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FY 2002

Annual Progress Report for the
Light Vehicle Propulsion & Ancillary Subsystems Program

Submitted to:
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Office of FreedomCAR & Vehicle Technologies
Vehicle Systems Team

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I. INTRODUCTION

On behalf of the U.S. Department of Energy's Office of FreedomCAR and Vehicle Technologies OFCVT, (formerly the Office of Advanced Automotive Technologies (OAAT)), we are pleased to submit the Annual Progress Report for fiscal year 2002 for the Light Vehicle Propulsion and Ancillary Subsystems (Vehicle Systems) program. This report reflects the work done in Vehicle Systems under the OAAT before it was re-organized as the OFCVT. In 2003, this report will reflect the activities of the Vehicle Technologies Team under OFCVT and will include technology developments in heavy vehicles, power electronics & electric machines, field-testing & evaluations, and energy storage R&D.

Mission

The mission of the Vehicle Systems program is to facilitate the development of competitive, consumer-acceptable propulsion and ancillary subsystems for light vehicles (automobiles, light trucks, and SUVs) that, (1) achieve significantly improved levels of fuel economy, (2) comply with projected emission regulations and safety standards, and (3) are capable of operating on domestically produced fuels.

Program Goals and Objectives

The goal of the Vehicle Systems program is to support the OAAT goals by the:

- Development and validation of models and simulation programs to predict the fuel economy of and emissions from advanced passenger vehicles;
- Development of component and subsystem performance targets for a range of vehicle platforms;
- Development and validation of advanced propulsion subsystem and auxiliary subsystem technologies;
- Benchmarking of commercially available vehicles and vehicle components to ensure that the OAAT-developed technologies represent significant advances over commercially available technologies, and
- Validation of the achievement of the OAAT vehicle-level objectives.

The objective of the Vehicle Systems program is to set performance targets for light vehicle platforms, validate that the targets are achieved using Hardware-in-the-Loop to emulate a vehicle operating environment, and help define future R&D directions for the FCVT program. The Vehicle Systems program also reviews and evaluates the integration of components developed by the Energy Conversion and Energy Management teams. The main challenge is to predict, through laboratory testing and computer simulation models, how individual technology components will perform in a propulsion subsystem operating in a vehicle environment.

2002 Program Activities

Through many of its technology research programs, OAAT has supported, since its inception, the government-industry Partnership for a New Generation of Vehicles (PNGV), a cooperative research and development partnership between the federal government and the United States Council of Automotive Research (USCAR), which comprises of Ford, General Motors and DaimlerChrysler. In February 2002, the government and USCAR launched FreedomCAR. The vision of FreedomCAR is to develop affordable full-function cars, SUVs and light trucks that are free of the use of foreign oil and are free of harmful emissions, without sacrificing safety, freedom of mobility and freedom of vehicle choice. Instead of single vehicle goals, FreedomCAR emphasizes the development of technologies applicable across a wide range of passenger vehicles.

The activities of the Vehicle Systems program are divided into four areas described in this report:

I. Technology Requirements Definition
   1) Develop simulation programs and models to project vehicle performance;
   2) Provide guidance to technology developers and the OAAT Energy Conversion and Energy Management teams through cascading the vehicle performance targets to the subsystem and component level targets;

II. Propulsion Subsystem Technology Development
   Develop and test strategies to optimize propulsion subsystem performance for fuel economy, emissions, and cost, using hardware-in-the-loop and simulation techniques,

III. Vehicle Ancillary Load Reduction
   Develop technologies to minimize energy losses from ancillary subsystems for passenger comfort, and

IV. Technology Validation Testing
   Validate the achievement of targeted performance from OAAT technologies.

The abstracts in this volume summarize the work being conducted by the national laboratories in support of the program's goal and objectives. Each abstract also provides specific accomplishments and future directions for the activity. For further information, please contact the DOE Program Manager named in the abstract.

Future Directions
In FY 2003, OAAT will become the Office of FreedomCAR and Vehicle Technologies, with its mission and goals aligned with FreedomCAR mission and goals. Vehicle Systems team will assume overall Vehicle Technology team responsibilities, which will include heavy hybrid vehicles and parasitic loss reduction projects that were previously under the Office of Heavy Vehicle Technologies (OHVT), as well as power electronics & electric machines, field testing & evaluations, and energy storage technology activities that are currently separate from Vehicle Systems.

Vehicle Technology Program activities will focus on developing and validating advanced vehicle simulation programs, especially for fuel cell vehicles; providing guidance to other OFCVT programs by setting performance targets; and developing and validating propulsion and ancillary subsystem and component technologies that will be applicable to a wide range of light and heavy vehicle platforms.

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Office of Advanced Automotive Technologies

II. TECHNOLOGY REQUIREMENTS DEFINITION

During 2002, improvement and validation of ADVISIOR and PSAT simulation models continued at the National Renewable Energy Laboratory and Argonne National Laboratory. Work also continued at Oak Ridge National Laboratory for the development of automotive system cost modeling and emission control modeling. ADVISOR and PSAT were used in a variety of applications to support advanced vehicle performance analyses and propulsion subsystem technology development and testing (see section III). A tool, referred to as the technical targets tool or T3, was developed at the National Renewable Energy Laboratory to determine how well FreedomCAR technical targets apply to the various vehicle classes in meeting vehicle performance criteria. The tool also links to a fuel usage model, which determines the benefits from advanced vehicles on national fuel usage.

A. Simulation Model Development

1. Improvement, Validation and Application of Advanced Vehicle Simulator Program (ADVISOR)

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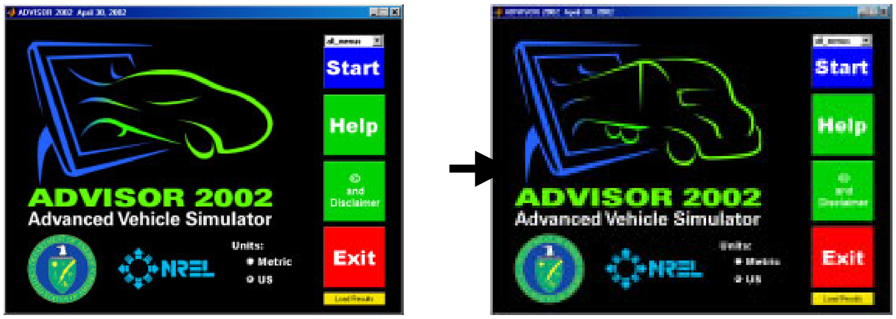
Objective

- Apply flexible vehicle systems modeling tools to analysis problems that help guide the Office of FreedomCAR & Vehicle Technologies research programs.
- Develop and support validated vehicle systems modeling tools.
- Expand and improve ADVISOR's electric modeling capability.

Approach

- Use specifications from a variety of component suppliers, original equipment manufacturers, the U.S. Department of Energy (DOE) subcontracted partners, and ADVISOR users to expand ADVISOR databases.
- Continuously keep ADVISOR users informed of changes and improvements to the tool through the Web site, user group discussions, and simulation modeling conferences.
- Use data from vehicle and component testing at NREL, other national laboratories, and industry partners to ensure validity of model predictions.
- Determine relevant vehicle analysis problems and work with industry partners to generate possible solutions and scenarios.
- Leverage industry's vehicle expertise and electric models to create additional Saber/ADVISOR co-simulation configurations.

Accomplishments



ADVISOR 2002 Startup Screen

(Morphs from car to truck to symbolize added capabilities for heavy vehicles)

- ADVISOR 2002 was released to the public through the National Renewable Energy Laboratory (NREL) Web site (www.ctts.nrel.gov/analysis). Over 6000 people from around the world have now downloaded one or more versions of the ADVISOR software. Key improvements include,
  - Configurable subsystems now used in Simulink models for easier swapping of models within a block diagram.
  - New Delta-SOC correction based on ratio of change in stored battery energy to total fuel energy used
  - Ultracapacitor model with Maxwell data
  - Rolling resistance model provided by Michelin
  - Fuzzy logic from Ohio State University (updated to include simultaneous emissions and fuel use control)
  - Direct link with Ansoft SIMPLORER® for electrical system co-simulation
  - Files added to allow Sinda/Fluint co-simulation with ADVISOR for transient air conditioning system analysis
  - Executable for running ADVISOR analyses from outside of MATLAB
  - New command line tool for doing engine map modifications, plotting, and studies
  - Speed-dependent auxiliary loads and other configurable auxiliary load models implemented using configurable subsystems
  - New functionality added to adv_no_gui.m to allow autosizing
  - A batch auto-update function to assist users in transitioning from previous versions of ADVISOR to ADVISOR 2002
  - Engine scaling by bore and stroke is now available
  - Heavy vehicle tire information added to the wheel/axle model in ADVISOR
  - Heavy vehicle engine emission models using neural networks are available
  - New heavy duty components have been added
  - Ability to customize the ADVISOR menus for multiple users or projects
  - GUI files have been converted to *.fig format to allow easier customization

- Created additional Saber/ADVISOR co-simulation configurations
  - Series hybrid configuration with motor, generator, regulator, high voltage battery, low voltage battery, DC/DC converter, and accessory loads modeled in Saber.
  - Parallel hybrid configuration with motor, regulator, high voltage battery, low voltage battery, DC/DC converter, and accessory loads modeled in Saber.
  - Simplified custom co-simulation setup. Now industry can co-simulate their custom Saber models to determine fuel economy and performance trade-offs with ADVISOR.

- ADVISOR continues to be used as a ‘common ground’ tool for bringing industry partners together on projects that focus on lowering fuel consumption and include advanced technologies.

Future Directions

- Improve, validate, support, and apply ADVISOR to satisfy the needs of DOE, the auto industry, and the ADVISOR users.
- Evaluate fuel cell hybrid vehicle system design trade-offs.
- Develop and apply Target Cascading process to the generation of component technical requirements that will provide significant national oil displacement.
- Improve speed of Saber/ADVISOR co-simulation.
- Further improve custom Saber/ADVISOR co-simulation implementation.

Introduction

In 1994, NREL created the ADvanced VehIcle SimulatOR (ADVISOR) through what is now the DOE Office of FreedomCAR and Vehicle Technologies. ADVISOR's goal is to help the automotive industry model vehicle systems using computer tools to supplement building and testing of vehicle systems. NREL has expanded the tool's capabilities over time, and now has an easy-to-use interface, pull-down menus, improved results screens, validated component information, and many vehicle system designs to choose from. ADVISOR can be downloaded free of charge from the Vehicle Systems Analysis Web site (www.ctts.nrel.gov/analysis). More than 6000 users from around the world have downloaded the software to evaluate vehicle systems and various vehicle configurations (see Figure 1).

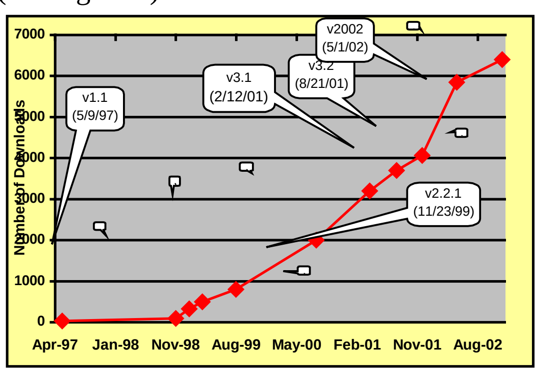


Figure 1. Number of downloads by ADVISOR version and release date

ADVISOR was originally created to do top-level analysis on light duty vehicle propulsion systems. Over time it has evolved into more areas through co-simulation with other software and more in depth modeling. Some examples of the increased capability are: Ability to link with Saber for detailed motor and electrical models, modeling of heavy duty vehicle components, and optimization routines, to name a few.

Approach

Several steps were taken to improve and apply ADVISOR. Specifications from a variety of component suppliers, original equipment manufacturers, and the U.S. Department of Energy (DOE) subcontracted partners expanded ADVISOR's databases. ADVISOR users were updated on changes and improvements to the tool through the Web site, user group discussions, and simulation modeling conferences. Data was collected from vehicle and component testing at NREL, other national laboratories, and industry partners to ensure validity of model predictions. Important and relevant vehicle analysis problems were solved with industry partners. Industry's vehicle expertise and electric models were leveraged to create additional Saber/ADVISOR co-simulation configurations.

Results

Since ADVISOR was released to the public through the NREL Web site, more than 6000 people from around the world have downloaded the software. This allows more people to have free access to state-of-the-art hybrid vehicle data in an easy to use model to execute vehicle simulations. This has a significant impact on increasing the level of knowledge people have about hybrid vehicles in the auto industry OEMs, their suppliers, academia, and small businesses (that otherwise might not be able to afford to invest in developing or purchasing such a model). The increasing number of publications around the world that reference ADVISOR are an indication that the tool is being used and has impact on system analysis including hybrid and fuel cell vehicle analysis. Additionally, users of ADVISOR have used the tool to perform analysis on vehicles such as motorcycles and railway vehicles.

To foster interaction with and between members in the ADVISOR user community, an updated web page is available (see Figure 2). The ADVISOR user can link to the community website which has a forum for facilitating discussions among users and an upload/download area for file sharing.

