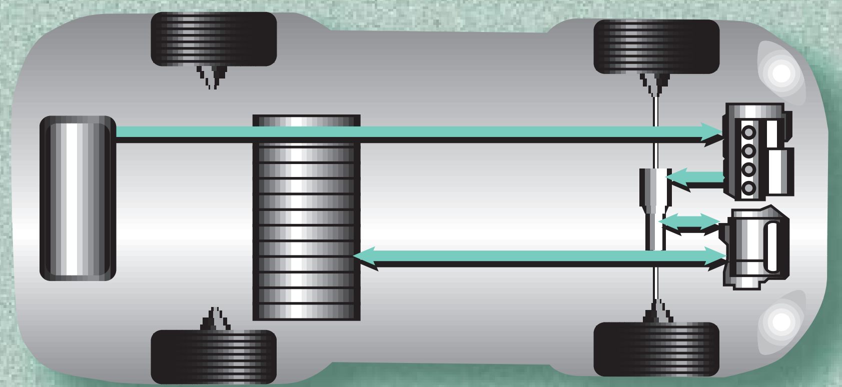
VEHICLE PROPULSION & ANCILLARY SUBSYSTEMS

2001 ANNUAL PROGRESS REPORT



U.S. Department of Energy

Energy Efficiency and Renewable Energy

Office of Transportation Technologies

A C K N O W L E D G E M E N T

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

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Office of Advanced Automotive Technologies
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FY 2001

Annual Progress Report for the Vehicle Propulsion & Ancillary Subsystems Program

Submitted to:

**Energy Efficiency and Renewable Energy
Office of Transportation Technologies
Office of Advanced Automotive Technologies
Vehicle Systems Team**

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Vehicle Propulsion and Ancillary Subsystems**

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I. INTRODUCTION

Vehicle Propulsion and Ancillary Subsystems Program

On behalf of the U.S. Department of Energy's Office of Advanced Automotive Technologies (OAAT), we are pleased to introduce the Fiscal Year (FY) 2001 Annual Progress Report for the Vehicle Propulsion and Ancillary Subsystems Program. This introduction serves to briefly outline the nature, progress, and future direction of the program.

The mission of the Vehicle Propulsion and Ancillary Subsystems Program is to facilitate the development of propulsion and ancillary subsystems for light-duty vehicles (automobiles, light trucks, and SUV's) 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 Propulsion and Ancillary Subsystems Program is to support the OAAT goals by:

- Development of component and subsystem performance targets for a range of vehicle platforms
- Development and validation of models and simulation programs to predict the fuel economy of and emissions from advanced light-duty passenger vehicles
- Development and validation of vehicle propulsion subsystem and auxiliary subsystem technologies,
- Benchmarking of commercially available components and vehicles 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 Vehicle Propulsion and Ancillary Subsystems team 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 methods, how individual technology components will perform in a propulsion subsystem operating in a vehicle environment.

Through many of its technology research programs, the DOE Office of Advanced Automotive Technologies (OAAT) has supported the government/industry Partnership for a New Generation of Vehicles (PNGV), a cooperative research and development (R&D) partnership between the federal government and the United States Council for Automotive Research, which comprises of Ford, General Motors, and DaimlerChrysler, since its inception. The PNGV leadership is now re-evaluating the partnership goals to identify changes that will maximize the potential national petroleum-savings benefit of the emerging PNGV technologies. When these PNGV goal changes have been defined, the OAAT will adjust the focus of its technology research programs accordingly.

Future Directions

In FY 2002, the Vehicle Propulsion and Ancillary Subsystems program will focus on the development of performance targets for component technologies that will be applicable to the full range of light-duty vehicle platforms. Propulsion subsystem component technologies will be validated for performance in simulated vehicle platforms through hardware-in-the-loop testing and computer modeling. An integrated systems approach will be utilized to identify automotive applications with energy savings potential and provide technological solutions that can be transferred to industry partners.

The abstracts in this volume summarize the work being conducted by the national laboratories in support of the program's goals and objectives. The DOE program manager named with each abstract can be contacted for further information.

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II. NATIONAL RENEWABLE ENERGY LABORATORY SUPPORT

IIA. Integrated Systems Approach for Energy-efficient Vehicle Design — Digital Functional Vehicle

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Objective

- Demonstrate an integrated systems approach to specific industry problems with a potential for energy savings.
- Develop process and systems needed to solve specific real-world problems using math-based software to integrate design of experiments, probabilistic designs, finite element modeling, optimization, and modeling of system dynamics.
- Work directly with industry partners to include improved fuel economy and emissions considerations into future production components and vehicles.

Approach

- Work with industry and software partners to identify appropriate 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

- Performed design of experiments to come up with a simplified yet accurate tire model in order to save weight by using the model to more accurately predict loads on the vehicle transmitted by the tire.
- Investigated weight savings, stiffness, and energy absorption capability using aluminum rather than steel on a B-pillar design.
- Developed a braking system model to allow investigation of alternatives in brake rotor cooling.
- Demonstrated improved battery performance through simulation of battery thermal management strategies.
- Body-in-white weight reduction via probabilistic durability modeling of manufacturing variations.

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 process to fuel cell problems in 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.

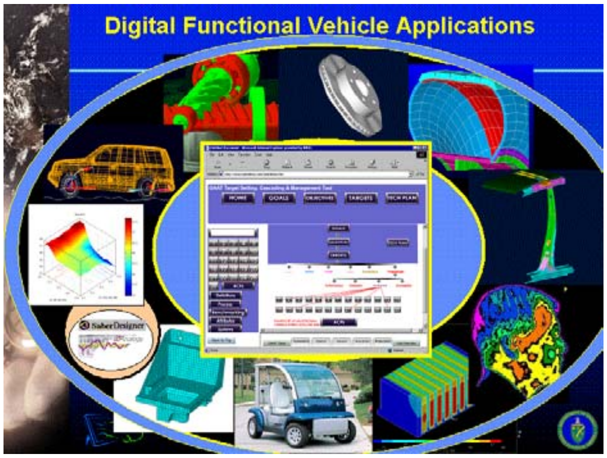

Figure 1. Digital Functional Vehicle Applications

Approach

The technical approach is to use auto industry supported software tools, such as ANSYS, ADAMS, Saber, Fluent, iSIGHT, etc., as part of an integrated analysis process. This leverages the significant experience and data already existing within industry in these tools, but provides us an opportunity to highlight the energy aspect of the design decisions being made. Additionally, we work directly with the auto industry software suppliers so 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. The overall approach is to work with the auto industry on specific R&D projects with 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.

Results

The projects from FY01 included:

- Performing design of experiments to develop a simplified yet accurate tire model in order to save weight by using the model to more accurately predict loads on the vehicle transmitted by the tire.
- Investigating weight savings, stiffness, and energy absorption capability using aluminum rather than steel on a B-pillar design.
- Reducing weight of braking system through investigating alternatives in brake rotor cooling.
- Demonstrating improved battery performance through simulation of battery thermal management strategies.
- Body-in-white weight reduction via probabilistic durability modeling of manufacturing variations.

FY02 activities will include demonstrating energy savings from applying an integrated modeling process to an OEM or supplier problem, then publishing the process publicly. This may involve carrying probabilistic information about the design (thickness- or density variability) throughout the design, analysis, and optimization process to yield a more reliable and lighter design.

We will also work with an OEM and/or tire supplier to finalize and validate the tire model, leading to more accurate load predictions and subsequent weight/energy savings.

Conclusions

In FY01, 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 FY02 will be to focus the effort on a smaller number of projects and emphasize fuel savings impact of the process on each specific project.

Publications / Presentations

"Digital Functional Vehicle Status Update," Wipke, K., Vlahinos, A., Peeples, J., Penney, T., presented at DOE on October 18, 2001.

"ADVISOR and the Digital Functional Vehicle Process," Wipke, K., presented at IAT Hybrid Electric Vehicle Workshop, Austin, TX, September 2001.

"6-sigma quality level designs with ANSYS PDS," Vlahinos, A., and Kelkar, S., presented at Automotive CAE Seminar, Eaton Innovation Center, November 2001.

"Using Behavioral Modeling to Build Smart Parts that Design Themselves," Vlahinos, A., presented at 2001 Colorado Pro/E User Conference, Louisville Colorado, November 2001 (awarded the best user presentation).

"Body-in-White Weight Reduction via Probabilistic Modeling of Manufacturing Variations," Vlahinos, A., Kelkar, S., SAE International Body Engineering Conference 2001 paper # 01IBECA-6, October 2001 (awarded best conference paper award).

"Digital Functional Vehicle," Vlahinos, A., presented at the SAE Colorado Section Meeting, March 2001.

IIB. Optimization Tools for Hybrid 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 vehicle systems analysis and evaluation
- Provide integrated advanced optimization capabilities to users of ADVISOR
- Demonstrate the needs for and the applicability of advanced optimization methods on specific hybrid vehicle analysis problems.

Approach

- Manage subcontract with Vanderplatts R&D to develop an application-programming interface (API) to provide additional flexibility and integration between VisualDOC, MATLAB, and ADVISOR.

- Work with University of Michigan to review derivative-free optimization algorithms for hybrid vehicle analysis.
- Apply optimization algorithms to specific hybrid vehicle configuration trade-off studies with an emphasis on fuel cell vehicles.

Accomplishments

- Completed the development of an application-programming interface (API) between VisualDOC 2.0 and MATLAB.
- Completed the review of derivative-free optimization methods and their effectiveness for hybrid vehicle systems analysis.
- Created necessary files for linking ADVISOR with 4 different optimization tools including, VisualDOC, MATLAB Optimization Toolbox, DIRECT, and iSIGHT.
- Presented the results of a fuel cell hybrid SUV design study (8 design variables, 6 constraints) at the iSIGHT Automotive User's Conference.

Future Directions

- Apply appropriate optimization algorithms to multi-disciplinary analysis of hybrid vehicle systems including the areas of structural design and air conditioning systems.
- Disseminate lessons learned with regard to optimization algorithm applicability to hybrid vehicle analysis.
- Present results of fuel cell vehicle application studies at EVS-18 and ASME IMECE conferences.
- 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 an 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 we supported subcontracts with Vanderplatts R&D and the University of Michigan. Vanderplatts R&D focused on developing an application programming interface for more flexibility in accessing the optimization tools from MATLAB and ADVISOR. The University of Michigan was tasked with evaluating the effectiveness of derivative-free optimization algorithms for hybrid vehicles. NREL's primary focus in this area has been problem definition and application of the tools to generate solutions.

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. This allows the user to iteratively run ADVISOR without 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).

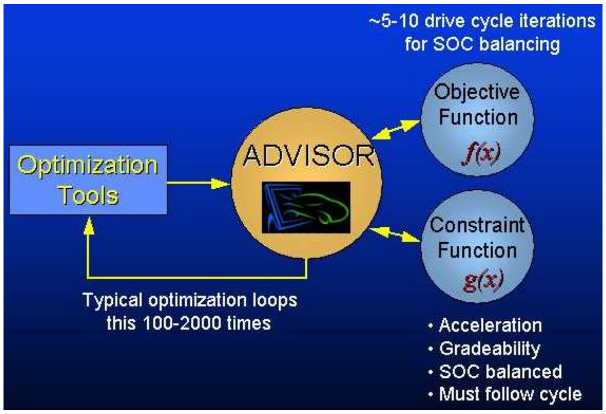

Figure 1. ADVISOR in an Optimization Loop

Based on our initial observations, we have been very impressed and pleased 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 been 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.

NREL 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.

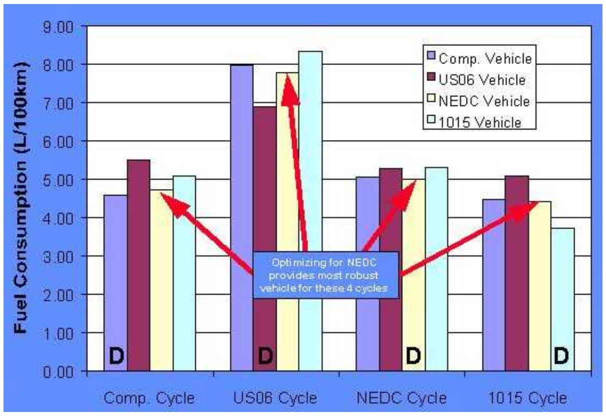

Figure 2. Optimization of vehicle for drive cycle impacts fuel economy

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 on the resulting optimal design.

We intend to disseminate the results of the studies completed thus far and to complete other variations on the existing studies to provide significant 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

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

"Hybrid Vehicle Optimization Using iSIGHT and ADVISOR," Markel, T., iSIGHT User's Conference. May 2001.

"Development and Evaluation of Optimization Tools for Hybrid Vehicle Analysis," Markel, T., Wipke, K., Milestone Report, April 2001.

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

"University of Michigan Subcontract Final Report," Michelina N., Whitehead, J., June 2001.

"Application of Optimization Tools to ADVISOR of Vehicle Systems Analysis ," Sway-Tin, M., Li, J., Markel, T. Presented at 2001 Joint ADVISOR/PSAT User Conference. August 2001.

"Design and Performance of Derivative-Free Optimization Algorithms Used with Hybrid Electric Vehicle Simulations," Whitehead, J., Master of Science in Mechanical Engineering Thesis. University of Michigan, July 2001.

"Vanderplatts R&D Subcontract Final Report," Venter G. Vanderplatts, G., June 2001.

IIC. ADVISOR Improvement, Validation, and Application

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Objective

- Apply flexible vehicle systems modeling tools to analysis problems that help guide the Office of Advanced Automotive Technologies (OAAT) research programs.
- Develop and support validated vehicle systems modeling tools.

Approach

- Use specifications from a variety of component suppliers, original equipment manufacturers, and the U.S. Department of Energy (DOE) subcontracted partners 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 unsure validity of model predictions.
- Determine relevant vehicle analysis problems and work with industry partners to generate possible solutions and scenarios.

Accomplishments

- ADVISOR (versions 3.1 and 3.2) advanced vehicle simulator was released to the public through the National Renewable Energy Laboratory (NREL) Web site (www.ctts.nrel.gov/analysis). Over 4000 people from around the world have now downloaded one or more versions of the ADVISOR software. Key improvements include:
  - Documented the GUI-free operation to make it easier for users
  - Added new two capacitor/three resistor battery model
  - Developed template scripts for linking ADVISOR with various optimization tools
  - Devised fuzzy logic controller for parallel hybrid vehicles
  - Revised Honda Insight control strategy
  - Implemented VSOLE for estimating vehicle solar load impacts
  - Added flexible grade and acceleration test routines
  - Developed interactive simulation capabilities
  - Enhanced ability to perform batch and multi-cycle analysis runs from the GUI
  - Added new configurations including an adaptive control strategy, parallel hybrids with automatic transmissions
  - Enhanced ability to interpolate warm-up impacts on fuel consumption and emissions from empirical data or equations
  - Included many new data files for components, drive cycles, and test procedures
- Held the 2001 Joint ADVISOR/PSAT Vehicle Systems Modeling User Conference on August 28-29, 2001 with more than 70 attendees from around the world.
- Developed co-simulation linkages between ADVISOR and ADAMS/Car, Saber, and Sinda-Fluint.
  - Improved the correlation between the model predictions and true vehicle operation for the Honda Insight and Toyota Prius based on collected vehicle test data.
- Completed studies of power and battery requirements for Partnership for a New Generation of Vehicles (PNGV)-type vehicles with both high voltage and 42 V voltage buss.
- Incorporated emission control device models developed by Oak Ridge National Laboratory.
- Developed ADVISORLite, and new Community Web site to foster interaction among users. Also surveyed users to better understand their needs and why they value ADVISOR.

Future Directions

- Improve, validate, support, and apply ADVISOR to satisfy the needs of DOE, the auto industry, and the 4000 ADVISOR users.
- Evaluate fuel cell hybrid vehicle system design trade-offs.
- Develop and apply co-simulation linkage between ADVISOR and Saber for hybrid electric vehicles.
- Develop and apply Target Cascading process to the generation of component technical requirements that will provide significant national oil displacement.

Introduction

In 1994, NREL created the ADvanced VehIcle SimulatOR (ADVISOR) through the DOE Office of Transportation Technologies (OTT). 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 4000 users from around the world have downloaded the software to evaluate vehicle systems and various vehicle configurations (see Figure 1).

In the past, vehicles were designed and tested using hundreds of hardware prototype vehicles. Complete vehicles were built early in the design process in order to gain initial data on the design, and this process was repeated multiple times. ADVISOR helps solve this problem and provides an opportunity to reduce time to production.

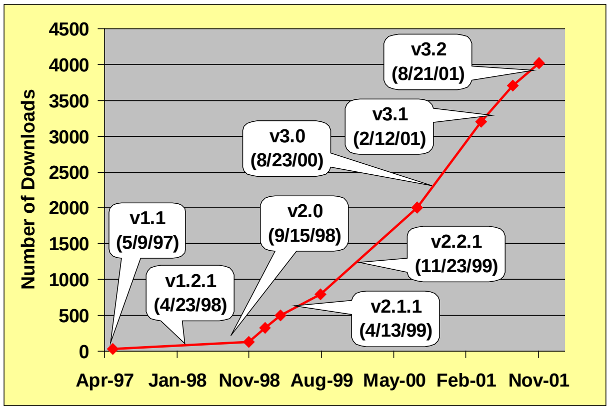

Figure 1. Number of downloads by ADVISOR version and release date.

Approach

Quickly gaining an understanding of an advanced vehicle design's sensitivity to change is a major benefit of using a tool like ADVISOR early in the vehicle design process. Improving the time to production and saving money are both important benefits to using simulation tools. In addition, ADVISOR uses specifications from a variety of component suppliers and original equipment manufacturers. The information in the ADVISOR component and vehicle database is validated by industry, NREL, and ADVISOR users. Although auto manufacturers have similar in-house tools, ADVISOR provides an objective standard through which the companies can simulate vehicle performance and emissions benefits using components developed by many different suppliers.

Results

Since ADVISOR was released to the public through the NREL Web site, more than 4000 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 and 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 buy such a model).

In order to benchmark HEVs and generate data to validate and improve the models, the ADVISOR team worked with NREL's Battery Thermal Management and Auxiliary Loads teams to instrument and collect chassis dynamometer and on-road data for a Honda Insight and a Toyota Prius (see Figure 2). NREL contracted a local

Figure 2. NREL's Honda Insight undergoes testing at Environmental Testing

chassis dynamometer test facility to measure fuel economy, emissions, and battery performance under various driving and ambient conditions. NREL used this data to implement significant improvements to the Honda Insight energy management strategy in ADVISOR, which showed good agreement with test results. The testing revealed important performance, control strategy, and battery thermal management issues in these two different vehicle designs and also quantified the dramatic effect of air conditioning on fuel economy for both vehicles.

To foster interaction with and between members in the ADVISOR user community, a user conference was held and a new community Web site was introduced (see Figure 3). The user conference, jointly held with the PSAT users, provided the more than 70 attendees the opportunity to share their work with their peers. The new user community website has a much improved forum for facilitating discussions among users and an upload/download area for file sharing.

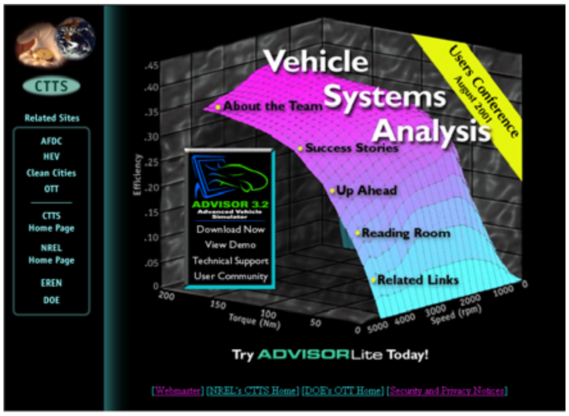

Figure 3. Vehicle Systems Analysis Web Site allows users to download ADVISOR and get User Conference information.

Supporting the development and validation of the tool is important; however, our primary activity with ADVISOR is to provide analysis support to DOE. This year we completed several studies using ADVISOR. ADVISOR was used to understand a variety of battery characteristic trade-offs as applied to hybrid electric vehicles. It was confirmed that a 300 Wh battery pack was appropriate for a PNGV-type hybrid electric vehicle. Likewise ADVISOR was used to quantify the electric motor power requirements necessary for a PNGV-type vehicle over a variety of driving conditions. These insights provide useful information to the DOE and PNGV technical teams while reviewing the targets of their research programs.

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.

Conclusions

NREL will continue to further improve, validate, support, and apply ADVISOR to satisfy the needs of DOE, the auto industry, and the 4000 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. The co-simulation between ADVISOR and Saber for hybrid vehicles will be completed and applied to a real problem. A large 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. Finally, 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.

Publications

"Test Results and Modeling of the Honda Insight using ADVISOR," Kenneth K.J., et al, SAE 2001-01-2537, SAE Future Transportation Technology Conference, August 2001.

"Joint ADVISOR/PSAT Vehicle Systems Modeling User Conference Proceedings," August 28-29, 2001, Southfield, Michigan.

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

"Benchmarking of OEM Hybrid Electric Vehicles at NREL," Kelly, K.J., Rajagopalan, A., NREL/TP-540-31806, National Renewable Energy Laboratory, Golden, CO, August 2001.

"Joint ADVISOR/PSAT Vehicle Systems Modeling User Conference Proceedings," August 28-29, 2001, Southfield, Michigan.

"Degree of Hybridization Modeling of a Fuel Cell Hybrid Electric Sport Utility Vehicle," Atwood, P., Gurski, S., Nelson D.J., and Wipke, K., BSAE Publication 2001-01-0236. *Proceedings of SAE Congress 2001*. Detroit, Michigan Jan. 2001.

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

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"ADVISOR-Saber Co-simulation for Single-Voltage and Dual-Voltage Conventional Vehicles" Johnson, V., Brooker, A., Wipke, K. NREL Milestone Report, June 2001.

"Completion of ADAMS/Car-ADVISOR Linkage Milestone Report," Brooker, A. NREL Milestone Report, June 2001.

"42 Volt Energy Storage System Targets for a Dual Voltage System: Focusing on Requirements During Engine off and Restart," Brooker, A., Presentation, Sept. 2001.

"Technology Roadmap for the 21st Century Truck Program: A Government-Industry Research Partnership. Section 4.2: TRANSIT BUS," Contributions by O'Keefe, M. Report No. 21CT-001. December 2000.

IID. Saber/ADVISOR Co-simulation

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Objective

- Expand ADVISOR's fuel economy prediction capability by creating a Saber co-simulation option.
- Improve electrical component modeling.
- Add new vehicle components and configurations to ADVISOR.

