the Japan Toyota Prius Using PSAT,"* DOE report, March.

1.9. 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

- Assessed alternative powertrains and body-in-white materials for advanced technology vehicles to demonstrate the cost-effectiveness of component level DOE/FreedomCAR technical goals;
- Implemented the linkage of performance model Advanced Vehicle Simulator (ADVISOR) to automotive system cost model for vehicle fuel economy estimation; and
- Demonstrated mass and cost relationships between powertrain and vehicle glider in order to provide inputs to the Technical Targets Tool for the estimation of potential oil savings from a particular vehicle class.

Future Directions

- Develop mass and cost relationships between powertrain and vehicle glider for all thirteen U.S. Environmental Protection Agency (EPA) vehicle classes considered by the Technical Targets Tool; and
- Develop "Cost Roll-Ups" of advanced vehicle designs covering all three light-duty vehicle platforms;
- 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 cost modeling framework to a new definition of vehicle subsystems, employing the sizing routines of ANL powertrain and chassis, 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 demonstrate how component level U.S. Department of Energy (DOE)/FreedomCAR goals would translate to the overall vehicle affordability in addition to enhancing the modeling framework capability in terms of vehicle fuel economy estimation and providing cost inputs to the Technical Targets Tool.

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 spreadsheet-based modular structure provides the "open" design allowing for future expansion—particularly the information on advanced technologies of subsystems as they become available.

Results

To date, the modeling framework was limited to vehicle component sizing and costing at the level of 30+ vehicle components. The framework was enhanced to estimate vehicle fuel economy by integrating sizing information at the major component level to the performance model ADVISOR. Component sizing inputs considered in the fuel economy estimation is mainly limited to major powertrain components, consistent with the definition of components used in ADVISOR. The integration of these two modeling frameworks is user-friendly where fuel economy runs could be made fairly quickly without any immense need for the input data preparation.

An automotive system cost model was also demonstrated for one vehicle class (i.e., Ford Explorer 2 WD) to provide cost inputs to the Technical Targets Tool currently under development by the National Renewable Energy Laboratory (NREL). This has allowed consideration of change in the vehicle cost (i.e., the new technology vehicle vs. the baseline conventional vehicle) as one of the factors in the penetration of different vehicle classes to estimate oil savings for the particular vehicle class relative to the baseline. Aggregate glider mass and cost relationships were developed as a function of powertrain mass. This allowed the estimation of change in vehicle cost resulting from the advanced powertrain technology.

To determine the cost-effectiveness of various component options at the vehicle level, scenarios encompassing five alternative powertrains (compression-ignition internal combustion engine [ICE], parallel hybrid spark-ignition ICE, parallel hybrid compression-ignition ICE, direct hydrogen fuel cell, and gasoline reformer-based fuel cell) and three body options (steel, glass fiber reinforced polymer composites, and carbon fiber reinforced polymer composites) for a mid-size vehicle under two different timeframes (2002 and 2010) were considered. The cost-effectiveness among the competing technology options was evaluated both within the same timeframe and between the two timeframes. The assumptions for various powertrain-related parameters defining these scenarios are based on DOE/FreedomCAR and Vehicle Technologies (FCVT) Program technical targets in order to examine how they would impact the commercial viability of advanced technology vehicles. The relative cost-effectiveness of the various options was considered in terms of production cost and fuel economy (derived using the ADVISOR model) and the viability of various options within two timeframes were determined and compared against the estimates available from the literature today.

Figure 1-19 shows relative production cost vs. fuel economy for alternative powertrain and lightweight body material options for a mid-size vehicle. Various options are grouped under four major categories. Among the five alternative powertrain options, direct hydrogen and gasoline reformer-based fuel cell vehicles are estimated to cost 2.4 and 3.1 times, respectively, the baseline vehicle today. Pure diesel and hybrid diesel vehicles have a smaller cost penalty (i.e., about 1.3 times the baseline vehicle). The diesel vehicles' higher costs result from today's high cost emission control equipment, including electronics, to meet the Tier 2 emission standard. Fuel economy of these advanced powertrain vehicles ranges from 38 to 60 mpg or 9–70% improvement from the baseline vehicle. Affordability of the advanced vehicles becomes more favorable by 2010 if the DOE/FCVT technical and cost targets can be met. Specifically, the fuel cell vehicles become competitive with the baseline vehicle, with production cost only 1.1 times the baseline vehicle production cost. Both pure diesel and hybrid diesel vehicles will cost less in 2010 due to technology advancements, but they will face a small cost penalty (i.e., about 6%) compared to the baseline vehicle due to emission control requirements. By meeting the technical targets in 2010, fuel economy improvements of these vehicles are substantial, ranging from 44 mpg to 80 mpg, the latter value being that of the direct hydrogen fuel cell vehicles.

The production cost penalty of the three alternative body options was found to be less than those of the five alternative powertrain options. A production cost penalty of less than 10% was obtained in 2002, and it dropped to 2% by 2010 for the aluminum body material option. These production cost penalties are in the range of those obtained for alternative powertrain options in 2010. The fuel economy resulting from alternative body material options are in the range of 41–43 mpg compared to 41 mpg for the baseline vehicle in 2010. This is the maximum value obtained in the case of carbon fiber reinforced polymer composites that offer the greatest weight reduction potential. In the near-term, the alternative body material options may offer cost-effective fuel economy potential in niche applications, but in the long-term, advanced powertrain technologies would dominate if the technical targets can be met. However, it is most likely that a combination of powertrain and body material options will be used in the commercial applications to harness the most fuel economy potential in a cost-effective way. As the few advanced technology commercial vehicles available today contain a mix of technology options, including both powertrain and body material technology options, a comparison against those may not be appropriate here. However, results in terms of relative cost-effectiveness of various technologies obtained in this study compare favorably with other existing studies in the literature today. The use of different sets of performance goals, component characteristics, simulation models, and baseline vehicles used in the various studies makes comparison difficult for specific parameter estimates. There is a greater need for additional examination of the cost-effectiveness of mass reduction.

Future Directions

During the coming year, it is suggested that mass and cost relationships between vehicle powertrain and glider demonstrated for the Technical Targets Tool developed by NREL be extended to all 13 EPA vehicle classes. In addition, a limited number of "Cost Roll-Ups" will be developed for several generic vehicle configurations covering all three light-duty vehicle platforms (i.e., passenger car, pick up truck and SUV) of interest to the FreedomCAR Partnership. Cost Roll-Ups will be developed 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 (AHHPS) program.

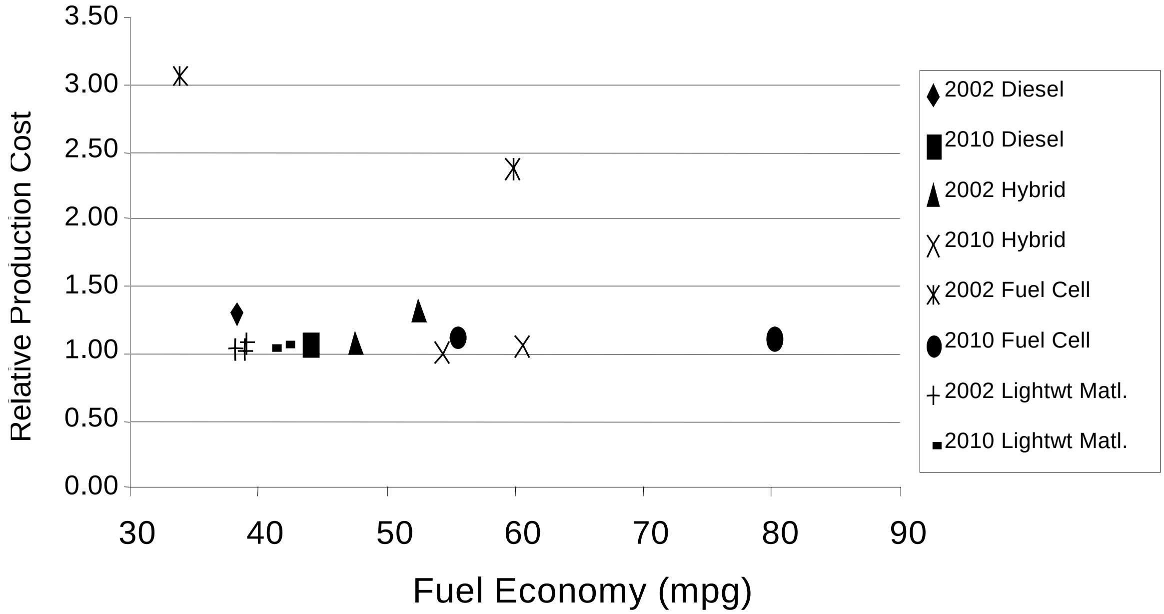

Figure 1-19. Relative production cost vs. fuel economy for alternative powertrain and lightweight (lightwt) body material options for a mid-size car

II. TECHNOLOGY VALIDATION AND BENCHMARKING

Overview

This section describes the activities related to laboratory validation of advanced propulsion subsystem technologies for hybrid electric vehicles (HEVs). It describes activities for benchmarking commercially available vehicles and components to ensure that FreedomCAR and Vehicle Technologies (FCVT) Program-developed technologies represent significant advances over technologies that have been developed by industry.

Validation and benchmarking require the use of internationally accepted test procedures and measurement methods. Argonne National Laboratory (ANL) engineers have developed the standards and protocols, which have been widely accepted and adopted by 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. The propulsion system hardware components: batteries, inverters, electric motors, and controllers are further validated in simulated vehicle environments to ensure that they will meet the vehicle performance targets established by the government-industry technical teams.

The major facility that supports these activities is the Advanced Powertrain Research Facility (APRF), a state-of-the-art automotive testing laboratory operated by ANL. The 4-wheel dynamometer allows accurate testing of hybrid vehicles with regenerative brakes. During 2003, its emissions measurement instrumentation was upgraded to enable the accurate measurement of ultra low emission vehicle (ULEV) emissions.

2.1. International Test Standards and Protocols for Laboratory Testing

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Objectives

- Develop state-of-the-art testing techniques for hybrid electric vehicles (HEVs) and fuel cell vehicles (FCVs) to enable internationally acceptable test results;
- Participate in the appropriate standards activities in the U.S. (e.g. within the Society of Automotive Engineers [SAE]; and
- Cooperate with the technical committees in support of the European Union and United Nations rulemaking activities.

Approach

- Develop and verify testing protocols for HEVs and FCVs; and
- Meet with representatives of the European Commission (EC) Research Directorate and associated laboratories to discuss cooperative activities to develop common research protocols.

Accomplishments

- Completed 40 drive cycle tests with the Honda Insight. Found a trend line for state-of-charge (SOC) correction;
- Tested the HEV in 2WD or 4WD modes to reveal differences in regenerative braking behavior. Did not observe any measurable difference;
- Determined that fuel economy is not impacted as a result of augmented braking; and
- Meetings with the EC reconfirmed the need for common protocols and specific follow-up meetings were arranged to further define the scope and mechanism for cooperation.