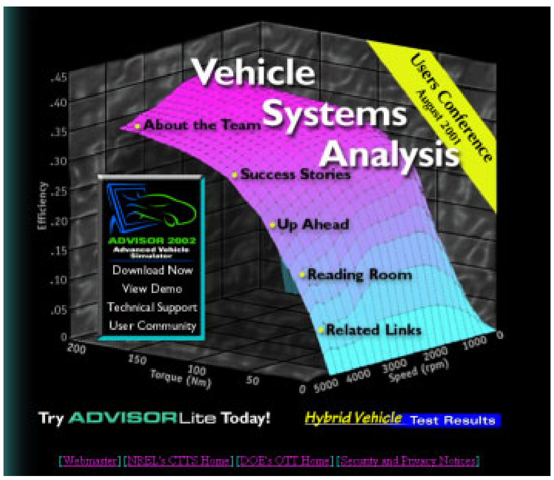


Figure 2. Vehicle Systems Analysis Web Site allows users to download ADVISOR and get analysis-related material and support

The current linkage between ADVISOR and existing optimization tools has been used extensively to understand some of the vehicle configuration trade-offs associated with fuel cell hybrid vehicles. It was shown that the drive cycle over which fuel economy is measured can significantly influence the component sizes and the energy management strategy employed in a fuel cell hybrid SUV.

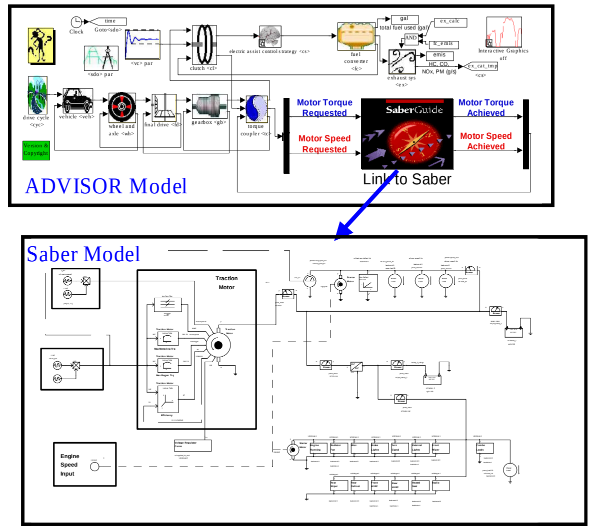


Figure 3. Saber/ADVISOR parallel co-simulation. An example of linking Saber models in ADVISOR

Industry can now use the Saber/ADVISOR co-simulation to evaluate their Saber models' impact on fuel economy and performance. Delphi Corporation supplied electric Saber models and vehicle expertise to assist in the creation of the series hybrid and parallel hybrid co-simulation configurations. They are now using the co-simulation internally.

Conclusions

NREL will continue to further improve, validate, support, and apply ADVISOR to satisfy the needs of DOE, the auto industry, and the 6000 ADVISOR users. This will involve continuing to push the envelope in the field of optimization while also focusing on application to hybrid vehicles and general applicability to multi-disciplinary analysis. An emphasis will be placed on the evaluation of fuel cell and fuel cell hybrid vehicles technology and concepts as they relate to the vehicle systems. A significant effort will be applied to the development of a process to cascade the goals of national oil displacement down to a vehicle and its subsystem to generate justifiable technology development targets. Finally, the Saber/ADVISOR co-simulation speed will be increased to improve usability.

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

Markel, T., Wipke, K. Nelson, D. "Optimization Techniques for Hybrid Vehicle Analysis Using ADVISOR," ASME International Mechanical Engineering Conference, November 2001, New York.

MacBain, J., Conover, J., Brooker, A. "Complete Propulsion and Electrical System Analysis for 42V Single and Dual Voltage Traditional Vehicles," 42V PowerNet Conference, November 2002, Munich, Germany

O'Keefe, M., Hendricks, T., Lustbader, J., Brooker, A. "Enhancements to NREL System Analysis Tools to Improve Auxiliary Load Modeling and Air Conditioner Modeling for Heavy Vehicles" NREL, July 2002
Kelley, K. "Modeling Tools for Predicting the Impact of Rolling Resistance on Energy Usage and Fuel Efficiency for Realistic Driving Cycles" NREL—presented at the International Tire Exhibition and Conference in Akron, OH (September 10-12th, 2002)

O'Keefe, M.P. and Vertin, K. "An Analysis of Hybrid Electric Propulsion Systems for Transit Buses." NREL Milestone Completion Report, June 2002.

Markel, T., Wipke, K., Nelson, D. "Vehicle Systems Impacts of Fuel Cell System Power Response Capability." FutureCAR Congress, June 2002.

Markel, T., Brooker, A., Hendricks, T., Johnson, V., Kelly, K., Kramer, B., O'Keefe, M., Sprik, S., Wipke, K. "ADVISOR: a systems analysis tool for advanced vehicle modeling" Journal of Power Sources Volume 110, Issue 2 22, August 2002 Pages 255-266.

Hendricks, T., O'Keefe, M. "Heavy Vehicle Auxiliary Load Electrification for the Essential Power System Program: Benefits, Tradeoffs, and Remaining Challenges." Society of Automotive Engineers. Paper No. 2002-01-3135. Presented at the International Truck and Bus Meeting and Exposition 18-20 Nov. 2002. 11 pps.

2. Transient Simulation Model for Emulation and Validation of Advanced Automotive Powertrain Technologies

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Objective
- Develop subsystem-level fuel cell (FC) simulation models for incorporation in the Propulsion Systems Analysis Toolkit (PSAT)
- Create a direct link between modeling & simulation and Hardware-In-the-Loop (HIL)
- Conduct vehicle systems studies to assess advanced powertrain options

Approach
Subsystem-level Fuel Cell Models for Incorporation into PSAT
- Modify ANL's detailed GCTool direct hydrogen fuel cell simulation model into a simpler engineering (GCTool-ENG) model
- Develop the modified GCTool-ENG model for a specific fuel cell vehicle
- Modify the GUI and develop scaling algorithms to integrate the GCTool-ENG model into PSAT.

Direct Link Between Modeling & Simulation and Hardware-In-the-Loop
- Directly link the virtual environment of PSAT and the hardware environment in the APRF to support an integrated approach to analysis and hardware/control software development.
- Modify PSAT to match the transient and control aspects of each component. These modifications include:
  - Enhanced transmission and motor models
  - Enhanced powertrain controller and control strategies
  - Addition of signal conditioning block to allow specific component controllers.

Vehicle Systems Studies to Assess Advanced Powertrain Options
- Conduct well-to-wheel study of fuel cell, hybrid and conventional vehicles in conjunction with GREET
- Assess impact of advanced component technologies
- Analyze impact of hybridization and optimized powertrain technologies

Accomplishments
- Incorporated direct hydrogen FC transient model into PSAT
- Completed linkage from PSAT to PSAT-PRO and demonstrated in the HIL test cell at the APRF with a pre-transmission parallel hybrid powertrain.
- Completed comparative study of FC well-to-wheel energy efficiency
- Completed study of the trade-offs between fuel economy and NOx emissions using fuzzy logic control

Future Directions
- Continue development of subsystem-level FC models for use in PSAT based on detailed component-level models in GCTool, including a pressurized gasoline reformer fuel cell system.
- Continue support of HIL activities in the APRF by enhancing component models, integrating physiological (equation-based) models as needed, analyzing vehicles/powertrain systems and defining/refining control strategies.
- Continue to support technology validation activities in the APRF with vehicle system studies to provide testing profiles and control strategies.

Introduction
Fuel cell technology is a key element in the future plans of DOE, as reflected in the FreedomCAR program objectives. Many fuel cell system configurations and fuel sources are being considered, resulting in a broad range of estimates of system efficiency and eventual air quality benefits. Therefore, the objective of the ANL modeling & simulation activity is to translate the latest detailed fuel cell component/subsystem models for use in a vehicle-level model that can be used to analyze the overall efficiencies and emissions benefits of various fuel cell and hybrid propulsion configurations.

Approach
Subsystem-level Fuel Cell Models for Incorporation into PSAT

The responsibility for detailed fuel cell systems analysis within the DOE program resides in another division at ANL and, for several years, they have been developing an extremely detailed physiological model, GCTool. For use in vehicle level analysis, the challenge is to simplify the GCTool model so that it can be integrated into PSAT while retaining its transient characteristics. Appropriate modeling resources within ANL were combined to develop a simplified model of a direct hydrogen pressurized fuel cell system, the first in a series of fuel cells that are being modeled to meet the needs of DOE and the Fuel Cell Technical Team of the FreedomCAR Program. The model covers a power range from 5kW to 200kW in discrete 5kW steps (i.e., a fuel cell system is ‘designed’ for each step and translated for use in PSAT – the model results are not scaled for different power levels). Figure 1 is an example of the model results, showing the dependence of fuel cell efficiency on initial (starting) conditions.

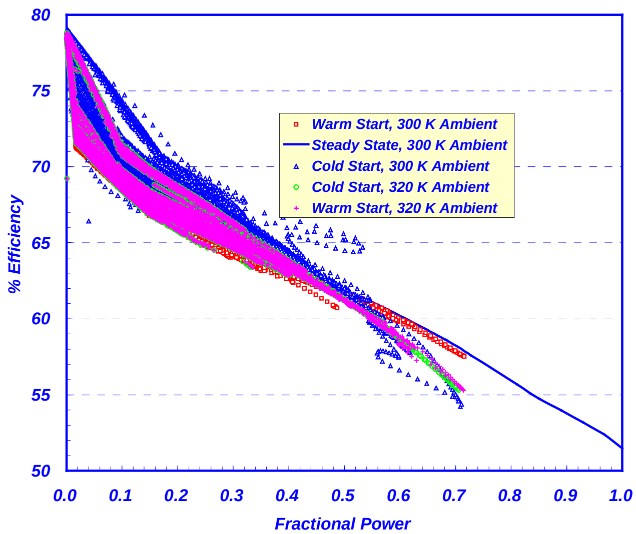


Figure 1. Example of Hydrogen Fuel Cell Simulation Results – Efficiency vs. Fractional Power

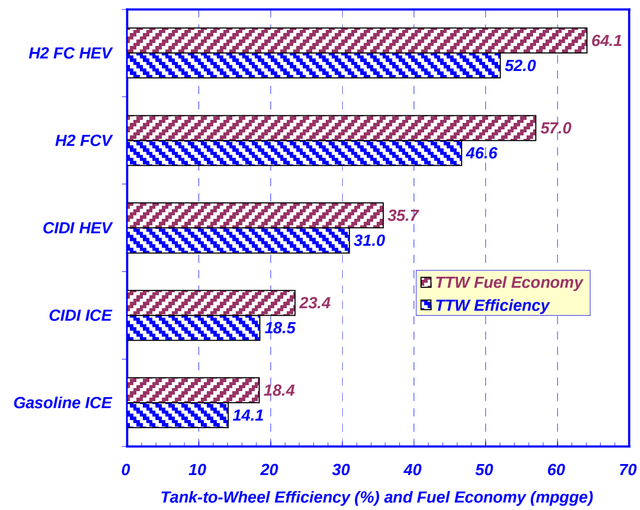
Direct Link Between Modeling & Simulation and Hardware-in-the-loop

Directly linking the virtual environment of PSAT and the hardware environment in the APRF is necessary to support an integrated approach to analysis and hardware/control software development. This approach ensures consistent vehicle-level assumptions and control strategies when a component or system is tested on a dynamometer in the APRF and allows direct comparison of simulated and test results. PSAT was modified to match the transient and control aspects of each component and a direct translator was developed to produce PSAT-PRO code, the control software used for Rapid control Prototyping (RCP) and HIL projects in the APRF.

Vehicle Sytem Studies to Assess Advanced Powertrain Options

ANL is also the developer of GREET, a model to predict the impact of technology on greenhouse gases. The capabilities of PSAT and GREET have been combined to perform a preliminary 'well-to-wheels' efficiency analysis for a variety of advanced vehicles and fuels. The results comparing greenhouse gas emissions and efficiency are summarized in the figures 2 and 3.

Figure 2. Well-to-tank (WTT) and tank-to-wheel (WTW) emissions comparison



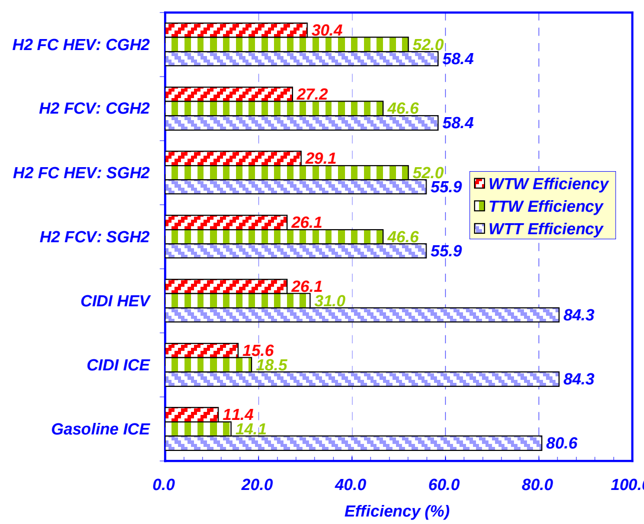


Figure 3. Well-to-tank (WTT), tank-to-wheel (TTW) and well-to-wheel (WTW) efficiency comparison

Results

The significance of these analyses is that the overall efficiency of a hybrid vehicle with a diesel engine (CIDI HEV) is predicted to equal that of a fuel cell vehicle fueled at a station where hydrogen production occurs (H2 FCV:SGH2) and within 4% of all other fuel cell vehicle and fueling options. However, the comparison of greenhouse gas emissions is not as close, predicted to be 25-45% higher for the same vehicles.

