2000-01-1562

Innovative Techniques for Decreasing Advanced Vehicle Auxiliary Loads

John P. Rugh
René S. Howard
Robert B. Farrington
Matthew R. Cuddy
Daniel M. Blake
National Renewable Energy Laboratory (NREL)

ABSTRACT

At the U.S. Department of Energy's National Renewable Energy Laboratory (NREL), one of the goals of the Center for Transportation Technologies and Systems is to develop innovative techniques for reducing automobile fuel usage and tailpipe emissions by decreasing the auxiliary loads on the propulsion system of advanced vehicles. The power required to cool the passenger compartment can significantly reduce the range of an electric vehicle (EV) and the fuel economy of a hybrid electric vehicle (HEV). We are investigating several ways to decrease auxiliary loads.

INTRODUCTION

Until recently, there has been little motivation in the United States to reduce the impact of air conditioning on fuel economy and emissions. But a new U.S. emissions test, the Supplemental Federal Test Procedure (SFTP), will measure tailpipe emissions with the air conditioning system operating. This new test provides an incentive for automakers to reduce the size of automotive air conditioning systems. Air conditioners are typically sized for a peak soak temperature (found, for example, in Phoenix). The challenge is to reduce the energy usage of the air conditioner without compromising passenger comfort. The test procedure consists of the current emissions test (called the Federal Test Procedure or FTP), an air conditioning test (SCO3), and a high-speed, high-acceleration test (USO6). Details of the tests are shown in Table 1. The SFTP applies to vehicles with a gross vehicle weight under 2608 kg (5750 lb). The air conditioning portion of the SFTP will contribute 37% of the total tailpipe emissions. Although there is no plan to expand the use of the SFTP to measure fuel economy, reducing the weight of the air conditioning system of a mid-size vehicle by 9.1 kg (20 lb) results in about a 0.04 km/L (0.1 mpg) increase in fuel economy on the current combined city/highway test.

Table 1. Supplemental Federal Test Procedure Specifications

	FTP	SC03	US06
Time(s)	1877	594	600
Max. speed, km/h (mph)	91.2 (56.7)	88.2 (54.8)	129.2 (80.3)
Max. acceleration, km/h/s (mph/s)	5.8 (3.6)	8.2 (5.1)	12.9 (8)
Distance, km (miles)	17.8 (11.1)	5.8 (3.6)	12.9 (8)
Contribution to total emissions value	35%	37%	28%

INVESTIGATIVE APPROACH

Using the tools described below, we took an integrated, systems-level approach to evaluating energy-efficient alternatives to automotive climate control.

ADVISOR

NREL's ADvanced VehIcle SimulatOR is designed for quick analysis of the performance and fuel economy of conventional, electric, and hybrid vehicles. ADVISOR can be used to model vehicle efficiencies, to assess impacts of applying innovative technologies to existing vehicle configurations, to develop novel energy management strategies, and to integrate simulated and real-life assessments.

The analysis presented here illustrates the capability of ADVISOR. We used ADVISOR to model a conventional vehicle and a high-fuel-economy vehicle. We estimated the impact of auxiliary loads on the fuel economy of these vehicles during four driving cycles. The driving cycles used are those scheduled for use in U.S. EPA certification procedures: FUDS (an urban driving cycle), HWFET (a highway driving cycle), SC03 (an air conditioning driving cycle), and US06 (a high-speed, high-acceleration driving cycle). The conventional vehicle is modeled as a 1406-kg (3100-lb), 3.0-L, spark-ignition engine, with an 800-W base auxiliary load resulting in a combined city/highway fuel economy of 11.4 km/L (26.8 mpg). The high-fuel-economy vehicle is modeled as a 907-kg (2000-lb), 1.3-L, direct-injection, compression-ignition engine, parallel hybrid with a base auxiliary load of 400 W and a resulting combined fuel economy of 34.6 km/L (81.5 mpg). Figure 1 shows the impact of auxiliary load on the fuel economy over the SCO3 cycle. The fuel economy of a nominally 80-mpg vehicle could drop to about 50 mpg if the auxiliary loads increase from 400 W to 2000 W. Clearly, a large auxiliary load is unacceptable for a high-fuel-economy vehicle.