Future Directions

- Continue participation in these activities to ensure that U.S. Department of Energy (DOE)/Argonne National Laboratory (ANL) test standards are state-of-the-art and provide the basis to comprehend the technical trends and future requirements for hydrogen-fueled engines or fuel cells.

Introduction

The globalization of automotive manufacturers and cooperative development agreements for HEVs and FCVs, require sound test standards. Rulemaking activities already underway in the European Union will directly impact the test standards for vehicles developed and sold in those countries. This task includes cooperative activities to support the development of standards that are technically sound and can be fairly implemented globally.

Approach

Advanced Powertrain Research Facility (APRF) staff had attended a meeting of the Heavy-Duty HEV test procedure task force at the SAE 2002 Truck and Bus Conference to discuss some of the major issues that went into the SAE J2711 electric vehicle test procedure. Following this, meetings were held to discuss cooperation with the European Commission and their supporting laboratories for the standardization of research protocols for advanced propulsion systems.

The 4WD twin-axle dynamometer facility at the APRF was used to develop and confirm a SOC-correction algorithm as a part of HEV testing protocol development. ANL provided the test data for a MY00 Honda Insight (Figure 2-1) to the U.S. Environmental Protection Agency (EPA) and the California Automotive Research Board (CARB), which resulted in evaluating the effectiveness of the SOC correction.

The SOC correction scheme is an important factor in testing and analyzing the fuel economy of advanced vehicles with on-board electrochemical energy storage, such as internal combustion engine (ICE) and fuel cell/battery hybrids. This scheme has been proposed as one of the areas to be addressed by the international research community due to the potential impact on test procedures for global automotive manufacturers and to the common needs of government-sponsored research.

Figure 2-1. MY00 Honda Insight on new 4WD Dynamometer at the APRF

HEV data from the 4WD dynamometer were also analyzed to evaluate differences between EPA's 2WD dynamometer test results for a MY04 Toyota Prius.

Results
A trend line for SOC correction was found for urban and highway test cycles. Tests also confirmed that the vehicle's braking behavior does not change as a function of 2WD and 4WD modes and the fuel economy does not change as a result of augmented braking.

Working relationships have been established with EPA, CARB, SAE, and EC testing and rulemaking community.

An abstract has been submitted for the SAE congress to present the HEV SOC correction methods for testing and vehicle simulation.

Conclusions
Participation in these activities will ensure that DOE test facilities, instrumentation, and protocols will meet the highest standards for automotive testing.

2.2. Validation of Lithium-ion Battery and Electric Drive Technologies

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Objectives

- Characterize advanced hybrid electric vehicle (HEV) and fuel cell vehicle (FCV) technology components developed under the FreedomCAR and Vehicle Technologies (FCVT) Program research and development (R&D) programs to verify that they meet specified performance; and
- Validate that the vehicle will meet FCVT performance targets with the new component.

Approach

- Characterize an advanced battery pack (SAFT Li-ion), cycle the battery using the Partnership for a New Generation of Vehicles (PNGV) hybrid battery test cycle, and compare data with previous test data supplied by manufacturer;
- Verify baseline performance of an advanced electric drive system (UQM INTETS);
- Integrate drive system into a chassis for testing on the vehicle dynamometer at the Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory (ANL); and
- Test the battery and the drive unit over standard drive cycles in conjunction with the ANL fuel cell vehicle emulator on the chassis dynamometer at the APRF, using hardware-in-the-loop (HIL) testing techniques.

Accomplishments

- Verified that the battery and the drive unit met the performance specifications; and
- Validated potential application of the Li-ion battery and the UQM INTETS drive system in a fuel cell vehicle.

Future Directions

- Validate other advanced HEV and FCV components and subsystems as they become available.

Introduction

The United States Advanced Battery Consortium (USABC) had contracted with SAFT to develop a battery for hybrid vehicle applications. After delivery, the battery pack was successfully tested at the U.S. Department of Energy's (DOE's) Idaho National Engineering and Environmental Laboratory (INEEL) in FY 2002. The battery was then shipped to ANL for testing in a vehicle environment.

UQM Technologies, Inc. completed the development of an integrated electric drive (INTETS) under a DOE SBIR contract in FY 2002. The INTETS drive along with test data were provided to ANL for validation testing.

Approach and Results

<u>Li-Ion Battery Pack Validation</u>

Battery models based on ANL's Chemical Engineering Division test data are being received as part of preparation for simulating various FCVs in the Powertrain Systems Analysis Toolkit (PSAT). A plot of battery pack resistance based on the PNGV High Pulse Power Capability (HPPC) test is shown in Figure 2-2. The data were also analyzed using the Li-Ion model written by Paul Nelson.

Japan Prius data was pre-selected to answer the question: "If the Prius had a Li-Ion battery pack, would the fuel economy improve?" The Li-Ion battery pack was tested using power profiles from chassis dynamometer tests.

The battery was also tested for transient cycles. Several cycles were run using both Japan and U.S. Prius test data.

The results show that the fuel economy would increase on a Japan model Prius on the hot-505 cycle from 40.3 to 41.1 mpg, a 0.8 mpg (2%) gain, based on a state-of-charge (SOC)-Correction plot with the Li-Ion battery data (Figure 2-3).

<u>INTETS Drive System Verification</u>

In order to test it on the APRF vehicle dynamometer, the drive was modified and installed in a test chassis. Validation testing included:

- Maximum torque, acceleration and regeneration
- Efficiency vs. speed
- Response time and slew rate
- Steady-state command and response

A robust process was developed to get very accurate data, which correlated well with the UQM-provided data. Cycle efficiency was also tested under the Urban and Highway drive cycles at various road loads for two simulated fuel cell vehicle platforms.

Figure 2-4 shows the INTETS drive system mounted on a mule vehicle under test in the APRF. An example of the efficiency data is shown in Figure 2-5. The results correlate with UQM provided data for the same motor system.

Conclusions

The SAFT battery meets USABC specifications.

The UQM INTETS is suitable as a drive for the fuel cell vehicle. However, the motor supplied for testing had numerous problems that had to be fixed by UQM engineers. The motor and drive will require further testing and development before commercial introduction.

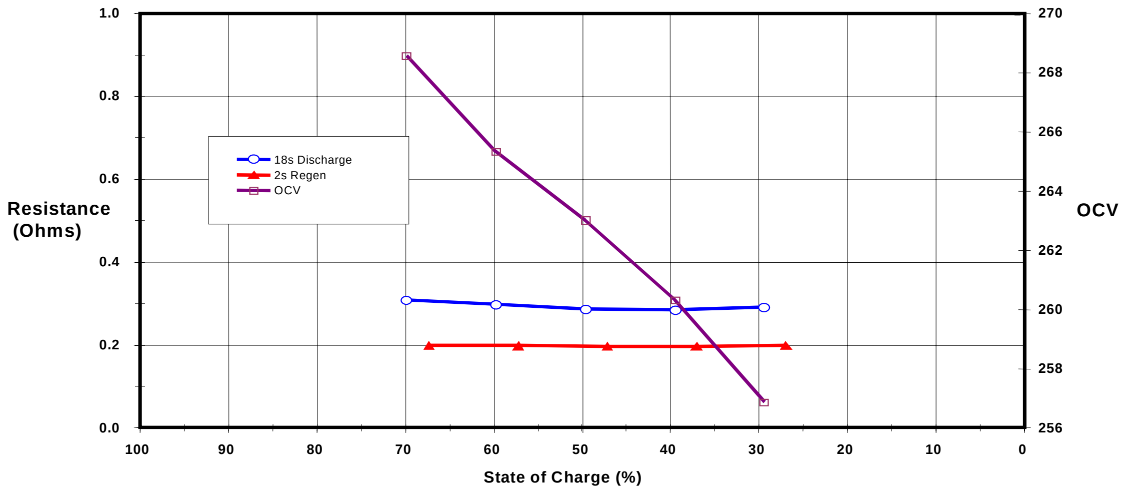

Figure 2-2. Open circuit voltage and pulse resistance vs. SOC for SAFT America Li-ion 276V, 6 AH HEV test pack

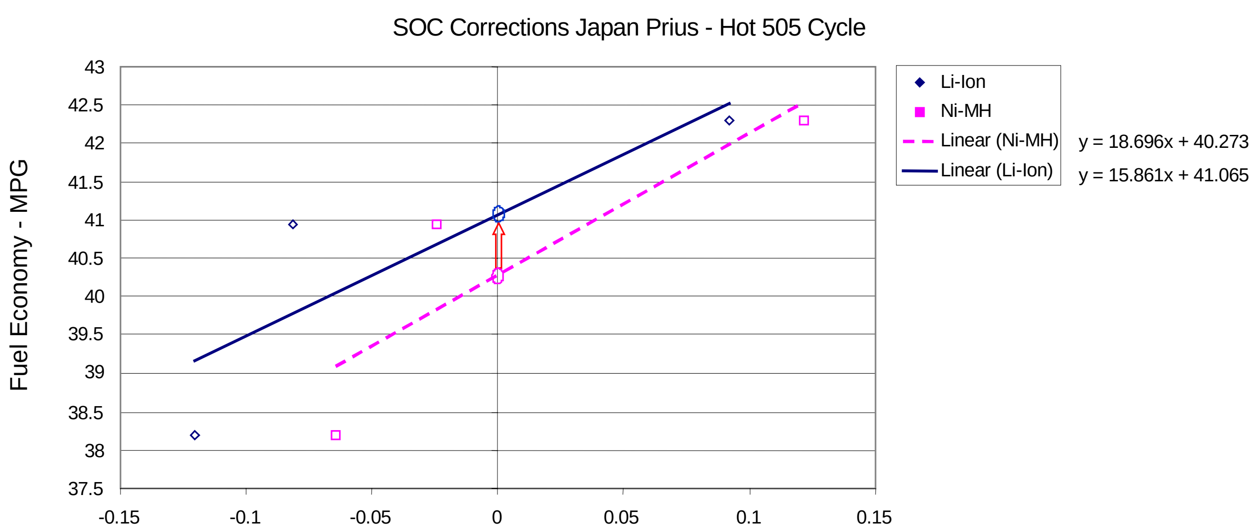

Figure 2-3. SOC corrections provide MPG result for Prius Ni-MH battery and SAFT Li-Ion battery