Publications

Rousseau,.A., Ahluwalia, R., Deville, B., and Zhang Q., *Well-to-wheel Analysis of Advanced SUV Fuel Cell Vehicles*, SAE paper 03P-374, SAE World Congress, Detroit, MI, USA (to be presented March 2003)

Rousseau, A., Saglini, S., Jakov, M., Gray, D., and Hardy, K., *Trade-Offs Between Fuel Economy and NOx Emissions Using Fuzzy Logic Control with a Hybrid CVT Configuration*, 19th International Electric Vehicle Symposium (EVS19), Busan, Korea (October 2002).

Rousseau, A., Modeling Control and Validation of Fuel Cell Transient Behavior, presented to Future Car Congress, Arlington, VA, USA (June 2002).

Rousseau, A., Multi-platform drivetrain study using PSAT, presented to Future Car Congress, Arlington, VA, USA (June 2002).

3. Applications of Digital Functional Vehicle Process

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Objective

- Enable and accelerate new fuel-efficient automotive technologies (HEVs, fuel cells, light-weight designs) by removing technical barriers through the application of advanced CAE modeling techniques and innovative design processes.
- Develop processes and systems needed to solve specific automotive industry problems 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.
- 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.
- Develop integrated system of software tools and provide solutions to industry partner. Report results to industry and DOE, and transfer process to industry.

Accomplishments

- Developed and disseminated analysis techniques using reliability based optimization to produce lightweight designs that meet six-sigma quality criteria.
- Developed a reusable workflow that uses probabilistic design techniques to achieve a robust design accounting for manufacturing variations and eliminates catalytic converter failure.

- Demonstrated improved battery performance through simulation of battery thermal management strategies.
- Published eight papers that described the process and its implementation on automotive applications with energy savings potential.
- Presented and disseminated the analysis techniques to the engineering community at several PTC, ANSYS, SAE, and DOE conferences.
- Presented and disseminated the analysis techniques to automotive executives at the Daratech's Intelligent Digital Prototyping Strategies workshop.
- Received four "best paper/presentation" awards based DFV publications and presentations.
- Worked with industry partners to identify and kick-off several new DFV applications in advanced automotive and fuel cell industry.

Future Directions

- Further quantify the energy savings associated with the application of Digital Functional Vehicle.
- Identify new projects with Ford, General Motors, and DaimlerChrysler that will develop and apply the process further with even stronger ties to the impact on energy consumption.
- Investigate potential application of Digital Functional Vehicle processes to remove technical barriers in fuel cell problems industry.
- 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 Digital Functional Vehicle (DFV) process. The DFV process involves working with industry to take a more integrated systems approach to analyzing and making 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 creating 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 (see Figure 1).

This project was started with NREL, Parametric Technologies Corporation (PTC), and a few select suppliers in 1998. In FY00, 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 FY01, 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 FY02 we continued working with Advanced Engineering Solutions and focused on disseminating the DFV process to industry. We also stressed developing new partnerships interested in applying DFV on key technical barriers in fuel cells and other advanced vehicle technologies.

Approach

The DFV approach is focused on the implementation of math-based modeling tools early in the design process and utilizes innovative design techniques that lead to efficient load path generation such as topology optimization and behavioral modeling. We have shown how 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).

The overall approach is to work with the auto industry on specific projects on which industry is engaged, and then publicly present the process that was used (without proprietary data or results) so that others may benefit from the process improvements. We use 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 highlighting the energy aspect of the design decisions. Additionally, working directly with the auto industry software suppliers ensures that the improvements the DFV process brings (in terms of highlighting the energy impacts of decisions) will be carried through into their production software releases.

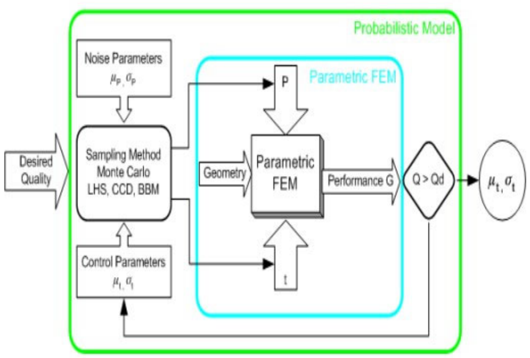

Figure 1. Example of Integrated DFV Process

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. 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 FY02 include:

- Developed and disseminated analysis techniques using reliability based optimization to produce lightweight designs that meet six-sigma quality criteria.
- Developed a reusable workflow that uses probabilistic design techniques to achieve a robust design accounting for manufacturing variations and eliminates catalytic converter failure.
- Demonstrated improved battery performance through simulation of battery thermal management strategies.
- Published and presented eight papers that described the process and its implementation on automotive applications with energy savings potential.
- Received four "best paper/presentation" awards based DFV publications and presentations.

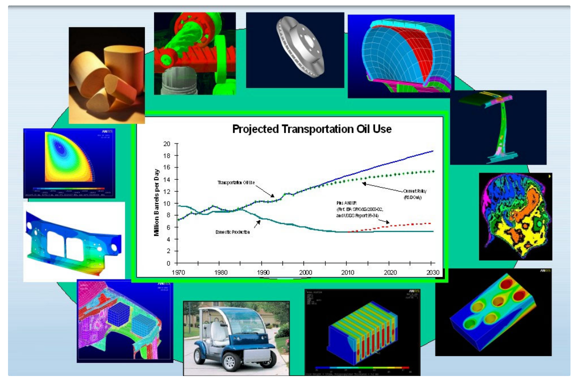

Figure 2. Digital Functional Vehicle Applications

Conclusions

In FY02, NREL was able to successfully integrate key CAE tools and to demonstrate the application of the Digital Functional Vehicle process on multiple projects in partnership with industry. The thrust in FY03 will be to focus the effort on a smaller number of projects with an emphasis on applying DFV on key technical barriers in fuel cells and other advanced vehicle technologies.

Publications / Presentations

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Vlahinos, A., Kelkar, S., Reh, S., SeCaur, R., Pilz, S. "Reliability Based Optimization within the CAD Environment." Proceedings of the 2002 ANSYS Users Conference on April 23, 2002.

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Vlahinos, A. "Designing for Six-sigma quality levels with Behavioral Modeling." Proceedings of the 2002 PTC/User World Event Europe in Berlin, Germany, May 12, 2002.

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4. Automotive System Cost Modeling

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Objective

- 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
- Develop a repository of cost data about various component-level technologies being developed today for new generation vehicles

Approach

- A bottom-up approach defining the vehicle as five major subsystems consisting of total 36+ components
- Performance and system interrelationships are considered to estimate system and subsystem costs for calculating total vehicle production cost
- A spreadsheet-based modular structure to provide "open" design and allow for future expansion

Accomplishments

- Model validation for the baseline passenger car vehicle platform including vehicle system sizing and cost
- Implementation of the relationships between vehicle weight and various chassis subsystems

- Model enhancements to estimate costs of other light-duty vehicle types, i.e., pick up trucks and sport-utility vehicles (SUVs) for seven original specific vehicle configurations considered in the model
- Cost target analysis of advanced vehicle designs using PNGV/FreedomCAR vehicle subsystem level targets

Future Directions

- Develop a credible database of a limited number of technologies at the vehicle subsystem level supported by the Office of FreedomCAR and Vehicle Technologies
- Validate the baseline model developed for pick up trucks and SUVs
- "Cost Roll-Ups" of advanced vehicle designs covering all three light-duty vehicle platforms

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Introduction

An early understanding of the key issues influencing cost of advanced vehicle designs is vital for overcoming cost problems and in the selection of alternative designs. The affordability issue remains a concern with the recent FreedomCAR program, where the focus has shifted to a longer timeframe, hydrogen-powered fuel cell vehicles, and technology development applicable across a wide range of vehicle platforms. The recent collaboration among the vehicle engineering technical team (VETT), Argonne National Laboratory, ORNL, and support from IBIS Associates, Inc. has resulted in adapting the automotive system cost model (under development over the past few years by ORNL) in a modular 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 work has been on relative production cost estimation via a uniform methodology, allowing a comparison of alternative technologies under consideration by the FreedomCAR community.

Approach

It is important that the cost assessment of advanced vehicle designs be performed at the vehicle system/subsystem level to examine how its impacts of a specific technology translates to at the vehicle level. This approach provides the system synergism effect by taking into consideration the interrelationships among various systems/subsystems of a vehicle. Total production cost of advanced vehicle designs is estimated based on cost estimates made at the level 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

The cost model now incorporates other light-duty vehicle platforms, i.e., pick up truck and SUV as well as mid-size passenger cars, besides implementing the relationships developed between the vehicle weight and non-powertrain component weights. These relationships were derived based on the first principles of physics and represented as a power function in terms of % change in weight. Specific relationships were developed for eight chassis subsystems considered in the modeling framework.

Enhancement of the model to include other light-duty vehicle platforms, considered the appropriateness of the ANL powertrain sizing routines which were found to be applicable with the use of appropriate vehicle physical attributes for these two other light-duty vehicle platforms. The general behavior of the sensitivity of vehicle weight to the sizing of chassis subsystems was found to be within reason, though there was not enough datapoints of marginally different systems and accompanying vehicle masses to confirm absolute accuracy. Data at the 30+ vehicle subsystem level defined in the model were collected, representing current production and advanced pick up truck and SUV technologies. In several instances, e.g., engine data of passenger cars were found to be applicable for these two other light-duty vehicle platforms as well. For several vehicle subsystems where data were unavailable, estimates in most cases were based on scaling of the passenger car estimate.

Four baseline scenarios based on the current production vehicles were considered to evaluate the enhanced modeling framework. These vehicles were: Ford Ranger, Ford Explorer, Chevy S-10, and Chevy Trailblazer. Data for these vehicles were collected from various sources, including direct interviews with OEM and supplier engineers and designers, published literature, and prior studies by IBIS Associates. Inc. etc. Total production cost of these baseline vehicles were estimated to be considerably lower than the published manufacturer's suggested retail price (MSRP), i.e., about 70% of MSRP in the case of pick up trucks. Two specific scenarios of Jeep Commander 2 were also considered to demonstrate the capability of the enhanced modeling framework to estimate the cost of advanced light truck technologies.

Capabilities of the model were demonstrated by projecting the cost of advanced design vehicle costs based on today's Office of FreedomCAR and Vehicle Technologies (OFCVT) developed technologies and cost targets set by PNGV 2004 and FreedomCAR 2010. Figure 1 shows the estimated production cost (in terms of a ratio of the conventional vehicle) of a reformer-based fuel cell (FR) vehicle. The production cost of reformer-based fuel cell vehicles is estimated to be higher than the direct-hydrogen fuel cell vehicles. It is estimated that today's reformer-based fuel cell vehicle would cost about 2.1 times the conventional vehicle, compared to 1.7 times estimated in the case of direct-hydrogen fuel cell vehicle. This is mainly due to the difference in its specific power cost (i.e., \$300/kW vs. \$200/kW). It was observed that with reductions in specific power and the cost of fuel cell system and to a lesser extent the body-in-white cost (resulting from \$1/lb aluminum sheet and large scale production volume), the production cost of reformer-based fuel cell vehicles would reduce to 1.2 times the conventional vehicle if PNGV 2004 targets are met. However, the production cost of this vehicle will approach that of the conventional vehicle if the FreedomCAR 2010 targets are met, which was also observed for the direct hydrogen fuel cell vehicles. Total vehicle curb mass is also estimated to reach the PNGV 2004 target in this case.

Conclusions

It is important that the system level automotive cost modeling framework be continued to satisfy the needs of DOE. During the coming year, it is suggested that the automotive system cost model development be continued working in collaboration with the DOE technical team leaders and FreedomCAR technical teams who are involved at the specific vehicle subsystem level technology development. The focus of

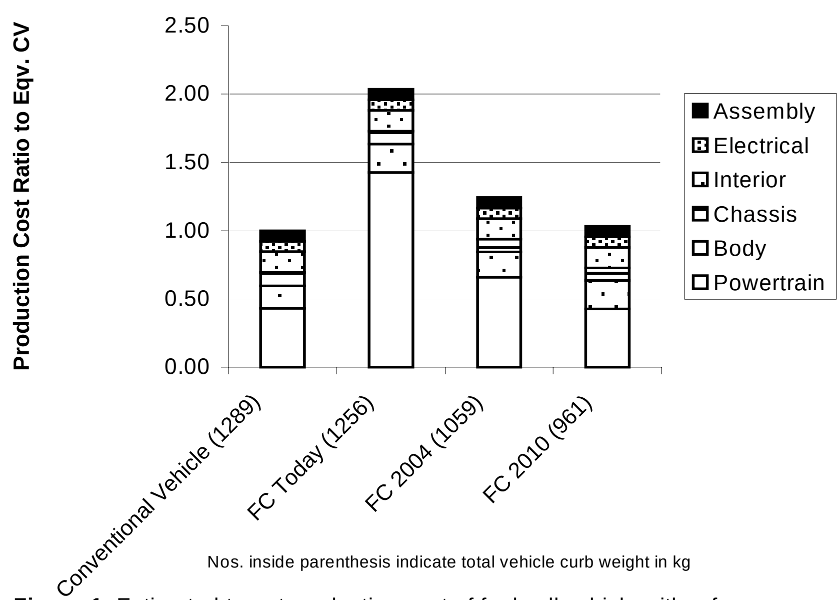

Figure 1. Estimated target production cost of fuel cell vehicle with reformer

this work will be to develop a credible cost database on a selected number of technologies, currently being supported by DOE/Freeedom-CAR research community. The model will also be validated to a baseline pick up truck and SUV vehicle configurations based on enhancements made during the last year. 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 FreedomCAR. Cost Roll-Ups will be developed to demonstrate the relative cost sensitivity of the model due to a change in technology either for motors, batteries, engines, or materials in the body.