Approach

- Work with industry to leverage their Saber vehicle component models and vehicle expertise.
- Modify ADVISOR to make co-simulation option transparent to the users.
  - Create additional graphical user interfaces in ADVISOR to completely define the Saber portions of the model.
  - Develop the communication between ADVISOR and Saber to operate in the background.
- Provide the option to use an industry standard tool, Saber, in conjunction with ADVISOR.
  - Improves Advisor's flexibility to allow industry to use their existing Saber models in ADVISOR.
  - Takes advantage of Saber's electrical circuit solving capability.
- Improve ADVISOR's component database by adding:
  - Saber's component library to be used with ADVISOR.
  - An industry supplied database of 21 different types of auxiliary loads, each with typical load levels for different vehicle types from sub-compact car to SUV.
  - Additional vehicle components, including a generator, DC/DC converter, and voltage regulator.

- Expand ADVISOR's electrical modeling capability to use voltage and current based:
  - Auxiliary loads.
  - Vehicle components.

Accomplishments

- The communication method between ADVISOR and Saber for the co-simulation has been completed.
- The co-simulation expanded ADVISOR to include:
  - A dual-voltage configuration.
  - A single-voltage configuration with time varying electrical loads.
  - Saber's component library.
  - Several industry provided models, including a generator, DC/DC converter, and a regulator.
- Electric vehicle component models are more accurately modeled.

Future Directions

- Work with industry to demonstrate and utilize the co-simulation.
  - Complete a dual voltage battery sizing project.
  - Publish a paper on the project model, method, and results.
- Expand the co-simulation with additional configurations including:
  - Series hybrid electric vehicle.
  - Parallel hybrid electric vehicle.

Introduction

The National Renewable Energy Laboratory (NREL) develops ADVISOR, an ADvanced VehIcle SimulatOR, to determine how different vehicle components and configurations can improve fuel economy. Saber is a software tool commonly used for vehicle component modeling. Creating a co-simulation between ADVISOR and Saber leverages the benefits of both (see Figure 1). It creates more accurate electrical component modeling and adds a large number of available vehicle components from Saber.

Approach

NREL worked with Delphi Automotive Systems to develop the Saber/ADVISOR co-simulation by means of a 50/50 cost-shared contract. Working with an industry partner to develop the co-simulation provided two major benefits. One, it ensured the most relevant vehicle configurations would be developed. Two, it leveraged the industries' existing Saber component models.

Co-simulation offers several advantages. First, Saber is an industry standard tool. It is already commonly used in the automotive industry for electrical component modeling. By creating a co-simulating between Saber and ADVISOR, industry can use their existing Saber models as part of a full vehicle system analysis to determine the impact their components have on fuel economy. Second, it improves ADVISOR's component database. Saber has its own components to choose from, and industry can readily provide many more. A third advantage to the co-simulation is it improves ADVISOR's electrical component modeling by using current and voltage based models.

Co-simulation between ADVISOR and Saber

Figure 1. Saber/ADVISOR co-simulation

Results

The Saber/ADVISOR co-simulation has been successfully completed. ADVISOR now includes additional components, configurations, and analysis detail.

The Saber/ADVISOR co-simulation expanded the number of components usable in ADVISOR. ADVISOR can now use the Saber library components. It can also use the generator, DC/DC converter, regulator and 21 auxiliary load models provided by industry. With the addition of new components, new configurations are also possible.

The co-simulation added two specific configurations and the capability for users to create any "custom" configuration. The two specific configurations include a 42-volt/14-volt dual-voltage and a single voltage electrical architecture. The co-simulation not only adds components and configurations, but also greater detail to the model.

The co-simulation is setup to capitalize on Saber's solver for the electrical portions of the model. This allows for more detailed and accurate voltage and current based models for the electrical portions of ADVISOR.

Conclusions

The Saber/ADVISOR co-simulation has added value to ADVISOR. ADVISOR can now model additional relevant components and configurations with confidence and accuracy. Confidence is maintained because the existing acceptance of Saber as a modeling tool. Accuracy is improved with the change to a voltage and current based electrical systems model. With the co-simulation, ADVISOR now offers more components, configurations, and detail in modeling vehicle fuel economy.

Publications

"Dual Voltage Electrical System Simulations," MacBain, J., Conover, J., SAE Publication Transitioning to 42-Volt Electrical Systems, SAE SP-1556, pages 9-18, August, 2000.

"Co-Simulation of Automotive Propulsion Systems," MacBain, J., and Conover, J., EVS 18 Berlin, 2001.

"Co-Simulation of Electrical and Propulsion Systems," MacBain, J., and Conover, J., SAE FFT, 2001.

"Simulation of Stop/Start Systems," MacBain, J., and Conover, J., EVS 18 Berlin, 2001.

IIE. Vehicle Auxiliary Load Reduction Project

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Objective

Develop innovative techniques and technologies that will reduce the energy used for vehicle auxiliary loads, manage peak loads, and optimize climate control systems and strategies. The short-term goal is to reduce the amount of fuel used for vehicle air-conditioning by 50% compared with today's vehicles by developing cost-effective solutions in partnership with industry. The long-term goal is to work with industry to achieve a 75% reduction in air-conditioning fuel use through long-term R&D on technologies such as heat-generated cooling and component miniaturization.

Approach

- Work with industry to research and develop innovative climate control strategies that will cost-effectively reduce the amount of fuel used for vehicle air-conditioning by 50% compared with today's vehicles.
- Analyze, develop, and test advanced peak load reduction technologies including heat pipes, heat-generated cooling systems, heat-generated electricity, and component miniaturization.
- Implement advanced cabin peak soak temperature reduction technologies on industry-collaborative vehicle testing projects.
- Use vehicle system level testing to validate integrated modeling methodology.

Accomplishments

- Completed vehicle testing of two Lincoln Navigators in a collaborative effort with Ford and Tier 1 suppliers to measure the impact of advanced technologies on reducing vehicle soak temperature, including solar infrared reflective glazings, visibly reflective glazings, reflective shades, gas-filled body insulation, reflective roof surfaces, and active and passive parked car ventilation.
- Completed vehicle testing of Jeep Grand Cherokee in a collaborative effort with DaimlerChrysler to validate integrated modeling techniques.
- Developed and tested passively cooled instrument panel using heat pipes.
- Completed assessment of heat-generated cooling opportunities.
- Completed review of state-of-the-art component miniaturization.
- Completed optimization software for heat-generated electricity with thermoelectric devices.
- Completed optimization software for transient air-conditioning systems.

Future Directions

- Validate integrated modeling tools in industry sponsored vehicle test.
- Demonstrate heat-generated cooling concepts.
- Demonstrate heat-generated electric concepts.
- Optimize parked-car ventilation techniques.
- Model and test climate control seats in collaboration with industry.
- Investigate component miniaturization to improve overall system efficiency.

Introduction

NREL has the lead responsibility with DOE's Office of Transportation Technologies (OTT) to research, assess, and develop vehicle auxiliary load reduction strategies.

The vehicles of today and tomorrow are in need of systems that reduce vehicle auxiliary loads. For mid-sized vehicles, air-conditioning systems can increase NOx emissions by 80% and increase CO emissions by 70% while increasing fuel consumption by 35%. Smaller and lighter climate control systems will not only reduce emissions but also reduce fuel consumption. Each 20-lb. reduction in weight leads to a 0.1-mpg increase in fuel economy.

Reducing vehicle auxiliary loads will increase vehicle efficiency and reduce emissions. Vehicles of the future, such as hybrid electric vehicles, will need these innovations because they will have smaller sized engines that will not be able to handle peak air-conditioning loads or cabin heating requirements without serious fuel economy impacts.

Approach

NREL is conducting research and development with several industry partners including DaimlerChrysler, Ford Motor Company, Johnson Controls, Delphi, Visteon, 3M, Southwall, Denso, Valeo, and PPG.

The team completed testing of a Jeep Grand Cherokee (Figure 1) in conjunction with DaimlerChrysler and two Lincoln Navigators in partnership with Ford. Advanced climate control strategies were implemented in these two types of sport utility vehicles (SUV).

Figure 1. Jeep Grand Cherokee from DaimlerChrysler being tested at NREL

The test results provided data for validating NREL's integrated modeling process as well as measuring the effectiveness of different peak load reduction technologies.

Beyond reducing the cabin peak soak temperature, an alternative power source for the climate control system is needed. More than twice as much thermal energy is rejected as heat than is produced in mechanical power (Figure 2). Using the engine waste heat to produce cooling and electricity is a prime opportunity to improve vehicle fuel economy.

Results

DaimlerChrysler provided a Jeep Grand Cherokee and PPG provided advanced solar-reflective windows to NREL for vehicle testing. Data were taken to evaluate the effect of the advanced glazing as well as parked car ventilation techniques. The temperatures predicted by the cabin/thermal fluid model correlated well with the test data.

Ford provided two Lincoln Navigators with thermo-electrically heated and cooled seats. Guardian International and PPG both provided sets of advanced solar reflective glazing. Solutia provided visibly reflective glazing, BOS provided reflective shades, LBL provided gas-filled insulation body panels, and 3M provided visibly reflective film. Aluminum foil was used to predict maximum solar energy rejected by surface treatments (Figure 3). Both active and passive ventilation techniques to reduce cabin peak soak temperature were tested.

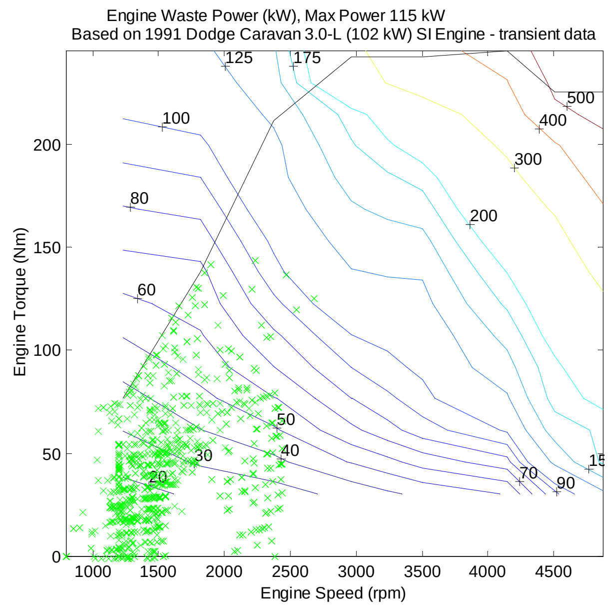

Figure 2. Map of waste power (kW) of a 115-kWengine with X's showing engine operating points over the FTP drive cycle

Figure 3. Lincoln Navigators from Ford, baseline vehicle and vehicle modified with foil

The solar reflective glass cooled the interior temperature of the vehicles by between 2°C to 5°C, permitting a smaller air-conditioning compressor to be used. The passive ventilation system reduced the difference between the cabin temperature and ambient by 35% while the active system (Figure 4) reduced the temperature difference by more than 40%.

NREL also tested a simulated instrument panel with passive heat pipe cooling (Figure 5) in an effort to reduce vehicle soak temperatures using technologies that industry has identified as promising. Test results show that heat pipes cooled the instrument panel by nearly 20°C and the air temperature by 9°C to 12°C while maintaining a uniform temperature across the instrument panel during the day.

Figure 4. Active ventilation test on Lincoln Navigator from Ford Motor Company

Figure 5. Simulated instrument panel with heat pipe cooling

Conclusions

Our nation uses about 7.5 billion gallons of gasoline per year for powering vehicle air-conditioning systems. This is equivalent to about 10% of our crude oil imports.

Each degree Celsius reduction in cabin soak temperature can lead to a 4% reduction in compressor power. A 10°C reduction in cabin soak temperature would improve fuel economy by up to 1.5 miles per gallon for an SUV; or reduce fuel use for air-conditioning in an SUV by about 50%.

Vehicle air-conditioning systems are a prime candidate for reducing the amount of oil the U.S. imports. Near-term and longer-term technologies exist to reduce our nation's fuel use for vehicle air-conditioning.

Publications

"Advanced Porous Ceramic Heat Exchangers in Automotive Thermal Management Systems," Hendricks, T.J., Technical Paper presented at International Mechanical Engineering Congress and Exposition 2000, Nov. 6, 2000.

"Experimental Demonstration of Heat Pipe/Two-Phase-Flow Systems for Vehicle Passenger Cabin Cooling," Hendricks, T.J., and Thoensen T., Technical Paper presented at 2001 ASME International Mechanical Engineering Congress & Exposition November 2001.

"Effect of Solar Reflective Glazing on Ford Explorer Climate Control, Fuel Economy, and Emissions," Rugh, J., Hendricks, T., and Koram, K., Technical Paper presented at International Body Engineering Conference & Exposition 2001, October 2001.

"The Impact of Metal-Free Solar Reflective Film on Vehicle Climate Control," Rugh, J., Farrington, R., and Boettcher J., Technical Paper presented at Fifth International Vehicle Thermal Management Systems Conference, May 2001.

"Component Miniaturization and Heat-Generated Cooling Opportunities," Hendricks, T.J., and Johnson, V., DOE Milestone Report, July 2001.

"Reduction in A/C Fuel Use Milestone," Rugh, J., Milestone Report to DOE, September 2001.

"Air-Conditioning Threat to HEV Fuel Economy and Emissions," <u>The Clean Fuels and Electric Vehicle Report</u> January 2001.

"Air Condition Stresses HEV Performance," <u>Hybrid Vehicles</u>, Vol. 3, Issue 1, January 2001.

“Advanced Vehicles: Are they a Dream of the Future, or Today’s Reality?” Brodt-Giles, D., Transportation for China, March 2001.

“Vehicle Cabin Cooling System for Capturing and Exhausting Heated Boundary Layer Air from Inner Surface of Solar Heated Windows,” Farrington, R., and Anderson, R., Patent Number 6,186,886, February 13, 2001.

“Passive Cooling System for a Vehicle, ” Hendricks, T.J., and Thoensen, T., patent filed May, 5, 2001.

IIF. National Vehicle Air-Conditioning Fuel Use Analysis

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Objective

- Determine the magnitude of energy used across the nation to create thermally comfortable cabins in light-duty vehicles via air conditioning (AC). The results of this analysis help us determine the national fuel use impact of advanced climate control technologies.

Approach

- Use a bottoms-up approach to estimate the fuel used for AC in light-duty gasoline vehicles. A thermal comfort model using Fanger’s heat balance equations determined AC usage based on the premise that if a person were dissatisfied with the thermal environment (temperature and humidity), he or she would turn on the air conditioning.
- The thermal comfort results were then combined with transportation statistics on when people drive, where they live, and how far they drive in a year.
- Vehicle simulations, supported by vehicle testing results with and without air conditioning, determined the fuel use penalty of using AC in cars and light-duty trucks.

Accomplishments

- This study estimated that up to 6% of U.S. annual petroleum consumption is used for vehicle air conditioning, equivalent to 10% of U.S. crude oil imports, or 0.5 million barrels of oil per day.
- NREL created a methodology to determine vehicle AC fuel usage. With varying modeling assumptions, AC fuel use ranged from 2% to 8% of the U.S. annual petroleum consumption.
- Optimization of vehicle cabins or AC systems now has an established metric of impact. Thus, reducing the amount of energy used for air conditioning in a vehicle by 75% could reduce the nation’s fuel consumption by 5.6 billion gallons, or equivalently reduce the crude oil imports by 7.5%.

Future Directions

- Use the study to estimate fuel use impacts of vehicles with advanced cooling concepts.
- Estimate the fuel saved through time as new vehicles are introduced into the U.S. market.

- Enhance the study and update the fuel impacts by including the advanced thermal comfort model for non-uniform thermal environments that is currently under development with University of California, Berkeley.
- Expand the study to include examining reduced tailpipe emissions seen with reduced air conditioning load.

Introduction

Vehicle air conditioning (AC) loads are the most significant auxiliary loads present in vehicles today. AC energy use even outweighs energy loss to rolling resistance, aerodynamic drag, or driveline losses for a typical 27-miles per gallon (mpg) vehicle (Figure 1). The fuel economy of a vehicle therefore drops substantially when the AC compressor load is added to the engine. For a conventional 27-mpg vehicle, fuel consumption increases 35% with the AC on, and for a 80-mpg hybrid, fuel consumption increases 128% with AC use over the SC03 drive cycle.

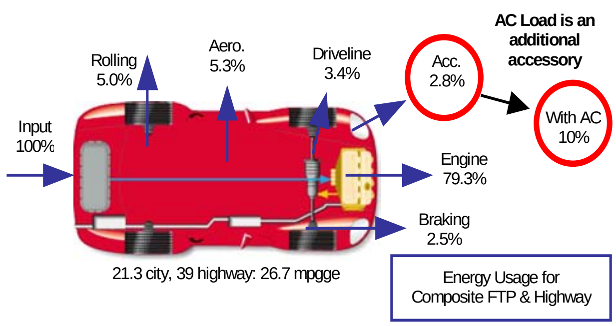

Figure 1. Percent vehicle energy uses/losses in a conventional 27-mpg Vehicle

Approach

NREL's study answered the question: how much fuel does vehicle air conditioning actually use? The study used a bottoms-up approach to estimate the fuel used for AC in light-duty gasoline vehicles. Environmental conditions such as temperature, radiation, and humidity were obtained in 116 cities. The data were representative of conditions observed over 30 years (1961-1990). A thermal comfort model using Fanger's heat balance equations (see Figure 2) determined AC usage based on the premise that if a person were dissatisfied with the thermal environment (temperature and humidity), he or she would turn on the air conditioning.

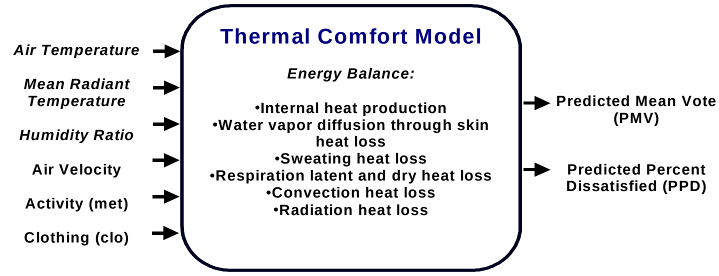

Figure 2. Thermal comfort flow chart

The study used the same thermal-comfort based approach, but with slightly varying thermal comfort inputs, to show a range of values for national AC fuel use. The varying thermal comfort inputs were related to the mean radiant temperature (MRT) of the driver's vehicle and the amount of clothing he or she wore. For example, "ambient mean radiant temperature" represented a case where all cars were parked inside, and "soak MRT" represented a case where all cars were parked outside in the sun. "Summer attire" meant people wore light summer clothing (e.g. slacks, light shirt), and "suit" represented the case where people wore professional attire. No one of these four cases represents the entire population all of the time. The case of "Soak Mean Radiant Temperature" and "Summer Attire" was chosen as the representative result for the fuel used for air conditioning vehicles. Figure 3 shows the percent of time that people use the air conditioning as it varies across the U.S. for the representative case (soak MRT, summer attire).

The thermal comfort results were then combined with transportation statistics on when people drive, where they live, and how far they drive in a year. Vehicle simulations determined the fuel use penalty of using air conditioning in cars and light-duty trucks.

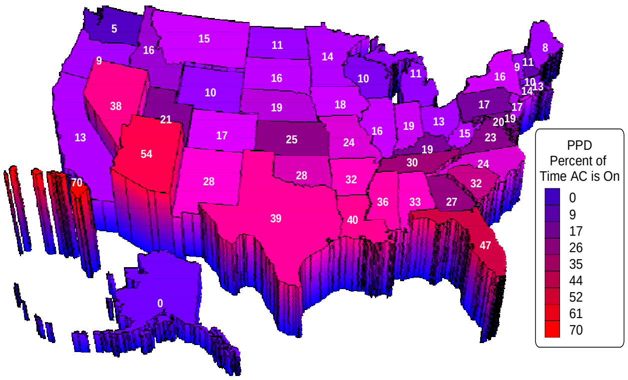

Figure 3. Percent of time the AC is on. Those in Arizona use the AC 54% of the time, Hawaii 70%, and Florida 47%.

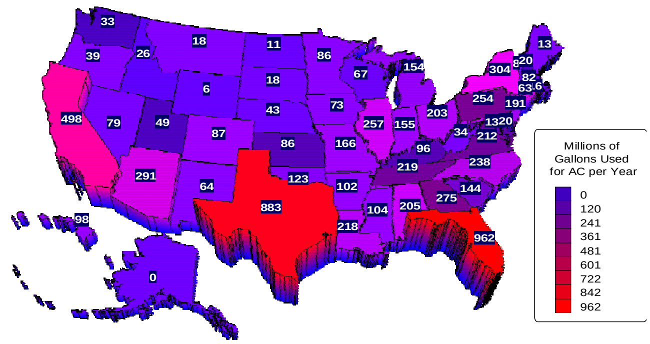

Figure 4. Millions of gallons used for light-duty vehicle air-conditioning. Estimated U.S. usage is 7.5 billion gallons per year for summer clothing and a vehicle soaking in the sun.

Results

This study estimates that up to 6% of U.S. annual petroleum consumption is used for vehicle AC, equivalent to 10% of U.S. crude oil imports, or 0.5 million barrels of oil per day (Figure 4). These values are for the representative thermal comfort case of a person in summer clothing entering a vehicle that has been soaking in the sun.

A methodology was created to determine vehicle AC fuel usage. With varying modeling assumptions, AC fuel use ranged from 2% to 8% of the U.S. annual petroleum consumption (Table 1).

Table 1. Grid of thermal comfort results: AC use as a percentage of U.S. consumption (the representative case is highlighted)

		Mean Radiant Temperature	
		Ambient	Soak
Clothing	Summer	2.2%	6.0%
	Suit	3.9%	7.7%

Optimization of vehicle cabins or AC systems now has an established metric of impact. Thus, reducing the amount of energy used for air conditioning in a vehicle by 75% could reduce the nation's fuel consumption by 5.6 billion gallons, or equivalently reduce the crude oil imports by 7.5 percent.

If new vehicles beginning in 2010 show a 75% reduction in fuel used for air conditioning, the fleet will over time be replaced with these advanced vehicles. For example, assuming a 1.4% increase in fuel use per year, 0.44 million barrels per day of oil could be saved by 2022 by using these vehicles with advanced climate control systems (Figure 5).

Conclusions

This study used a bottoms-up approach to determine the amount of fuel used for light-duty vehicle air conditioning based on occupant thermal comfort. Representative data over 30 years in cities throughout the U.S. gave temperature, radiation, and humidity variations throughout the day and year. The study integrated this environmental data, driver behavior, a basic thermal comfort model, vehicle simulations, and U.S. population and vehicle statistics to determine the final AC fuel use numbers.