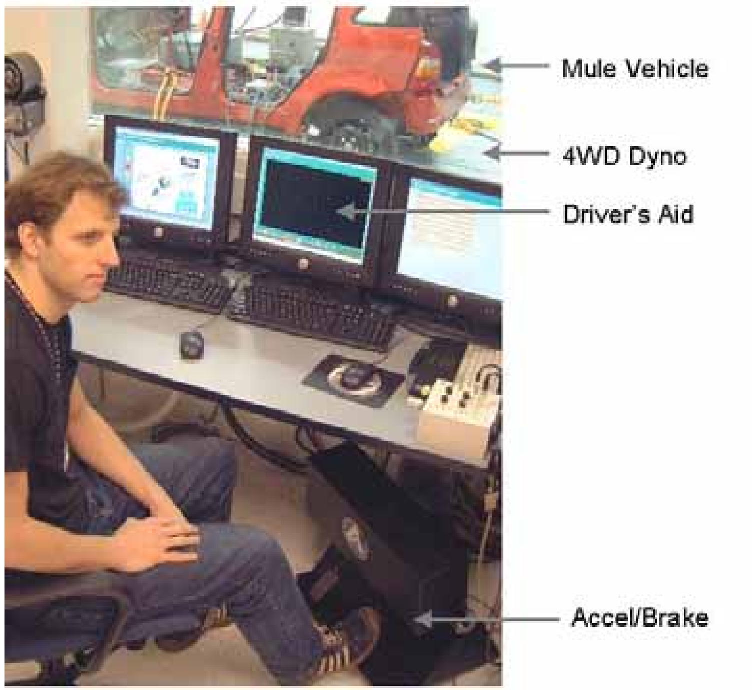

Figure 2-4. UQM INTETS mounted on a mule vehicle under test at the APRF

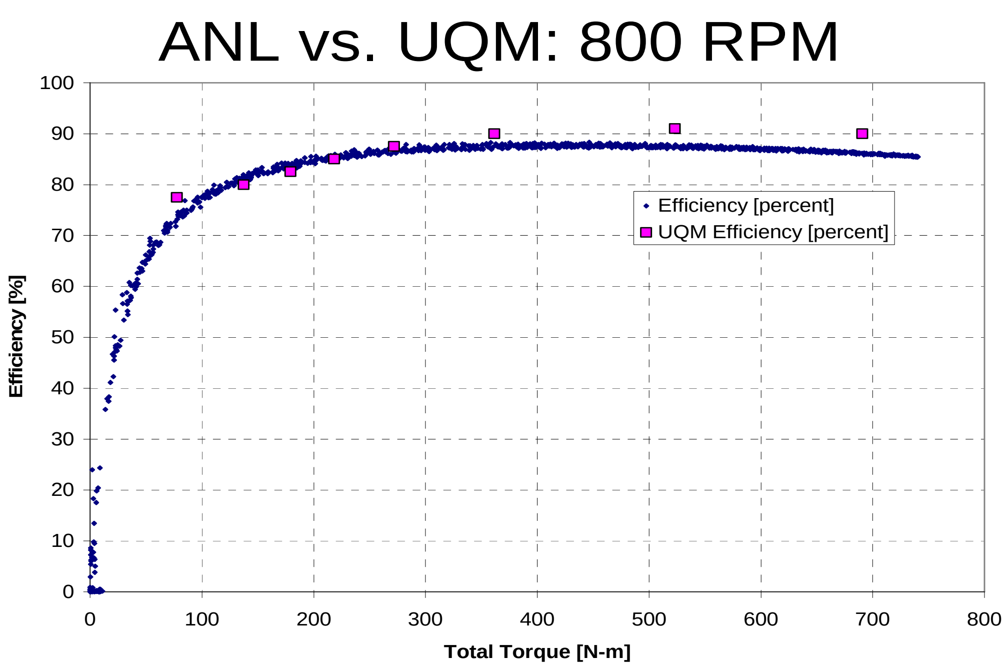

Figure 2-5. Comparison of ANL efficiency data with manufacturer's data

2.3. Benchmarking of Hybrid Electric Vehicles (HEVs) and Fuel Cell Vehicles (FCVs)

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DOE Technology Manager: Lee Slezak

Objectives

- Benchmark available vehicles/propulsion components to assess development status and set appropriate technology development targets; and
- Contribute to an understanding of competitive vehicle technologies (i.e., the Toyota Prius) and specific implementations.

Approach

- Assess the technologies of prototype and commercially available hybrid and fuel cell vehicles;
- Acquire, modify and instrument the subject vehicles for testing in the Advanced Powertrain Research Facility (APRF); and
- Acquire and analyze data; document results.

Results

- Obtained insights on the hybrid electric vehicle (HEV) engine/powertrain controls for optimum fuel economy, emissions and service life;
- Benchmarked an experimental Ford F-150 truck, using a 50-50 mixture of natural gas and hydrogen; and
- Prepared test plans and equipment for mapping emissions and fuel economy data for a MY04 Prius.

Future Directions

- Benchmark MY04 Toyota Prius in the APRF; and
- Acquire and benchmark a fuel cell vehicle (FCV).

Introduction

Vehicle/technology benchmarking is a critical part of defining technology development requirements (a core function of the U.S. Department of Energy [DOE]). Argonne National Laboratory (ANL) has the facilities, instrumentation and staff to test and validate the performance of vehicles and components in simulated vehicle environments. This project will acquire, instrument, and test vehicles and technologies of interest to DOE at a level of detail that would be sufficient to characterize the vehicle performance and allow a detailed analysis of its technology advances.

Approach

The computer host for the dynamometer was enhanced to provide immediate results for analysis after testing. The data collected included instantaneous emissions, fuel economy and dynamometer speed. A vehicle-specific analysis page obtained during the tests is shown in Figure 2-6. The change in battery state of charge, measured as ampere-hours, its trend, open circuit voltage and pack resistance are shown.

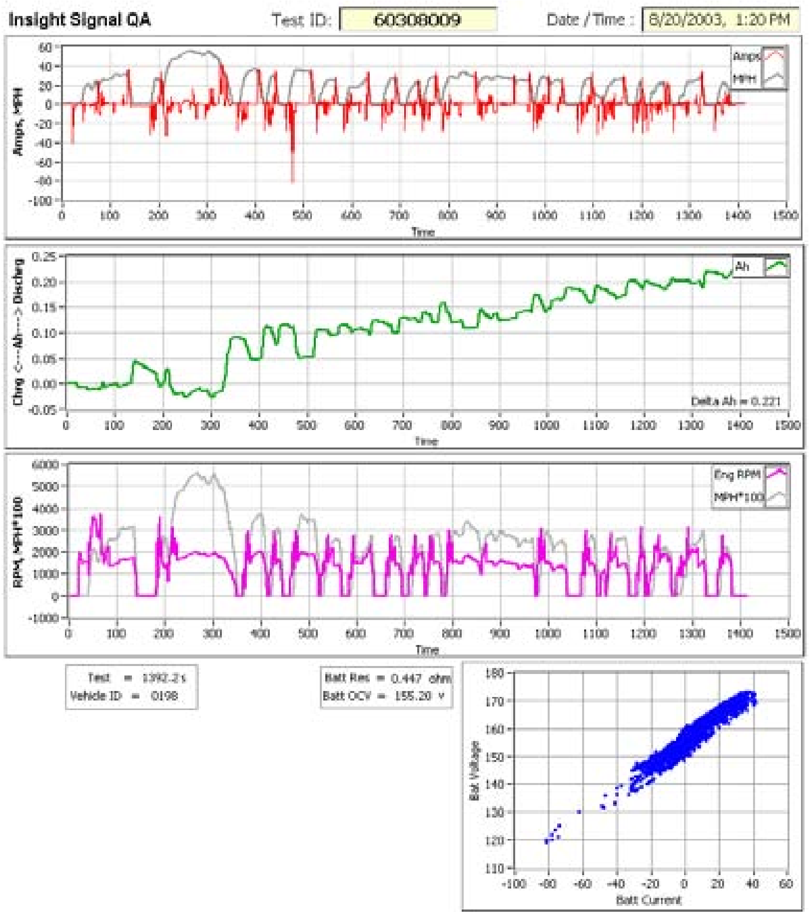

Figure 2-6. Typical HEV operation analysis printout

Arizona Public Service and the Idaho National Engineering and Environmental Laboratory (INEEL) provided an experimental Ford F-150 truck for emissions testing. The truck runs on a 50-50 mixture of compressed natural gas and hydrogen. Special gas was ordered in “type K” cylinders to fuel the truck. The gas was mixed according to California Air Resources Board (CARB) natural gas fuel specifications to ensure repeatability and traceability. The testing was a good shakedown for the Host control system and improvements to the system have been completed. Figure 2-7 shows the resulting emissions measurements.

A planning document for testing MY04 Prius was prepared for discussion with the vehicle systems technical team. A number of new options were explored for measuring engine torque with minimal modifications to the powertrain. A detailed test plan was developed and approved.

As a preliminary test, Prius engine ignition timing test data were obtained. This testing utilized a new piece of ANL equipment that was integrated into the facility and can read On-Board Diagnostic Generation II (OBDII) engine data from the vehicle’s diagnostic port directly into the data acquisition system. This benchmarking effort is key to analyzing HEV engine and powertrain controls for optimum fuel economy without compromising emissions and service life targets (Figure 2-8).

Conclusions

Reliable measurements of emissions and fuel economy can be obtained from dynamometer tests in the APRF. Planning for benchmark testing the MY04 Toyota Prius has been completed and test plans have been approved.