5. Downstream Emissions Control (Aftertreatment) Modeling

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Objective

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

Approach

- Develop low-level, physically based models of emissions control devices.
- Utilize industry-developed prototype emissions control devices in a laboratory to generate calibration and verification data for the models.

Accomplishments

- Improved the initial low-level model of a Catalyzed Diesel Particle Filter and translated it into MATLAB format for implementation in higher-level systems models.
- Completed the low-level model of a NOx storage and reduction catalyst and translated it into MATLAB format for implementation in higher-level systems models.
- Developed and implemented a laboratory apparatus and protocol for generating the required model parameters and calibration data for future samples of NOx storage and reduction catalysts.
- Began a low-level model of urea-SCR NOx reduction devices and acquired a commercial catalyst for characterization at ORNL.

Future Directions

- Complete laboratory characterization of prototype NOx storage catalyst and finalize model for use in vehicle-systems models.
- Complete model of catalyzed diesel particle filter, including the ability to simulate regeneration.
- Develop and implement a laboratory apparatus and protocol for generating the required model parameters and calibration data for urea-SCR reduction catalysts.
- Improve and complete a MATLAB function for the low-level model for a urea-selective catalytic reduction system.

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 (as well as fuel efficiency gains), it is unlikely that advanced, highly efficient vehicles can meet the stringent 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 design.

Approach

Although these technologies are still maturing for vehicle usage, prototype devices are in use for research and development. While a thermochemically 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

Previous work in this area focused on developing a model for a catalyzed diesel particle filter (DPF), a diesel oxidation catalyst (DOC), and a lean NOx trap (LNT). The DPF and DOC models have been distributed and are currently in use. During early work with the particle filter, it was not possible to model the regeneration behavior of the filter, which was an objective in the most recent modeling work. The most recent work also focused on calibrating and streamlining the LNT model. The biggest challenge was to produce an integrated functional form of the model that would accommodate the three different operating functions: adsorption of NO_X from the exhaust stream during lean engine operation; release of stored NO_X during the early stages of regeneration; and chemical reduction of released NO_X during regeneration. A MATLAB function that simulates all of these steps in a seamless way has now been developed. Special parameter files have also been developed to supply the model with the required kinetic constants and physical properties information. These files can be supplemented in the future as information about more candidate LNT materials becomes available. The ORNL team is working with NREL staff to help with the interfacing of the MATLAB function and supplemental files.

The earlier version of the NOx adsorber model included a simplified analytical integration of the differential NOx balance equations during the adsorption phase of the operation. These simplifications were relaxed in the updated model so that it would give more accurate predictions during rapid engine transients. This required implementing a numerical integration scheme that can handle the stiffness associated with the nonlinear sorption isotherm. The release of NOx from the storage sites and its subsequent reduction during the regeneration are also now better understood and more efficiently handled by the code. Typical model results are compared with experimental data from the ORNL benchflow reactor in Fig. 1 for a Pt/K2O/alumina NOx storage catalyst.

Measurement of the kinetic parameters for new candidate sorber materials will be added to the model parameter files as these materials are tested (e.g., from the CLEERS LNT Focus Group). The current model has also been constructed such that additional predictive capabilities for the effects of sulphur poisoning and subsequent desulfation operation can be readily added as experimental data for these processes become available.

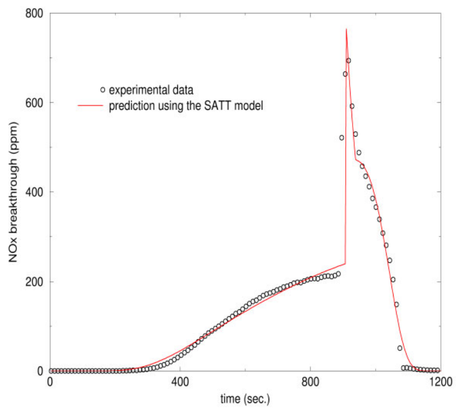

Figure 1. Comparison of predicted and experimental NOx breakthrough profiles for a sample of candidate Pt/K2O/alumina-coated monolith

The previously developed DPF model has been modified to allow simulation of both particulate capture and oxidative regeneration in cases where the two processes are occurring simultaneously (continuously regenerating mode) as well as sequentially. The key modeling issue here is to numerically integrate the differential heat and mass balances to account for the depletion and accumulation of particulate matter as well as rise in temperature due to the oxidation heat release. The output produced by the model function includes the internal filter temperature as well as the exiting gas mass flow rate, temperature, and composition (mole fractions of O2, CO and CO2). The accurate prediction of CO fraction in the outflow is critical in terms of emissions regulations or for modeling any other after treatment device that may be downstream of the filter.

Example results from the updated DPF model are illustrated in Fig. 2. In this case, the predicted wall temperature of a Corning EX-80 filter (14" length, 11.25" diameter) is compared with experimental measurements. The predictions are well within the error margins expected from a low-order model that can be integrated much faster than real time. This example corresponds with experiments (SAE 960136) that used a Ceria fuel additive to catalyze soot oxidation.

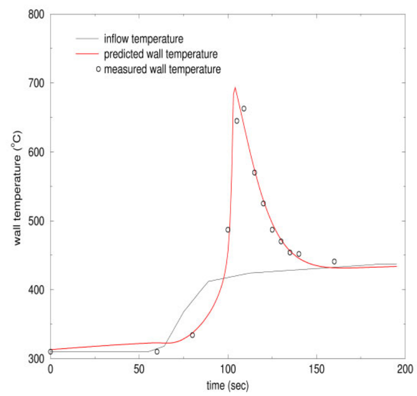

Figure 2. Comparison of predicted and experimental internal filter temperatures for a Corning EX-80 filter loaded with diesel particulate. In this case, regeneration was triggered by a gradual rise in inlet gas temperature

As for LNT's, the dynamic behavior of DPF's depends strongly on heterogeneous reaction kinetics. The required kinetic parameters are supplied from supplemental parameter files that are generated from experimental data on the different filter materials. No changes need to be made to the model itself (i.e., the MATLAB function) to simulate new filter materials or particulate matter with unusual properties. However, there is a clear shortage at present of available kinetic data.

In the example case, the kinetic parameters used included the effects of fuel-borne catalyst. Though it is unclear if fuel-borne catalysts will be a desirable option in the future, the example illustrates the flexibility of the model for different scenarios. In this case, the highly time-resolved experimental measurements were very suitable for comparison with the model predictions. In general, such measurements are not currently available for filters with catalysts directly impregnated in the filter material. However, the generic construction of the model makes it easy to switch between these two types of catalyst modes. In addition to including the kinetics for soot oxidation with O2, the DPF model is being modified to include kinetics for soot oxidation with NO2. This feature will enable simulation of coupled DPF-LNT systems.

Work has just been initiated on a urea-selective catalytic reduction (SCR) model. The key issues here are to account for both urea thermolysis (vaporization and conversion of the aqueous urea spray to ammonia) and subsequent heterogeneous catalysis of the NOx reduction by ammonia. We are using the differential mass balance code structure already developed for the LNT model for both stages of the urea-SCR device, but we expect to maintain two separate modules of code for the thermolysis and reduction stages, respectively. Within the thermolysis stage, we expect to rely heavily on existing correlations for simulating the heat and mass between the exhaust gas and urea spray droplets.

Kinetics from the open literature will be used initially for simulating the urea to ammonia and NOx reduction reaction rates. As soon as possible, however, experimental data from the ORNL benchflow reactor using prototype sections of SCR catalyst monolith will be used to develop improved expressions for the global kinetics. Modifications are being made to the ORNL benchflow system to allow separate measurements of urea thermolysis and NOx reduction rates.

Conclusions

Highly-efficient vehicle designs are likely to require the use of advanced emissions control technologies in order to meet future emissions requirements put forward by the EPA. 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 NOx adsorbers, diesel particulate filters, and urea selective catalytic reduction. The diesel oxidation catalyst, lean NOx adsorber, and diesel particulate filter models are all now available for shakedown testing in higher-level system models. Additional parameter file generation for each of these models is planned, and the models have been structured to allow future improvements based on the availability of new experimental data (e.g., the effects of fuel sulfur). Development of a similar urea-selective catalytic reduction model is currently underway.

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

B. Technical Target Development

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Objective

For fuel cell, hybrid electric, and conventional vehicle technologies:

- Determine which of the light vehicle component and system technical targets that, when implemented, would create vehicles with the largest potential market penetration (therefore the largest potential impact on national oil use savings)
- Using ADVISOR, analyze the potential for vehicles that meet the technical targets to penetrate a realistic, multi-platform market; i.e., vehicles of different classes and performance expectations
- Estimate the potential national oil use savings due to market penetration of vehicles that meet the technical targets (national oil use savings is the figure of merit)

Approach

- Define the light vehicle market in terms of EPA vehicle size classes
- Work with an industry expert to collect performance and physical data to represent the current fleet for each vehicle class
- Program the technical team targets (T3) tool in Matlab and create easy-to-use GUIs that allow the user to easily modify the technical targets and certain oil use parameters
- Use ADVISOR for each vehicle class to:
    - Simulate a new technology vehicle (NTV) based on the technical targets input by the user and the physical data for that class
    - Run performance and drive cycle tests
    - Determine the size and weight of the new technical components that will meet or come closest to meeting class performance (range, acceleration, gradability) and physical (powertrain/fuel system volume) attributes
    - Set a penetration index to “yes” for each class where the NTV meets the class’ performance specifications and physical constraints
- Translate the ADVISOR output (market penetration index, fuel economy) into national oil use with a model based on the DOE Quality Metrics approach that generates annual oil use estimates through 2030
- Use the Quality Metrics annual data, but let the user select a market penetration curve that defines the rate at which the new technology vehicle will be adopted into the marketplace
- Compare oil use of a strictly conventional vehicle market with that of a market penetrated by new technology vehicles

Accomplishments

- Created a spreadsheet-based demonstration version of the technical targets tool
- Completed the market characterization study that defined the current performance and physical characteristics of each EPA vehicle size class.
- Created and debugged a spreadsheet version of the Quality Metrics-based national oil use model
- Programmed Matlab control code that runs ADVISOR to test the new technology vehicles for penetration into each EPA vehicle size class. The code uses ADVISOR’S Autosizing routine rather than the full-blown optimization routine to simulate the new technology vehicle.
- Created an integrated beta test version of the T3 tool in Matlab, including graphical user interfaces for program input and output. Embedded the following routines and data into the program:

  - market characterization data
  - current set of technical target tables
  - ADVISOR control code
  - national oil use model
  - numerous bar and line graphs that describe different aspects of the analysis results
- Began debugging the integrated beta test version of the T3 tool.

Future Directions

- Complete debugging of the beta version of the T3 tool, and present the tool to key DOE and industry individuals. Create a plan for continuing the work based on feedback from the presentation.
- Substitute ADVISOR's full blown optimization routine for the Autosizing routine used in the beta version and compare the results.
- Perform design-of-experiments targets optimization for fuel cell technology.
- Add hybrid electric vehicle and conventional vehicle technologies to the T3 tool and perform design-of-experiments targets optimization for these options.
- Investigate other options for calculating the figure of merit (national oil use savings); for example, using more sophisticated modeling tools
- Investigate other options for the current definition of the figure of merit (national oil use savings); for example, using increase in national average fuel economy as the figure of merit
- Monitor future trends in automotive design for ways to improve the market characterization approach.
- Investigate a more rigorous way to define available powertrain space in conventional vehicles.

Introduction

In 2001, the National Renewable Energy Laboratory (NREL) started working with an auto industry expert on a way to assess the potential impact of DOE's Office of Transportation Technologies' 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 at a time 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.

Broadening the goal to incorporate advanced technologies into many vehicle platforms better aligned R&D with market realities, but brought into question how appropriate the previous, single-platform based set of technical targets were. With the program's goals more market oriented, we needed a way to link the technical targets to this multi-platform market. This link would then allow us to optimize the set of technical targets based on their potential impact in the marketplace.

Approach

The process of creating the technical target-marketplace link began in 2001 as a joint effort between NREL and Teamworks, Inc. The concept was to create a tool, referred to as the technical targets tool or T3, that would cascade a set of technical targets input by the user up to their potential to reduce national oil use. The path for this involved defining the market in terms of EPA's vehicle size classes, and describing each class's performance and physical attributes. Key attributes including acceleration, gradability, range, and size of the advanced vehicle components (i.e., can they fit into the same size vehicle while leaving the required passenger and cargo space?) were examined. These attributes were then used to develop the specifications that an advanced technology vehicle must meet to penetrate the segment of the market represented by that class.

The T3 tool allows the user to alter a set of technical targets that serve as the basis for simulating the advanced vehicle. The advanced vehicle simulation would iterate on component specifications to determine if the vehicle could meet both the technical targets input by the user and the specifications demanded by the market for each market segment or vehicle class. The advanced technology vehicle is deemed able to penetrate those market segments if a solution is found.

The T3 tool uses ADVISOR to perform vehicle simulations and to run the simulated vehicles through the appropriate drive cycle to define their fuel economy. Once ADVISOR completes the analysis for all EPA classes, the T3 tool sends the vehicle class results—a penetration index of “yes” or “no” and fuel economy—to the oil use model. This model is based on the work done by DOE to produce annual quality metrics that determine the impacts of its transportation programs. We used the data contained in the Quality Metrics 2002 Final Report to construct our oil use model. The model estimates annual oil use by projecting new vehicle sales, average miles traveled, and conventional vehicle fuel economy for each class.