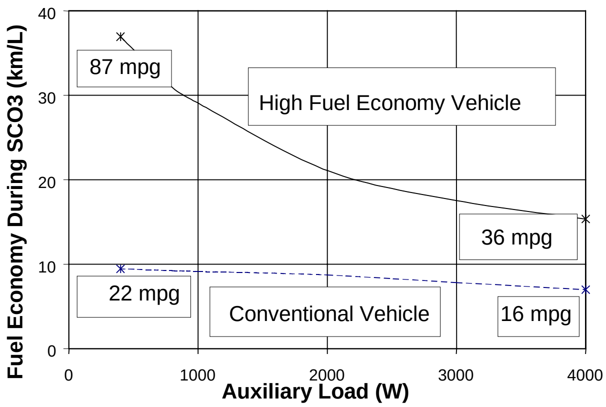

Figure 1. Auxiliary load impacts on fuel economy

THERMAL COMFORT MODEL

NREL has developed a transient thermal comfort model that estimates a person's comfort level in a vehicle during winter warm-up or summer cool-down. The current model predicts an overall thermal sensation based on a variety of inputs, including air temperature, air velocity, radiant temperature, humidity, body mass, clothing type, and metabolism. It also has the capability to measure heat exchange by conduction such as from a heated or cooled seat. This model has been validated using a series of in-car jury evaluations. NREL is also working with the University of California at Berkeley to develop a transient model that will predict thermal sensation variations over the body.

The key to effective climate control is to make the occupants comfortable using as little energy as possible. Air conditioning, especially during the initial cool-down period following a hot soak in the sun, represents the biggest climate control load on a vehicle. Thermal comfort modeling is useful in ensuring comfort at a minimum level of energy use because it can provide an integrated, systems-level approach to evaluating alternatives to cabin climate control. It is insufficient to look only at cabin air temperature or heat added or removed from the cabin air, because alternatives such as heated or cooled seats affect the cabin air very little, but can have significant impacts on occupant thermal comfort.

Thermal comfort models start with a heat balance of the occupant in the cabin environment (air, radiant, and contact surface temperature versus time; air velocity, and humidity; initial body temperature; body mass; clothing type; and metabolic heat generation) to predict physiological parameters such as core and skin temperature, blood flow, sweating, and shivering as a function of time. The final step is to apply a statistical correlation relating these parameters to comfort parameters such as Thermal Sensation Value (TSV) and Predicted Percent Dissatisfied (PPD). TSV is a numerical scale expressing thermal sensation (0 is neutral; 1, 2, and 3 are increasingly warm sensations; -1, -2, and -3 are cold). PPD is simply the predicted percentage of the population that would be dissatisfied with the current thermal conditions.

Utilizing boundary and initial conditions from a test program performed at NREL, the usefulness of the thermal comfort code can be demonstrated. Our tests exposed a vehicle to full sun and 38^{o}C ambient air. After 2 hours, the baseline vehicle reaches a cabin air temperature of 82^{o}C. However, with ventilation, the vehicle reaches only 66^{o}C. This results in a significant difference in thermal comfort. Figures 2a & b show thermal discomfort peaks after about 3 minutes as the core body temperature increases. Note that although it is possible to dissatisfy 100% of the population (at 3 minutes in the upper figure), it is not possible to satisfy 100% regardless of the allowable conditioning time.