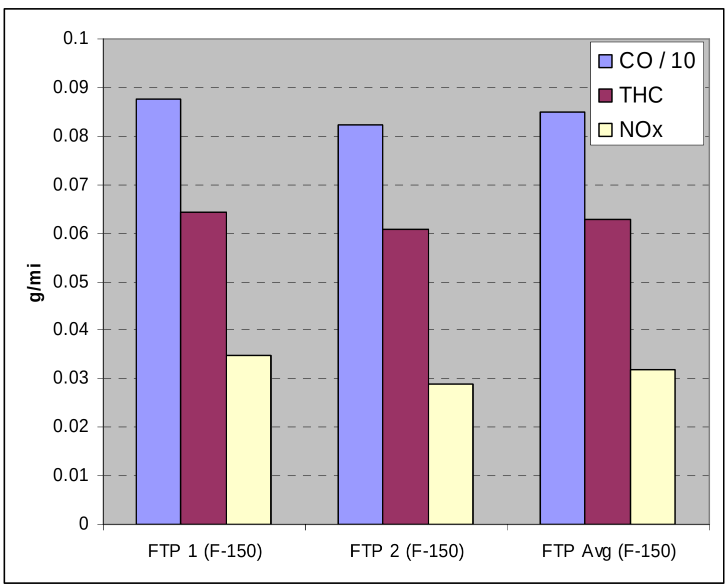

Figure 2-7. Ford F-150 50% natural gas (NG) / 50% H_2 Emission Results

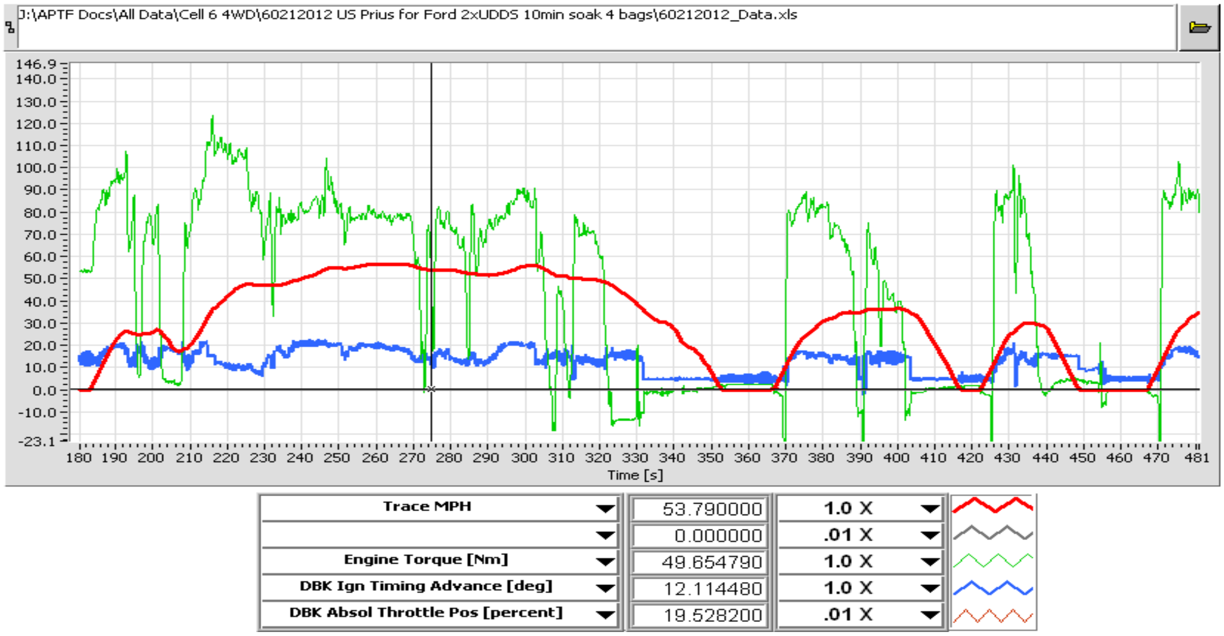

Figure 2-8. Prius ignition advance (bottom trace) during part of the Federal Test Procedure (FTP) cycle test

2.4. Advanced Powertrain Research Facility (APRF)

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Objectives

- Provide and maintain a state-of-the-art vehicle test facility with accurate instrumentation and data acquisition equipment; and
- Provide capability for hardware-in-the-loop testing of advanced vehicle components.

Approach

- Upgrade facility for testing hydrogen fuel vehicles; and
- Improve support systems for safety, air humidity, dynamometer cooling, and engine exhaust management.

Accomplishments

- Dedicated the 4WD addition to the Advanced Powertrain Research Facility (APRF) in November 2002;
- Completed improvements to 4WD chassis dynamometer data acquisition computer to provide immediate availability of comprehensive test cycle results;
- Completed installation of hydrogen gas distribution system; and
- Tested a correlation vehicle on loan from Ford to verify consistent emissions data within specified error range.

Future Directions

- Improve control of tailpipe exhaust back pressure to maintain it at atmospheric pressure within 1" of H_2O; and
- Continue maintenance and upgrades to ensure maximum availability of the facility for benchmarking and validation tests.

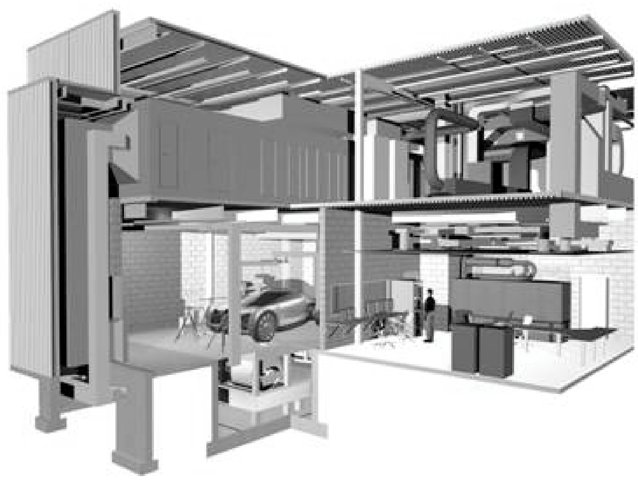


Figure 2-9. Cutaway view of Advanced Powertrain Research Facility (APRF)

Introduction

The APRF (Figure 2-9) was developed to test experimental hardware in support of U.S. Department of Energy's (DOE's) vehicle efficiency and emissions objectives. With the building addition and commissioning of the Super Ultra-Low Emission Vehicles (SULEV) 4WD dynamometer facility completed in FY 2002, DOE now has one of the most advanced vehicle test facilities in the country. This task includes the necessary maintenance and upgrades of equipment and facilities as well as compliance with safety guidelines/ regulations and quality control procedures.

Approach

Extensive planning was completed for the addition of a gaseous hydrogen distribution system in the 4WD test cell. A hardware supplier, contractors and a gas supplier have been identified. The key components for this system have been ordered.

The combustible gas detection sensors within the 4WD test facility were interlocked with air handling unit-1 (AHU-1), the main air handling unit for the test cell, in preparation for testing gaseous fueled vehicles on a routine basis. If a gas release were to occur at a level of 25% lower explosive limit (LEL) or greater, AHU-1 would ramp up to full speed (26,000 cfm—two air changes per minute) with maximum fresh air supplied to the test cell and maximum exhaust of the test cell air to the exterior of the building with no recirculation. This system was tested and validated.

Options for better control of tailpipe exhaust backpressure were investigated. This is important so that exhaust gas is not pulled from the vehicle tailpipe and backpressure in the vehicle exhaust system is not increased. Either scenario can affect the engine (exhaust gas recirculation) EGR rate. The ideal situation is to have the tailpipe exhaust maintained at atmospheric pressure within 1.0" H_2O regardless of engine throttle position. In order to accomplish this, a second damper with feedback control was installed into the supply duct of AHU-4 in the 4WD test facility. The result was a significant improvement in active control of exhaust system backpressure to a level within ±1.0" H_20 during the Federal Test Procedure (FTP) and HWFEW driving cycles.

The system automatically responds to changes in vehicle load or changes in the chosen venturi for exhaust gas mass flow measurements.

A new smooth bore, 3” straight pipe exhaust system, adjustable for different vehicles, was completed and tested successfully. Heated blankets for the piping sections were specified and ordered to maintain an internal pipe temperature of 185°C. This ensures that condensate does not drop out of the exhaust gas between the vehicle tailpipe and the emissions sample point in the dilution tunnel. New electrical power was provided to a Proportional, Integral, Derivative (PID) loop control enclosure on the test cell wall.

In order to validate the 4WD dynamometer, the emissions equipment, and the particulate measuring equipment, two heavy-duty Cummins Dodge Ram pick-up trucks were rigorously tested. The vehicles were run at various drive cycles including the US06, an aggressive, high-speed drive cycle, to obtain both fuel economy and emissions data. In all, more than 30 tests were completed.

Several software and hardware changes were made to the air handling unit controls for tighter and more responsive temperature control.

The 4WD chassis dynamometer “Host” computer was upgraded to save data more effectively and to allow modular processing routines at run-time. Immediate availability of comprehensive test cycle results in print-out and electronic forms will facilitate post-processing.

Cost analysis was performed to compare on-site equipment calibration vs. outside vendors. As a result, some equipment will now be sent for calibration by a local vendor.

Extensive troubleshooting of the Burke Porter 4WD dynamometer was required when the ability to raise or lower the rear dynamometer centering lifts and roll covers was lost. Mechanical changes to the dynamometer were completed so this problem will not reoccur.

Results

The most significant event during FY 2003 was the dedication of the 4WD addition to the APRF. Argonne National Laboratory’s (ANL’s) Center for Transportation Research capabilities in simulation, emulation and validation were successfully demonstrated to over 100 visitors, including DOE management and local and federal politicians.

Conclusions

The APRF provides reliable and accurate data on the performance and emissions of advanced automotive systems in a controllable environment. ANL data compares very well with data gathered on the same diesel vehicles at another test laboratory.

III. ADVANCED VEHICLE TESTING ACTIVITY

Overview

The Advanced Vehicle Testing Activity (AVTA) develops vehicle test procedures with input from industry and other stakeholders to accurately measure real-world vehicle performance. The performance and capabilities of advanced technologies are benchmarked to support the development of industry and U.S. Department of Energy (DOE) technology targets. The testing results provide data for validating component, subsystem, and vehicle simulation models and hardware-in-the-loop testing. AVTA provides guidance to fleet managers and the public for acquiring advanced technology vehicles. Light-duty testing activities are conducted by Idaho National Engineering and Environmental Laboratory (INEEL) in partnership with an industry group led by Electric Transportation Applications, Inc. medium- and heavy vehicle testing activities are conducted by the National Renewable Energy Laboratory (NREL) in conjunction with various truck fleet and transit bus operators. The testing results are presented in a uniform format to allow users to compare the performance of different types of vehicles. AVTA findings are primarily disseminated through the AVTA's worldwide web pages (http://eere.energy.gov/vehiclesandfuels/avta.gov). Additional methods include publication of papers and presentations at industry conferences such as those sponsored by the Society of Automotive Engineers and the Electric Drive Transportation Association.

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

Baseline Performance Testing
The objective of baseline performance testing is to provide a highly accurate snapshot of a vehicle's performance in a controlled testing environment. The testing is designed to be highly repeatable. Hence it is conducted on closed tracks and dynamometers, providing comparative testing results that allow "apple-to-apple" comparisons within respective vehicle technology classes. A typical baseline performance testing result fact sheet is shown in Figure 3-1.