Figure 1. **The graphical user interface that serves as the entry screen for the Technical Targets Tool**

The T3 tool lets the user input a market penetration curve that splits the new vehicle sales into conventional vehicles and advanced technology vehicles over time. This penetration curve is applied to those vehicle classes with a penetration index set to “yes”. The T3 tool runs a base oil use case that assumes only conventional vehicles enter the marketplace and an advanced technology vehicle case that factors in the advanced technology vehicle penetration rate. The impact of the advanced technology defined by the technical targets input by the user is defined as the difference in oil use between the two cases.

Results

The Technical Team Targets project has developed a software tool that links the technical targets used as R&D goals to their potential impact on national oil use. The first version of the tool was spreadsheet based and demonstrated the concept of cascading technical targets up to national oil use. The spreadsheet version was replaced by a beta version of the tool that was developed in Matlab using the latest in object oriented programming environments. The tool presents simple graphical user interfaces allowing the user to modify and submit a set of technical target inputs, oil use model adjustments, and select from a number of outputs that describe the results of the analysis. Vehicle simulations are run in ADVISOR to discern the segments of the light vehicle market an advanced technology vehicle based on those targets could penetrate. This, in turn, feeds into a model that projects the impact of this market penetration on national oil use through 2030. This beta version was completed and debugging began at the end of FY02.

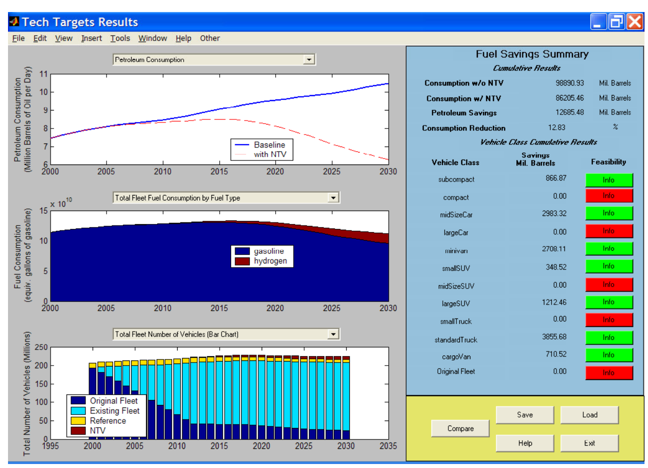

Figure 2. **The graphical user interface that presents the output of the analysis**

Conclusions

In FY02, NREL was able to successfully create a software tool that translates the potential impact of R&D vehicle component-level goals on future oil use in the United States. This tool gives DOE program management the ability to set technical targets based on the ultimate measure of the program's success— a reduction in the nation's oil imports. Work in FY03 will focus on checking and improving the accuracy and usability of the tool and using it to analyze and optimize the current set of technical targets.

III. PROPULSION SUBSYSTEM TECHNOLOGY DEVELOPMENT

The simulation and modeling tools (ADVISOR and PSAT) were used to analyze the performance of advanced hybrid vehicle components and subsystems. ANL completed the assembly of the Advanced Powertrain Research Facility (APRF) and a unique integrated set of supporting tools to simulate, emulate and validate advanced automotive powertrain technologies. This capability allows DOE to analyze candidate technologies, test and validate newly developed components and powertrains using Hardware-In-the-Loop (HIL) and/or Rapid Control Prototyping (RCP) techniques as well as test 2-wheel and 4-wheel drive vehicles using the latest equipment to measure fuel efficiency and emissions. Improved battery models were incorporated into ADVISIOR and battery performance was analyzed to assess methods to improve thermal management so as to enhance performance and extend battery life. This section summarizes the objectives, approach and significant results of these activities.

A. Advanced Optimization Methods for Vehicle Systems Analysis

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Objective

- While working with commercial software vendors and academic groups, evaluate existing and develop improved optimization algorithms and methods geared towards hybrid electric vehicle systems analysis and evaluation.
- Provide integrated advanced optimization capabilities to users of ADVISOR.
- Demonstrate the need for and the applicability of advanced optimization methods on specific hybrid electric vehicle analysis problems.

Approach

- Apply appropriate optimization algorithms to specific hybrid vehicle configuration trade-off studies with an emphasis on fuel cell vehicles.
- Disseminate lessons learned with regard to optimization algorithm applicability to hybrid vehicle analysis.
- Present results of fuel cell vehicle application studies at international conferences.

Accomplishments

- Presented a review of optimization algorithms and their applicability for hybrid electric vehicle design optimization at the ASME IMECE.
- Presented study results demonstrating the impacts of drive cycle assumptions on optimal fuel cell hybrid vehicle design at EVS-18.
- Created a distributed computing environment to allow individual analyses of an optimization study to be evaluated in parallel. As a result, the available computing resources can be applied to rapidly analyze multiple design scenarios.
- Used DIRECT to derive an optimal vehicle energy management strategy for an OEM powertrain concept.
- Analyzed the influence of the fuel cell system power response capabilities on the optimal fuel cell hybrid and neat vehicle design and presented the study results at FutureCAR Congress.

- Provided initial assessment of gasoline reformer warm-up impacts on fuel cell vehicle fuel economy.

Future Directions

- Apply appropriate optimization algorithms to multi-disciplinary analysis of hybrid electric vehicle system design and disseminate study results.
- Add the ability for ADVISOR users to easily distribute multiple analyses to available computing resources via integration with available distributed computing software tools.
- Explore the possibilities for improving efficiency of optimization methods by linking derivative-free and gradient-based algorithms.

Introduction

Vehicle design and analysis by manual iteration can be a very time consuming and inefficient process. Optimization tools provide the engineer with the ability to automate the iterative design process and to ensure some acceptability of the final solution using quantitative tolerances and constraints. Conventional optimization methods use gradients based on sample data points to determine search directions and step sizes. The determination of fuel economy and performance of a hybrid electric vehicle that can be compared with other vehicle designs requires state of charge (SOC) balancing. As a result, tolerances must be used and noise is introduced into the response. Conventional gradient-based tools can become quite confused by the noise in the response values. They also only know information about their local surroundings and thus cannot guarantee that the solution is the globally optimum solution. Derivative-free and globally focused algorithms seem to be undeterred by noise in the response and can provide greater confidence in the global optimality of a solution.

Approach

Others have completed significant work in the area of optimization techniques. Therefore, our approach has been to partner with those who have extensive knowledge in this field and apply the tools to real analysis problems. During the past year NREL's primary focus in this area has been problem definition and application of the tools to add to the general knowledge of optimal HEV design.

Results

Our first application of the tools was to a simple 2D surface with several local minima and one global optimum. This was used to improve our understanding of how the various tools approach the problem and which ones would be well suited for application to ADVISOR.

To link these tools to ADVISOR we use its GUI-free functionality, allowing user to iteratively run ADVISOR without graphical user interface (GUI) intervention. The optimization routines are wrapped around ADVISOR and iteratively call it to calculate both objective and constraint responses for various input variable settings (see Figure 1).

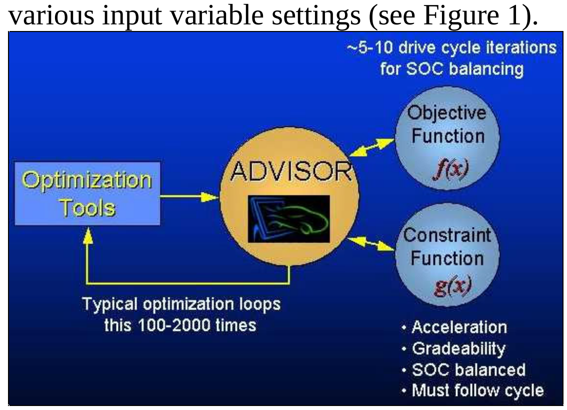

Figure 1. **ADVISOR in an Optimization Loop**

Based on our experience, we have been very impressed with the DIRECT derivative-free algorithm that was highlighted in the conclusions of the work with the University of Michigan. We have applied it extensively to the optimization of a fuel cell hybrid SUV.

In our fuel cell hybrid SUV studies we have focused on understanding the impacts of various vehicle parameters on the resulting fuel economy and performance attributes. We have allowed the optimization routine to vary the sizes of components and the energy management strategy parameters with the objective of maximizing fuel economy, while providing acceleration and grade performance equivalent to that of a comparable conventional SUV.

We also evaluated the impacts of the drive cycle over which the fuel economy is computed on the resulting optimal vehicle design (see Figure 2). The study highlighted the fact that more aggressive cycles like the US06 will move the vehicle design toward a smaller battery pack and larger fuel cell while less aggressive cycles like the NEDC (New European Drive Cycle) prefer systems with larger battery packs and smaller fuel cells. Vehicles designed for less aggressive cycles also exhibited more thermostatically control behavior, while more aggressive cycles pushed the control towards a more load-following strategy. In the end, it was observed that the NEDC cycle provided a robust vehicle design.

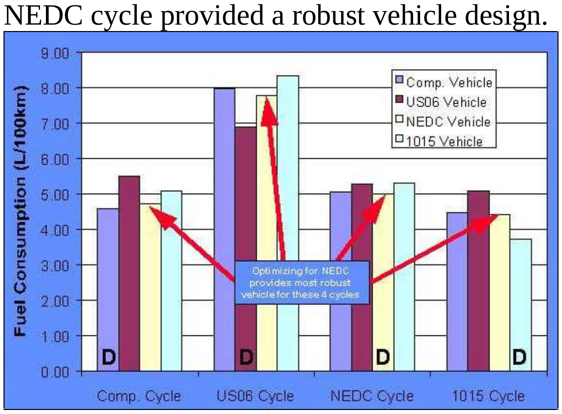

Figure 2. Optimization of vehicle for drive cycle impacts fuel economy (the "D" represents vehicles that were optimized for that particular cycle)

Following this drive cycle impacts review, we studied the impacts of fuel cell system power response characteristics. In this study, new vehicles with component sizes and control parameters optimized for fuel economy were derived for fuel cell systems with a range of response characteristics. Vehicles both with and without energy storage were considered. To complete this study in a timely fashion, the newly created Distributed Computing Laboratory resources (Figure 3) were employed.

In Figure 4 we see that, through optimization of the vehicle design, the fuel economy of the hybrid fuel cell vehicle was maintained regardless of the fuel cell response characteristics. While for the neat (no energy storage) case the fuel economy drops significantly with increasingly longer fuel cell response times.

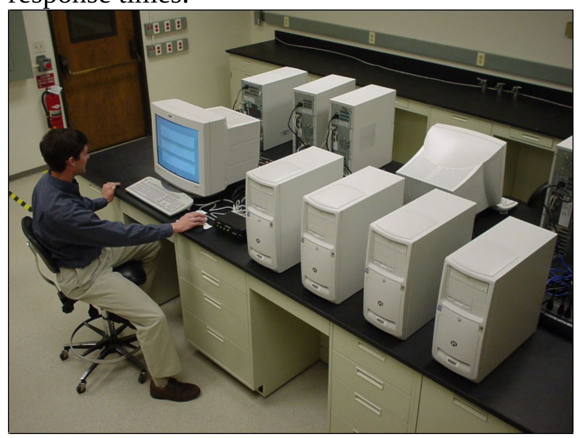

Figure 3. Distributed Computing Laboratory

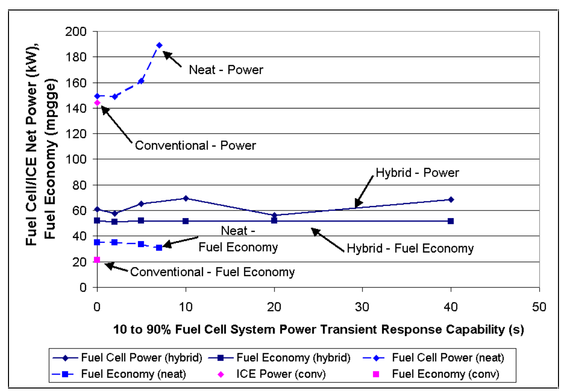

Figure 4. Optimal hybridization provides fuel cell vehicle design flexibility

Conclusions

The development, evaluation, and application of optimization tools have highlighted the importance of optimization in vehicle systems analysis. ADVISOR has been demonstrated as an effective response generating tool through its GUI-free implementation. Various commercial and publicly available algorithms have been linked to ADVISOR using the GUI-free connection. Recent applications of the tools have been focused on the optimization of a fuel cell hybrid SUV. We have looked at the variation of both component sizes and the energy management strategy parameters to improve fuel economy. Our analysis of this vehicle configuration has demonstrated the influence of drive cycles and component characteristics on the resulting optimal design.

The results of the studies completed thus far have been disseminated to the public. We intend to complete other variations on the existing studies to provide insight into the sensitivity of fuel cell hybrid vehicle systems configuration as a function of various vehicle characteristics. To improve the efficiency of the derivative-free algorithms, we will evaluate the possibilities performing optimization in a distributed computing environment and the linking of gradient-based routines with derivative-free routines.

Publications / Presentations

Markel, T., Wipke, K, Nelson, D. "Optimization Techniques for Hybrid Vehicle Analysis Using ADVISOR," ASME International Mechanical Engineering Congress and Exposition, Nov. 10-16, 2001. New York.

Markel, T., Wipke, K., Nelson, D. "Vehicle Systems Impacts of Fuel Cell System Power Response Capability" FutureCAR Congress, June 2002.

Wipke, K., Markel, T., "Optimization of Hybridization and Energy Management Strategy" 18th Electric Vehicle Symposium. October 2001.

B. Development of Hardware-In-the-Loop (HIL) and Rapid Control Prototyping (RCP) Capabilities

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Objectives

- Develop Hardware-In-the-Loop (HIL) capability at ANL's Advanced Powertrain Research Facility (APRF)
- Demonstrate HIL capability using PSAT-PRO control software.