The amount of fuel used for air conditioning is significant. In absolute terms, 7.5 billion gallons of gasoline are used in the U.S. for air conditioning light-duty vehicles. Put in relative terms, the AC fuel use is equivalent to 6% of domestic petroleum consumption, or 10% of crude oil imports.

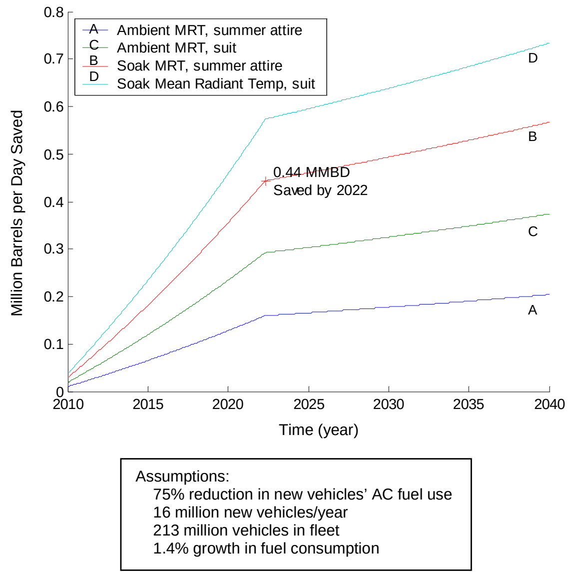

Figure 5. Millions of barrels per day (MMBD) saved through 2040 with a 75% reduction in fuel used for AC in vehicles after 2010

The range of fuel used for vehicle air conditioning based on different thermal comfort inputs was 2.7 to 9.7 billion gallons of gasoline. Optimization of vehicle cabins or air conditioning systems now have an established metric of impact.

Thus, reducing the amount of energy used for air conditioning a vehicle by 75% could reduce the nation's fuel consumption by 5.6 billion gallons, or equivalently reduce the crude oil imports by 7.5%.

Ways to reduce the amount of energy used for cabin environment control are multiple and include optimized conventional AC systems, advanced window glazings for reduced peak cabin soak temperatures, localized cooling, parked car ventilation, or use of alternative cabin cooling such as heat generated cooling via exhaust gases.

Publications

"Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range," Farrington R., and Rugh, J, Technical Paper presented at Earth Technologies Forum, October 2000.

"Fuel Used for Vehicle Air Conditioning: A State-by-State Thermal Comfort-Based Approach," Johnson, V., Technical Paper written and submitted for Future Car Congress, June 2002.

IIG. Integrated Numerical Modeling for Vehicle Auxiliary Load Reduction

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Objective

Work with the automotive industry to develop and validate an integrated modeling process that predicts fuel economy, tail-pipe emissions, and human thermal comfort for advanced climate control systems. The automotive companies are under pressure to deliver vehicles to market more quickly and less expensively than ever. Numerical modeling reduces time and costs. However, modeling climate control systems is a complex, multi-disciplinary problem beyond the capability of a single supplier. The goal is to use the integrated modeling process to investigate techniques to reduce our nation's fuel use for vehicle climate control.

Approach

- Identify requirements for a suite of software tools to perform a numerical model of a vehicle climate control system including: solar radiation model, glazing optical thermal model, cabin thermal/fluid model, transient two-phase air-conditioning model, human physiological model, human psychological model and vehicle simulation model.
- Develop tools that meet the design requirements if none are commercially available.
- Link the numerical tools to allow quick and easy prediction of fuel economy, vehicle emissions, and human thermal comfort.
- Work with industry to analyze climate control strategies that will reduce the amount of fuel use for vehicle air-conditioning.

Accomplishments

- Developed a solar radiation model that calculates the solar spectral irradiance incident on the vehicle as a function of location, weather, and vehicle orientation. Model data are available for 239 locations in the United States and U.S. territories.
- Developed an interactive vehicle solar load estimator (VSOLE) to predict the transmitted, absorbed, and reflected energy of vehicle glazings for various light sources, vehicle types, vehicle orientation, and sun locations.
- Validated the cabin thermal/fluid model through a collaborative project with DaimlerChrysler.

Future Directions

- Integrate a parametric modeling cabin tool into the modeling process.
- Link the cabin thermal/fluid model to the transient A/C model.
- Develop a human thermal comfort model and link it to the cabin thermal/fluid model.
- Validate the integrated modeling process on an industry collaborative project.

Introduction

The air-conditioning compressor is the largest auxiliary load on today's automobile engines and significantly impacts fuel economy and tailpipe emissions. Recent tests indicate that A/C use increases emissions of NO_x by about 80% and CO by about 70% over the SCO3 drive cycle. It also reduces fuel economy by about 20%. However, research shows the potential to reduce the A/C load on the engine and improve the real world fuel economy without impacting comfort or safety.

Since A/C systems are typically sized for a cooldown from a worst-case soak condition, NREL is investigating techniques to reduce the peak soak temperature enabling the A/C system size to be reduced. NREL is also looking at improved delivery systems and alternative methods to cool the passenger compartment. It is important to understand how advanced cooling techniques will impact human thermal comfort and fuel economy. We can predict the impact of these cooling techniques on the vehicle before conducting tests by using a vehicle integrated modeling process.

Predicting the impact of advanced climate control technologies on occupant comfort, fuel economy, and tailpipe emissions is challenging because of the many driving factors and complex interactions. Occupant comfort is influenced by solar inputs, glazing properties, A/C system operation, temperature, and velocity flow fields, as well as an occupant's physiological and psychological responses to environmental conditions. We have applied this process in collaboration with DaimlerChrysler, PPG, and Johnson Controls to evaluate advanced climate control technologies.

Approach

The models used in the vehicle integrated modeling process are diverse, complicated, and cover many engineering disciplines. We used commercial software when available, and developed models when existing software do not meet design requirements. The diverse models were then linked together to enable a smooth analysis process. An overview of the vehicle modeling process is shown in Figure 1.

The interior geometry of a vehicle is typically defined by CAD data or, in the case of vehicles under development, not defined. Using a parametric modeling tool, a generic vehicle is morphed to the appropriate dimensions and mesh is generated in preparation for cabin thermal/fluid modeling using computation fluid dynamics analysis software (CFD).

A solar radiation model and vehicle solar load tool provide solar boundary conditions for the cabin thermal/fluid model. A transient A/C model developed at NREL provides the conditioned air boundary condition for the CFD analysis and a link to the vehicle simulation software, ADVISOR, through the compressor load. The cabin thermal/fluid model predicts the flow and temperature field within the passenger compartment and passes this information to a thermal comfort model to assess occupant thermal confort.

<u>Results</u>

Glazing Model

A key input to the cabin thermal/fluid model that ultimately determines the temperature rise above ambient during a soak simulation is the solar load. With today's advanced solar reflective glazings, it is critical to understand the spectral properties of the irradiance and the glazing in order to perform accurate calculations. NREL has developed a vehicle solar load estimator (VSOLE) to predict the transmitted, absorbed, and reflective power of vehicle glazings. VSOLE also allows for easy comparison of different types of glass, different solar sources such as indoor lamps, and the ability to monitor solar load versus time.

VSOLE was written in Matlab and is easily accessed with a graphical user interface (GUI). The program takes into account the angle of incidence and calculates the transmitted, reflected, and absorbed power based on the radiation source, vehicle geometry, vehicle orientation, and glazing type. All glazing surfaces are assumed to be flat, constant thickness, uniform properties, and of regular shape. The calculation of the optical properties as a function of wavelength and angle uses a single-pane approximation for glass. An example of the VSOLE GUI is shown in Figure 2.

Solar Radiation Model

The solar radiation model developed at NREL provides radiation source data for VSOLE and is accessed from within the VSOLE GUI through the "pick a city" option in radiation-source pull-down menu. The solar radiation model calculates the solar spectral irradiance incident on the vehicle as a function of location, weather, and vehicle orientation. Model data are available for 239 locations in the United States and U.S. territories in the form of weather and sun position data. An example of the solar radiation model GUI is shown in Figure 3.

The spectral irradiance is calculated over a range of 300-2500 nm at 5 nm intervals. The irradiance and corresponding weather data are available at one hour intervals. Plots of the daily and hourly data assist in selecting the desired environmental conditions. Weather data can be used to define boundary conditions for a CFD analysis. After the city, month, day, and hour are selected, the spectral irradiance and sun position are returned to VSOLE to enable calculation of the transmitted, reflected, and absorbed power solar power for a vehicle in the selected city. These data can be used to define the solar loads for the cabin thermal/fluid model.

Cabin Thermal/Fluid Model

The purpose of the cabin thermal/fluid model is to predict the flow field inside the passenger compartment, as well as the surface temperatures and temperature and humidity of the air. As part of a collaborative project with Daimler-Chrysler, NREL modeled a Jeep Grand Cherokee soak test using environmental conditions from an actual Colorado test day. The transmitted and absorbed

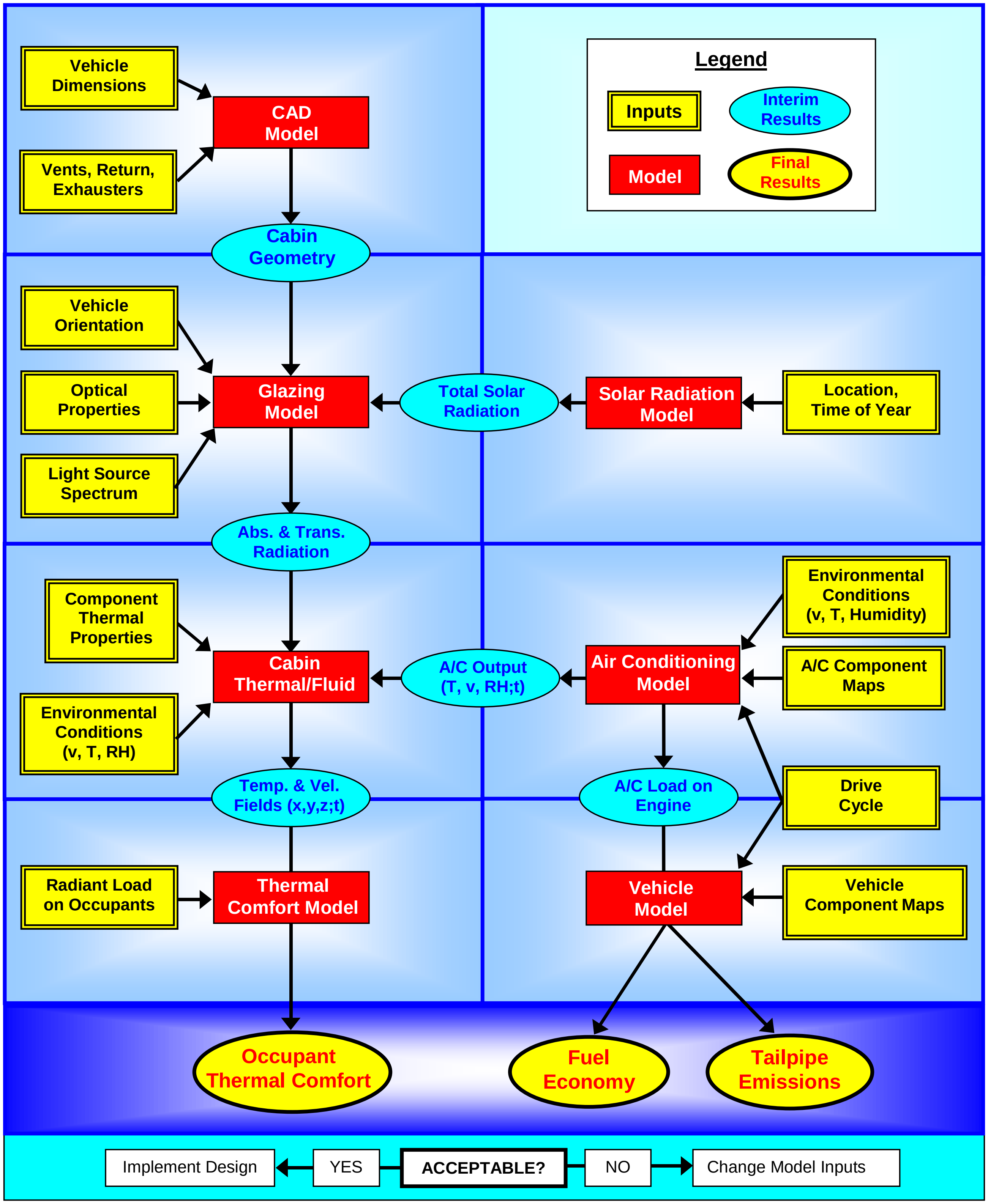

Figure 1. Overview of Integrated Modeling Process

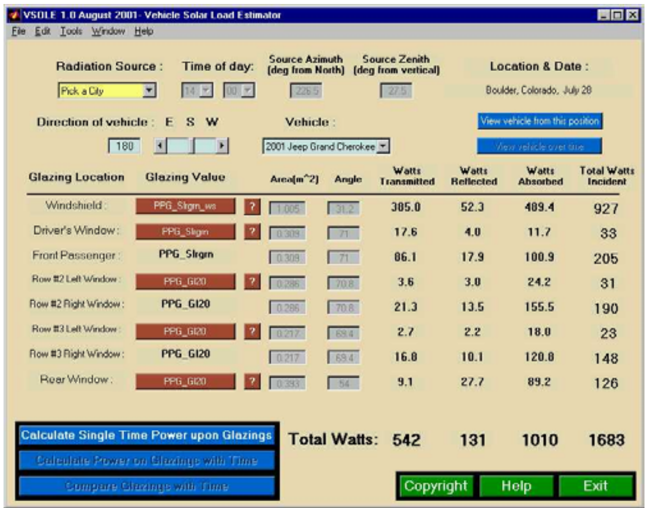

Figure 2. VSOLE Interface

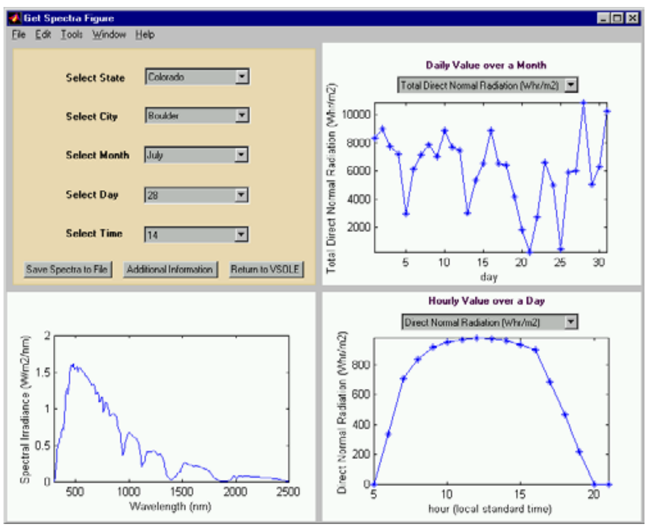

Figure 3. Solar Radiation Model GUI

solar radiation for each glazing were generated by the VSOLE model. Figure 4 shows the interior surface temperature with the instrument panel attaining the highest temperatures due to the large area exposed to direct sunlight and the low convection heat transfer coefficient. The predicted temperatures correlated well with the test data as shown in Figure 5.

Transient A/C Model

NREL has developed a detailed transient air conditioning system/ simplified cabin model using SINDA/FLUNT analysis software and integrated it with the ADVISOR vehicle systems analysis software. This transient one-dimensional, thermal-hydraulic model captures all the relevant physics of transient A/C system performance, including two-phase flow effects in the evaporator and condenser, system mass effects, air side heat transfer on the condenser/evaporator, vehicle speed effects, temperature-dependent properties, and integration with a simplified cabin thermal model. It predicts typical transient A/C compressor power requirements, system pressures and temperatures, system mass flow rates, and two-phase/single-phase flow conditions throughout the A/C system flow circuit. It also predicts transient cabin temperature conditions during a user-defined drive cycle.

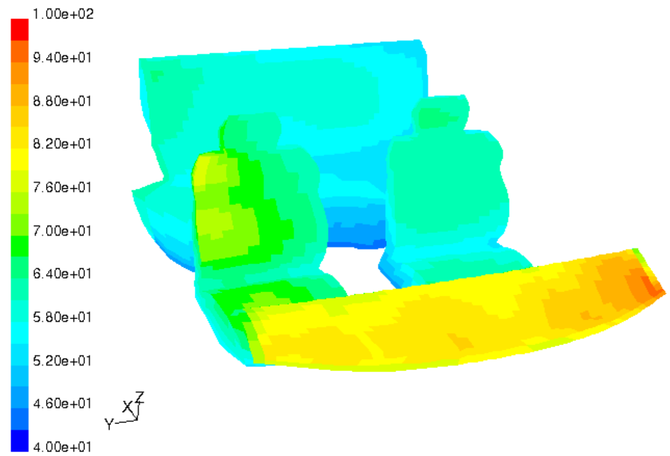

Figure 4. Interior Wall Temperatures (°C)

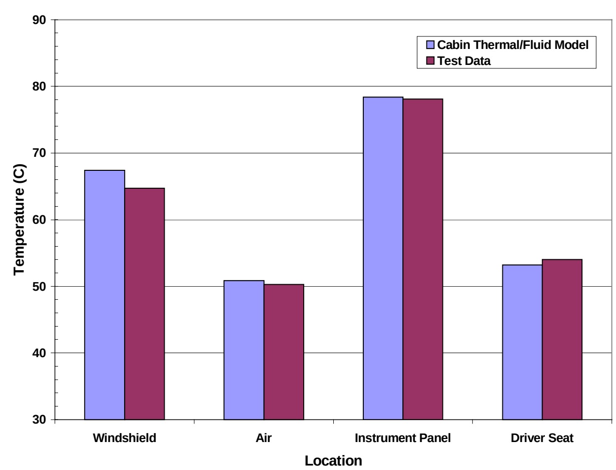

Figure 5. Predicted versus Actual Temperatures

Using the transient A/C model to simulate a white Ford Explorer in November in Phoenix, the A/C compressor power can be reduced 4% for every degree Celsius reduction in cabin air temperature.

Conclusions

NREL is developing with industry the following tools that enable integrated vehicle modeling: parametric CAD, glazing, solar radiation, cabin thermal/fluid, transient A/C, human thermal comfort, and the ADVISOR model. A significant challenge is to link these models in a seamless manner. The goal is to use the integrated modeling process to evaluate advanced concepts that may reduce the peak soak temperature and improve passenger comfort. The ultimate benefit is improved efficiency of vehicle climate control systems and reduced fuel use.

Publications

"Integrated Modeling to Predict Occupant Thermal Comfort," Farrington, R., Barber, G., Hendricks, T., Marion, W., Markel, T., McGuffin, R., and Rugh, J., technical paper prepared for the 7th International Automotive Technologies Association Conference, May 2001.

"Integrated Vehicle Modeling," Rugh, J., milestone presentation to DOE, September 2001.

"Integrated Modeling Process for Evaluating Automobile Climate Control Systems," Rugh, J., technical paper written and submitted to Future Car Congress 2002, June 2002.

"Vehicle Air Conditioning Systems: Transient Modeling, Optimization, and MATLAB Integration," Hendricks, T.J., technical paper prepared for the 2001 Annual International SINDA/FLUINT Users Conference, February 2001.

"Design and Transient Simulation of Vehicle Air Conditioning Systems," Cullimore, B.A., and Hendricks, T.J., technical paper prepared for the 5th Vehicle Thermal Management Systems Conference & Exhibition, May 2001.

"Optimization of Vehicle Air Conditioning Systems Using Transient Air Conditioning Performance Analysis," Hendricks, T.J., technical paper prepared for the 5th Vehicle Thermal Management Systems Conference & Exhibition, May 2001.

IIH. Human Thermal Comfort Model and Manikin

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Objective

Develop computational and experimental models of human thermo-physiology and the mental perception of thermal comfort in order to develop vehicle climate control systems that achieve optimal occupant thermal comfort at minimum power consumption.

Approach

- Develop a numerical model of human thermal physiology and psychology.
- Build a thermal manikin that can be placed in actual vehicles, which will respond to the transient and extremely non-uniform thermal environments inside vehicle cabins.

Accomplishments

- A leg segment of a thermal manikin was fabricated demonstrating the following.
  - Realistic sweating rates using porous metal skin for the first time ever.
  - Fast transient thermal response times.
  - Fully wetted skin with high spatial resolution.
- A thermal physiological model consisting of a human body shape, tissues, and circulation system has been developed.
- The apparatus to thermally condition local body segments for the thermal psychological model has been built.

Future Directions

- Develop a psychological model from a series of human subject tests that examine local thermal comfort.
- Couple body segments to produce global comfort.
- Couple the Human Thermal Comfort Model to models of external environmental conditions to evaluate. and optimize the performance of climate control systems.

Introduction

Current vehicle climate control systems are dramatically overpowered because they are designed to heat/cool the entire cabin from an extreme condition to room temperature in a specified period of time. Typical vehicle air conditioning systems require 4,000 Watts of mechanical power, whereas the human body only dissipates roughly 100 Watts.

NREL is developing a numerical model of human thermal physiology and psychology, and a thermal manikin that can be placed in actual vehicles, all of which will respond to the transient and extremely non-uniform thermal environments inside vehicle cabins. Industry can then use these tools to develop climate control systems that achieve optimal occupant thermal comfort but at minimum power consumption.

The computational tool under development is a Human Thermal Comfort Model. The purpose of this model is to predict the physiological and psychological response of a human to a transient non-uniform thermal environment. The physiological model is a finite element model of the human thermal physiological systems and thermoregulatory systems.

The experimental tool under development is an Advanced Thermal Manikin. The Thermal Manikin is also being engineered to respond to a transient non-uniform thermal environment in the same manner as a human.

Approach

The Thermal Comfort Project at NREL is organized into the development of three predictive tools. These include a physiological model of the human thermal system, a psychological model of human thermal comfort, and a thermal comfort manikin for real vehicle testing.

Human Thermal Physiological Model

NREL has chosen to upgrade and improve the Kansas State University (KSU) finite element model for the NREL Human Thermal Comfort Model (see Figures 1 and 2). A finite element model will allow a much more precise simulation of the detailed interface between the human body and complex geometry of the seats and vehicle cabin.

Psychological Thermal Comfort Model

A project is underway to develop a psychological model that can convert the distribution of static and dynamic temperatures into local and global perceptions of thermal comfort.

The project consists of three general tasks:

- Task 1 is to develop an apparatus that can control the static and dynamic temperature of each body segment.
- Task 2 is to conduct the human subject tests to determine the thermal comfort sensitivity of each body segment.
- Task 3 is to develop a mathematical model that can predict local and global thermal comfort based on measurements from the tests.