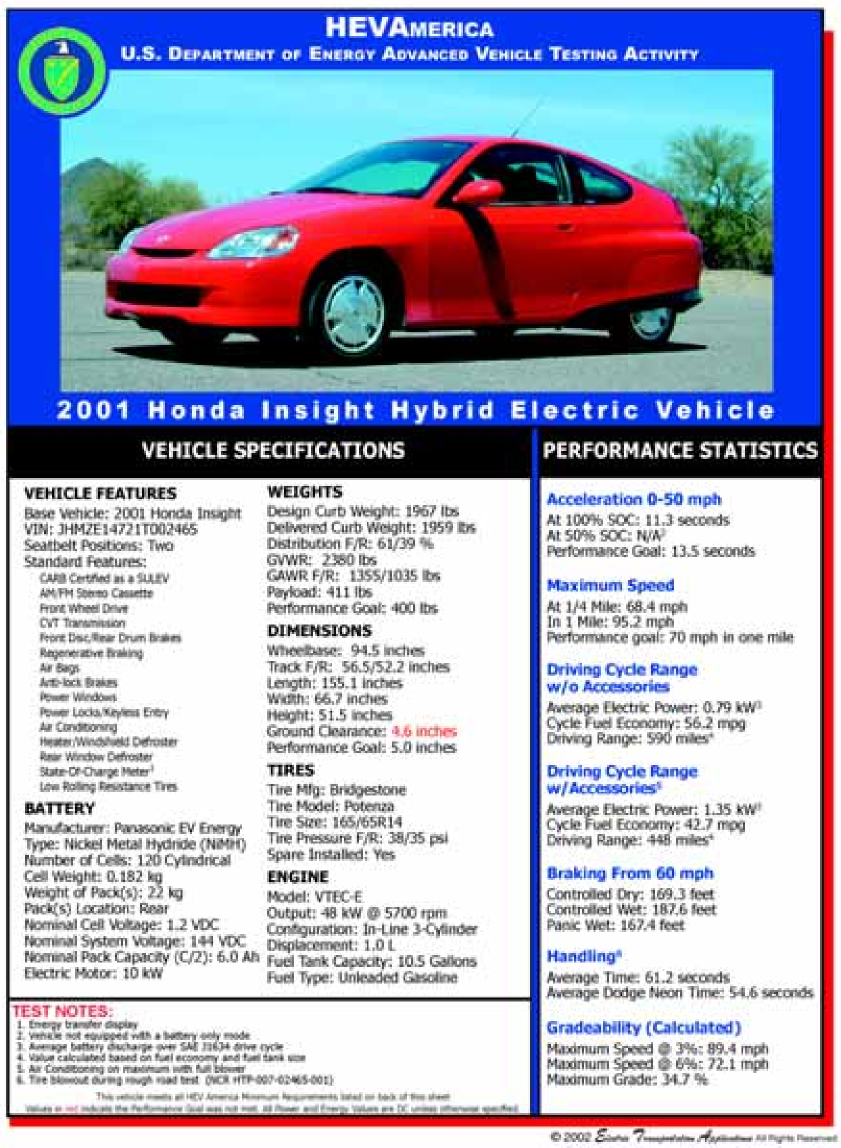
Accelerated Reliability Testing
The objective of accelerated reliability testing is to quickly accumulate several years' worth of mileage on each test vehicle. The tests are generally conducted on public roads and highways and testing usually lasts for 12 to 15 months per vehicle. The miles to be accumulated depend on the vehicle technology being tested. For instance, the testing goal for pure electric vehicles (EVs) is to accumulate 25,000 miles per vehicle within one year. This is three or four times the number of miles a full-size EV is normally driven in one year. For hybrid electric vehicles (HEVs), because of their higher speeds and greater ranges between fueling, up to 100,000 miles are accumulated in 12 to 15 months. This is approximately eight times the average miles driven by light-duty internal combustion engine (ICE) vehicles in a single year. Generally, two or three vehicles of each model are tested to ensure accuracy.

Accelerated testing provides reliable estimates of the fuel economy, operations and maintenance requirements, general vehicle performance, engine and component (such as energy storage system) life, and life-cycle costs. These data are useful to the fleet manager or other potential purchasers for making purchasing decisions.

Fleet Testing
Fleet testing provides a real-world balance to other testing methods. Some fleet managers prefer fleet testing results to the more controlled baseline performance or the accelerated reliability testing.

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

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



HEVAMERICA

U.S. DEPARTMENT OF ENERGY ADVANCED VEHICLE TESTING ACTIVITY

2001 Honda Insight Hybrid Electric Vehicle

VEHICLE SPECIFICATIONS

VEHICLE FEATURES
Base Vehicle: 2001 Honda Insight
VIN: JHMZE14721T002465
Seatbelt Positions: Two
Standard Features:
- CARB Certified as a SULEV
- AM/FM Stereo Cassette
- Front Wheel Drive
- CVT Transmission
- Front Disc/Rear Drum Brakes
- Regenerative Braking
- Air Bags
- Anti-lock Brakes
- Power Windows
- Power Locks/Keyless Entry
- Air Conditioning
- Heater/Windshield Defroster
- Rear Window Defroster
- State-Of-Charge Meter[1]
- Low Rolling Resistance Tires

BATTERY
Manufacturer: Panasonic EV Energy
Type: Nickel Metal Hydride (NiMH)
Number of Cells: 120 Cylindrical
Cell Weight: 0.182 kg
Weight of Pack(s): 22 kg
Pack(s) Location: Rear
Nominal Cell Voltage: 1.2 VDC
Nominal System Voltage: 144 VDC
Nominal Pack Capacity (C/2): 6.0 Ah
Electric Motor: 10 kW

WEIGHTS
Design Curb Weight: 1967 lbs
Delivered Curb Weight: 1959 lbs
Distribution F/R: 61/39 %
GVWR: 2380 lbs
GAWR F/R: 1355/1035 lbs
Payload: 411 lbs
Performance Goal: 400 lbs

DIMENSIONS
Wheelbase: 94.5 inches
Track F/R: 56.5/52.2 inches
Length: 155.1 inches
Width: 66.7 inches
Height: 51.5 inches
Ground Clearance: 4.6 inches
Performance Goal: 5.0 inches

TIRES
Tire Mfg: Bridgestone
Tire Model: Potenza
Tire Size: 165/65R14
Tire Pressure F/R: 38/35 psi
Spare Installed: Yes

ENGINE
Model: VTEC-E
Output: 48 kW @ 5700 rpm
Configuration: In-Line 3-Cylinder
Displacement: 1.0 L
Fuel Tank Capacity: 10.5 Gallons
Fuel Type: Unleaded Gasoline

PERFORMANCE STATISTICS

Acceleration 0-50 mph
At 100% SOC: 11.3 seconds
At 50% SOC: N/A[2]
Performance Goal: 13.5 seconds

Maximum Speed
At 1/4 Mile: 68.4 mph
In 1 Mile: 95.2 mph
Performance goal: 70 mph in one mile

Driving Cycle Range w/o Accessories
Average Electric Power: 0.79 kW[3]
Cycle Fuel Economy: 56.2 mpg
Driving Range: 590 miles[4]

Driving Cycle Range w/Accessories[5]
Average Electric Power: 1.35 kW[3]
Cycle Fuel Economy: 42.7 mpg
Driving Range: 448 miles[4]

Braking From 60 mph
Controlled Dry: 169.3 feet
Controlled Wet: 187.6 feet
Panic Wet: 167.4 feet

Handling[6]
Average Time: 61.2 seconds
Average Dodge Neon Time: 54.6 seconds

Gradeability (Calculated)
Maximum Speed @ 3%: 89.4 mph
Maximum Speed @ 6%: 72.1 mph
Maximum Grade: 34.7 %

TEST NOTES:
1. Energy transfer display
2. Vehicle not equipped with a battery only mode
3. Average battery discharge over SAE J1634 drive cycle
4. Value calculated based on fuel economy and fuel tank size
5. Air Conditioning on maximum with full blower
6. Tire blowout during rough road test (NCR HTP-007-02465-001)

This vehicle meets all HEV America Minimum Requirements listed on back of this sheet
Values in red indicate the Performance Goal was not met. All Power and Energy Values are DC unless otherwise specified.

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Figure 3-1. Baseline performance testing results fact sheet for a Honda Insight hybrid electric vehicle (HEV) that underwent HEVAmerica testing

During FY 2003, baseline performance testing was carried out for hydrogen and compressed natural gas (CNG) engine-powered vehicles. Benchmarking and accelerated reliability testing was carried out for ICE-battery hybrid electric vehicles. Fleet testing was carried out for neighborhood and urban electric vehicles, LNG engine-powered refuse trucks, and CNG and hybrid electric transit buses. A hydrogen/CNG fueling station that produces hydrogen on site was commissioned and test procedures had to be developed to conduct many of the tests. Such projects and test results are described next.

3.1. Testing of Hydrogen-Blend Fueled Internal Combustion Engine (ICE) Vehicles

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DOE Technology Manager: Lee Slezak

Objectives

- Gain an understanding of hydrogen infrastructure requirements, including hydrogen production, storage, blending and delivery; and
- Assess the safety and reliability of using hydrogen/compressed natural gas (CNG) blends for fueling internal combustion engine (ICE)-powered vehicles.

Approach

- Use the Arizona Public Service Hydrogen (H)/CNG Pilot Plant in Phoenix to fuel a 100% hydrogen ICE Mercedes Benz van and two H/CNG ICE Ford F-150 pickups; and
- Fleet test 12 additional H/CNG-powered ICE test vehicles to provide H/CNG ICE vehicle operating knowledge in a government fleet and a utility fleet in the greater Phoenix area.

Results

- No safety problems were encountered with fueling or operating the vehicles with various blends of hydrogen with CNG;
- The vehicles demonstrated consistent, reliable behavior; and
- Hydrocarbon and carbon monoxide emission levels were reduced below levels observed with pure CNG vehicles. Oxides of nitrogen (NO_x) levels were increased for the 15% H/CNG blend.

Future Directions

- Consider testing additional hydrogen and H/CNG vehicles that become available; and
- Test 100% hydrogen-fueled ICE Ford pickups for baseline performance.

Introduction

Federal regulation requires energy companies and government entities to utilize 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 (H/CNG) 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 H/CNG blends in existing CNG vehicles.

Approach

<u>H/CNG Filling Station</u>

The Arizona Public Service (APS) Alternative Fuel Pilot Plant (Figure 3-2) is a model hydrogen, compressed natural gas (CNG), and H/CNG 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. The hydrogen is compressed to 6,000 psi and stored in a high-pressure storage tank. 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; and the water purification, nitrogen, and helium equipment are located in an adjacent building.

The fueling station is located outside the buildings. Both hydrogen and CNG dispensing are performed in the same manner. One hose dispenses hydrogen into the vehicle with a pressure rating of up to 5,000 psi. The other hose dispenses hydrogen-enriched CNG and 100% CNG at a vehicle pressure rating of up to 3,600 psi.

Figure 3-2. Hydrogen fueling station in Phoenix, AZ., with the fueling dispensers in the foreground

30% H/CNG Tests

To perform this evaluation, a work plan was developed to test the acceleration, range, and exhaust emissions of a Ford F-150 pickup truck operating on 100% CNG and blends of 15 and 30% H/CNG. This work was conducted by Electric Transportation Applications. The vehicle had previously been tested in fleet operation, using a blend of 30% H/CNG.

Test vehicle. The test vehicle was a model year 2000, F-150 regular cab pickup truck equipped with a factory CNG engine (Table 3-1) and 3,600 psig carbon steel fuel tanks with an 85-liter capacity. It was modified by NRG Tech in Reno, Nevada to run on a blend of CNG and up to 30% hydrogen (by volume). The modifications include turbocharging, ignition modifications, and exhaust gas recirculation. Parametric performance testing with H/CNG-blended fuels was conducted in May and June 2003. At the beginning of this test program, the vehicle had accumulated 31,678 miles, operating with H/CNG fuel.