Approach

- Complete and validate mechanical, electrical, and signal (control, instrumentation, and data acquisition) interfaces for HIL
- Develop baseline control strategy for a CIDI CVT parallel hybrid powertrain
- Implement PSAT-PRO control code for emulated hybrid vehicle operation over a drive cycle
- Model and simulate a vehicle application for a wheel motor
- Demonstrate emulation of a FC vehicle with adjustable performance characteristics

Accomplishments

- Completed the CIDI CVT parallel hybrid powertrain test cell, data acquisition system, ANL Safety Plan and Safety Review
- Demonstrated control of all individual powertrain components (i.e., engine, motor, CVT, CVT hydraulic pump, battery, clutch and dynamometer) and integrated powertrain using PSAT-PRO
- Completed the motor-only test stand, ANL Safety Plan and Safety Review
- Demonstrated optimal control of variable gap axial flux NGM motor

- Demonstrated fuel cell emulation with the ABC-150 programmable power supply.

Future Directions

- Continue the study of hybridization on diesel emissions
- Study the effect of integrated control of the hybrid powertrain and after-treatment on diesel emissions
- Continue support to the fuel cell vehicle emulation activities

Introduction

Hardware-In-the-Loop (HIL) and Rapid Control Prototyping (RCP) capabilities allow new component/subsystem technologies and powertrain control strategies to be assessed in an emulated vehicle environment, minimizing the need to fabricate vehicle prototypes. ANL is developing this capability at the Advanced Powertrain Research Facility (APRF).

Approach

Develop HIL Capability

Development of an integrated virtual and physical test environment includes designing and implementing the hardware, software and experimental techniques to test components, subsystems or systems in a test fixture that is controlled using simulation (i.e., an 'emulated' environment). Based on the program direction received in FY01, components for a parallel diesel hybrid powertrain procured (or fabricated) and the assembled in the test cell. FY02 activities included completion and validation of the mechanical, electrical and signal (control, instrumentation and data acquisition) interfaces, component modifications for improved efficiency or control and software modifications and verification to insure safe and reliable operation, signified by passing the ANL Safety Review.

Figure 1. **HIL powertrain test cell**

Demonstrate HIL Capability Using PSAT-PRO Control Software

HIL capability was demonstrated by the successful implementation of powertrain system control in the APRF, using PSAT-PRO and a control strategy that was developed in PSAT. The techniques were also demonstrated with the variable gap axial flux NGM motor (optimal control to increase efficiency) and the ANL Emulated FC Vehicle (EFCV) on the chassis dynamometer. This test setup combines an emulated fuel cell with a real battery and electric vehicle chassis to determine battery requirements for starting and peak power.

Results

The initial target of the HIL/RCP activity was to control the engine to operate as prescribed by PSAT (i.e., to achieve minimum fuel consumption/emissions) while emulating vehicle operation over a realistic driving cycle. Keeping the engine operating in an efficient region requires precise control of the transmission ratio and the power sharing between the engine and motor. The first of the graphs (Figure 2) shows how integrated control of the transmission and motor was used to keep engine operation in a relatively small region of the engine map while the vehicle was performing a driving cycle. Figure 3 illustrates how the transmission ratio changes when wheel speed changes to keep the engine at an optimal speed range. Figure 4 shows the torque provided by the engine and the motor, illustrating how the motor makes up the torque difference to follow the driving cycle.

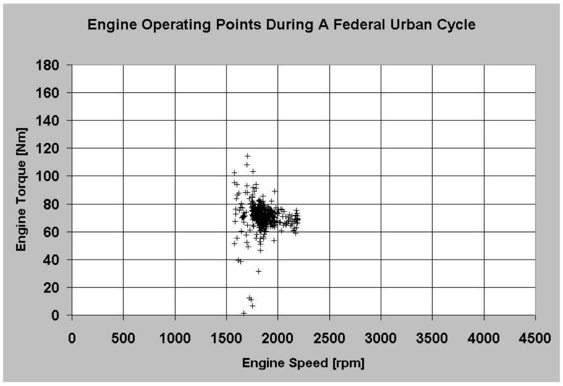

Figure 2. **Result of powertrain control to insure efficient engine operation**

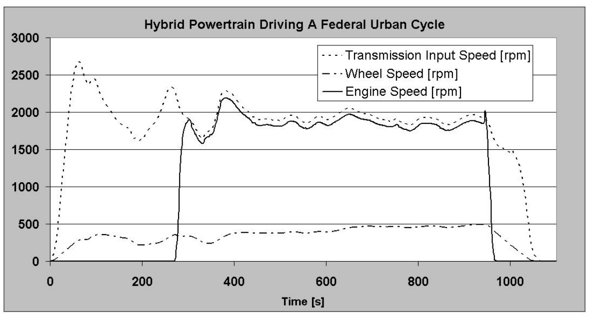

Figure 3. **Example of transmission ratio control to keep engine near optimal speed range**

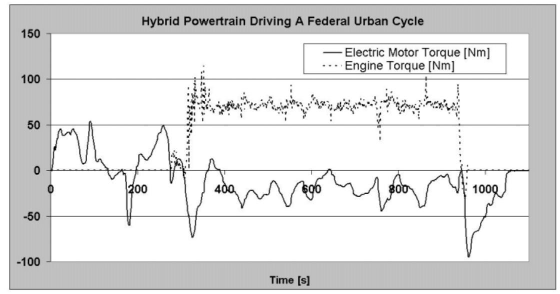

Figure 4. **Example of Motor Torque Control to Keep Engine Near Optimal Torque Range**

The NGM motor testing demonstrated that using HIL techniques in the technology validation process yields more useful information than standard testing would provide. The testing clearly demonstrated improved efficiency by optimally controlling the variable gap axial flux motor over a driving cycle. The graphs in Figure 5 compare the efficiency map for set gaps versus the optimal efficiency map, illustrating the expanded high efficiency operating area.

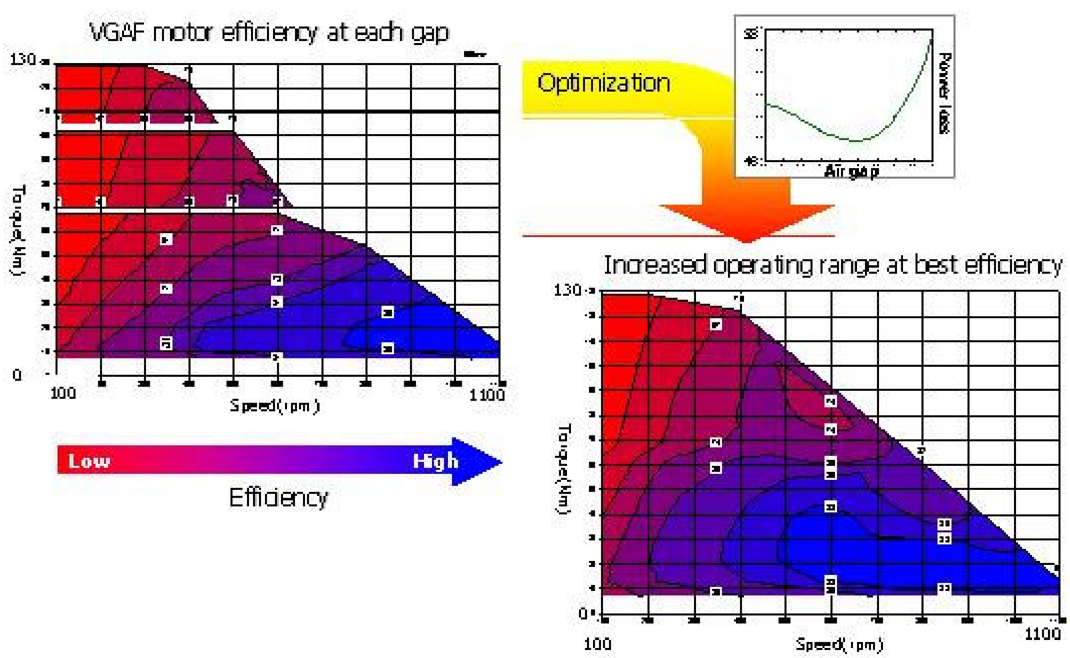

Figure5. Variable gap control optimization process for improved overall motor efficiency.

With the success of the motor-only HIL test stand and acquisition of portable HIL controls, the test stand was improved to allow easier integration of different motor types (expected to be delivered for validation in FY03) as well as improve access and safety. In addition, the stand was redesigned as a portable unit to allow HIL testing in locations outside the HIL test cell.

Publications

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Pasquier M., Duoba M., Hardy K., Rousseau A., Shimcoski D., *Evaluation of a CIDI Pre-transmission Parallel Hybrid Drivetrain with Continuously Variable transmission,* 19th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition (EVS19), Busan, Korea, (2002) (Poster session).

C. Energy Storage from a Vehicle System Perspective

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Objectives

- The overall objective is to improve the fuel economy and life cycle costs of advanced vehicles by improving thermal and electrical management to enhance performance and extend battery life.
- Evaluate the feasibility of a prototype concept for heating the HEV batteries to improve their poor performance at cold temperatures.
- Improve the electrical and thermal battery models for ADVISOR simulations.
- Validate a discretized battery pack model with the Saber-ADVISOR co-simulation for better energy management.
- Evaluate the benefits of using hybrid energy storage (battery + ultracapacitor) systems in hybrid electric vehicle (HEV) and electric vehicle (EV) applications.
- Measure the thermal characteristics of FreedomCAR batteries and perform thermal analysis to improve battery performance.
- Investigate thermal issues related to FreedomCAR batteries for improving their performance.

Approach

- Use state-of-the-art and unique equipment to characterize the thermal performance of batteries.
- Use finite element analysis to evaluate thermal performance of batteries and improve their thermal design.
- Demonstrate the feasibility of high-frequency alternating current (AC) power for preheating batteries.
- Continue the FY 2001 modeling work based on the guidance from the DOE- and industry-sponsored workshop on Development of Advanced Battery Engineering Models.
- Work with industry to develop a discretized battery pack model that captures the behavior of each cell and module in a pack.
- Identify thermal issues with batteries in vehicles under real driving conditions and develop tools to characterize and address these issues.
- Use advanced simulation tools to evaluate the benefits of using hybrid energy storage systems in HEV and EV applications.

Accomplishments

- Refined and updated a prototype for applying high-frequency (10–20 kHz) AC power to a battery pack.
- Assembled a nickel metal hydride (NiMH) battery pack consisting of 16, 7.2 V Panasonic modules and showed the feasibility of the high-frequency AC power in preheating batteries
- Updated the PNGV (Partnership for a New Generation of Vehicles) electrical performance model for a lithium ion (Li-Ion) battery to the ADVISOR energy storage library.
- Improved the resistance + capacitance (RC) battery model for the NiMH chemistry by adding a better state of charge (SOC) algorithm.
- Developed a new approach for modeling the thermal conditions in a battery pack by capturing the thermal response of each module.
- Developed models for Li-Ion and NiMH batteries in Saber and validated them with test data.
- Created a battery (sub) pack model in Saber consisting of as many as 10 cells or modules with variable battery parameters (SOC, temperature, resistance) for the two chemistries. A few of these subpacks can be combined to make a full pack consisting of 40 or more modules.
- Linked the Saber battery pack model to ADVISOR for co-simulation studies from a vehicle level perspective and used the model to investigate various unbalancing scenarios.
- Developed a simulation tool in a Matlab/Simulink environment for modeling hybrid energy storage (batteries, ultracapacitors, and various combinations) and linked it to ADVISOR for vehicle simulations.
- Verified the model by testing a directly coupled battery and ultracapacitor configuration.
- Developed a new optimization process using Direct, Matlab, and Excel to find the optimum battery–ultracapacitor configuration given an objective function and constraints.
- Obtained thermal characteristics of the latest FreedomCAR Li-Ion cells from Saft.
- Performed thermal analysis on a low cost liquid-cooled Saft Li-Ion module and proposed recommendations for improved thermal performance.

Future Directions

- Test and evaluate battery-preheating hardware to improve cold cranking of batteries in a vehicle.
- Use the Saber battery pack in conjunction with ADVISOR to investigate energy management strategies to prevent imbalances in a battery pack and improve fuel economy, acceleration, and gradability for different types of hybrid vehicles.
- Continue to work with original equipment manufacturers (OEMs) and battery developers to improve the thermal designs of batteries so life and performance targets can be achieved by thermal characterization and analysis of advanced batteries.
- Develop a standard test procedure for thermal evaluation of battery packs.
- Design and fabricate a large battery calorimeter for thermal characterization of 42 V FreedomCAR batteries.
- Refine energy management control systems to optimize the effectiveness of the ultracapacitor–battery combination and verify it with hardware in the laboratory.

Introduction

Over the past several years, NREL has worked on battery and other energy storage devices from a system's perspective. The overall goal has been to enable electrical energy storage technologies to achieve their full potential in a vehicle environment under real-world driving conditions. We have focused on improving the thermal performance of batteries through thermal characterization, modeling, analysis, and management. We have also developed battery and energy storage models and simulation tools to investigate the benefits of energy storage systems in advanced EVs, HEVs, and fuel cell vehicles (FCVs).

NREL has had the lead responsibility for evaluating thermal characteristics of batteries and for helping the battery and automobile industries develop improved battery thermal management strategies. Proper thermal design and management of batteries in EVs and HEVs is an important task as it can affect the performance and life of the battery and thus the vehicle performance, fuel economy, and cost to consumers.