Thermal Comfort Manikin

NREL has been working with an industry partner, Management Technology Northwest (MTNW), to build a life-size manikin, which will simulate how human passengers respond to non-uniform, transient thermal conditions (heat, cold, solar radiation, air velocity, and temperature) in an automobile. The thermal comfort manikin will be controlled by a finite element physiological model, which provides outputs to a psychological model that predicts the occupant's perception of local and global thermal comfort.

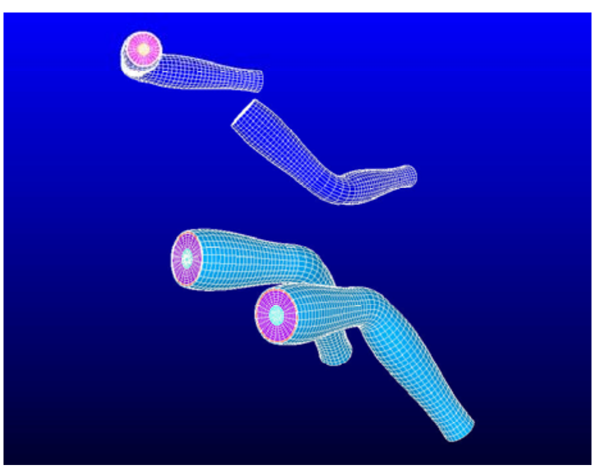

Figure 1. Physiological model of arm and leg tissue mesh.

The manikin is expected to take two years to build. The first year consisted of research and development. The second year is building the manikin. The overall objective of the program is to develop a thermal manikin that will respond to a transient non-uniform thermal environment similar to a human.

Results

Human Thermal Physiological Model

Improvements have been made to the existing KSU model to develop a model that can very closely simulate human thermal response. This improved human thermal model will be coupled to the external thermal field models for thermal comfort testing.

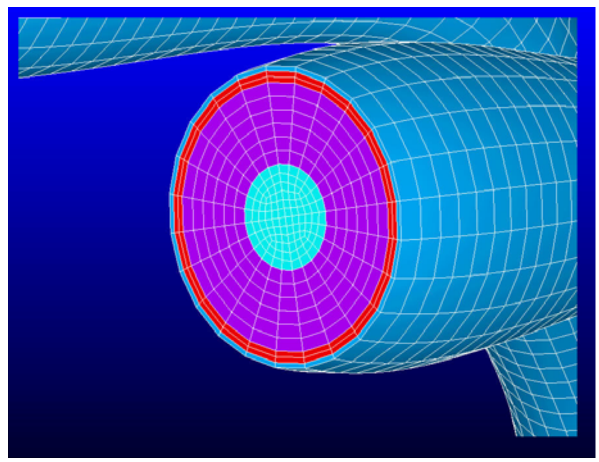

Figure 2. Physiological model mesh, showing bone, muscle, fat, and skin in a limb.

The physiological model of the human body now incorporates limb and body shapes, which are scalable to any human body. It also incorporates internal tissue (bone, muscle, fat, skin) and a functional convection circulation system, complete with simulated blood flow through big arteries and veins. A simulated torso has also been developed which includes a heart, lungs, and intestines. Blood profusion on a smaller scale is now in the works.

Psychological Thermal Comfort Model

The University of California at Berkeley has completed its design of human subject tests related to the psychological model. The tests are scheduled to begin soon. The university has developed an innovative way of measuring body core temperature, which involves the use of "ingestible thermalmeter pills" (see Figure 3). The pills, swallowed by human subjects, contain crystals that transmit temperature information to a wireless receiver.

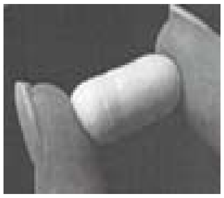

Figure 3. Ingestible thermalmeter pill

Thermal Comfort Manikin

A leg segment of the manikin was fabricated (see Figure 4) demonstrating the following:

- Realistic sweating rates using porous metal skin for the first time ever
- Fast transient thermal response times
- Fully wetted skin with high spatial resolution
- Simultaneous operation of 16 surface segments, each with independent control of heating, sweating, and temperature sensation.

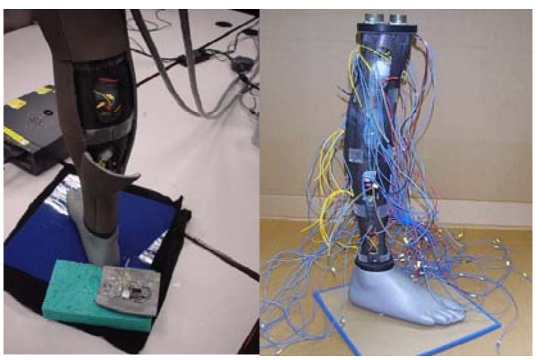

Figure 4. MTNW successfully fabricated a thermal comfort manikin leg with sweating capabilities.

A recently developed prototype system for the thermal comfort manikin mimics human breathing. Room temperature air is pushed through a heated water chamber to create warm, fully saturated air, which matches the volume, temperature, and humidity of human breath. MTNW is building the life-size manikin, which will simulate how a passenger responds to non-uniform, transient thermal conditions (heat, cold, solar radiation, air velocity, and temperature) in an automobile.

Conclusions

The vehicle Thermal Comfort Project at NREL consists of three main components, which include the physiological model, a psychological comfort model, and a thermal manikin. All three components should be completed by January 2003. These tools will then be available for use by industry to develop more effective and efficient thermal comfort systems. The numerical thermal comfort models and thermal manikin will be the first thermal comfort tools that can accurately predict the human physiological and psychological response in both actual and simulated non-uniform transient thermal environments.

The manikin is an important tool for industry because it can be used to evaluate consumer comfort in vehicles while helping to evaluate technologies designed to reduce vehicle auxiliary loads and downsize the air-conditioning systems in vehicles.

Publications

"Modeling of Human Thermal Comfort," McGuffin, R., 2001 SAE Digital Human Modeling Conference, July 2001.

"Advanced Thermal Manikin," McGuffin, R., 47th International Instrumentation Symposium of the Instrument Society of America, June 2001.

"Modeling of Human Thermal Comfort," McGuffin, R., 2001 SAE Vehicle Thermal Management Conference, July 2001.

"NREL Thermal Comfort Models," DOE Milestone Report, July 2001.

"Thermal Comfort Manikin," DOE Milestone Report, August 2001.

"Development of an Advanced Thermal Manikin for Vehicle Climate Evaluation," Burke, R., and McGuffin, R., 4IMM Conference, September 2001.

II-I. Transient Air Conditioning System Analysis & Optimization

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Objective

- Work with the automotive industry to develop and validate vehicle transient air conditioning system models that predict A/C power requirements on the engine, cabin thermal/fluid boundary conditions, and impacts on human thermal comfort.
- Integrate those models with NREL's ADVISOR vehicle analysis software to predict A/C system impacts on fuel economy, tail-pipe emissions, and human thermal comfort for advanced climate control systems.
- Conduct transient computational modeling of the A/C system allows capture of the important transient phenomenon (e.g., dynamic two-phase flow and temperature/pressure/quality effects) and their impacts on system design for more environmental conditions more quickly and less expensively than costly vehicle/system testing. Assist automotive companies that are under pressure to identify and fabricate optimized A/C systems that are effectively integrated with the entire vehicle's energy management system more quickly and less expensively than ever.
- Model the vehicle A/C system as part of the entire vehicle climate control system in a sophisticated, multi-disciplinary analysis environment.
- Use the transient A/C modeling process to investigate design methodology, control strategies, and design techniques to reduce our nation's fuel use for vehicle A/C system operation.
- Work with the automotive industry to develop and validate vehicle transient air conditioning system models that predict A/C power requirements on the engine, cabin thermal/fluid boundary conditions, and impacts on human thermal comfort. Integrate those models with NREL's ADVISOR vehicle analysis software to predict A/C system impacts on fuel economy, tail-pipe emissions, and human thermal comfort for advanced climate control systems. Vehicle A/C systems are controlled by and exposed to transient boundary and vehicle drive conditions. Transient computational modeling of the A/C system allows one to capture the important transient phenomenon (e.g., dynamic two-phase flow and temperature/pressure/quality effects) and their impacts on system design for more environmental conditions more quickly and less expensively than costly vehicle/system testing. Modeling the vehicle A/C system as part of the entire vehicle climate control system is a complex, multi-disciplinary problem beyond the capability of a single supplier. The goal is to use the transient A/C modeling process to investigate design methodology, control strategies, and design techniques to reduce our nation's fuel use for vehicle A/C system operation.

Approach

- Identify the appropriate software tools capable of performing transient analyses of transient, two-phase, multi-constituent flow in a vehicle A/C system flow loop and capable of multi-variable optimization of the A/C system.
- Develop the transient A/C system model that is linked to both simplified (i.e., <10 volume elements) and sophisticated (i.e., > 500 volume elements) finite element cabin thermal/fluid models.
- Work with industry to analyze climate control strategies that will reduce the amount of fuel use for vehicle air-conditioning.

Accomplishments

- Developed a detailed transient, two-phase A/C model in SINDA/FLUINT analysis software that includes optimization capability.
- Integrated the transient A/C model with a simplified, 2-node cabin thermal/fluid model to analyze transient cabin cool-down conditions in response to the dynamic A/C system thermal/fluid performance.
- Initiated multi-variable A/C system optimizations that included the effect of coupled, interdependent component effects on A/C system design.
- Linked the transient A/C model and the ADVISOR (Advanced VehIcle SimulatOR) software to determine the fuel use impact of a smaller A/C compressor.
- Integrated the SINDA/FLUENT transient A/C model and simplified the cabin thermal/fluid model with the VSOLE vehicle solar load estimator software.
- Optimized electric-driven A/C systems for advanced vehicle climate control.

Future Directions

- Integrate the transient A/C model with the cabin thermal/fluid model developed as part of the integrated modeling task.
- Populate the transient A/C model with industry-specific component models to analyze A/C systems of interest to industry.
- Validate the transient air conditioning model with "real system" experimental data on an industry collaborative project.
- Continue system optimization studies of dynamically-controlled, electric-driven A/C systems for future advanced vehicle platforms.

Introduction

The air-conditioning (A/C) compressor is the largest auxiliary load on today's automobile engines and significantly impacts fuel economy and tailpipe emissions. Recent tests indicate that A/C use increases emissions of NO_x by about 80% and CO by about 70% over the SCO3 drive cycle. It also reduces fuel economy by about 20% in conventional vehicles. In addition, recent NREL tests have shown that A/C system operation in the Toyota Prius and Honda Insight hybrid electric vehicles (HEV) reduces fuel economy by approximately 35%. Research indicates that there is significant potential to reduce A/C power demands on the engine and improve real world fuel economy, without impacting comfort or safety.

A/C systems are typically sized for transient cooldown from worst-case thermal soak conditions with little regard or emphasis on system energy usage and management. NREL is investigating techniques to 1) optimize vehicle A/C systems to reduce their power demands on the vehicle engine, and 2) optimize the vehicle A/C system within the overall vehicle optimization process, while maintaining system performance requirements important to human thermal comfort.

Predicting the impact of advanced A/C systems and control strategies on occupant comfort, fuel economy, and tailpipe emissions is challenging because of the many critical factors and complex interactions. A/C system performance is dictated by component performance specifications, cabin thermal (including solar) loads, dynamic two-phase flow conditions, vehicle drive cycle, front-end air velocity and flow conditions, and ambient temperature. We are working on a systems analysis and optimization process in collaboration with DaimlerChrysler, General Motors, Delphi Automotive Systems, Visteon Climate Control, and Valeo Climate Control to evaluate and integrate advanced A/C systems and climate control technologies.

Approach

NREL has developed a detailed transient air conditioning system/simplified cabin model using SINDA/FLUNT analysis software and integrated it with the ADVISOR vehicle systems analysis software. Figure 1 schematically shows the typical vehicle A/C system (using R-134a) modeled by transient A/C system analysis. This transient one-dimensional, thermal-hydraulic model captures all the relevant physics of transient A/C system performance, including two-phase flow effects in the evaporator and condenser, system mass effects, air side heat transfer on the condenser/evaporator, vehicle speed effects, temperature-dependent properties, and integration with a simplified cabin thermal model. The model predicts typical transient A/C compressor power requirements, system pressures and temperatures, system mass flow rates, and two-phase/single-phase flow conditions throughout the A/C system flow circuit. The transient A/C system model is also integrated with a simplified vehicle cabin thermal/fluid model so we can predict cabin thermal response to the A/C system performance. This cabin model predicts transient cabin temperature conditions during a user-defined drive cycle. In the near future we will integrate the transient A/C system model with a more sophisticated cabin thermal/fluid model developed in the integrated modeling task.

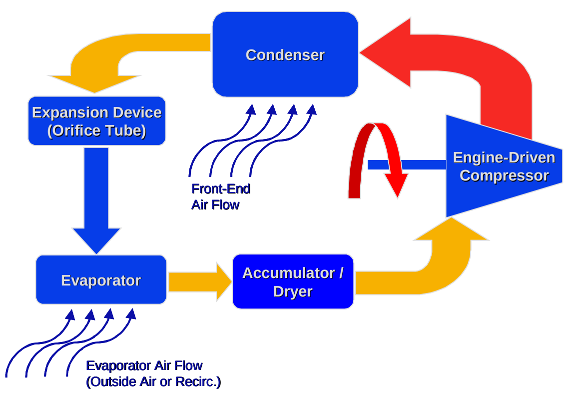

Figure 1. Typical Vehicle Air Conditioning System With Belt-Driven Compressor

The transient A/C system model has also been integrated with the VSOLE solar load estimator model. VSOLE currently predicts transient solar thermal loads on a vehicle cabin, which in turn are used by the cabin thermal/fluid model within the transient A/C system model to predict cabin temperature response. This shows the capability of integrating the transient A/C model with a cabin thermal/fluid model and the VSOLE solar load estimator to predict integrated effects. VSOLE was written in Matlab and is easily accessed with a graphical user interface (GUI). The program takes into account the angle of incidence and calculates the transmitted, reflected, and absorbed power based on the radiation source, vehicle geometry, vehicle orientation, and glazing type. All glazing surfaces are assumed to be flat, with constant thickness, uniform properties, and of regular shape. The calculation of the optical properties as a function of wavelength and angle uses a single-pane, no-wave-interference model for glass. An example of the VSOLE GUI available in the ADVISOR / SINDAFLUINT co-simulation is shown in Figure 2. We will ultimately integrate this capability with a passenger thermal comfort model in the integrated modeling task.

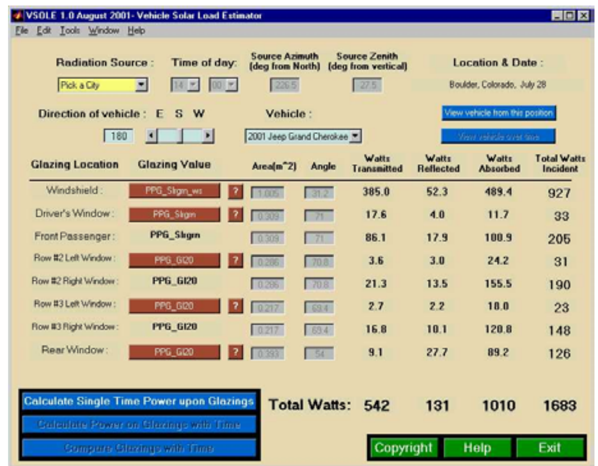

Figure 2. VSOLE Interface

Results

System Transient Behavior

The transient A/C system research has given NREL/DOE tremendous insights and understanding into the transient behavior of current A/C systems. Figure 3 shows the variation in compressor power with time for a vehicle driven in the SCO3 drive cycle. The compressor power is shown to vary from 40% to 140% of average compressor power over the SCO3 drive cycle. Figure 4 shows the variation in system pressures with time on the high pressure side and low pressure side of the expansion device in a typical vehicle A/C system.

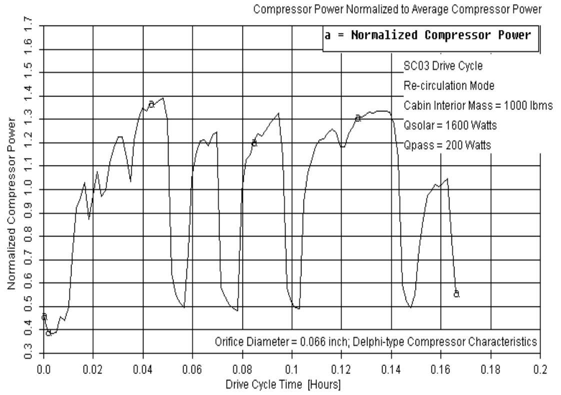

Figure 3. Time-Dependent A/C Compressor Power Over the SCO3 Drive Cycle.

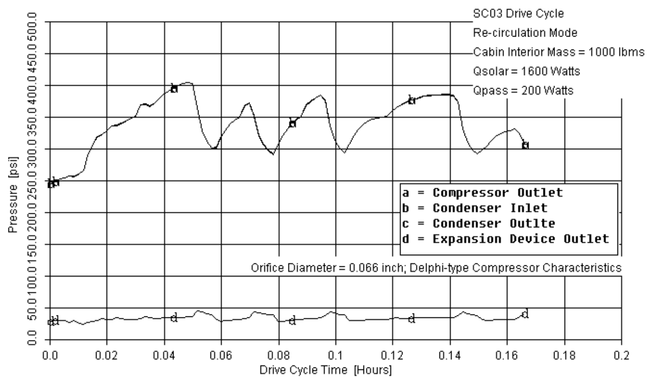

Figure 4. Time-Dependent System Pressure Profiles Over SC03 Drive Cycles.

This research has also shown that the condensation and evaporation front locations within the condenser and evaporator move during dynamic drive cycle conditions. Drive cycle effects create dramatically variable heat transfer coefficients in both the condenser and evaporator as exemplified in Figure 5 for the condenser. The condensation and evaporation front movement also can be changed significantly by employing different compressors and expansion devices. These system dynamics within any given vehicle drive cycle must be captured to truly optimize a vehicle A/C system. The transient A/C model allows us to account for and track these front movements within the condenser and evaporator for various system configurations and optimize the system performance while accounting for the highly dynamic flow and heat transfer conditions.

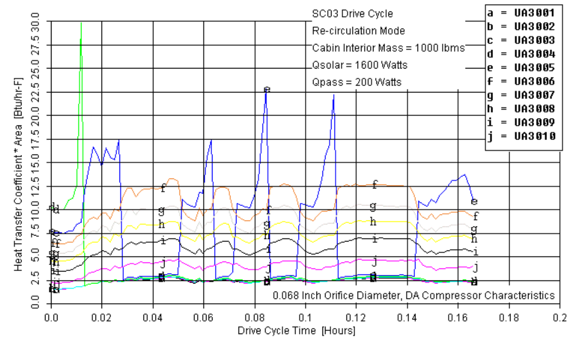

Figure 5. Condenser and Evaporator Heat Transfer Coefficients are Strong Functions of Time and Location Within Flow Path

System Optimization

The truly transient behavior of the many critical and interdependent A/C system performance parameters makes multi-variable design optimization imperative to improve system performance. Initial multi-variable optimization of the overall A/C system showed that a 50% increase in A/C system COP (Coefficient of Performance) was possible simply by simultaneously optimizing system components and their interdependent effects. In one optimization study, the relationship between the compressor displacement and expansion device diameter was found to be critical for increasing system performance, as the optimum combination created optimum high pressure profiles shown in Figure 6 over the SC03 drive cycle. The optimum combination also created optimum flow quality conditions in the condenser as shown in Figure 7.

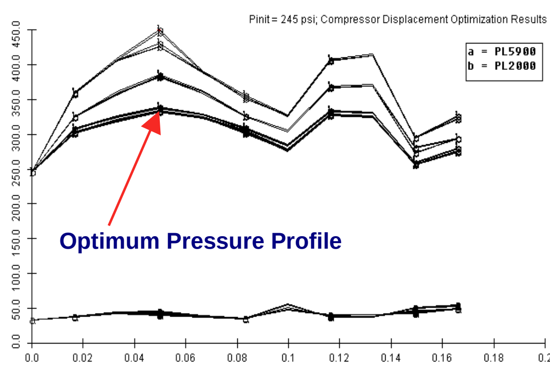

Figure 6. Optimum Pressure Profiles During SC03 Drive Cycle

The transient A/C model was also used to study the multi-variable optimization of electric-driven compressor A/C systems for advanced vehicles. Electric-driven A/C systems offer the potential to operate the A/C compressor and the system at optimum speeds and conditions rather than be dictated by engine and drive cycle speed. Our transient A/C analysis has shown that these electric driven A/C systems can significantly increase performance and reduce system energy usage. Figure 8 shows the compressor driven by an alternator/motor combination. Electrically-driven systems that are dynamically controlled are being studied in conjunction with our work on electric-driven systems. The system optimization results have shown that A/C system COPs greater than 3 are possible for properly optimized, dynamically-controlled, electric-driven A/C systems over SC03 and US06 drive cycles.

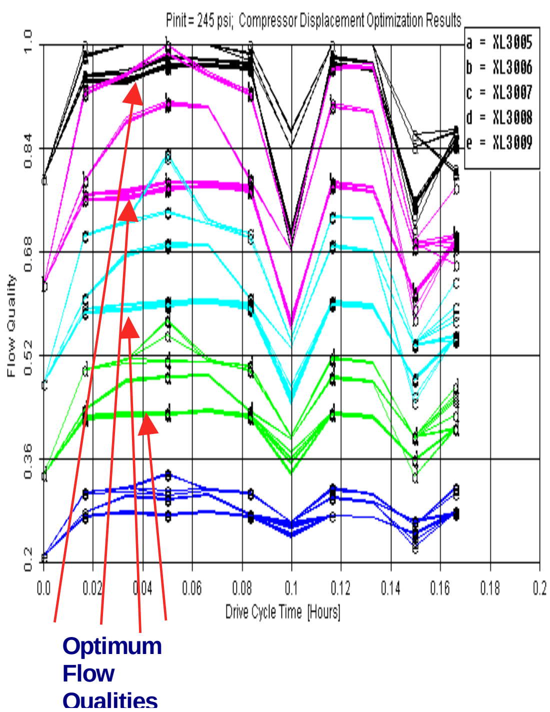

Figure 7. Optimum Flow Quality Profiles During the SC03 Drive Cycle

This COP is about twice the COP that present day vehicle A/C systems operate at and represents a tremendous opportunity to reduce A/C system energy usage and increase vehicle fuel economy.