Table 3-1. Ford F-150 factory specifications

Engine	5.4 L V8
Factory HP	230 HP
Curb weight	5,170 lb
GVWR	7,650 lb

Fuel Economy and Range Testing. The range of the F-150 test vehicle was tested at the Arizona Proving Grounds (APG), in accordance with the Hydrogen ICE Vehicle Constant Speed Fuel Economy Tests Procedures, for 100% CNG and blends of 15 and 30% H/CNG. Tests were performed at a constant speed of 45 mph, using the 4.2-mile-long high-speed oval track at the APG. The vehicle was driven 60 miles on each fuel and the amount of fuel used was determined through the mathematical relationship between pressure, temperature, and mass for a perfect gas. From these calculations, the fuel economy in gasoline gallon equivalents (GGE) was determined and can be found in Table 3-2. Vehicle range was calculated from the fuel economy and the capacity of the fuel tanks (85 liters) filled to 3,600 psi.

As shown in Table 3-2, degradation of vehicle range was significant with the 30% H/CNG fuel, due to the lower energy content of hydrogen when compared to CNG on a volumetric basis. The decrease in range between 100% CNG and 30% H/CNG would require a 16.4 % increase in onboard fuel storage volume to maintain vehicle range. In the case of the F-150 test vehicle, this would require the addition of a 14-liter fuel tank. With a blend of 15% H/CNG, the range degradation was less than 10%, which should have a negligible impact on vehicle utility in fleet operation.

Table 3-2. Range and fuel economy at a constant speed of 45 mph for CNG, and H/CNG blends

Fuel	Fuel Economy (miles/gge)	Range (miles)
CNG	23.3	122
15% H/CNG	22.6	110
30% H/CNG	23.5	102

Emissions Testing. Exhaust emissions showed significant reductions over gasoline for nonmethane hydrocarbons (NMHC), CO, NO_X, and CO_2. However, CH_4 and HC increased with the introduction of the methane-based CNG (Table 3-3). Much of the reductions in CO, NO_X, and CO_2 emissions are achieved by switching from gasoline to CNG. Additional CO reductions are achieved with higher percentage blends of hydrogen in CNG. However, NO_X increases with the higher-percentage blends.

Acceleration Performance Testing. As expected, the performance (in terms of acceleration) of the F-150 test vehicle degrades with increasing amounts of hydrogen in the fuel (Table 3-4). However, much of the performance loss results from the initial switch from a liquid fuel (gasoline) to a gaseous fuel (CNG). The degradation in acceleration resulting from use of hydrogen in the fuel does not have a significant impact on the drivability until blends approaching 30% hydrogen are used.

Degradation of acceleration can be remedied by either increasing the amount of fuel and air entering the engine cylinders or by directly injecting hydrogen into the cylinder to avoid the displacement of air by the hydrogen fuel. However, this requires additional vehicle modifications, which does not appear to be economically practical for introducing blended fuels into existing CNG fleets.

<u>50% H/CNG Tests</u>

Test vehicle. The high-percentage-blend H/CNG test vehicle is a model year 2001 Ford F-150, originally equipped with a 5.4L gasoline engine. It was modified to run on a blend of CNG and hydrogen by NRG Technologies, Inc. by installing a supercharger, exhaust intercooler, ignition modifications and equipped with three hydrogen tanks.

Quantum Technologies, located in Irvine, California, manufactured the hydrogen-rated fuel storage tanks. The tanks have an inner polymer liner that is not prone to hydrogen embrittlement, a carbon fiber reinforced shell, and a tough external shell that enhances damage protection. The tanks have a maximum actual working pressure of 4,400 psi and a service pressure of 3,600 psi. Each tank weighs 120 lb and has a capacity of 3 kg of hydrogen at 15°C.

Emissions Testing. Table 3-5 shows the reduction in emissions due to the use of high-percentage-blend (50% H/CNG) F-150, compared to that of the gasoline-fueled F-150. The results show a considerable decrease in all measured emission levels (excluding methane). Total hydrocarbon emissions decreased slightly. Carbon monoxide emissions measured 0.879 g/mi, which is well under the 1 g/mi California Super Ultra-Low Emission vehicle (SULEV) standard. The most noteworthy achievement of this vehicle, however, is its virtually zero nitrogen oxide emissions.

Results

The primary goal of testing the high-percentage-blend F-150 on H/CNG fuel was to evaluate the safety and reliability of operating such a system. No safety problems were encountered with fueling or operating the F-150 using either 30% or 50% hydrogen-blend fuel. The vehicle demonstrated consistent, reliable behavior and had no operating problems. The vehicle achieved very low emissions compared to gasoline engines and has near zero NO_x levels.

Table 3-3. Emissions testing results using blended fuels

	Percentage Change in Emission Species					
Fuel Type	NMHC	CH_4	HC	CO	NO_X	CO_2
Gasoline	Base	Base	Base	Base	Base	Base
CNG	−80	+967	+35	−63	−34	−24
15% H/CNG	−78	+1000	+40	−70	−26	−27
30% H/CNG	−89	+1050	+37	−73	−25	−28

NMHC = nonmethane hydrocarbons CH_4 = methane HC = total hydrocarbons
CO = carbon monoxide NO_x = oxides of nitrogen CO_2 = carbon dioxide

Table 3-4. Acceleration to 60 mph for various fuels

Fuel Blend	Time to 60 mph (seconds)	Degradation from CNG F-150	Degradation from Gasoline F-150
Gasoline[1]	8.6 (1)	---	Base
CNG	10.10	Base	17.4 %
15% H/CNG	10.97	8.6 %	27.6 %
30% H/CNG	12.68	25.5 %	47.4 %

[1] 2001 Ford F-150 with 5.4L V-8 engine and automatic transmission, as reported by edmunds.com.

Table 3-5. Percent reduction in emissions (H/CNG versus gasoline-fueled F-150)

HC	CO	NO_X	CO_2
3.5%	43.3%	97.0%	16.7%

HC = total hydrocarbons; NOx = oxides of nitrogen; CO = carbon monoxide; CO_2 = carbon dioxide.

The addition of hydrogen to the CNG fuel of the high-percentage-blend F-150 did not impact the reliability of the vehicle during this limited test. Emissions from the blend were extremely low compared to the gasoline F-150 and to the SULEV standard and the vehicle exhibited near-zero nitrogen oxide emissions.

<u>15% H/CNG Tests</u>

The primary objective of operating a group of vehicles on a blend of 15% H/CNG to evaluate the safety and reliability of operating the vehicles on H/CNG fuels and the interface between the vehicles and the hydrogen-fueling infrastructure. A secondary objective was to quantify vehicle emissions, cost, and performance. To support these objectives, the Advanced Vehicle Testing Activity (AVTA) is operating a fleet of twelve CNG vehicles on 15% H/CNG. The vehicles include a Dodge Ram Wagon Van and General Motors Sierra pickups, S-10 pickups, and Blazers. Because the Dodge van was operated the most during FY 2003 and received the most testing, it is discussed below. All vehicles continue to operate during FY 2004.

By blending CNG with 15% hydrogen, emission levels were generally reduced. Nitrogen oxide emissions, however, increased substantially. The rise in NO_x levels from the H/CNG-fueled Dodge van occurred in phases 1 and 3 of the Federal Test Procedure (FTP)-75 test (cold start and hot start phases, respectively). Phase 1 NO_x emissions increased by 70% and phase 3 NO_x emissions increased by 142%. During phase 2, the transient phase, NO_x emissions were actually reduced by 40% from the HCNG-fueled van compared to the pure-CNG-fueled van. The rise in NO_x levels during phases 1 and 3 can be attributed to the fact that the vehicle had no engine modifications and was not optimized to burn H/CNG blends.

The safety and reliability of the Dodge Ram Wagon Van have been excellent. Further testing of the effects of using 15% hydrogen/85% CNG fuel is required to determine long-term effects of the fuel on vehicle components and performance. Testing of all vehicles will continue into FY 2004.

Publications

Karner, D. and J.E. Francfort. December 2003. *Arizona Public Service – Alternative Fuel (Hydrogen) Pilot Plant Design Report.* INEEL-03-00976. Idaho National Engineering and Environmental Laboratory. Idaho Falls, ID.

Karner, D. and J.E. Francfort. November 2003. *Hydrogen/CNG Blended Fuels Performance Testing in a Ford F-150.* INEEL-03-01313. Idaho National Engineering and Environmental Laboratory. Idaho Falls, ID.

Karner, D. and J.E. Francfort. January 2003. *Hydrogen-Fueled Mercedes Sprinter Van Operating Summary.* INEEL-03-00009. Idaho National Engineering and Environmental Laboratory. Idaho Falls, ID.

Karner, D. and J.E. Francfort. January 2003. *Low-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary.* INEEL-03-00008. Idaho National Engineering and Environmental Laboratory. Idaho Falls, ID.

Karner, D. and J.E. Francfort. January 2003. *High-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary.* INEEL-03-00007. Idaho National Engineering and Environmental Laboratory. Idaho Falls, ID.

Karner, D. and J.E. Francfort. January 2003. *Dodge Ram Wagon Van – Hydrogen/CNG Operations Summary.* INEEL-03/00006. Idaho National Engineering and Environmental Laboratory. Idaho Falls, ID.

3.2. Testing of Hybrid Electric Vehicles (HEVs)

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Objective

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

Approach

- Perform baseline performance and accelerated reliability tests on 3 HEV models; and
- Put selected HEVs in fleets to obtain fuel economy under actual road conditions.

Results

- Baseline performance was almost identical for all 3 HEVs tested;
- The 3 types of HEV exhibited varying fuel economies: 38.1 mpg for Honda Civic, 41 mpg for '02 Toyota Prius, and 45.8 mpg for Honda Insight; 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 2004 and 2005; and
- Ascertain HEV battery life by accelerated reliability testing.

Introduction

Today's light-duty hybrid electric vehicles (HEVs) use a gasoline internal combustion engine (ICE) and electric traction motor with 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 ICE engine may run on alternative fuels such as hydrogen, methane, hydrogen blended with compressed natural gas (H/CNG), propane, or natural gas. The Advanced Vehicle Technology Analysis and Evaluation (AVTAE) activity needs to benchmark and test each type of HEV to compare the advantages and disadvantages of each technology.

Approach

During FY 2003, the Advanced Vehicle Testing Activity (AVTA) performed baseline performance testing and accelerated reliability testing on three HEV models: the Toyota Prius, Honda Insight, and Honda Civic. A few HEVs were also employed in fleet testing.
HEV-specific testing experience was obtained first by testing the Prius and the Insight on the relatively lower-cost Pomona Loop, then by developing the HEV baseline performance testing specifications and procedures.

Results

The baseline performance tests included zero to 50 mph acceleration, maximum speed at a quarter mile and one mile, and maximum speed on 6% grade. The testing results are shown in Figure 3-3. The results of accelerated reliability and fleet testing on 16 HEVs are summarized in Table 3-6.