Understanding the thermal properties and behavior of batteries and packs will help us understand how to develop modules and packs with better thermal performance. In addition to improved fuel economy and performance, a properly designed thermal management system will extend battery life and thus save energy because fewer batteries will be produced. NREL's Battery Thermal Management Web site (http://www.ctts. nrel.gov/BTM) provides further details about this project.

Since batteries are key to developing successful EVs, HEVs, and FCVs, accurate models to predict their behavior are essential. NREL works to develop battery electrical and thermal performance models for simulation tools such as ADVISOR and PSAT, which simulate the performance and fuel economy of advanced conventional vehicles, EVs, and HEVs based on component models, configuration and control strategies, and drive cycles. ADVISOR is used to evaluate technologies, select and size components, and identify research directions. In addition to developing battery models for "single" modules, we recently started to develop a complete battery "pack" model consisting of multiple modules with different behaviors and investigate ultracapacitors and their combination with batteries for advanced vehicles.

Approach

As part of DOE's FreedomCAR and Vehicle Technology Program, NREL provides DOE, the U.S. automobile industry, and battery developers with an integrated approach to battery thermal characterization and analysis and electrical and thermal performance modeling for ADVISOR vehicle simulations. NREL's Energy Storage project team works hand in hand with industry to thermally and electrically characterize batteries, develop models, and offer design improvements for HEV and EV modules and packs.

NREL uses a unique calorimeter to measure heat capacity and heat generation from batteries. Infrared thermal imaging, flow visualization, thermal testing and analysis, and computational fluid dynamics are all used to assess and evaluate batteries. NREL uses the latest PNGV Battery Test Manual to test and develop models and its battery testing equipment to generate data and develop validated battery models. These models are then used in vehicle simulators to evaluate their impacts on vehicle performance. We used testing and simulation to develop a complete battery "pack" model and evaluate the benefits of combining ultracapacitors with batteries for energy storage in HEVs.

Results

Battery Preheating. We used finite element analysis to evaluate four alternative heating approaches and found that the internal core heating battery was the most effective method for raising battery temperature, and thus performance, quickly in cold weather. In FY 2002, we evaluated the feasibility of a prototype concept for preheating HEV batteries by applying high frequency alternating current (AC) power to improve their poor performance at cold temperatures. We continued to work with the University of Toledo and achieved the following:

- Refined and updated the prototype heater circuit to apply high-frequency (10–20 kHz) AC power to a battery pack. In this design, half the pack is charged and the other half is discharged through an inductor.
- Assembled a NiMH battery pack consisting of 16, 7.2 V Panasonic modules from a wrecked Prius.
- Initial results indicate high-frequency heating is feasible: applying a 60 A, 10 kHz current to the battery pack at -20°C restored the resistance (and thus power) to a value fairly close to its 25°C value.

The results were presented at the 2002 Future Car Congress. For FY 2003, we plan to collaborate with engineers from DaimlerChrysler to develop hardware for on-board vehicle use.

Battery Model Improvement. Based on recommendations we received during the DOE-industry-sponsored workshop on Development of Advanced Battery Engineering Models in Crystal City, Virginia, in August 2001, we improved our battery models for ADVISOR simulations by adding an improved implementation of the PNGV battery model that resulted in a 10% improvement in predicting SOC and marginally better prediction of voltage for a Li-Ion battery over a US06 drive cycle. Our implementation clarified a few steps in the PNGV Battery Test Manual for more efficient development of battery models. We improved the SOC estimator in the RC battery model in ADVISOR by changing to amp-h integration from voltage-based estimation. With this change the RC model improves SOC predictions typically by an order of magnitude (10X) based on model predictions versus laboratory data estimations. The battery thermal model in ADVISOR uses a lumped capacitance approach for the whole pack; so all the cells are the same temperature. We developed a thermal circuit in the Saber discretized battery model to determine how differences in the thermal properties of individual batteries (such as via manufactured variations) affect the overall energy exchange in an HEV battery pack.

Complete Battery "Pack" Modeling. The battery pack model in ADVISOR treats the pack as a "single" large module. So our purpose was to enhance the capability of ADVISOR by developing a battery pack with the ability to capture variability from module to module. We have worked closely with industry including Delphi and Avant! to develop this discretized battery pack model that captures the behavior of each cell and module in a pack. We created a validated battery (sub)pack model in Saber consisting of as many as 10 cells or modules with variable battery parameters (SOC, temperature, resistance) for the two chemistries. A few subpacks can be combined to make a full pack consisting of 40 or more modules. The Saber battery pack model was linked to ADVISOR for co-simulation studies from vehicle level perspective. An initial co-simulation study with a Prius-type HEV showed that a mildly imbalanced battery pack could reduce the vehicle fuel economy by 3%–4%. However, this number could be higher if the SOC is not tightly controlled; as is the case with Prius to protect the battery.

Hybrid Energy Storage Evaluation. This work was initiated based on interest from industry to evaluate the benefits of using hybrid energy storage (battery + ultracapacitor) systems in HEV and EV applications. We used advanced simulation tools to model the storage system's electrical components (batteries, ultracapacitors, controllers) using Mathwork's SimPowerSystems block set that could be easily linked to Mathwork's Matlab/ Simulink and thus ADVISOR. We verified the model by testing a directly coupled battery and ultracapacitor configuration. The hybrid energy storage model was to ADVISOR for vehicle simulations. As part of this process, we developed a novel approach to allow a variable time step Matlab/Simulink model (such as hybrid energy storage) to be simulated together with a fixed time step Matlab/Simulink model (such as ADVISOR). This new modeling process allows detailed component models to run much faster concurrently with ADVISOR and is applicable to detailed modeling of many components in advanced vehicles. We developed a new optimization process using Direct, Matlab, and Excel to find the optimum battery–ultracapacitor configuration given an objective function and constraints. We applied the new process to a modified Honda Insight parallel hybrid vehicle and showed that an Insight with a smaller battery pack and fewer battery modules or a small combination of battery and ultracapacitor can deliver similar performance while overall volume and weight can be reduced with appropriate interface electronics.

Thermal Characterization of Batteries. The Energy Storage Team collaborated with industry to measure thermal characteristics of the following batteries: Saft Li-Ion batteries for FreedomCAR program, Panasonic valve regulated lead acid battery for AC Propulsion, NiMH batteries from Panasonic, and Li-Ion polymer from Compact Power. Using a unique battery calorimeter and cycler, we measured the heat capacity of each battery and the heat generation from each module under various driving cycles and PNGV profiles at various temperatures and found that the lithium batteries generated the least amount of heat, and thus were more energy efficient. We obtained thermal images of the batteries and used high-speed time-lapsed videography to compress hours and minutes of thermal images into seconds. Thermal imaging indicated that lithium batteries had very uniform temperature distribution. The heat generation and heat capacity data were used in the thermal analysis of batteries for improving thermal design.

Thermal Analysis of Batteries. We used finite element analysis to evaluate the thermal performance of batteries under various loads. Per the FreedomCAR Energy Storage Technical Team's request, we worked with SAFT America on thermal analysis of low-cost liquid-cooled Li-Ion batteries. We performed thermal analysis on four different concepts to cool a 12-cell module with liquid. We also investigated the flow rate and pressure drop requirements so the cooling concept uses a small amount of energy to pump liquid. Based on our recommendation, SAFT is building battery modules for delivery to the FreedomCAR program for testing and evaluation.

Conclusions

NREL has been working on testing, characterizing, analyzing, and developing technologies to efficiently control the thermal performance of batteries in EVs and HEVs. In addition to the improved fuel economy and performance, a properly designed thermal management system will extend the life of batteries and thus lead to low production numbers of batteries. NREL has also developed and improved math-based models for "single module" and "battery packs" and has simulated the hybrid energy storage systems. In FY 2003, NREL will continue to work with industry to improve thermal performance of batteries and develop models that enable evaluation of advanced energy storage concepts for EVs and HEVs.

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IV. VEHICLE ANCILLARY LOAD REDUCTION

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Objectives

- Assess vehicle air conditioning system performance and its impact on fuel economy and emissions
- Research and develop innovative techniques and technologies that will reduce the fuel used for vehicle auxiliary loads
- Assess thermal comfort, fuel economy, and emissions using an integrated modeling approach
- Develop computational and experimental models of human thermo-physiology and perception of human comfort

Approach

- Validate integrated modeling tools in industry-sponsored vehicle test
- Demonstrate transient electric air-conditioning system optimization technique for FreedomCAR applications
- Complete fabrication of thermal comfort manikin including physiological-based control system and local and global perception of thermal comfort
- Develop conceptual design of combined fuel cell stack and cabin thermal and humidity management system, including waste heat cooling and heating opportunities

Accomplishments

- Performed vehicle soak tests with techniques to reduce the peak soak temperature using a Jeep Grand Cherokee provided by DaimlerChrysler
- Applied an integrated modeling process to a joint project with Johnson Controls to assess the impact of a new HVAC concept on ventilation flows and human thermal comfort
- Used transient air conditioning models to simulate and optimize the performance of an electric-driven air conditioning system for a light-duty vehicle
- Developed an optimization technique to investigate design objectives separately or simultaneously in order to identify optimum compromise AC systems
- Developed a psychological thermal comfort model that is capable of predicting human thermal comfort in transient asymmetric thermal environments
- Designed and fabricated all components of a thermal manikin, ADAM (ADvanced Automotive Manikin) to assess thermal comfort in actual vehicle thermal environments
- Completed analysis and design of a metal hydride heat pump for a fuel cell vehicle utilizing waste heat
- Initiated work on a joint project with DaimlerChrysler and Millennium Cell to analyze the water balance requirements in a fuel cell vehicle with a hydrogen on demand (HOD) hydrogen supply system using sodium borohydride ($NaBH_4$)

Future Directions

- Use the integrated modeling process to evaluate advanced concepts that will reduce peak soak temperature and improve passenger comfort
- Develop creative motivating factors to entice the U.S. automotive industry to adopt an integrated modeling design approach
- Validate the thermal manikin against human test subjects and demonstrate to OEMs and suppliers
- Develop a heat-generated cooling laboratory to develop prototypes of waste-heat cooling systems

Introduction
Fuel used for vehicle climate control significantly impacts our nations energy security by deceasing the fuel economy of the 216 million light duty conventional vehicles in the U.S. It can also reduce the fuel economy of and high fuel economy vehicles by up to 50%. To address these issues, NREL works closely with industry to develop techniques to reduce the ancillary loads, such as climate control, in vehicles. We are conducting research in order to improve vehicle efficiency and fuel economy by controlling the climate in the vehicle, while still keeping the passengers comfortable. As part of this effort, we are conducting research into integrated modeling, air-conditioning optimization techniques, thermo-physiological modeling, and waste heat cooling and heating opportunities.

Approach
NREL uses a variety of tools to achieve the goal of researching and developing innovative techniques and technologies that will reduce the fuel used for vehicle auxiliary loads. Specifically, NREL has led efforts to:

- Validate integrated modeling tools in industry sponsored vehicle tests
- Demonstrate transient electric air-conditioning system optimization techniques for FreedomCAR applications
- Design and fabricate a thermal comfort manikin including a physiological-based control system and a model for local and global perception of thermal comfort
- Develop a conceptual design of combined fuel cell stack and cabin thermal and humidity management systems, including waste heat cooling and heating opportunities

Results
Validate integrated modeling tools in industry sponsored vehicle tests. NREL used a Jeep Grand Cherokee provided by industry partner DaimlerChrysler to perform vehicle soak tests. Using the cabin thermal fluid model and VSOLE (cabin radiation model), the cabin interior temperatures were predicted for 3 different soak tests. The predicted temperatures matched the test data well and validated the models. Then the correlated model was used to investigate techniques to reduce the peak soak temperature. After incorporating solar reflective glass, ventilation, and reflective paint, a 7.9°C reduction in cabin air temperature was predicted which results in a 6.3% improvement in fuel economy if the A/C system is downsized in response to the reduced initial temperature.

The integrated modeling process was also applied to a joint project with Johnson Controls (JCI). JCI wanted to assess the impact of a new HVAC concept on ventilation flows and human thermal comfort. The capability of the parametric meshing tool used in the integrated modeling process was verified. The results show there is a potential thermal comfort benefit to locating HVAC units under the driver and passenger seats. An additional benefit is that the passenger seat HVAC could be turned off when the seat is not occupied thereby reducing the load on the engine and reducing climate control fuel use.

Demonstrate transient electric air-conditioning system optimization techniques for FreedomCAR applications. NREL used its transient air conditioning (A/C) models to simulate and optimize the performance of an electric-driven air conditioning system for a light-duty vehicle. NREL investigated two system design objectives: 1) maximize the A/C system Coefficient of Performance (COP), and 2) maximize the A/C system cooling capacity over the SC03 and US06 drive cycles.

NREL also developed an optimization technique that allowed us to investigate each design objective separately, or simultaneously in order to identify optimum compromise systems that could potentially satisfy, to the extent possible, both design objectives together. Results show that not only are system designs to satisfy each design objective very different, but there is a sharp demarcation between the system design regimes for optimizing these system objectives. This research also shows that it is possible to achieve dynamically controlled, electric-driven A/C systems with system COPs above 3. This compares with current state-of-the-art A/C systems which only have COPs ~1.5. Consequently, it is possible to reduce the amount of energy used by a vehicle A/C system by a factor of 2, if they are dynamically controlled, electrically driven, and properly optimized.