Conclusions

Vehicle A/C systems represent the major auxiliary energy consumption system within current vehicles and future hybrid electric vehicles. NREL has developed a detailed transient air conditioning system/simplified cabin model using SINDA/FLUNT analysis software and integrated it with the ADVISOR vehicle systems analysis software and VSOLE solar thermal load estimator. The model is used to investigate transient A/C system performance for various A/C system configurations and to optimize A/C system designs, including electric-driven compressor systems. NREL is working with industry to upgrade this modeling tool and validate it with real system experimental data. It has been used for cabin thermal response studies, to study and understand optimized system performance, and to optimize advanced A/C system configurations such as electric-driven systems. Electric-driven systems have shown potential for much higher performance than current vehicle A/C systems, leading to significantly lower A/C system energy demands on the vehicle and higher vehicle fuel economy. This model is a critical part of NREL's Digital Functional Vehicle and integrated modeling process to evaluate advanced concepts that can increase vehicle fuel economy and reduce vehicle emissions.

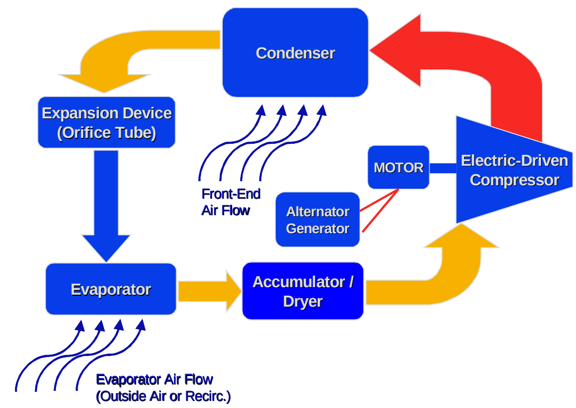

Figure 8. Electric-Driven Compressor A/C System

Publications

"Vehicle Transient Air Conditioning Analysis: Model Development & System Optimization Investigations," Hendricks, T.J., NREL Technical Report #NREL/TP-540-30715, June 2001.

"Integrated Modeling to Predict Occupant Thermal Comfort," Farrington, R., Barber, G., Hendricks, T., Marion, W., Markel, T., McGuffin, R., and Rugh, J., technical paper prepared for the 7th International Automotive Technologies Association Conference, May 2001.

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"Optimization of Vehicle Air Conditioning Systems Using Transient Air Conditioning Performance Analysis," Hendricks, T.J., technical paper prepared for the 5th Vehicle Thermal Management Systems Conference & Exhibition, May 2001.

IIJ. Exhaust Waste Heat Recovery System Analysis & Optimization

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Objective

- Develop high-performance (HP) and cost-effective (CE) energy conversion technologies for automotive applications that can assist in reducing the nation's reliance on imported foreign oil.
- Develop high-performance and cost effective energy conversion technologies that can recover and convert low-grade vehicle exhaust waste thermal energy into high-grade electrical energy useful for operating various vehicle auxiliary electrical loads.
- Design and optimize performance of HP/CE energy conversion technologies to satisfy vehicle requirements in advanced vehicle applications.
- Demonstrate HP/CE energy conversion technologies and quantify/characterize their performance in advanced vehicle systems including hybrid electric vehicle platforms.

Approach

- Identify and assess various energy conversion technologies for capability to meet automotive system requirements for performance, system location, cost/benefit, and system integration.

- Develop the advanced multi-segment thermoelectric system modeling tool in MatLab/Simulink environment to analyze coupled heat exchanger and advanced thermoelectric system performance.
- Link with ADVISOR to evaluate impacts on advanced vehicle fuel economy and emissions.
- Perform system level design and performance analyses for various vehicle types and drive cycles.

Accomplishments

- Completed development of a detailed model in MatLab/Simulink analysis software that includes optimization capability.
- Integrated the transient air-conditioning (A/C) model with a simplified, 2-node cabin thermal/fluid model to analyze transient cabin cool-down conditions in response to the dynamic A/C system thermal/fluid performance.
- Initiated multi-variable system optimizations that included the effect of coupled, interdependent heat exchanger/thermoelectric system effects.
- Linked the model and the ADVISOR (Advanced VehIcle SimulatOR) software enabling the fuel use impact of advanced thermoelectric waste heat recovery systems to be determined.
- Optimize advanced thermoelectric systems for sport utility vehicles (SUVs), light-duty vehicles, and heavy-duty vehicles and various drive cycles.

Future Directions

- Demonstrate advanced thermoelectric system performance in advanced vehicle systems including hybrid electric vehicle platforms.
- Validate the advanced TE model with "real system" experimental data on an industry collaborative project.
- Continue system optimization studies for light-duty vehicles, SUV's and heavy-duty vehicles.

Introduction

About 33% of the fuel energy content in current internal combustion engine vehicles is lost as waste heat in the vehicle's exhaust stream. That represents approximately 20kW of energy in the form of thermal energy flowing down every vehicle's exhaust system. Figure 1 shows energy equivalent gallons of gasoline wasted every year for a given average daily driving time by the 240 million light-duty vehicles nationwide via vehicle exhaust waste thermal energy.

The number of gallons of gasoline is extremely large and contributes tremendously to the nation's reliance on imported foreign oil. Figure 2 shows the typical total waste energy from a 3.0L engine across its entire engine map. Under some driving conditions the waste thermal energy in the vehicle exhaust can be even higher than the 18 kW given above. This research seeks to develop design approaches and energy recovery systems to help recover a significant portion of this wasted energy and reduce the nation's reliance on imported oil.

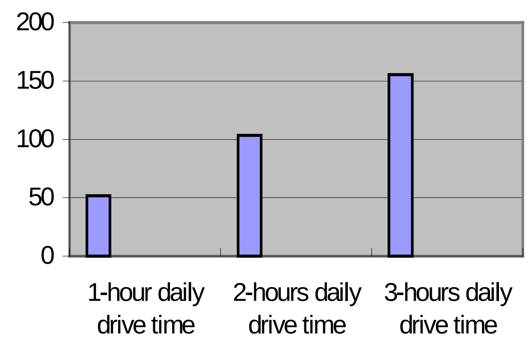

Figure 1. Energy Equivalent Gallons of Gasoline (Billions) Per Year Wasted in Vehicle Exhaust Stream.

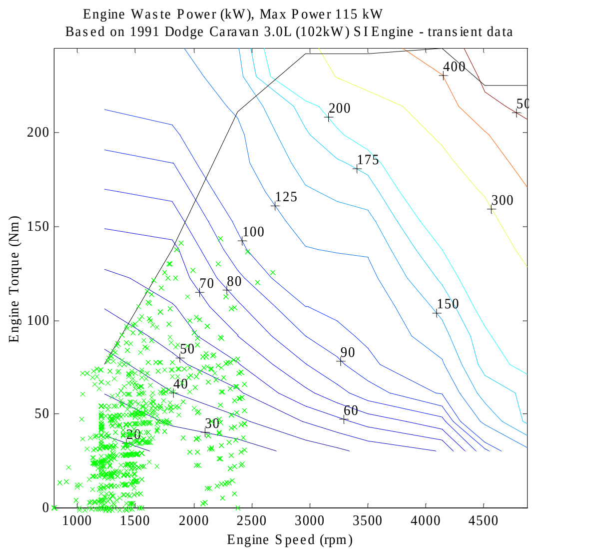

Figure 2. Engine Waste Power Available from a 3.0L SI Engine in 1991 Dodge Caravan

Several energy conversion technologies are being investigated to capture a portion of this waste thermal energy, including advanced thermoelectric (TE) systems, thermophotovoltaic (TPV) systems, and thermionic systems. Advanced thermoelectric systems currently appear to have the best potential for satisfying automotive system requirements for performance, system location, cost/benefit, and system integration. Thermionic and TPV systems typically require operating temperatures higher than that available in current light-duty and heavy-duty vehicles. Thermionic and TPV systems also are typically expensive with no current avenue identified for achieving cost-efficient systems affordable to the automotive industry. System reliability high enough to satisfy automotive systems requirements also have not been demonstrated by thermionic and TPV systems. TE systems have demonstrated very high reliability in the space program, being used to reliably power such spacecraft as the Galileo and Voyager spacecraft on deep-space missions for many years.

Past TE systems in all applications, including spacecraft missions, have suffered from high-cost and low performance due to the fundamental limitations of their SiGe, PbTe and BiTe material systems. New opportunities exist to apply TE systems to a number power system needs, including automotive systems, because of recent discoveries of new, better performing TE materials.

Approach

The two most actively researched advanced TE systems are those based on (1) quantum-well TE materials and (2) newly-characterized advanced segmented TE materials such as skutterudites and Zn_4Sb_3 alloys. Quantum-well TE materials have only recently been investigated, and will require many years and much research investment to demonstrate long-term reliable performance. The second TE material set above is more mature and closer to achieving long-term reliable performance. Figure 3 shows the measured ZT value of the newly-characterized skutterudite and Zn_4Sb_3-alloys TE materials, and a comparison with older TE materials used in past systems.

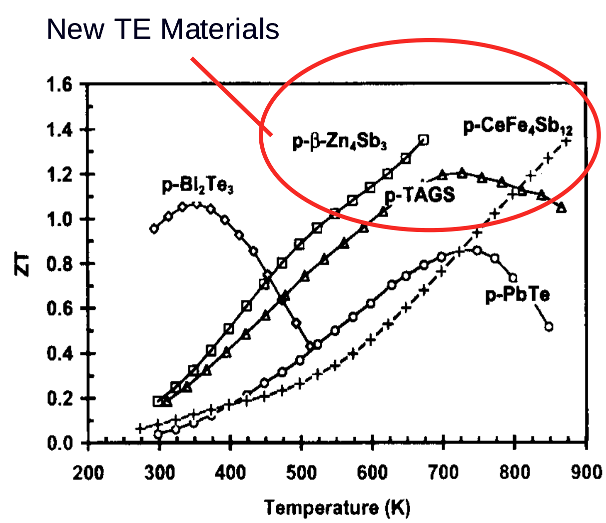

Figure 3. ZT Performance of newly characterized TE materials is significantly higher and creates new power system opportunities.

NREL has developed a detailed advanced thermoelectric system analysis model within the MatLab/Simulink mathematical analysis software. This model allows us to quickly evaluate numerous TE system design configurations and system requirements. The model has also now been linked with NREL's ADVISOR vehicle analysis software to allow us to evaluate impacts on vehicle fuel economy and emissions. Industry partners indicating interest in our advanced TE system design and analysis work include DaimlerChrysler, General Motors and Visteon Corporation. Industry in particular would like to produce high-grade electrical power from the low-grade exhaust waste heat to power various vehicle auxiliary loads (i.e., pumps, fans, lights). Once initial system performance and design tradeoff studies have been completed NREL will engage a supplier to help develop an advanced TE prototype system to demonstrate performance and validate the analytic design models and predicted performance.

Results

NREL's TE system performance studies have begun to quantify the system performance parameters and potential power output available at various locations along the vehicle exhaust line using the segmented TE materials shown in Figure 3. Figure 4 shows the three prime candidate locations, which have been identified from discussions with our industry partners.

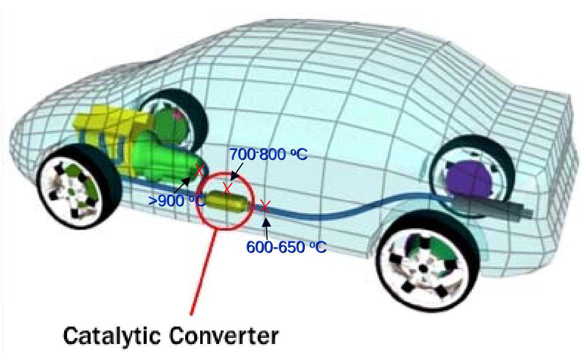

Figure 4. Prime Exhaust Line Locations for Waste Heat Recovery System.

Immediately out of the engine, the gas flow temperatures are approximately 900°C or higher depending on the drive cycle. At the catalytic converter, the gas flow temperature is approximately 700-800°C, while downstream of the catalytic converter the gas flow temperatures decrease to approximately 600°C. This research has quantified the system design tradeoffs of the various exhaust gas locations. It currently appears that the best location for such a advanced TE power system is on the catalytic converter.

Initial system design results show the system power output maximizes at certain TE hot side temperatures (i.e., approximately 400°C) for an exhaust gas temperature of 700°C because of the tradeoff between heat exchanger performance and TE device performance (Figure 5). The exhaust gas flow rates shown in Figure5 are typical of those in various light-duty vehicles and SUVs. Figure 6 shows the required cold side cooling mass flow rates required for various TE hot side and cold side temperature combinations and an ambient temperature of 27°C. As TE cold side temperature decreases to near ambient, the required cold side cooling mass flow rates become prohibitively large. Consequently, these are temperature regimes that must be avoided in final system designs.

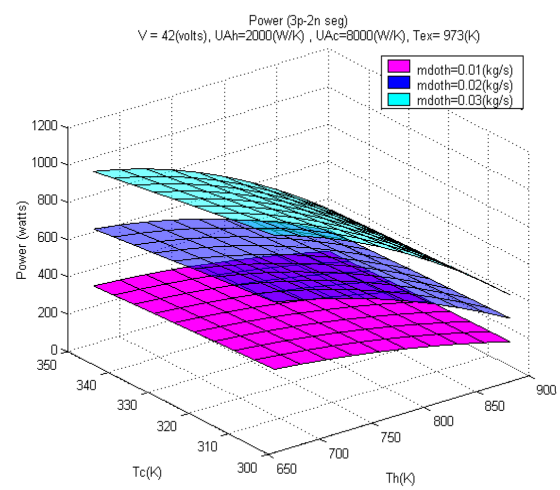

Figure 5. System power output is strongly dependent on TE hot side and cold side temperature and exhaust mass flow rate.

Figure 7 shows the typical maximum efficiency / maximum power behavior for such an advanced TE system using the advanced TE materials in Figure 2. Conversion efficiencies range from 11-13.5% for system power outputs of 1000-1100 watts and an exhaust gas temperature of 800°C and an ambient temperature of 27°C.

The automotive industry, Daimler Chrysler, General Motors, and Visteon Corporation, are all interested in systems producing 1000 watts or more so these TE design studies apply directly to the automotive industries requirements. These analytic results show the important system

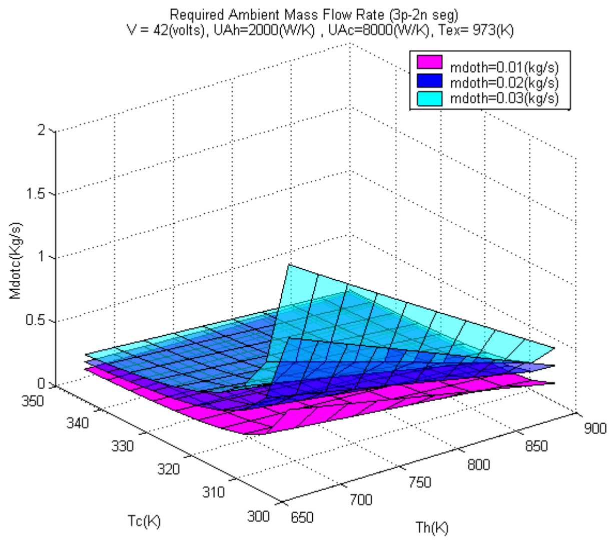

Figure 6. Cold side cooling flow rate can be a strong function of TE hot side and cold temperature and exhaust mass flow rate.

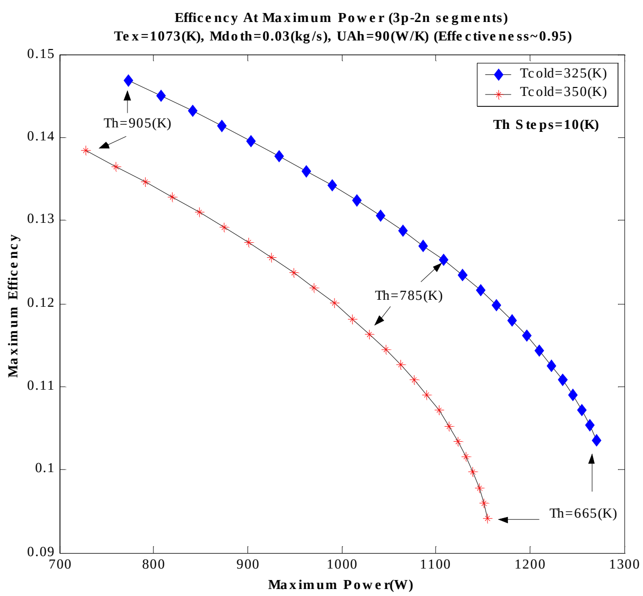

Figure 7. Typical maximum efficiency / maximum power behavior for an Advanced TE system Using the Advanced TE Materials.

tradeoffs and performance characteristics of such a TE power system.

Conclusions

NREL has developed a comprehensive advanced TE power system analysis tool in MatLab/Simlulink to evaluate the vehicle exhaust waste heat recovery benefits and system performance characteristics. The analytic tool is now linked with NREL's ADVISOR vehicle system analysis software to evaluate the impact vehicle exhaust waste heat recovery on vehicle fuel economy. System investigations have revealed some important system performance characteristics and critical system design information such as optimum location, power output, and cold side cooling mass flow rate requirements. The opportunities for such advanced TE systems to reduce our nation's reliance and addiction to imported foreign oil is enormous. Current estimates indicate that the energy equivalent of at least 51 Billion gallons of gasoline are thrown away annually nationwide down our vehicles' exhaust streams.

Publications

"Advanced Thermoelectric Systems for Automotive Thermal Energy Recovery", Lustbader, J. and Hendricks, T.J., NREL Internal Technical Seminar, August 2001.

IIK. Battery Thermal Characterization and Management

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Objective

- To characterize thermal performance of batteries to develop more effective and energy-efficient thermal management strategies for battery packs in electric and hybrid electric vehicles.
- To improve the performance of battery packs and thus fuel economy of vehicles while avoiding premature calendar and life cycle of batteries. Extending battery life will result in saving energy and materials since manufacturers don't need to produce as many batteries.
- To evaluate techniques for heating batteries quickly and efficiently in electric and hybrid vehicles during cold seasons.

Approach

- Collaborate with auto and battery industry for battery thermal characterization and analysis of prototype hybrid vehicles.
- Use an integrated approach in thermal characterization, analysis, design, testing, and management of battery modules and packs.
- Use a unique calorimeter to measure heat capacity and heat generation from batteries. Utilize infrared thermal imaging, battery cyclers, flow visualization, thermal testing and analysis, and computational fluid dynamics to assess batteries.
- Benchmark state-of-the-art production hybrid vehicle battery packs.
- Analyze and demonstrate various battery heating techniques for cold seasons.

Accomplishments

- Obtained thermal characteristics (heat generation, heat capacity, and thermal images) of PolyStor lithium-ion (Li-Ion), Panasonic nickel-metal-hydride (NiMH), and Compact Power lithium-polymer (LiP) batteries.
- Collaborated with DaimlerChrysler to test and analyze thermal behavior of batteries in prototype hybrid vehicles and provided energy-efficient thermal management strategies that enabled the use of a NiMH battery without exceeding specified temperature limits.
- Benchmarked the thermal management system in a North American version of Toyota Prius and found that under most testing conditions it does a good job in keeping the batteries within the specified temperature range.
- Evaluated four battery-heating techniques and found that electric internal core heating was the most effective method and used less energy. We worked with University of Toledo to demonstrate the electric internal core heating technique and found that a 60Hz alternating current (AC) through the battery terminals effectively heats batteries.
- Received an R&D 100 award from R&D Magazine for a charging algorithm that extends the life of electric vehicle lead-acid batteries by 300% to 400%.

Future Directions

- Continue to collaborate with auto and battery industries to test and analyze energy efficient battery thermal management strategies in hybrid vehicles.

- Work with the Partnership for a New Generation of Vehicles (PNGV) battery developers to thermally characterize batteries by measuring heat capacity and heat generation and evaluating thermal imaging of batteries under development.
- Evaluate a prototype for heating batteries during cold seasons.

Introduction

Over the past several years, the National Renewable Energy Laboratory (NREL) has had the lead responsibility for evaluating thermal characteristics of batteries and assisting the battery and auto industry with developing improved battery thermal management strategies. Proper thermal design and management of batteries in electric vehicles (EV) and hybrid electric vehicles (HEV) is an important task since it can affect the performance and life of the battery and thus the vehicle performance and fuel economy.

Understanding the thermal properties and behavior of batteries and packs will lead to an improved understanding of how to develop modules and packs with better thermal performance. In addition to the improved vehicle fuel economy and performance, a properly designed thermal management system will extend the life of batteries 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.

Approach

NREL's Battery Thermal Management Project team works hand-in-hand with industry to evaluate batteries and offer design improvements for HEV and EV modules and packs.

As part of the U.S. Department of Energy's (DOE) Hybrid Electric Vehicle Propulsion Program, NREL assists the U.S. auto industry and battery developers in designing an integrated approach to thermal characterization, analysis, design, testing, and management of battery modules and packs (see Figure 1). 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 its capabilities to instrument and test battery packs from production HEVs, either out of vehicle or in vehicle (on-road and on dynamometer). NREL computer aided design tools are used for analyzing various methods for heating batteries in cold seasons. As part of a collaboration with industry, NREL uses battery cyclers and thermal imaging to investigate charging methods to extend the life of the EV lead acid batteries.

Results

The Battery Thermal Management Team collaborated with industry to measure thermal characteristics of the following batteries: Panasonic NiMH batteries for DaimlerChrysler, a PolyStor lithium-ion polymer gel battery for PNGV, and a new lithium-polymer from Compact Power. Using a unique battery calorimeter and cycler, NREL measured the heat capacity of each battery and the heat generation from each module under various driving cycles. NREL found that the lithium batteries generated the least amount of heat, and thus were more energy efficient.

Figure 1. Ahmad Pesaran and Mark Mihalic evaluate batteries (donated by industry partners) at NREL's Battery Thermal Management Test Facility

Thermal imaging indicated that lithium batteries had very uniform temperature distribution.

Four power-conditioning units, two large environmental chambers (all excess equipment from a DOE/Ford HEV subcontract), and several overhead power trays and cables enhanced the capabilities of the battery thermal management laboratory. The environmental chambers give NREL the ability to test batteries at temperatures between -60°C and +200°C. The power units enable NREL to test batteries, ultracapacitors, and fuel cells for DOE and industry projects.

NREL collaborated with DaimlerChrysler and its battery supplier to evaluate the effectiveness of two approaches (air and liquid cooling) to thermally manage battery packs installed at various locations in a HEV prototype. As part of its efforts to benchmark production hybrid vehicles and components, NREL tested a North American version of the Toyota Prius. The battery team instrumented and tested the vehicle and its battery pack on a chassis dynamometer. The battery pack was also tested out of the vehicle in an environmental chamber to obtain its thermal characteristics (see Figure 2). The results indicated that the battery thermal management system in the Prius keeps the batteries within the specified temperature range under most testing conditions. The information was shared with industry.