Conclusions

The fleet and accelerated reliability fuel economy testing results by month of operation are graphed in Figure 3-4. The largest impact on fuel economy is from the use of the air conditioning during the summer months.

New HEVs available from U.S., Japanese and European manufacturers will be benchmarked during FY 2004 and 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

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

Table 3-6. HEV accelerated reliability and fleet testing results as of November 2003

Number of models in testing	Total test miles	Miles per gallon
6 Honda Insights	302,000	45.8
4 Honda Civics	248,000	38.1
6 Toyota Prius ('02)	344,000	41.0

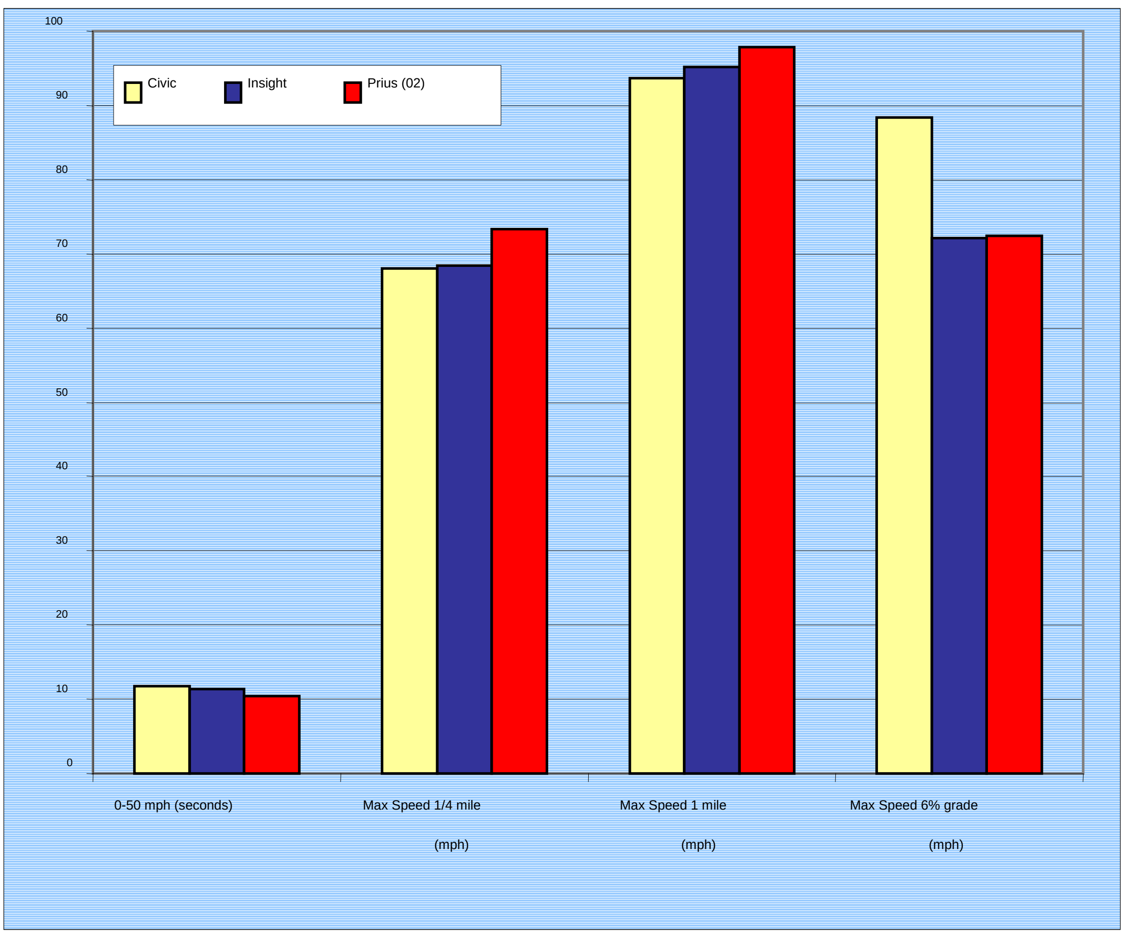

Figure 3-3. Baseline performance testing showed that the HEVs exhibit comparable performance

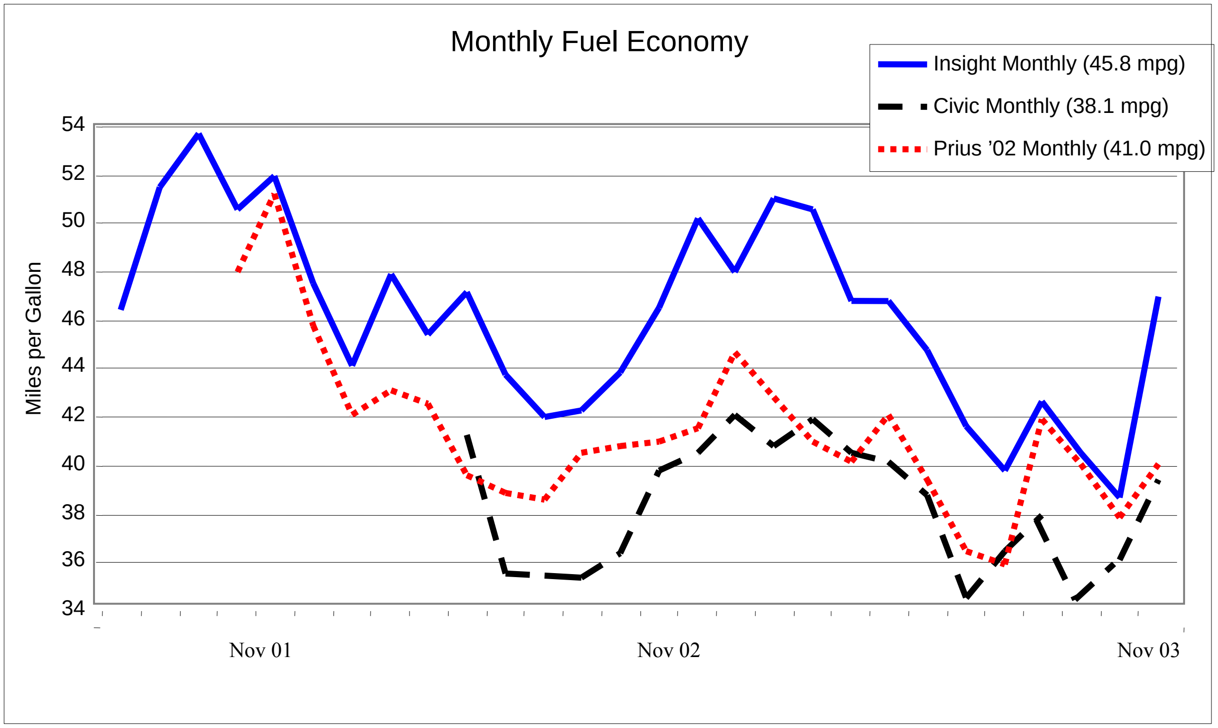

Figure 3-4. Fuel economy results showing impact of air-conditioning load during the summer months

3.3. Testing of Neighborhood Electric Vehicles (NEVs)

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Objective

- Develop test procedures, obtain baseline performance data, and gain fleet test experience to reduce the uncertainties about the performance and reliability of neighborhood electric vehicles (NEVs).

Approach

- Develop NEV baseline performance testing specifications and procedures;
- Initiate baseline performance testing of 10 NEVs during FY 2003; and
- Fleet test four dozen NEVs, with some using fast chargers.

Future Activities

- Up to a 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 four-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 including Liddo, Western Car, Club Car, Giliberti, *feel good cars,* and Lamborghini.

Approach
The operating characteristics of NEVs do not make them good candidates for accelerated reliability testing. With more than 15,000 on the road, more NEVs have been deployed in the United States than any other class of pure electric vehicle (EV). However, most 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 initiated the baseline performance testing of 10 NEVs during FY 2003 (Figure 3-5), after developing NEV baseline performance testing specifications and procedures. In addition, four dozen NEVs are being fleet tested, with some fast charged.

Results
A majority of NEVs tested had a range of approximately 35 miles per full charge (Figure 3-6) with energy efficiencies of greater than 6 miles per kilowatt-hour (Figure 3-7). They are quickly becoming popular as community vehicles in warmer states and with private and government fleets in specific applications. 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*).

Figure 3-5. NEVs being weighed

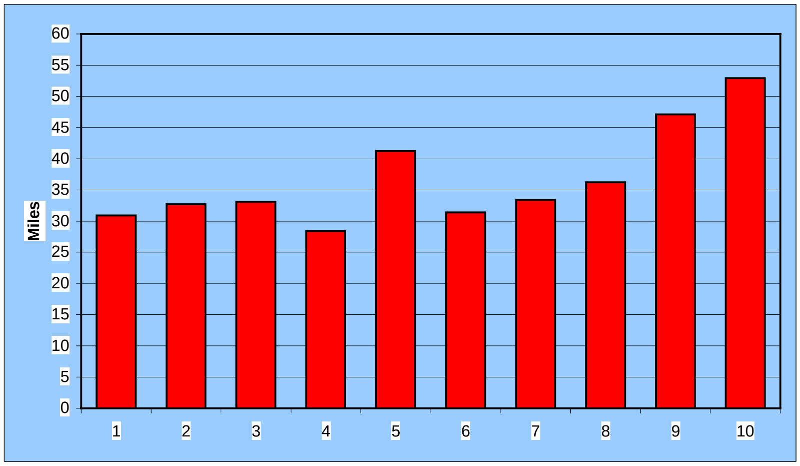

Figure 3-6. Range testing results for 10 NEVs, collected during NEV baseline performance testing

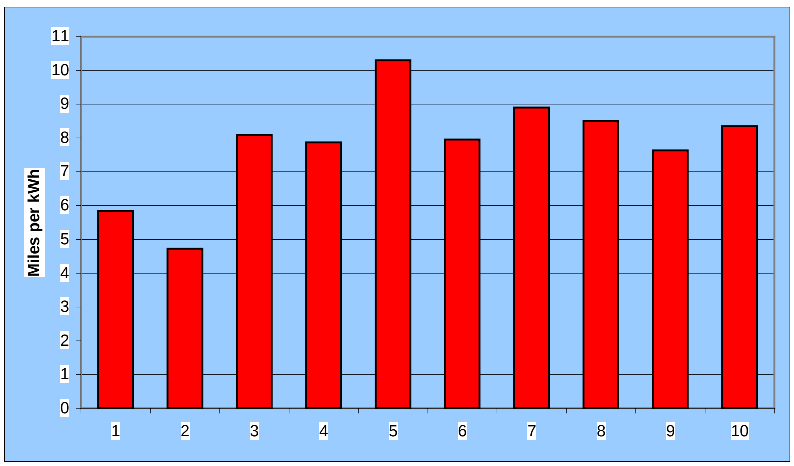

Figure 3-7. Miles per kilowatt-hour energy efficiency of NEVs

3.4. Urban Electric Vehicles (UEVs) Testing

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Objective

- Develop test procedures and obtain baseline performance data for urban electric vehicles (UEVs); and
- Gain fleet test experience to reduce the uncertainties about the performance and reliability of UEVs.