Design and fabricate a thermal comfort manikin including a physiological-based control system and a modes for local and global perception of thermal comfort. A thermal manikin, ADAM (ADvanced Automotive Manikin), has been developed to assess thermal comfort in actual vehicle thermal environments. The manikin was designed to closely simulate human thermal response and heat transfer in the transient asymmetric thermal environments found in vehicles. The manikin consists of 126 surface segments, which provides a spatial resolution of the thermal field of approximately 10 cm. The purpose of each surface segment is to sense the thermal field and provide independent control of surface heat output and sweat rate. Essentially, each surface segment mimics the human thermoregulatory system. The manikin geometry matches the average American male. It has prosthetic joints to provide close to the full range of human motion. The manikin is completely self-contained without any wires, hoses, or connections of any kind. It contains batteries, a sweat reservoir, and a wireless communication system. It has been designed to be very rugged and durable to withstand industry testing. The output of the manikin is the local and global perception of thermal comfort and sensation at each instant in time throughout a test. The manikin is controlled by the finite element physiological model, and the thermal comfort output is generated by the psychological thermal comfort model. This manikin is the first of its kind, and is more advanced than any previous manikin.

Develop a conceptual design of combined fuel cell stack and cabin thermal and humidity management systems, including waste heat cooling and heating opportunities. Analysis and design of a metal hydride heat pump for a fuel cell vehicle was completed and presented to the international community at the "International Symposium on Metal Hydrogen Systems" held in France in September 2002. Metal hydrides represent a unique way to capture the low-grade waste heat available in a fuel cell vehicle, as many other waste-heat capturing technologies require higher operating temperatures. The design included appropriate selection of materials to operate between 80°C as the waste heat temperature and 0°C as the temperature for cold air in the cabin. The analysis showed that the heat pump could achieve a coefficient of performance of 0.5. This resulted in cooling capacities of 3 kW for a small sedan and 7 kW for a sport utility vehicle. With a target of 5 kW cooling, the analysis shows that for implementing heat-generated cooling in a small sedan, additional techniques to reduce the required AC load are necessary.

Water balance within a fuel cell stack is critical for optimal performance. Using a hydrogen supply of a chemical hydride with its own water balance requirements adds additional complexity to the system, but also allows us to utilize features of the fuel cell by using the water generated from the fuel cell operation to feed back into the hydrogen supply system. Work was initiated in a joint project with DaimlerChrysler and Millennium Cell to analyze the water balance requirements in the fuel cell vehicle with a "Hydrogen on Demand (HOD)" hydrogen supply system using sodium borohydride ($NaBH_4$). The project determines appropriate control of the water in the hydrogen delivery system to maintain a water balance within the system. This involves changing the solution percentage ($NaBH_4$ to H_2O) between 30% in the storage location and 20% at the reaction site. By achieving this water balance, the HOD system is allowed a greater amount of hydrogen in the fuel reservoir, allowing increased vehicle range, or equivalently less fuel weight for a given amount of hydrogen. The 30% solution corresponds to a 6.4% H_2 by weight, which is in line with FreedomCAR targets.

The initial work with DaimlerChrysler and Millennium Cell has involved industry needs and project definition, thermal infrared imaging of the hydrogen generation from $NaBH_4$ process, and modeling of the process.

Conclusions

NREL is pursuing a variety of avenues in its efforts to improve vehicle efficiency and fuel economy by controlling the climate in the vehicle, while still keeping the passengers "comfortable." Because climate control loads significantly impact our national energy security and the fuel economy and tailpipe emissions of conventional and hybrid electric automobiles, NREL is working closely with industry to develop techniques to reduce the auxiliary loads, such as climate control, in a vehicle.

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V. TECHNOLOGY VALIDATION TESTING

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Objectives

- Validate the performance of DOE-developed technologies
  - UQM integrated electric drive (INTETS)
  - SAFT lithium-ion battery
  - Cummins diesel exhaust aftertreatment system
- Complete 4WD SULEV facility for accurate emissions testing of advanced light- and medium-duty vehicles under development

Approach

- Conduct efficiency measurements and identify system interface issues for UQM INTETS
- Characterize and validate the performance of SAFT lithium-ion battery under realistic vehicle operating conditions
- Install the Cummins diesel exhaust aftertreatment system in a vehicle and measure emissions
- Install major test systems and commission the 4WD SULEV facility at the APTF

Accomplishments

- Completed and initially operated the Emulated Fuel Cell Vehicle (EFCV), with the UQM motor, baseline lead-acid battery, and an emulated fuel cell, demonstrating the direct application of PSAT models (vehicle, drive and fuel cell) and HIL techniques to technology validation.
- Completed characterization testing of the SAFT Lithium-Ion battery at the ANL Battery Test Facility.
- Installed and commissioned all the major systems in the 4WD chassis dynamometer facility, including the dynamometer, emissions measurement, air handling, data acquisition, control system, and safety.

Future Directions

- Validate/verify the performance of the UQM integrated electric drive and the SAFT Li-Ion battery in the EFCV.
- Utilize the approach demonstrated by the EFCV and the 4WD dynamometer to validate additional DOE-sponsored technology.
- Study the impact of fuel cell performance (i.e., power and response time) on peaking power (battery/ultra-capacitor) requirements.
- Correlate the dynamometer and emissions measurement equipment with other test facilities using industry-standard calibration vehicles.
- Benchmark state-of-the-art/developmental vehicles that use non-standard fuels or are equipped with propulsion systems relevant to DOE activities.

Introduction

Vehicle level testing and component validation are necessary to confirm the performance of DOE- or externally-developed technology. For purposes of the DOE vehicle systems activity, ANL has defined validation to have three aspects: performance versus specifications, performance in a systems context and relevance to DOE objectives.

Approach

Validation of UQM Integrated Electric Drive and SAFT Li-Ion Battery in an Emulated Fuel Cell Vehicle (EFCV)

The UQM drive unit was developed under the Small Business Investment Research (SBIR) program and performance specifications were minimal (e.g., peak power capability). This level of information is not adequate for vehicle analysis or design, so ANL decided to assess the drive unit as part of a vehicle-level HIL project to be carried out on the 4WD dynamometer. The unit was delivered near the end of the fiscal year and a (surplus) vehicle chassis was stripped to serve as the test fixture. With ANL instrumentation and the new motoring dynamometer, realistic and complete motor efficiency measurements can be determined. System interface issues can be identified and vehicle-level results will be obtained when the unit is subjected to driving cycle testing.

The SAFT Lithium-Ion battery was developed under a DOE contract to meet the requirements of a high power peaking device under the PNGV program and had completed testing in the battery laboratory at INEEL. SAFT delivered the unit near the end of the fiscal year to the ANL Battery Test Facility in the CMT division for characterization using standard and transient cycle tests prior to installation at the APRF. ANL decided to assess this battery using the vehicle chassis and UQM drive unit to determine its capabilities under expected vehicle operating conditions. Since this intended to be a peaking battery, evaluation as part of an emulated fuel cell vehicle is planned. Figure 1 shows the EFCV configuration.

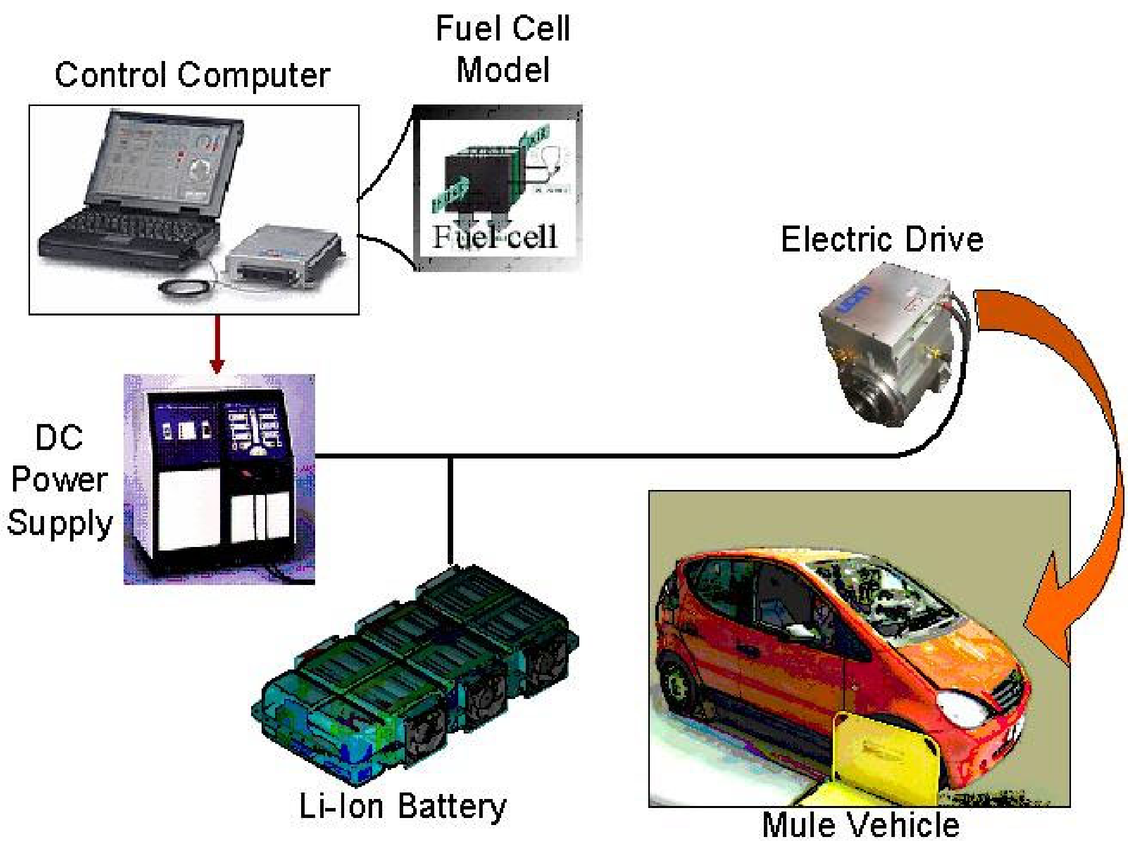

Figure 1. Emulated Fuel Cell Vehicle (EFCV) configuration

Cummins Diesel Exhaust Aftertreatment System
The Cummins after-treatment system was developed in a cooperative program with DOE to address the Nitrogen Oxides (NOx) and Particulate Matter (PM) in diesel engine exhaust. This compact exhaust aftertreatment system is dual leg and consists of a sulfur trap, NOx adsorbers, and catalyzed particulate filters (CPF). ANL's role in this effort was to provide the base vehicle, support the installation of the system and measure emissions.

Commissioning of 4WD SULEV Facility
The 4WD dynamometer was installed in FY01. In FY02, the major test systems were installed, integrated and commissioned. The systems were designed to handle the anticipated advanced technologies for light and medium-duty vehicle systems under development. Safety equipment (for detecting the presence of hydrogen) and data acquisition systems were specified and installed. Five main systems, including the dynamometer, emissions measurement, air handling, data acquisition and safety, were installed and put on-line over the course of the year. The key elements of each of the systems are summarized in the following paragraphs.

The 4WD dynamometer is fully programmable for precision testing and can handle up to 12,000 lb. vehicle weight and 250 hp per axle. The system has various modes of operation, including motoring, tractive effort and coastdown as well as calibration.

Air handling is a critical system since the background air must be cleaned for SULEV measurement. Very dry, clean exhaust gas dilution air enables the emissions bench to resolve the very low emissions of advanced vehicles (outside air is filtered and dehumidified; HC < 1ppm and H_2O < 10 grains/lb.). The stable temperature (within 2^oC) and humidity of the test cell provides repeatability necessary for accurate research results. The ventilation system for the test cell, rated at 26,000 cfm, is a key element of the safety system as well.
Data acquisition and the emissions measurement control system were developed by ANL to support testing advanced vehicles with extensive instrumentation and non-standard functionality. The system has an enhanced driver's aid and HEV-specific features. In addition, it is compatible with PSAT/PSAT-PRO for HIL/RCP and has integrated post-processing tools for data import, animation and validation.

Safety systems have been designed for future needs, with an extensive gas purge system with full-time scavenging and hazardous gas detection (CO, NO, NOx, HC and H_2). Substantial effort is required to meet the rigorous DOE/ANL standards, but these capabilities will allow hydrogen-fueled vehicles to be safely tested in the APRF.

A cutaway view of the 4WD SULEV facility is shown in Figure 2.

Results
The combination of PSAT, HIL techniques, the EFCV and the 4WD dynamometer demonstrates a cost-effective method for component validation. And since the same simulation and control technology is used in the HIL test cells, validation projects can be performed in either environment.

ANL completed the APRF and a unique integrated set of supporting tools to simulate, emulate and validate advanced automotive powertrain technology. This capability allows DOE to analyze candidate technologies, test and validate newly developed components and powertrains using HIL/RCP techniques as well as test 2-wheel and 4-wheel drive vehicles using the latest equipment to measure fuel efficiency and emissions.

The system is capable of measuring standard emissions categorized as SULEV, for Super Ultra Low Emissions Vehicle. In addition, the equipment can measure transient emissions (HC and NO <5 ms; PM < 1s) to allow more precise correlation between engine control parameters and exhaust emissions.

Figure 2. Cutaway view of the 4WD Addition to the Advanced Powertrain Research Facility (Design by Affiliated Engineers, Inc., Flad and ANL)

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- Burke E. Porter 4WD Chassis Dynamometer

- UQM Integrated Electric Traction System (INTETS) 75 kW Electric Drive
- Exhaust Aftertreatment Evaluation on A Diesel Vehicle
- Particulate Matter Emissions Measurement Using a Nephelometer System
- NGM/Portable Motor Test Stand - Change of Configuration