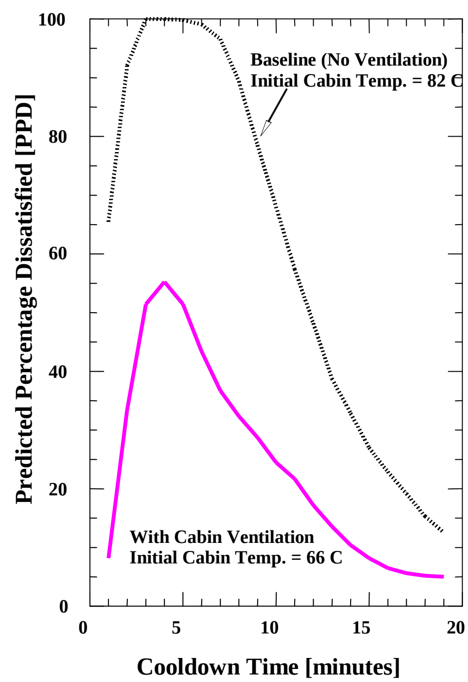

Figure 2a. Example of thermal comfort modeling-effect of cabin ventilation

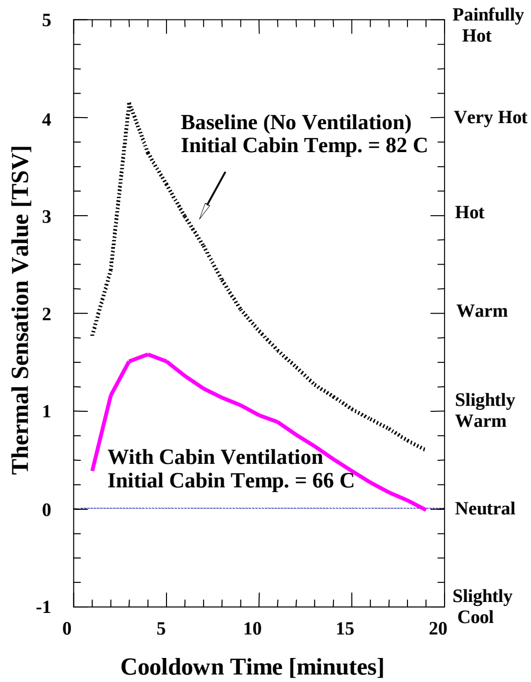

Figure 2b. Example of thermal comfort modeling- effect of cabin ventilation

INVESTIGATIONS

We are investigating several approaches to reducing peak and average air-conditioning loads on the engine. The techniques described here can be applied to conventional vehicles as well as EVs and HEVs. Our research in these areas is highlighted below.

ADVANCED GLAZINGS

Vehicle air conditioning systems in the United States are typically sized for adequate cool-down time for a peak cooling load in Phoenix, Arizona, with a solar load of 1 kW/m^2 and 49°C (120°F) ambient temperature. Such conditions lead to surface temperatures of more than 121°C (250°F) and cabin air temperatures of more than 82°C (180°F). The peak load can be two to four times greater than the steady-state cooling load. To reduce the size of the air-conditioning system, we must reduce the cabin soak temperature.

Solar energy enters the vehicle and raises the cabin soak temperature through two paths: the windows and the opaque components of the vehicle, such as the roof. Although it may seem intuitive to insulate the vehicle roof to reduce the solar gain, roof insulation can actually increase the cabin temperature, because the roof serves as a heat rejection path as the cabin temperature rises.

To determine the effectiveness of the advanced glazings, we used a co-heating technique. We measured the power of a ceramic heater required to maintain the cabin interior air temperature at a constant 60°C (140°F), eliminating the effect of the thermal capacitance of the vehicle interior. As the solar gains increased, the heater power decreased. The vehicle heat loss with the windows closed was estimated from the nighttime conditions when there was no solar radiation. An assumption implicit in this approach is that the vehicle heat loss during the day is approximately the same as during the night. The opaque gains were measured with 2.5 cm (1 in.) of foam insulation on the outside of all of the vehicle windows.

Using a Plymouth Breeze as the test vehicle, we measured the effect of advanced glazings by (1) applying a solar reflective film to all the vehicle windows and (2) using a commercially available ultraviolet and infrared reflecting windshield. We tested three windshields supplied by PPG: Solex®, a standard windshield in the United States; Solar Green®, a windshield used in European vehicles; and Sungate®, an advanced ultraviolet and infrared reflecting windshield.

A cabin soak test was performed without heaters, and the results are presented in Figure 3. A comparison of the temperature for the vehicle with and without the film, and with the windows closed showed that the film kept the cabin about 9°C (16°F) cooler for these particular conditions.

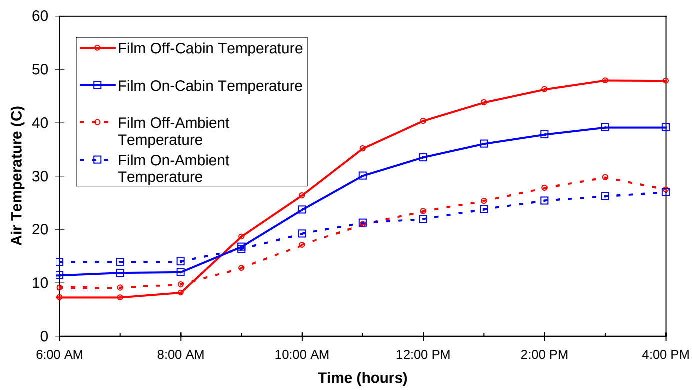

Figure 3. Vehicle soak temperature

For the co-heat test, the opaque case required the greatest heater power, and the case with the film off and windows closed required the least because the latter case has the greatest solar gain (see Figure 4). To calculate the normalized net thermal gain (see Figure 5), the heater power was integrated from sunrise to noon and normalized to the integrated solar radiation during the test, which fell within 4% of the solar radiation during the opaque test. The reflective characteristic of the film resulted in a thermal gain of 1.49 compared to 1.94 for the vehicle without film.