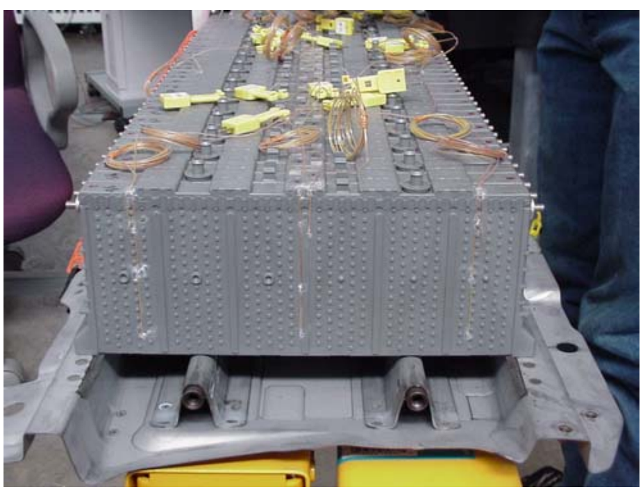

Figure 2. Toyota Prius NiMH battery pack under evaluation at NREL's Battery Thermal Management Laboratory.

The power and energy capabilities of today's advanced batteries are limited when temperatures are cold because of increased internal resistance. As a result, HEV performance may suffer and the vehicles may not be widely accepted by consumers. NREL analyzed various heating methods and found that electric heating of the battery internal core is the most efficient approach. Core heating reached a much higher temperature faster than the other heating techniques for the same amount of energy (see Figure 3). NREL, working with the University of Toledo, found that 60Hz AC heating is an effective core heating method to warm a non-operating battery at -40°C while delivering acceptable battery performance.

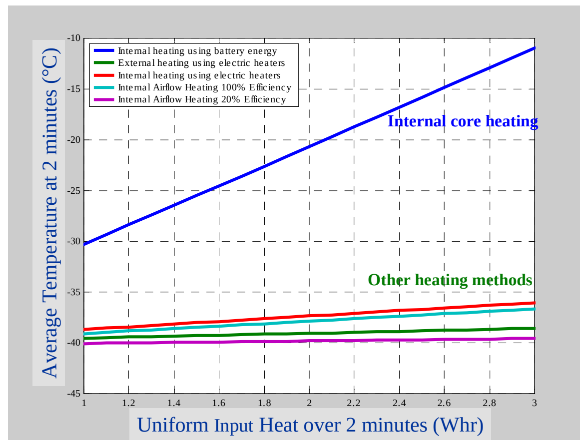

Figure 3. Internal battery core heating was found to be the most energy efficient method for increasing average battery temperature.

Lead-acid batteries are less expensive, more recyclable, and better-prepared for high-volume production; however, their relatively short deep life cycle has been a major hurdle for wider use—until now. NREL, working with Optima Batteries and Recombination Technologies, developed a current interrupt charging technique that extends the cycle life of lead-acid batteries by three to four times and makes them more competitive with nickel-metal hydride batteries (see Figure 4). Current interrupt charging (current a few seconds on and few seconds off repeatedly) reduces high battery temperature during charge. This year, NREL received a prestigious R&D 100 Award from R&D Magazine for the technology.

Conclusions

NREL has been working on testing, characterizing, analyzing, and developing technologies to efficiently control the thermal performance of batteries in electric and hybrid vehicles. In addition to the improved vehicle 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. Several battery modules and a production HEV battery packs were tested and provided insight for developing better thermal management systems. An energy efficient method to warm very cold batteries was identified and investigated.

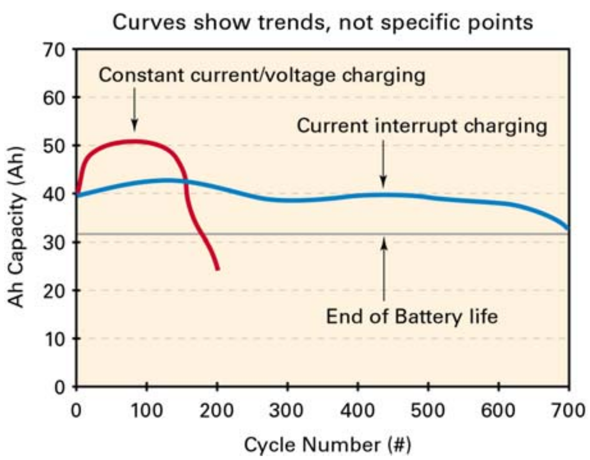

Figure 4. Current interrupt charging extends the life of lead-acid batteries by as much as four times compared to using standard constant current/voltage charging.

NREL received a R&D award for developing a charging method to extend the life of EV lead-acid batteries by three-four times. Next year, NREL will continue to collaborate with industry to characterize thermal performance of batteries to develop energy-efficient battery thermal management systems. NREL will characterize thermal properties (heat capacity, heat generation rate, and thermal images) of batteries from PNGV suppliers. NREL will evaluate a prototype electric core heating element to see if it can warm up batteries at very cold temperatures, while maintaining acceptable performance.

Publications/Presentations

"Charging Algorithms for Increasing Lead Acid Battery Life for Electric Vehicles," M. Keyser, A. Pesaran, and Bob Nelson, 17th Electric Vehicle Symposium, Montreal, Canada, October 16-18, 2000.

"Battery Thermal Management in EVs and HEVs: Issues and Solutions," A. Pesaran, Proceeding of the 1st Advanced Automotive Battery Conference in Las Vegas, NV, February 6-8, 2001.

"Thermal Characteristics of Selected EV and HEV Batteries," A. Pesaran, M. Keyser, M. Mihalic, Proceedings of the 17th Annual Battery Conference, Long Beach, CA, January 9 -12, 2001.

"Thermal Chracterization of Plastic Lithium Ion Cells," M. Keyser. A. Pesaran. D. Rivers, 18th International Seminars on Primary and Secondary Battereies, Fort Luaterdale, Florida, March 5-8, 2001.

"Thermal Evaluation of a Toyota Prius HEV Battery Pack – out of vehicle testing," M. Zolot, M. Kesyer, M.Mihalic, A. Pesaran, Milestone Report, National Renewable Energy Laboratory, Golden, CO, May 2001.

"Thermal Charcterization of Advanced EV/HEV Batteries," M. Kesyer, A. Pesaran, M. Mihalic, M. Zolot, Milestone Report, National Renewable Energy Laboratory, Golden, CO, June 2001.

"Thermal Evaluation of Battery Pack in Honda Insight HEV," M. Zolot, M. Kesyer, M.Mihalic, A. Pesaran, 36th Intersociety Energy Conversion Engineering Conference, Savannah, Georgia, July 29-31, 2001.

"Data Sources and Needs – Battery Thermal Characterization," M. Keyser, Workshop: Development of Advanced Battery Engineering Models, Crystal City, VA, August 14-16, 2001.

"Evaluation of Heating Methods for HEV Batteries for Cold Seasons," A. Pesaran, A. Vlahinos, T. Stuart, Milestone Report, National Renewable Energy Laboratory, Golden, CO, August 2001.

IIL. Battery Electrical and Thermal Modeling for HEV Simulations

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Objective

- To work with the battery industry to develop validated battery models for use in vehicle simulation tools such as ADVISOR and PSAT.
- To use an integrated approach to develop both electrical and thermal performance models for batteries in vehicle simulation tools.
- To obtain data for validating developed battery models.
- To develop a complete battery pack model consisting of multiple modules with different behavior.

Approach

- Collaborate with battery developers and the Partnership for a New Generation of Vehicles (PNGV) on identifying critical battery parameters that need to be modeled.
- Obtain data through collaboration with other national labs or through testing at the National Renewable Energy Laboratory (NREL).
- Use an integrated approach in testing electrical and thermal models of batteries for ADVISOR vehicle simulation software.
- Use the state-of-the-art software for simulating electrical systems for modeling different behaviors in a battery pack consisting of multiple modules.

Accomplishments

- Developed a new resistance plus capacitance model in the Matlab software environment for ADVISOR based on the PNGV Battery Test Manual.
- Obtained data on lithium-ion (Li-Ion) and nickel-metal-hydride (NiMH) batteries to generate and validate temperature-dependent battery models.
- Obtained thermal characteristics (heat generation, heat capacity, and thermal images) of lithium-ion, NiMH, and lithium-polymer cells provided by battery developers for input to existing thermal models.
- Developed a pack model in Saber (the state-of-the-art software for simulating electrical systems) that captures behavior of multiple modules in a pack.

Future Directions

- Continue to collaborate with auto and battery industry and other national labs to develop validated models for new advanced batteries for use in vehicle simulations tools.
- Validate the complete Saber battery pack model with a NiMH battery pack. Improve the thermal model of batteries in ADVISOR and Saber.
- Co-simulate the Saber pack model with ADVISOR for evaluating the impact of pack imbalances and hybrid energy storage concepts on vehicle fuel economy.

Introduction

Over the past several years, NREL has developed battery models for a vehicle simulation tool called ADVISOR. This tool simulates performance and fuel economy of advanced conventional, electric, and hybrid vehicles based on components' models, configuration and control strategies, and drive cycles. ADVISOR is used for technology evaluation, component selection and sizing, and identifying research directions. Since batteries are key to developing successful electric and hybrid vehicles, accurate models to predict their behavior are essential. Both electrical and thermal models are necessary for inclusion in the simulation tool. In addition to developing battery models for "single" modules, industry had an interest to modeling the behavior of a complete pack model consisting of multiple modules with different behaviors. Such a complete pack model allows users to investigate the variability between modules and assess unbalancing issues related to fuel economy. Further details on NREL's battery modeling efforts can be found on the Battery Thermal Management Web site http://www.ctts.nrel.gov/BTM.

Approach

As part of the U.S. Department of Energy's Hybrid Vehicle Propulsion Program, NREL provides the U.S. auto industry and battery developers with an integrated approach to battery electrical and thermal performance modeling for ADVISOR vehicle simulations (Figure 1). The Battery Thermal Management and Vehicle Systems Team at NREL collaborate on integrating their activities.

NREL continued to strengthen its relationship with battery developers to obtain recently developed batteries for testing and model development. The latest PNGV Battery Test Manual was used for testing and developing models. These models are then used in vehicle simulators to evaluate their impacts on vehicle performance. Thermal properties for different battery types were obtained for the existing thermal model. In collaboration with Avant! Corp., an electrical system simulator software (Saber) was used to capture individual module behavior in a battery pack.

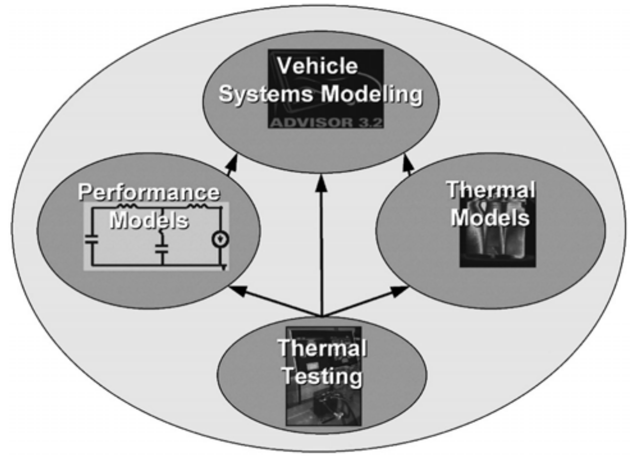

Figure 1. NREL's integrated battery modeling and testing approach.

A calorimeter was used to obtain thermal characteristics (heat generation, heat capacity) for the PolyStor lithium-ion gel, Panasonic nickel-metal-hydride, and Compact Power lithium-ion polymer batteries. NREL participated in a U.S. Department of Energy/Industry Workshop on Development of Advanced Battery Engineering Models and presented the integrated approach on battery thermal testing and electrical modeling for vehicle simulations. It was well received by industry.

Results

The Battery Thermal Management Team collaborated with industry to obtain Panasonic NiMH batteries for the DaimlerChrysler project and Saft lithium-ion cells for battery model development (Figures 2, 3). NREL added capacitive behavior to the existing resistive behavior in the ADVISOR model. The resistive and capacitive (RC) models were validated for two battery chemistries (Li-Ion and NiMH) at three temperatures (0, 25, and 40°C).

The existing battery pack model in ADVISOR treats the pack as a "single" large module. Industry has expressed interest in being able to capture the individual behavior of each module in the pack. In response to this, NREL initiated work on a complete battery pack model using Saber electrical systems simulator from Avant!. NREL first developed a battery model for a module in Saber. Voltage- limiting and variable power load controllers were added to the model to control the battery as it was used in different applications. The model was validated for Saft Li-Ion cells. Then, NREL researchers assembled battery pack models consisting of many Saber modules. Using the pack model, NREL investigated several cases with an unbalanced pack with modules at different resistances or state of charge and found that an unbalanced pack can lead to a 30% loss in energy from a battery pack.

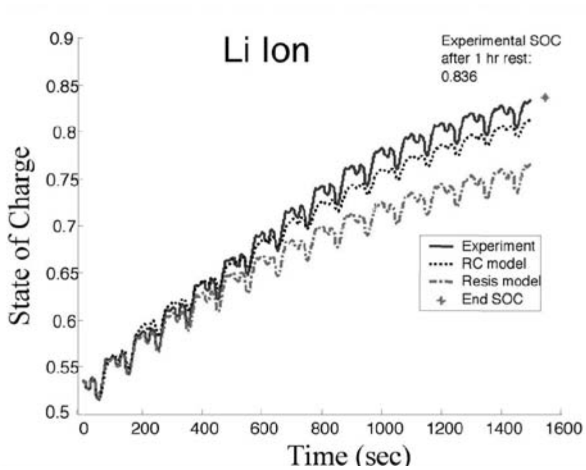

Figure 2. New RC battery model compares experimental data and is better than resistive model.

Figure 3. M. Zolot (left) and M. Keyser test batteries for validating models at the NREL Thermal Management Test Facility.

Conclusions

The development of validated battery models is essential for vehicle simulations. NREL has developed both electrical and performance models for advanced batteries and they are integrated within the ADVISOR vehicle simulation tool. Based on industry's interest, a complete battery pack model was developed that can capture the module-to-module behavior in a pack and can be used to evaluate the impact of unbalanced packs and hybrid energy storage concepts on HEV fuel economy.

NREL will validate temperature-dependent RC models for advanced batteries for use in ADVISOR and PSAT vehicle simulators. In addition, NREL will use Idaho National Environmental Engineering Laboratory and Argonne National Laboratory data for model generation of PNGV batteries. NREL will validate the complete battery pack model for evaluating balancing and hybrid energy storage concepts using ADVISOR-Saber co-simulations, while working work with Avant! and Delphi. NREL will also evaluate battery–ultracapacitor combinations for improving performance and life cycle of energy storage systems for HEVs.

Publications/Presentations

"Development of a Battery Pack Model and a Hybrid Energy Storage Model for ADVISOR," Kesyer, M., Zolot, M., Mihalic, M., Pesaran, A., Milestone Report, National Renewable Energy Laboratory, Golden, CO, October 2001.

"Temperature-dependent battery models for high power Li-Ion batteries," Johnson, V., Pesaran, A., and Sack, T., Proceedings of the 17th Electric Vehicle Symposium, Montreal, Canada, October 16-18, 2000.

"Battery Performance Models in ADVISOR," Johnson, V., Workshop on Development of Advanced Battery Engineering Models, Crystal City, VA, August 14-16, 2001.

"Battery Thermal Model in ADVISOR," Pesaran, A., Workshop on Development of Advanced Battery Engineering Models, Crystal City, VA, August 14-16, 2001.

"Data Sources and Needs – Battery Thermal Characterization," Keyser, M., Workshop on Development of Advanced Battery Engineering Models, Crystal City, VA, August 14-16, 2001.

III. ARGONNE NATIONAL LABORATORY SUPPORT

IIIA. Advanced Powertrain Test Facility (APTF)

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Objective

Design, construct and commission a state-of-the-art facility for conducting energy efficiency and emission tests on hybrid electric vehicles, sport utility vehicles, and future advanced-technology vehicles. The facility will include an electric four-wheel-drive chassis dynamometer with appropriate controls and instrumentation for highly accurate emissions and fuel consumption measurements.

Approach

- Obtain professional engineering/architectural services to assist with the final design and construction documents for a world-class facility capable of benchmarking and developing the most advanced powertrains for future cars and trucks. The facility will be capable of gaseous-fuel operation (including hydrogen) and will have the capability to add climate-controlled testing in the future.
- Complete construction of the extension to the current APTF to house the 4-wheel drive chassis dynamometer cell, control room, and a vehicle soak area.
- Install highly sensitive gasoline emissions measurement equipment capable of SULEV (super ultra low emission vehicle) standards and a full dilution tunnel for diesel particulate matter measurement to enable complete diesel emissions measurement capability.

Accomplishments

- New building shell construction was completed and funded by internal ANL sources (>$1,000K).
- State-of-the-art 4-WD chassis dynamometer built, delivered, and installed in pit.
- SULEV emission/CVS benches delivered and commissioned.
- Full-size dilution tunnel for both diesel/gasoline PM designed, built, and delivered
- Advanced background air purification and dehumidification system designed for accurate and repeatable measurement of extremely low exhaust emissions.

Future Directions

- Complete the Phase II construction of the 4-WD chassis dynamometer facility. Calibrate the 4-wheel drive dynamometer, install and calibrate equipment in the new facility. Build and optimize the climate control chamber for 4-WD dynamometer facility.

Introduction

ANL has the lead responsibility for a PNGV-related program with DOE's Office of Transportation Technologies (OTT) to conduct emission and energy efficiency tests on hybrid electric vehicles, sport utility vehicles, and future technology vehicles. These tests require a state-of-the-art electric four-wheel-drive chassis dynamometer in a climate-controlled environment with appropriate controls and instrumentation for highly accurate fuel and ultra-low exhaust emissions measurements. DOE's intention is to construct a world-class facility for the research and development of the most advanced powertrains for future cars and trucks.

Approach

The Advanced Powertrain Test Facility (APTF) is an integrated test facility capable of testing powertrain components and vehicles by means of state-of-the-art measurement equipment and control hardware. Two component dynamometers, a 2WD chassis dynamometer, and a 4WD dynamometer (FY02) share extensive emissions and fuel consumption measurement equipment, including specialized equipment, to support advanced vehicle component testing. A 150-kW battery tester/emulator was installed to allow testing of hybrid-electric vehicle (HEV) battery packs and electric motors, as well as to allow simulating battery pack performance, thereby enabling repeatable tests of HEV powertrains. Argonne conducts vehicle and component-level testing of commercially available and OAAT-developed HEVs to characterize and enhance these technologies and to help evolve and validate the PSAT and ADVISOR simulation models. These components can then be configured as one or more complete powertrains and operated over standard or custom driving cycles. With the help of the APTF, better, more accurate models and more advanced control strategies will be developed. ES/CTR staff obtained professional engineering/architectural services to assist with the design and construction documents for a world-class facility capable of benchmarking and developing the most advanced powertrains for future cars and trucks. To make this new facility useful, sensitive emissions measurement equipment for SULEVs (super ultra low emission vehicles) was included (along with a full dilution tunnel for particulate matter measurement), enabling complete diesel emissions testing capability.

Results

The APTF underwent periods of construction for the building infrastructure upgrade to support the new Pierburg dilute emissions bench and CVS. New electrical, process water, lab air, and exhaust utilities were extended to the temporary location until the equipment is permanently relocated into the new 4WD test facility. The new utilities, communication lines and exhaust utilities were then connected to this new equipment. The emissions gas bottle rack was expanded and new gas lines were routed to the emissions bench from the gas sources.

A new heated sample line and manifold system upgrade to the Pierburg AMA 2000 raw emissions bench was completed. This new system now incorporates one dedicated heat exhaust sample line for each of the four test cells, any of which is selectable from the controls at the emissions bench.

The Pierburg full-size dilution tunnel for both diesel/gasoline PM was designed, built, and delivered to ANL.

ANL staff visited Burke Porter Machinery in Grand Rapids, MI for acceptability testing and sign-off of the 4WD dynamometer. Basic training was provided. The Burke Porter 4WD dynamometer was received at ANL several weeks later. It took one full day to unload three truckloads of equipment into building 371. After several months of storage, the deck plates and the 4WD chassis dynamometer were installed (Figure 1) and the dynamometer is ready for electrical connections and commissioning.

Figure 1. Installation of the Dynamometer in the Pit

The new building shell construction was funded and completed from internal ANL sources (Figure 2). Advanced Mechanical Systems, Inc. was awarded the contract for the 4-Wheel-Drive Phase II construction. The majority of the construction will take place in FY 02.

Figure 2. New 4-Wheel Drive Chassis Dynamometer Building

An experienced subcontractor was selected to build the largest air-handling unit (25,000 cfm) at a plant in Virginia. Once the unit is built, tested, and signed off by ANL, it will be disassembled and shipped to ANL for installation.

The APTF team wrote, revised, and received approval on safety and quality assurance (QA) plans to ensure safe operation of facility and equipment.

Conclusions

Phase II Construction of the 4-Wheel Drive Dynamometer facility will be completed in Spring 2002. The chassis dynamometer and emissions equipment to support the current facilities and the 4WD chassis dynamometer, including a SULEV-capable Pierburg Emissions Bench and CVS and a full dilution tunnel for particulate will be installed and commissioned. Cross facility validation will continue by comparing the results of tests performed at APTF with those of identical tests performed at established auto industry test facilities. Beyond FY02, ANL plans to build a climate control chamber for the 4-wheel drive dynamometer facility, as requested by the Systems Analysis Tech Team, to extend its usefulness to DOE and industry.

IIIB. Component and Vehicle Testing and Mapping

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Objective

- Determine the performance, efficiency and emissions (where appropriate) of existing advanced HEV powertrain technology.
- Design test procedures, acquire and analyze test data in a manner suitable for the development and validation of component, subsystem and vehicle simulation models.

Approach

- Design test procedures and utilize ANL's extensive test equipment that is uniquely suited for extracting vehicle system data for model parameter inputs and validating systems simulation models (PSAT).
- Use two component dynamometers and the 2WD vehicle chassis dynamometer with ANL's data acquisition and control hardware and software.
- Utilize ANL's state-of-the-art Pierburg-based fuel measurement system and both ANL's raw and dilute (tailpipe) Pierburg emissions benches.
- In the case of the Prius engine testing, use ANL's in-situ engine torque cell design to provide accurate engine data.
- Develop custom software and hardware testing tools that will efficiently couple measured energy efficiency and detailed performance data with very accurate (and rapid response) fuel measurements and emissions measurements for each test "cell" in the APTF.