Approach

- Perform baseline performance, accelerated reliability, and fleet testing of TH!NK *city* UEVs;
- Collect demographics data from participants via the Internet; and
- Support Ford's 250 TH!NK *city* deployments in California and Atlanta.

Results

- Range of UEVs is 30 miles per charge under the Society of Automotive Engineers (SAE) J1634 test cycle; and
- Range is over 60 miles per charge at a constant 35 mph on a test track.

Future Activities

- Given the potential of this niche market and the potential use of UEVs to obtain California credits, additional UEVs will most likely be introduced, and the Advanced Vehicle Testing Activity (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 Transportation Safety Administration (NHTSA) as regular passenger vehicles, and are subject to the same Federal Motor Vehicle Safety Standards (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 only UEV available (Figure 3-8). It is undergoing baseline performance, accelerated reliability, and fleet testing, using the recently developed UEV baseline performance testing specifications and procedures. The AVTA is fleet testing 100 TH!NK *citys* in suburban New York State, just outside New York City. The 100 *city*s are being used as commuter vehicles from commuters' homes to train stations. 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 Ford's 250 TH!NK *city* deployments in California and Atlanta, with Ford supplying qualitative reports.

Results

Baseline performance tests using the recently developed UEV baseline performance testing specifications and procedures showed a range of 30 miles per charge under SAE J1634 dynamometer tests. The range increased to over 60 miles per charge at a constant speed of 35 mph on a test track.

Figure 3-8. TH!NK *city* urban electric vehicles parked and charging at the North White Plains, New York Metropolitan Train Station

Energy use for 100 TH!NK *citys* is being monitored under the Clean Commute Program in suburban New York State, both at the train stations and commuters' homes. The participant demographics for the commuters are shown in Figure 3-9.

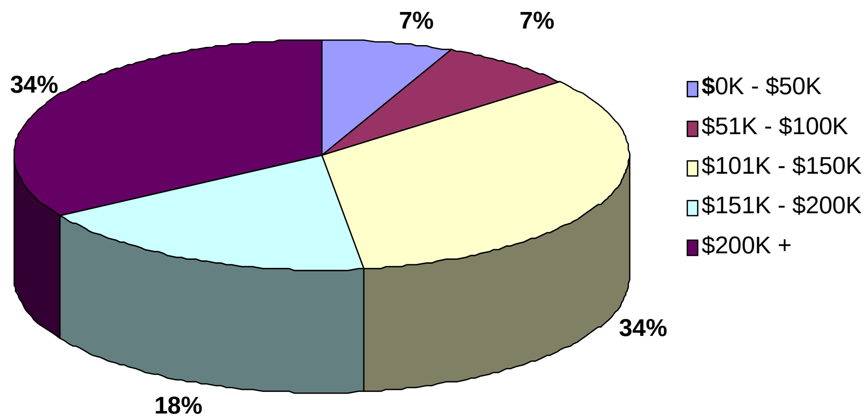

Figure 3-9. Household annual income distribution for participants in the New York Clean Commute TH!NK *city* urban electric vehicle program

Conclusions

As of 2003, the following conclusions can be reached for the Clean Commute Program:

- Clean Commute Program participants have driven nearly 150,000 miles since Program inception. During this period, they avoided the use of nearly 7,000 gallons of gasoline and avoided nearly 5,500 round trips in gasoline-fueled vehicles.
- Clean Commute participants average between 180 and 230 miles/month of vehicle use. No variation in vehicle use is currently detectable based on season of the year.
- Data collection efficiency is very good, with 80% of all Clean Commute Program participants having completed an initial survey and actively participating in data collection. Follow-up with participants failing to report monthly survey data has yielded complete mileage data. New York Power Authority (NYPA) and the AVTA plan to periodically request additional information from Clean Commute Program participants. Clean Commute Program participants will be compensated to maximize the response to these requests for additional information.
- While the majority of trips using the TH!NK *city* are for rail station commute, one third of the trips are for other family activities, indicating that the TH!NK *city* can integrate into family transportation.
- Over 90% of rail station commuting before the Clean Commute Program was in gasoline-fueled vehicles, indicating that the Clean Commute Program can have a significant affect on gasoline usage and emissions.
- Over 95% of all trips with the TH!NK *city* replaced trips that would have otherwise been taken in a gasoline-fueled vehicle, indicating that the TH!NK *city* vehicles are replacing gasoline vehicle trips, not just being used for additional trips.
- A few participants reported insufficient range, a large number of which incidents were within in a single month. These participants may require additional training or have unrealistic expectations for the vehicle mission.
- Events for which the vehicle did not charge were likewise dominated by a few participants reporting a large number of events. These appear to have been related to an extended charger outage, at their home or at their rail station, rather than to random charging failure events.
- Incidents of charge depletion on the road are infrequent, but numerous enough that

some advisory materials may be required for participants to assist them in estimating trip energy requirements.

- Failure-on-the-road events were frequent (9 events/100,000 miles) compared to equivalent internal combustion vehicles. This is also high compared to electric vehicles tested by the AVTA (Toyota RAV4, 1.5 events/100,000 miles).
- Vehicle repair frequency was high (35 events/100,000 miles) compared to equivalent internal combustion vehicles.
- Vehicle repair time was predominantly ten days to two weeks. In only a few instances was the vehicle repaired in one day.
- Most repair problems appear to be associated with the charging system and may relate to the charge connector.
- Program participant satisfaction is skewed by a few participants frequently reporting that they were completely dissatisfied (zero rating). This significantly reduces the average satisfaction rating. Some follow up work with these participants is warranted.

Many participants reported that they were completely satisfied with 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 in discussion to fleet test these vehicles. 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* demonstration suggests consumers like the vehicles. Given the potential of this niche market and the potential use of UEVs to obtain California credits, additional UEVs will likely be introduced. The AVTA will continue to baseline performance test new entrants and, depending on capabilities, also perform either accelerated reliability or fleet tests.

Publications

Francfort, J.E., October 2002. *TH!NK city – Electric Vehicle Demonstration Program, Annual Report 2001–2002.* INEEL-02/01297. Idaho National Engineering and Environmental Laboratory. Idaho Falls, ID.

3.5. 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 the U.S. Department of Energy (DOE) and other interested organizations, as needed.

Results

- Produced fact sheet for liquefied natural gas (LNG) refuse haulers, using an advanced compression ignition cycle engine; and
- Produced fact sheet on hybrid technology buses being demonstrated under New York City Transit's Clean Fuel Bus Program.

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. The Advanced Vehicle Testing Activity (AVTA) works with fleets that operate these vehicles in medium- and heavy-duty applications. The 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 2003 included:

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

<u>Fleet Evaluations</u>

In FY 2003, AVTA worked with two fleets to evaluate the performance of advanced technologies in service.

In 2001, *Norcal Waste* began operating a fleet of 14 liquefied natural gas (LNG) refuse haulers equipped with prototype Cummins-Westport ISXG engines. 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 FY 2003, AVTA began data collection on this fleet and produced a two-page fact sheet providing information on the fleet's clean fuel program and the technology being demonstrated. This fleet evaluation will be completed in the next year.

New York City Transit (NYCT) has been investigating clean fuel technologies for several years. One technology of high interest to NYCT is hybrid electric propulsion. In FY 2000, AVTA completed a year-long evaluation of 10 Orion VI buses with the prototype BAE SYSTEMS' HybriDrive™ hybrid propulsion system. 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 technology by purchasing 125 of these hybrids, which are the subject of the evaluation. In addition to the hybrid buses, NYCT is also receiving Orion VII CNG buses. These natural gas buses will be included in the evaluation. In FY 2003, AVTA completed the two-page fact sheet providing information on NYCT's Clean Fuel Bus Program and the BAE SYSTEMS hybrid technology. Data collection on the fleet will continue into the next year.

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. A team made up of staff from three organizations (the National Renewable Energy Laboratory (NREL), the Idaho National Engineering and Environmental Laboratory (INEEL), and Energetics) was formed to jointly conduct this work. During FY 2003, the team accomplished the following tasks:

- Drafted the Idle Reduction Demonstration Plan outlining the effort to gather in-use information on the performance of available idle reduction technologies and characterizing the cost, fuel savings, payback, and user impressions of various systems and techniques.
- Conducted an idle reduction needs assessment to gather industry input on current practices and needs for idle reduction technology.
- Drafted a Request for Proposal (RFP) for conducting demonstrations of idle reduction technology.
- Conducted a workshop to solicit industry input on the Demonstration Plan and RFP.
- Conducted a workshop to identify cost reduction strategies for idle reduction technology and identify key issues or barriers to implementing those strategies.

Short Term Technology Reports

The AVTA team completed several short-term reports during FY 2003.

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. The U.S. Department of Energy (DOE) program managers use this document to plan test and evaluation activities that focus resources where they will have the greatest impact. In FY 2003, AVTA produced an update of this document to include the most recent technology advancements in transportation. One point of interest from the update was the increase in hybrid demonstrations in transit fleets. Several transit agencies began small demonstration programs to investigate hybrid electric drive buses for their fleets. AVTA will closely monitor such activities for future evaluations.

Advanced Technology Vehicles in Service Fact Sheets. In addition to the two fact sheets mentioned above, AVTA produced fact sheets on advanced heavy-duty vehicles in service at two fleets in the United States in FY 2003. These fact sheets provide information on specific advanced technology and the fleet demonstrating the vehicles in service. Producing these fact sheets allows AVTA to report on available advanced technology vehicles without conducting a full evaluation. The most promising technologies will be selected for these evaluations to match funding levels for the year. The two fact sheets produced for FY 2003 include:

- City of Los Angeles Bureau of Sanitation is operating a fleet of dual-fuel LNG refuse trucks to reduce emissions in the LA area. Clean Air Power designed the system to use a small amount of diesel fuel to allow the LNG to operate in a compression ignition engine.
- Tempe Transportation Division is demonstrating a hybrid electric 22-foot transit bus that uses a natural gas fueled Capstone microturbine.

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 document tells potential users what to expect and what to plan for when implementing vehicles with electric propulsion systems into their fleets. This document also addresses the unique issues that electrical integration can pose for fleet personnel and points to the similarities between implementing electric propulsion and any other significant new technology. Publication of the document is expected in early FY 2004.

Results

Results from AVTA fleet evaluations have been well received by the industry. One specific fleet cited an AVTA report as justification for a large order of hybrid vehicles.

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 national laboratories to ensure that relevant vehicle data are collected to verify and enhance the various simulation models.