Accomplishments

Component Testing:

- NGM Motor - ANL has mapped and assessed the efficiency and performance of an axial-flux motor manufactured by New Generations Motor. Because the motor has an adjustable gap, comprehensive data (including efficiency) was mapped for various speeds, torques, voltages, and gap widths.
- Siemens AC Electric Motor - This spare equipment from the Ford HEV contract was installed on a fixture and mapped using ANL's 300HP transient dynamometer.

Vehicle Testing:

- Japan Prius - ANL performed over 70 test cycles of ANL's fully instrumented Japan Prius on the 2WD chassis dynamometer to acquire data for model validation and build a diverse database of transient engine fuel, emissions, and performance data for the artificial neural network-based engine emissions predictor.
- Honda Insight - ANL performed over 60 chassis dynamometer test cycles of ANL's fully instrumented Honda Insight.
- Ford P2000 - ANL performed about one dozen chassis dynamometer test cycles of ANL's fully instrumented (simultaneous analog sensor and CAN data) Ford P2000 prototype vehicle.
- CVT Honda Insight - ANL performed 17 chassis dynamometer test cycles of a partially instrumented CVT Honda Insight (vehicle loaned to ANL by Honda).
- SIDI CVT Toyota Opa - ANL began testing a partially instrumented Toyota SIDI CVT Opa vehicle.

Future Directions

- Continue testing high-efficiency electric motors, engines, transmissions, batteries and vehicles while paying particular attention to powertrain control strategy development for increased fuel economy and reduced emissions.

Introduction

The Advanced Powertrain Test Facility (APTF) at ANL is an integrated test facility capable of testing powertrain components and vehicles by using state-of-the-art measurement equipment and control hardware. The APTF is the principal DOE technology validating facility for research prototypes and commercially available light-duty propulsion components, systems, and vehicles.

Objective

The objectives of the program are to test components, powertrains, and vehicles to assess the outcomes of technology development activities, support the validation of simulation tools, and develop powertrain systems that can meet the objectives of lower emissions and dramatically improved fuel economy.

Approach

The test facilities at the APTF have been specifically designed to test and assess advanced components, subsystems and vehicles. Five separate dynamometer cells are available for testing. They are: Three separate component dynamometer cells (190HP, 300HP, and 25HP), an existing 2WD chassis dynamometer cell, and a 4WD dynamometer facility (FY02). The support equipment for the dynamometers enables precise measurements for testing engines, transmissions, and advanced electric motors. All comprehensive tests involving engines utilize direct fuel measurement for fast and accurate response. Emissions measurements using standard benches are augmented with fast-response (~5 to 10 mS) hydrocarbon and nitrogen oxides measurements. All test cells in the building share the extensive measurement system equipment that includes a 150-kW battery tester-emulator.

Results

NGM Motor Development Project

ANL partnered with NGM and George Washington University to test, characterize and define feasible vehicle applications for a highly efficient variable-gap electric motor (48 volt axial flux) based upon technology developed for solar-powered vehicles – the world's most efficient vehicle designs. Preliminary testing and simulation work done by NGM and George Washington University for ANL show that optimizing the gap as the vehicle is driven can offer significant energy savings in a series HEV configuration (5-17% depending upon drive cycle and comparison motor technology). The reason this approach was taken is this particular motor technology is well suited for fuel-cell vehicles. An added bonus is that the motor is designed to operate at wheel speeds, eliminating the need for expensive transmissions and simplifying integration into a fuel cell vehicle, which, no doubt, has significant packaging challenges.

ANL is currently testing a modified version of the motor that enables active gap control during operation (Figure 1). Testing continues at ANL to formulate an accurate assessment of this technology by leveraging ANL's advanced hardware-in-the-loop test methods. A very detailed and accurate fuel cell vehicle model can be run with interfaces with the dynamometer control system with the NGM motor being operated as if it were part of the rest of the vehicle. Important measurements and observations will be made that cannot be made entirely with simulation are the affect of the gap control strategy and the associated losses. The outcome of the investigation would perhaps show a more efficient vehicle-level technology that will help meet DOE's goals of developing technology for future highly efficient fuel cell vehicles.

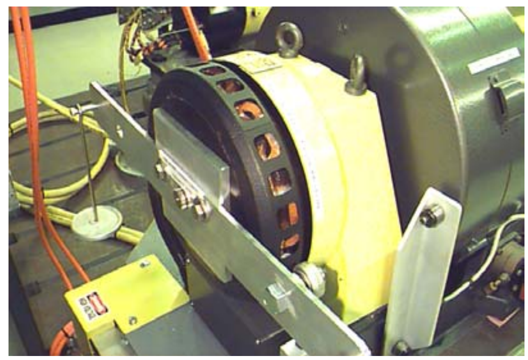

Figure 1. NGM Motor under test at the APTF

Siemens AC Motor Testing/Mapping

The 75 kW, 385 VDC, brushless electric AC synchronous induction motor manufactured by Siemens for Ford Motor Company for use in their electric Ford Ranger pick-up truck was mapped by ANL (see Figure 2). The data collection involved the signals needed for efficiency calculations (speed, torque, current and voltage) as well as three temperatures of the coolant fluid. Two different quadrants of motor operation were tested in this experiment, powering and regeneration in the forward rotational direction. The motor was tested at two different voltages of 350 and 375 volts. These are representative of the voltages that this motor would typically operate at in an EV or HEV. Not all of the area under the torque-speed curve of the Siemens motor could be mapped due to torque limitations of the dynamometer which have since been fixed by the dynamometer manufacturer. Therefore, the peak torque, and likely, the peak efficiency of the motor is found in this first data set. Table 1 shows the measured peak values excluding the peak torque, as it is

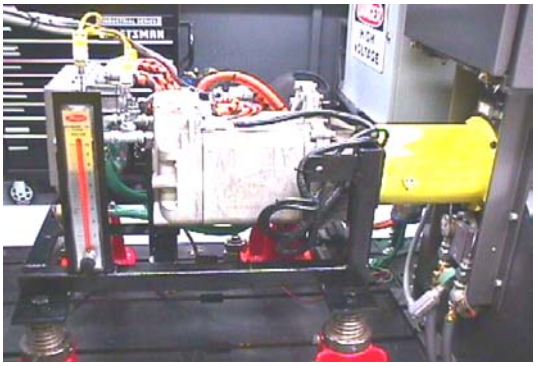

Figure 2. Siemens AC Electric Drive Under Test

Table 1. Peak Values From Mapped Area

350 Volts	Spd. (RPM)	Load	Eff. (%)
Peak Torque	N/A	N/A	N/A
Peak Efficiency	1200	250 ft-lbs	94.8
Peak Shaft Power	1400	45.0 kW	94.2
Peak Regen Torque	500	188 ft-lbs	80.0
Peak Regen Efficiency	1000	89.9 ft-lbs	89.9
Peak Regen Shaft Power	3000	14.8 kW	70.0
375 Volts	Spd. (RPM)	Load	Eff. (%)
Peak Torque	N/A	N/A	N/A
Peak Efficiency	1500	220 ft-lbs	89.2
Peak Shaft Power	1500	48.4 kW	89.2
Peak Regen Torque	500	203 ft-lbs	80.0
Peak Regen Efficiency	1000	97.0 ft-lbs	82.5
Peak Regen Shaft Power	3000	15.8 kW	70.2

confirmed that the peak torque is higher than what could be measured.

CIDI PSA 2.0L Engine Testing/Mapping

The PSA 2.0L CIDI engine (representing the latest European diesel technology) was installed in the CIDI test cell #2 and connected to the dynamometer and all required utilities. Signal instrumentation for pressures and temperatures were completed (see Figure 3). The engine was fired and run briefly but a fuel pressure sensor issue needed to be resolved before testing could resume. Troubleshooting continued with support from PSA.

Future work with this engine will include baseline mapping and transient fuel and emissions data collection for transient engine model development. In addition, the engine is configured to retain the stock clutch for engine-only hardware-in-the-loop testing.

Figure 3. PSA Engine with Transmission Modification to Retain Clutch

2001 U.S. Toyota Prius Modifications for Testing

The vehicle was received at ANL in August 2000. The vehicle was modified to accommodate a longer powertrain, and modifications to the exhaust system, brake booster, and fuel systems were completed (Figure 4). The engine was started and the powertrain was tested for abnormalities. Instrumentation signal wires for temperature, torque, etc. were routed from the sensors into the passenger compartment of the vehicle.

Modifications to the inverter were made so the DC bus voltage, generator current, and the traction motor current can be measured separately. The vehicle modifications and instrumentation wiring were complete by summer of 2001 (Figure 5), but because of other test priorities on the dynamometer, testing the US Prius was scheduled for the end of the 2001 calendar year.

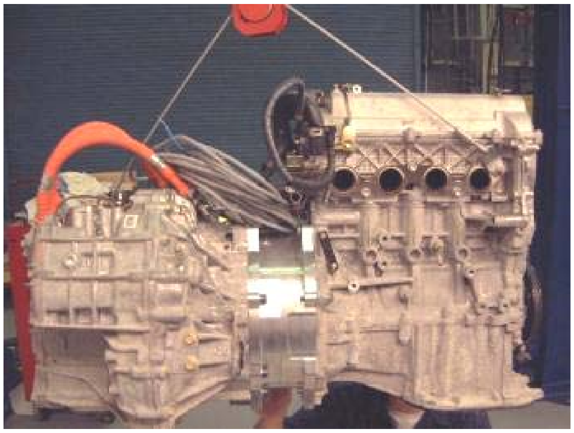

Figure 4. Installation of ANL's Japan Prius Torque Sensor Mounting in US Prius Powertrain

Figure 5. Final Assembly of US Prius

Honda Insight Testing for Validation

Over 60 tests were performed on the Honda Insight mild hybrid that allowed validation of the PSAT simulation tool and provided a thorough understanding of the technology problems and the potential of this HEV configuration. The testing employed advanced instrumentation (including axle torque), fast emissions, and highly accurate fuel consumption measurements (Figure 6).

CVT Honda Insight Cursory Testing for Validation

Honda loaned an automatic transmission (CVT) Honda Insight to ANL for a couple months of dynamometer and road testing. Various pertinent engine and transmission signals were collected along with emissions data. Several cycles were run for the purposes of later benchmarking a CVT version of the Insight model

Figure 6. Honda Insight (5-speed) on APTF Dynamometer

(Figure 7). The control strategy did indeed have significant differences – especially in regenerative braking. In addition, the vehicle tested much lower emissions than the 5-speed.

Figure 7. Honda's CVT Insight On-Test in the APTF

Ford P2000 Technology Validation and Testing for Model Validation

ANL performed validation testing of the P2000 – the first PNGV vehicle delivered to DOE. ANL collected data to assess the state of technology in this first-generation PNGV vehicle and to help validate the PSAT simulation tool (Figure 8). Test cycles run for PSAT validation included engine map verification, steady states, acceleration, and standard cycles (Figure 9).

For future work, this vehicle is the basis for assessing DOE-funded diesel after treatment emissions reduction efforts by Cummins. The after treatment hardware will be installed by Cummins and tested in ANL's APTF using its newly

Figure 8. CVT Insight and 5-Speed Insight Tested at Nearby Route 66 Raceway

Figure 9. Ford P2000 Prototype Vehicle Being Tested at the APTF

commissioned EPA certifiable full dilution particulate measurement system.

Preliminary Benchmark Testing of SIDI Toyota Opa

Before the vehicle was modified for installation of an in-situ torque sensor, the Opa was tested on the dynamometer to ensure the modifications did not adversely affect vehicle operation (Figure 10). The Opa fuel economy results are: 30 MPG city, 41MPG highway.

Conclusions

ANL's investment of dynamometers and data acquisition hardware and the development of custom-built time-saving post processing code has made it possible to receive components and vehicles and quickly instrument, accurately test them in-house, and report data. Techniques and

Figure 10. Benchmark Testing of Toyota Opa on ANL APTF Dynamometer

special procedures have been developed and optimized through interaction with ANL's PSAT development staff to provide a much higher level of model validation for DOE simulation tools than ever before.

No specific components or vehicles have been identified for benchmarking in 2002 and no specific tasks are planned. However, the need for in-situ component testing to validate models offers the opportunity to extract vehicle data of interest to DOE or the other national laboratories (within budget and schedule constraints). FY02 activities include in-situ powertrain testing of the Toyota Prius (US version) and Opa plus additional testing of the Ford P2000 with experimental after-treatment devices. Component testing includes validation testing of the lithium-ion battery and validation testing of the Lynx SEMA motor.

Publications/Presentations

Ng, H.K., Anderson, J.A., Duoba, M.J. and Larsen, R.P., "Engine Start Characteristics of Two Hybrid Electric Vehicles (HEVs) - Honda Insight and Toyota Prius", SAE 2001-01-2492, August 2001.

Duoba, M.J., Ng, H.K., Larsen, R.P., "Characterization and Comparison of Two Hybrid Electric Vehicles (HEVs) – Honda Insight and Toyota Prius", SAE 2001-01-1335, Feb. 2001.

IIIC. Predictive Control of Engines Using Neural Network Algorithms

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Objective

- Develop advanced transient engine emissions predictor based upon trained artificial neural network (NN) algorithms for more accurate vehicle simulation studies.
- Investigate predictive control possibilities with the application of neural networks.

Approach

Training a NN requires an engine to be run through a comprehensive learning profile by using actual test data. Model inputs and outputs required by the model are measured throughout the test. These inputs and outputs are fed into a neural network optimization structure designed specifically for engines, and a "best-fit" model is generated. Once the NN is established, test data never before exposed to the NN are fed into the model for validation.

Accomplishments

- A principal challenge of NN development is the defining the training data set that will ultimately provide the most accurate NN model with the least amount of resources expended in dyno testing, ANL has developed special software tools specifically designed to prescribe transient dynamometer operation in parametric fashion to more easily define all areas of operation.
- Preliminary validation results from a CIDI engine show a >95% correlation coefficient in predicting engine-out NO from fast (10Hz) transient emissions instruments.

Future Directions

- ANL will continue to develop NN models of engines and after-treatment devices to predict fuel usage, emissions, and accurately predict transient conditions during warm-up phases not easily characterized by 1^{st} order thermal techniques.
- These component models will be coded to be used in PSAT to show impact of transient control and reduction of cycle emissions in simulation studies.
- ANL will continue investigation and development of system-level neural and fuzzy logic control and optimization techniques.

Introduction

Current engine modeling techniques are not as robust as they should be to predict emissions and fuel consumption, especially for transient and warm-up operation. The application of artificial neural network algorithms in a transient engine model allows prediction of highly complex, non-linear, multi-dimensional associations between selected input parameters and outputs. This method offers a solution to the problem of inherent accuracy limitations in current look-up table-based engine models.

ANL has developed a process to test engines and generate transient emissions predictors that can be used in vehicle system simulation studies with models such as PSAT. The models are based upon trained neural networks that are fed with moderately fast (10Hz) emissions data from fast response emissions measurement systems. The strengths of this modeling method are the rapid generation of an accurate predictor and the ability to predict transient emissions. The neural network engine model outperforms map-based models especially during warm-up and during transients where highly non-linear responses are observed.

Approach

ANL will acquire sufficient engine data sets, define NN structures, and train the models. The engines involved in FY01 were the Mercedes-Benz 1.7 L common-rail CIDI engine provided by DOE/ANL, and the Prius 1.5 L port fuel-injected, spark-ignition engine. Data was collected with fast measurements of fuel (100mS), Nitrogen Oxide (NO), and particulates. The NO is measured using a fast NO (~5mS) Cambustion analyzer. Particulates were measured using the tapered element oscillating microbalance (TEOM) instrument – the current state-of-the-art in transient particulate measurements (future work will utilize ANL's unique and 10Hz in-house-developed Laser Induced Incandescence (LII) PM measurement device).

ANL will also investigate by using NN engine models to actively control various engine-operating parameters in real-time. Ultimately, the neural network can be expanded to encompass the control of an entire HEV powertrain, a much more difficult task, but one that has the potential of being able to actively optimize HEV system performance over a wide range of operating profiles. We will endeavor to implement both the modeling and engine control applications for neural net technology.

ANL's CIDI transient dynamometer controls were configured to allow testing of any predefined engine command vs. speed trace. A few tests were repeated more than once to quantify the repeatability of the dynamometer, engine, and measurement systems.

Two different types of training files were developed. One was based upon simple algebraic functions selected to provide fundamental transient with a well-controlled frequency spectrum. Various functions were superimposed together to generate the engine and dynamometer command files fed into dynamometer control system. Square wave functions were used to provide insight into engine slew rates. The other transient set types were based upon point-to-point torque and speed targets taken from vehicle model simulation results with vehicle parameters similar to the A-Class vehicle for which the engine is designed. Discrete-gear and CV transmissions were also selected.

Also performed in FY00 were dedicated tests on the Japan Prius that will be the training database for a 10Hz NN SI engine-out emissions predictor. Testing during warm-up was taken as part of the data set. More work in FY01 will result in a completed 10Hz Japan Prius engine model that predicts emissions during and after warm-up.

Results

The results indicate that the dynamometer response is very repeatable (indistinguishable variations), the engine torque response is also repeatable, and under similar warm-up conditions, the emissions correlate within 5% from test to test (Figure 1). The degree of test-to-test variability will determine the tolerance we should expect the NN model to be accurate within.

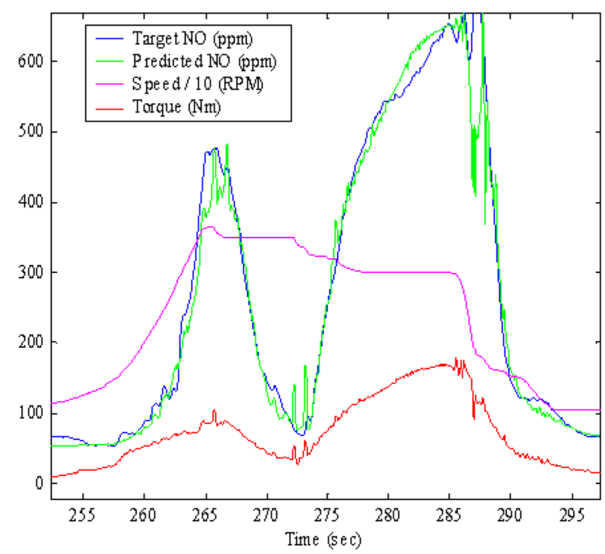

Figure 1. Validation Results Comparison of Measured vs. Predicted Transient NO for Mercedes 1.7L CIDI engine

The network was trained and optimized to achieve the lowest prediction errors and validated with data sets not originally used in the training data set. Final vehicle-level validation using the MB A-Class vehicle will show how effective this model can be to predict vehicle emissions in PSAT on a vehicle grams per mile basis.

Conclusion

Pioneering transient emissions instrumentation, testing procedures, and simulation of advanced compression-ignition direct-injection (CIDI) engines are used at ANL for DOE technology development and modeling efforts. ANL developed unique capabilities to simultaneously measure oxides of nitrogen (NOx) and particulate matter (PM) with data taken 10 times per second. The importance of developing this capability is to identify the precise conditions under which diesel emissions occur. These unique ANL-developed measurement capabilities, coupled with our extensive experience and advanced neural network prediction technology, give DOE a much greater chance of finding solutions to the seemingly intractable problems of diesel exhaust emissions.

ANL will continue NN development projects and possibly expand the work by incorporating NN-based adjustments to other component models. Applications of NN in component and system-level control will be explored.

ANL will continue NN development projects and apply them to PSAT as well as expand efforts to include engines of interest, such as a SIDI engine.

IIID. Hardware-in-the-loop Testing and Rapid Prototyping of Hybrid Powertrain Systems

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Objective

Develop a toolkit capable of going from modeling to prototyping by developing an integrated toolkit by using PSAT (PNGV System Analysis Toolkit), the modeling software, and PSAT-PRO, its companion prototyping software.

Approach

- Develop the best control strategy by using PSAT and incorporate it into a vehicle controller by using PSAT-PRO. With PSAT-PRO, users are able to control their prototypes in real time by using their own control strategy developed in PSAT.
- PSAT-PRO has been designed to calibrate component models. In fact, our test methodology is based on difference analysis between simulation results and test data. Since we use an integrated toolkit, we can go back in simulation and improve the model until simulation results match test data.

- With PSAT-PRO, we have the ability to control a dynamometer to simulate vehicle behavior. In this way, we can test only one component of the hybrid powertrain in the same configuration and conditions as if it were in a vehicle.

Accomplishments

Developed software that is highly linked to PSAT, while generic enough to go from modeling to prototyping for any kind of hybrid configuration. PSAT-PRO prototyping software gives the opportunity to analyze a hybrid system in different ways: Real Time Simulation, Hardware In the Loop (HIL), and Rapid Prototyping.

Future Directions

- Control a hybrid configuration on a test stand composed of a motor, an engine, and a CVT by using PSAT-PRO.
- Test an engine on a test stand, using HIL to control a low-inertia dynamometer to simulate an HEV's behavior.
- Improve post-processing tools and maximize the linkage with PSAT.

Introduction

Hybrid electric vehicles (HEVs) offer the potential to increase propulsion system efficiency and decrease exhaust emissions relative to conventional vehicles. The U.S. Department of Energy (DOE) and the auto industry are developing HEV technology as part of the Partnership for a New Generation of Vehicles (PNGV) program. Argonne National Laboratory (ANL) supports DOE and the PNGV program by evaluating new technologies in a vehicle systems context. Central to this ability to test and assess the performance of propulsion system components and subsystems is establishing a hardware-in-the-loop (HIL) capability. HIL testing allows individual components or groups of components to be operated and controlled on the test bench as if they were in a vehicle.

Approach

HIL capability enables quick and accurate assessment of the performance potential of advanced technology components developed as a result of R&D contracts or provided by suppliers. Current OATT R&D plans call for all components to be tested on the ANL HIL test bench to measure their performance, validate component simulations, and assess their performance in a vehicle system context.

In FY01, ANL began to assemble an entire HEV drivetrain to perform confirmatory HIL testing. ANL connected a drivetrain comprising innovative components and a pretransmission parallel hybrid with a continuously variable transmission (CVT) to a dynamometer. The dynamometer was modified to accurately simulate the mechanical and aerodynamic losses of a vehicle. The layout of this configuration is shown in Figure 1.

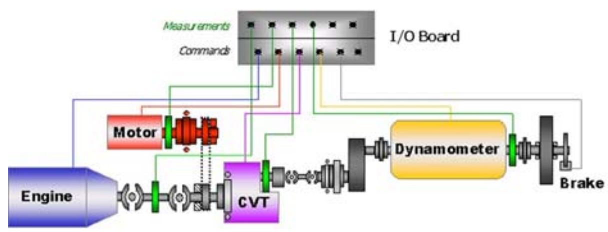

Figure 1. HIL Test Configuration for a CVT

The CVT offers opportunities for engine control that far surpass the capabilities of conventional multi-speed transmissions. This HEV configuration, using a CVT and parallel electric motor, allows the engine to be isolated from the demands by the vehicle on the powertrain. This means that the engine can be kept in the optimum RPM range for any driving demand and be more effectively used to maintain an optimum state of charge in the battery. The engine selected is a 1.7L Mercedes common rail, direct-injection diesel. Its size is roughly comparable to what may be used in a full-size PNGV HEV. For this reason, DOE is focusing several experimental projects at ANL and other national laboratories and contractors on this particular engine. The pretransmission parallel with the CVT configuration chosen for the first HIL drivetrain tests allows us to maintain the greatest amount of control of the engine and motor in order to meet CIDI vehicle-level emission standards for an HEV while significantly improving fuel economy.

Results

The torque converter and the reverse planetary gear of the CVT were removed to improve the efficiency of the conventional CVT. The oil pump was also removed – dramatically improving the CVT's efficiency by using a dedicated on-demand, off-board pump. To measure the CVT inputs without modifying the behavior of this component, we integrated a flat torque sensor into the transmission case. In order to have full control of the ultra-wide gear ratio (>6:1), the stock component was modified to add a ratio stepper motor control unit.

The dynamometer was modified to act like a vehicle. The dynamometer is controlled by applying the resisting torque that would be applied to the drive shaft in a real vehicle. To simulate the vehicle's inertia, a mass was added on the dynamometer shaft. A disk brake was added to the dynamometer shaft to apply the vehicle braking torque. With the modifications to the dynamometer, vehicles between 1,500 to 6,500 lb. can be simulated.

The drivetrain has been instrumented with three torque and speed sensors. The 1.7 L diesel engine came from a Mercedes-Benz A170. The motor, a permanent-magnet, traction-drive system from UQM was upgraded to produce 45 kW instead of 32 kW. The assembly employs aluminum in nearly all the coupling flanges and pulleys to lower the inertia of the entire rotating system.

The control strategy plays a crucial role in reducing emissions and increasing fuel economy. To apply an optimal level of control, input/output (I/O) hardware as well as software is needed. To achieve this control, ANL staff developed PSAT-PRO control software. PSAT-PRO makes it easy to explore real-world system behavior. It can be used to test and validate control designs in a real-time environment and make the necessary changes to optimize the control strategy. Thus, we are able to fine-tune a control strategy focused on emissions reduction and study whether hybridization with an optimal control strategy can overcome the current emissions using diesel engines in passenger car applications.

Conclusions

ES/CTR plans to control a hybrid configuration on a test stand consisting of a motor, an engine, and a CVT by using PSAT-PRO. Using the HIL principle, we plan to test an engine on a test stand controlling a low-inertia dynamometer to simulate a HEV's behavior. We also want to improve our post-processing tools and maximize the linkage with PSAT.

IIIE. VEHICLE SYSTEM MODELING AND ANALYSIS USING PSAT

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Objective

- Develop flexible, reusable simulation tool to represent transient, develop realistic control strategies and simulate emissions.

- Support Hardware-In-the-Loop (HIL) work with PSAT-PRO by providing seamless bridge between modeling and prototyping through transient modeling and realistic controls.
- Perform vehicle system studies to provide guidance to DOE.
- Further develop the PNGV System Analysis Toolkit (PSAT) under the direction and contributions of Ford, GM, and Daimler-Chrysler.

Approach

- The model architecture is “forward-looking,” meaning that component interactions are “real world.”
- This method is computationally more intensive than “backward-looking” architecture; however, the result is a tool that will allow the advanced powertrain designer(s) to develop realistic control strategies and assess component behaviors in a system environment by using realistic models.
- These models are developed using Matlab and Simulink

Accomplishments

- Released PSAT V4.0 and 4.1 (Figure 1).
- Refined, validated, and integrated PSAT to allow the users to simulate more than 150 configurations (including new 2*2WD and 4WD), develop control strategies, implement directly and test at the bench scale or in a vehicle, and run several simulations in a row in a short amount of time using compiled version.
- Enhanced PSAT GUI including new design, improved user-friendliness (i.e., easy implementation of new component models and data set), animation, test data import, post-processing…
- Validation of the Japan Prius and the Honda Insight within 5% fuel economy and 3% SOC
- Identified PSAT Customers, developed and performed a customer needs survey, evaluated the survey results, and adjusted plans.

Future Directions

- ES/CTR plans to not only extend PSAT capabilities by adding new drivetrain configurations, new control strategies, and new transient models, but also increase its flexibility and reusability, which are two key characteristics of PSAT.
- The number of users will be increased through use in universities and with key suppliers.
- A public version of PSAT will be released on the Internet.

Introduction

ANL has developed and utilized models in support of DOE’s advanced automotive R&D for several decades, addressing all aspects of a vehicle’s life cycle, from design and manufacturing through recycling. Advanced batteries, fuel cells, engines, control systems and advanced vehicles have been modeled, developed and tested in DOE’s facilities at ANL. This combination of analytical, development and testing experience has been applied to the latest version of the PNGV Systems Analysis Toolkit (PSAT), the forward looking model that simulates vehicle fuel economy, emission and performance in a realistic manner - taking into account transient behavior and control system characteristics. It is this realistic behavior that supports an ambitious software development goal for PSAT – to be transportable from the virtual world of component modeling and simulation to the emulated environment of component control in hardware-in-the-loop (HIL) testing and the physical environment of full powertrain control in a vehicle.

This capability, when combined with the engineering, development and testing resources at ANL, will substantially enhance DOE’s ability to realistically assess the potential of advanced automotive technologies and streamline the development process for promising technologies.

Figure 1. PSAT 4.0 and 4.1 were released in 2000.

Moreover, PSAT provides significant benefits to industry vehicle designers and university researchers as evidenced by their growing utilization of PSAT for both production-oriented and research design activities.

Approach

PSAT architecture is "forward-looking," meaning that component interactions are "real world." This method is computationally more intensive than "backward-looking" architecture; however, the result is a tool that will allow the advanced powertrain designer(s) to develop realistic control strategies and assess component behaviors in a system environment by using models closer to reality. These models are developed using Matlab and Simulink.

Results

PSAT allows the user to simulate more than a hundred configurations (conventional, series, parallel, and power split) while giving users the ability to choose appropriate configurations, depending on customer expectations. PSAT is well suited for development of control strategies, and by using accurate dynamics component models as its code, PSAT was implemented directly and tested at the bench scale or in a vehicle by using its extension for prototyping PSAT-PRO. PSAT also allows users to run several simulations in a row in a short amount of time using a compiled version. Proprietary and non-proprietary versions of PSAT were distributed to PNGV research partners.

The PSAT forward-facing vehicle simulation software has been developed and refined over the last few years, with increasing functionality and user base. ANL continuously refined PSAT new Graphical User Interface (GUI) to provide more flexibility to the users.

A clear understanding of "who is the customer" is mandatory. Regular measurement of customer satisfaction is done to maintain proper program perspective and direction.

The Toyota Prius (Japan version) and Honda Insight were instrumented to extract key component and vehicle data without interfering with the vehicle operation. The process demonstrated that PSAT is capable of predicting fuel economy within a few percent for all driving cycles and accurately reflecting transient component behavior on a sub-second scale (e.g., fuel rate and engine torque).

In addition, component models were enhanced, controls were refined and a new GUI was incorporated with more advanced post-processing capabilities. Models were added/refined for the clutch and torque converter – critical for predicting vehicle transient behavior and controlling the engine-transmission interface in HIL testing. Neural network engine models were added to predict transient emissions for complex hybrid systems (such as the Prius) as well as conventional vehicles where engines operate a substantial period of time in transient regimes. In addition, ANL laid the groundwork for fuel cell (FC) modeling for vehicle applications in FY02 by internally funding development of a simplified (prototype) version of GCtool that is compatible with PSAT.

Conclusions

ANL will continue to support and improve PSAT for use by the expanding user base to various PNGV technical teams and national laboratories, with developmental support from industry and universities. ANL will identify potential PSAT customers and then how to serve the specific customers of the PSAT vehicle simulation programs best. While much progress has been made in these areas, more work is needed to more fully integrate optimization into the analysis tools used by the systems analysis team.

Publications/Presentations

Rousseau, A., Deville, B., Zini, G., Kern, J., Anderson, J. and Duoba, M., "Honda Insight Validation Using PSAT," Future Transportation Technology Conference, Costa-Mesa, SAE paper 2001-01-2538

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

Rousseau, A. and Pasquier, M., "Validation of a Hybrid Modeling Software (PSAT) Using Its Extension for Prototyping (PSAT-PRO)", Global Powertrain Congress, Detroit, June 06-08, 2001.

Rousseau, A., and Pasquier, M., "Validation Process of a System Analysis Model: PSAT," SAE paper 2001-01-P183, SAE World Congress, Detroit, March 4-8, 2001.

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

An, F., and Rousseau, A., "Integration of a Modal Energy and Emission Model into the PNGV Vehicle Simulation Model: PSAT," 2001-01-0954 SAE World Congress, Detroit, March 4-8, 2001.

IIIF. Development of New Optimization and Control Tools

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Objective

- Investigate existing optimization algorithms, develop new robust and efficient optimization algorithms, and evaluate their effectiveness for PSAT.
- Continue investigating several control and energy management strategies, taking into account the dynamic behavior of the subsystems.

Approach

- Revisit the different optimization algorithms that have already been used and investigated for PSAT.
- Survey different optimization methods that have the greatest potential for robust and efficient search for the global optimum.
- Investigate and test global optimization algorithms in terms of efficient computation and robustness.
- Change the different available controllers in PSAT to digital controllers.
- Incorporate the effect of the transients in the components to help evaluate driveability issues.

Accomplishments

- Evaluated previous optimization and control work and selected future algorithms.
- Formulated an optimization and control problem for a specific vehicle configuration.
- Integrated the optimization algorithms with PSAT for the parallel configuration.
- Developed and integrated the control system with PSAT.
- Tested the optimization and control, and generated results.
- Optimized the fuzzy logic parameters using DIRECT algorithm developed by University of Michigan.
- Demonstrated the possibility to reduce NOx by 50% with almost no loss in fuel economy

Future Directions

- Further investigate existing optimization algorithms and develop new robust and efficient optimization algorithms (as necessary) and evaluate their effectiveness for PSAT.
- Tune the fuzzy logic parameters for the drivetrain configuration chosen for HIL and validate trade-off between fuel economy and emissions obtained from modeling.

Introduction

Since 1996, the PNGV System Analysis Technical Team has been working with University of Michigan (UM) and Oakland University (OU) in the area of optimization and control. While much progress has been made in these areas, more work is needed to more fully integrate optimization into the analysis tools used by the systems analysis team.

OU developed different energy management strategies for series and parallel hybrid vehicles. Those strategies were the basis for the energy management strategies that are currently in PSAT. The work at OU also helped in debugging and testing of the software. Phase II of the project is concentrating on using fuzzy control for the energy management strategies of parallel hybrid vehicles. The energy management strategies currently being developed are implemented as a discrete control system. In future work, we are looking to continue devising combined optimization of energy management and sizing of hybrid vehicles. The energy management and control strategies will also take into consideration the dynamic behavior of the components during control evaluation. Digital controllers will be designed and evaluated in the OU strategy to support hardware-in-the-loop activities.

The objectives of this project are to investigate existing optimization algorithms, develop new robust and efficient optimization algorithms (as necessary), and evaluate their effectiveness for PSAT. Another objective of this task is to continue investigating several control and energy management strategies, taking into account the dynamic behavior of the subsystems. Discrete control systems that will support the hardware-in-the–loop activities will be emphasized.

Approach

In the technical approach, the different optimization algorithms that have already been used and investigated for PSAT will be revisited. The advantages and disadvantages of each approach will be discussed. A survey of different optimization methods that have the greatest potential for robust and efficient search for the global optimum will be developed. Global optimization algorithms, in particular, will be investigated and tested in terms of efficient computation and robustness. Candidates for global optimizations are DIRECT, generic algorithms, and simulated annealing. The optimization tool should allow the user to choose parameters for the several components and control. The user can also define a fuel economy objective function with emission and performance constraints.

In the technical approach for the control and energy management strategies, the different available controllers in PSAT will be changed to digital controllers. This improvement will give more realistic performance and it will support the hardware-in-the loop activities. The controller's evaluation will also incorporate the effect of the transients in the components, which will help in the evaluation of driveability issues.

Results

ANL and OU evaluated the previous optimization and control work and selected future algorithms, formulated an optimization and control problem for a specific vehicle configuration, integrated the optimization algorithms with PSAT for the parallel configuration, developed and integrated the control system with PSAT, tested the optimization and control, and generated results. Preliminary analyses indicated that engine out NOx can be reduced by up to 50% with no loss in fuel economy for a CI engine in a hybrid powertrain by using fuzzy logic to minimize emissions (versus the previous PSAT control strategy targeting minimum fuel consumption).

Conclusions

OU developed a control strategy and incorporated it into PSAT on the basis of fuzzy logic to optimize the drivetrain, while the UM team developed a generic global optimization algorithm. Tests at the ANL Advanced Powertrain Test Facility (APTF) using PSAT-PRO will allow ANL to validate and improve the algorithm.

IV. OAK RIDGE NATIONAL LABORATORY SUPPORT

IVA. Downstream Emissions Control (Aftertreatment) Modeling

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Objective

To provide low-level models of advanced emissions control technologies that will facilitate inclusion of the benefits of these technologies in vehicle system-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

- Completed a low-level model of a Catalyzed Diesel Particle Filter, including laboratory characterization of an early prototype device.
- Completed a low-level model of a diesel oxidation catalyst, including laboratory characterization of a production device.
- Began a low-level model of a NOx storage and reduction catalyst. Acquired prototype device for characterization at ORNL.

Future Directions

- Complete laboratory characterization of prototype NOx storage catalyst and finalize model for use in vehicle-system models.
- Re-visit model of catalyzed diesel particle filter to investigate and improve upon the model to add regeneration modeling capability.
- Produce a 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 on 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 and for a diesel oxidation catalyst. These 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 is the task of an upcoming study to improve upon the initial model.

Current research focuses on development of a model for a NO_X adsorber. This technology poses many issues for developing a model. The device operates in three steps: adsorbing NO_X from the exhaust stream during lean engine operation, releasing stored NO_X during the early stages of regeneration, and chemically reducing the released NO_X during regeneration. The model must therefore take all three steps into account. Uncertainty in the chemical kinetics involved with these devices and application-specific characteristics complicate the model as well.

A low-order model made up of several algorithms to replicate the three steps mentioned above has been devised and is being calibrated with laboratory data from several sources. A Thomas model has been included in the NOX adsorber model to describe the storage of NOX in the device. Results from one calibration exercise are shown in Figure 1.

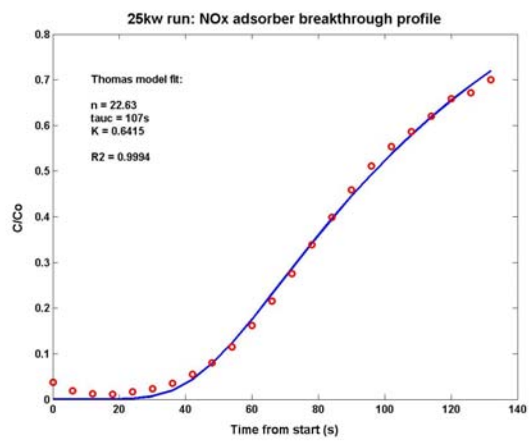

Figure 1. Thomas model for NO_X storage compared with laboratory data using a prototype.

As indicated, the model must also reproduce the NOX release and reduction steps. Figure 2 shows the NOX release and reduction during a regeneration pulse. At present the model overpredicts the chemical reduction taking place, but further calibration is expected to produce improved results. Overall, however, the model's performance is as expected.

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.

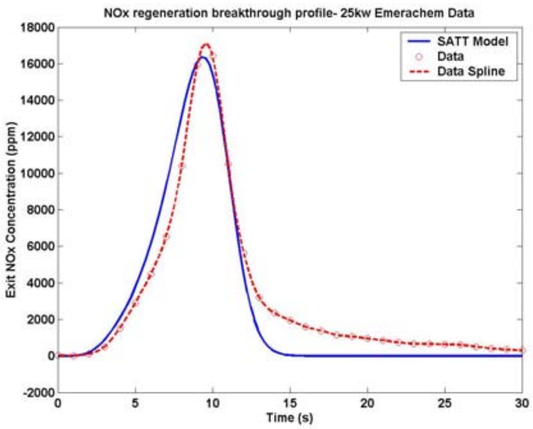

Figure 2. Model prediction of NO_X pulse during regeneration compared with laboratory data using a prototype.

It is possible to devise low-order models for emissions control technologies that faithfully reproduce the effects of these technologies for use in systems-level models of vehicles. Although these low-order models are not replacements for more computationally-intensive models aimed at device design, they are nonetheless important for including the beneficial effects of these technologies in vehicle-systems modeling and planning.

IVB. 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 PNGV affordability objectives
- Enable relative production-cost estimation via a uniform estimation methodology, allowing a comparison of alternative technologies under consideration by the PNGV 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

Modeling framework enhancements include logic, new definition of vehicle subsystems, and functional interrelationships among subsystems in joint collaboration with Argonne National Laboratory (ANL) and PNGV vehicle engineering technical team (VETT)

  – Implementation of ANL powertrain sizing routine consisting of seven specific vehicle configurations
  – Inclusion of technology cost information of some subsystems from the PNGV tech teams and the industry

Future Directions

- Develop a credible database of a limited number of technologies of interest to PNGV to facilitate baseline model calibration and "Cost Roll-Ups" for a few generic vehicle configurations of interest to PNGV
- Calibrate model through a baseline vehicle and perform relative production cost sensitivity for a selected number of technologies of interest to PNGV

Introduction

With support available since late last year from the PNGV vehicle engineering technical team (VETT), ORNL and ANL jointly continued the two-year automotive system cost model development, with some support from IBIS Associates, Inc. The focus of work has shifted to relative production cost estimation via a uniform methodology, allowing a comparison of alternative technologies under consideration by the PNGV community. The target vehicle initially in the model is a year 2010 production-volume passenger sedan (250,000 units) comparable in size/performance to a Ford Taurus, which is also the baseline for the PNGV program's target for improving the fuel efficiency by three times.

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. The total cost of advanced vehicles is 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 a new definition of vehicle subsystems along with the ANL powertrain-sizing routine. The ANL powertrain-sizing routine provides the capability to estimate the power and mass of typical hybrid electric (HEV) and fuel cell vehicle (FCV) configurations. The power and mass projections of various components are based on component specific power and efficiency values, with the capability to evaluate alternative HEV configurations and performance strategies. Seven specific vehicle configurations have been initially considered for the analysis: conventional, parallel power-assist charge sustaining HEV, series charge-sustaining HEV, battery-assisted charge-sustaining FCV with and without a reformer, and full hydrogen FCV with and without a reformer. Under the new definition of vehicle subsystems, a larger number of vehicle components were included under the powertrain subsystem, whereas the interior components were aggregated into a smaller number of groups due to invariant nature of the system. Implementation of the relatively simpler ANL powertrain sizing algorithm used in its hybrid electric vehicle cost model (HEVCOST) provides the standalone, system-level, vehicle-cost estimation capability, with the component-sizing and cost-estimation capability in a single model.

Figure 1 shows the modeling framework developed for the vehicle production cost estimation. The revised modeling framework provides the capability to sum up the cost of various vehicle subsystems and components after these have been properly sized through an iterative algorithm. Using the user-defined vehicle and the initial assumption of non-powertrain component mass, the powertrain components are sized. Non-powertain components are then sized based on their functional relationships with powertrain components. The scaling of various vehicle subsystems depends on their functionality in the vehicle, i.e., either fixed or variable with either vehicle weight, powertrain and material type or with all or some combination of these. The iterative sizing procedure continues until the vehicle performance and mass criteria for both powertrain and non-powertrain components are met. The estimated assembly cost is added to the estimated powertrain and non-powertrain costs to calculate the vehicle production cost.

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 PNGV technical teams who are involved at the specific system level cost modeling. The focus of this work will be to develop a credible database on a selected number of technologies, making use of the cost data available on specific technologies from various PNGV technical teams. The model will be calibrated to a baseline vehicle in addition to consideration of a limited number of “Cost Roll-Ups” for several generic vehicle configurations of interest to PNGV. 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. These model enhancements suggested during this year will enable technology trade-offs and the assessment of the impact of technology goals on a vehicle and fleet basis in the future.

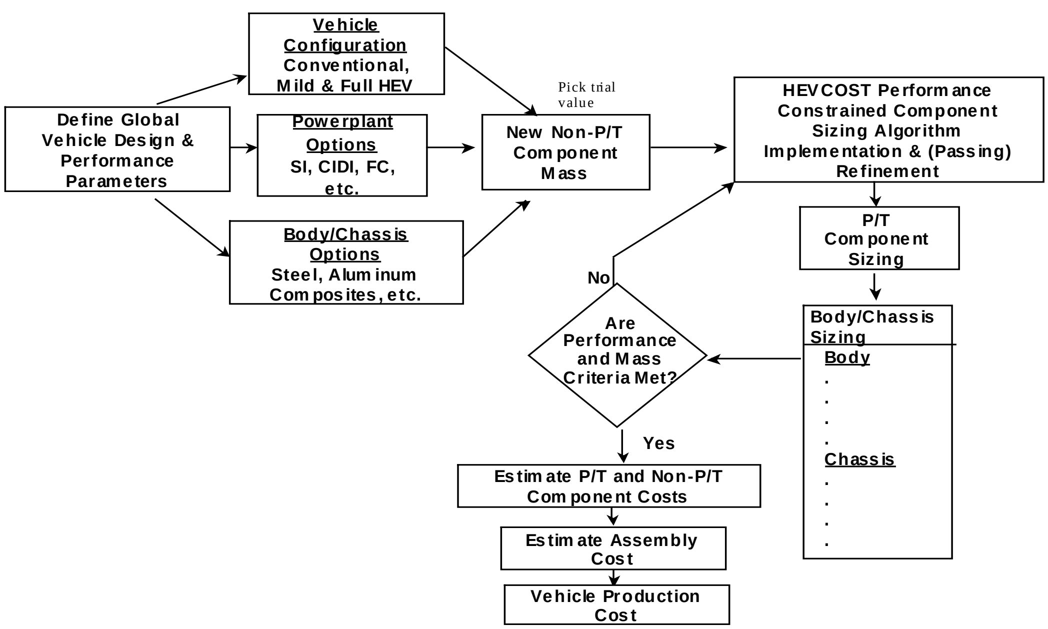

Figure 1. Modeling framework for vehicle production cost estimation.

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