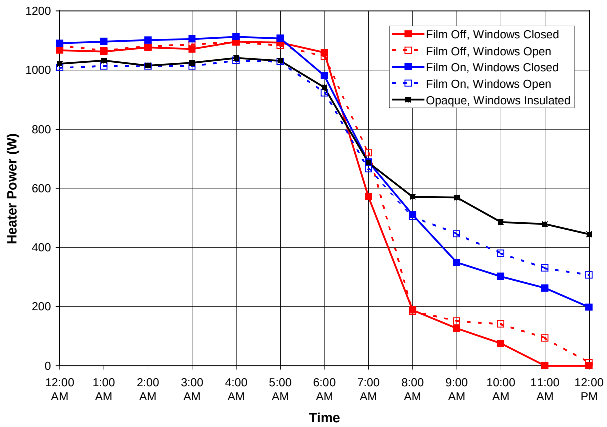

Figure 4. Measured heater power

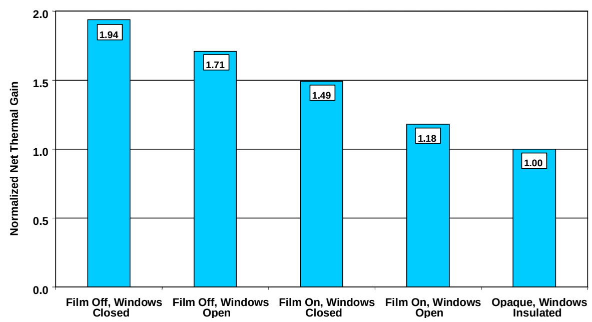

Figure 5. Normalized net thermal gain for window film and window open

The tests of commercially available windshields used the same standard automotive glass on the side and back windows. Hence, the difference in heater power is directly related to the change in windshield properties. At noon, Figure 6 shows the Sungate® windshield required 187 W more than the Solex® windshield, meaning that the Sungate® reduced the solar gain by 187 W under those conditions. The Solex® windshield had 17% more thermal gain than the Sungate® windshield.

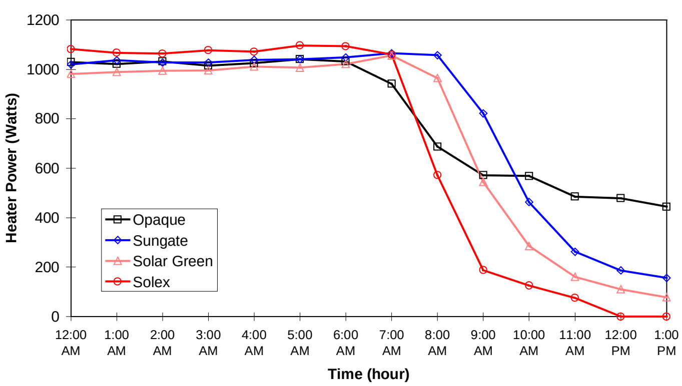

Figure 6. Measured heater power for windshield tests

The potential impact on fuel economy for a conventional mid-sized vehicle using the Sungate® windshield compared with the standard Solex® windshield is significant. The advanced windshield without any treatment on the side windows can reduce fuel consumption by 3.4% over the SCO3 drive cycle according to ADVISOR simulations performed at NREL.

VENTILATION CONTROL

Modern vehicles have large windows to increase the driver's visibility and improve the vehicle's appearance. However, while a vehicle is parked, these large windows turn the vehicle into a very efficient solar collector. Sunlight entering through the windows is converted to thermal energy that becomes trapped inside the vehicle (glass is transparent to short wavelength radiation and opaque to long wavelength radiation). Typically, vehicle interior stagnation temperatures range between 71°–82°C (160°–180°F) during the summer in many U.S. cities. Under severe summer conditions, vehicle interior stagnation temperatures can approach 104°C (220°F). The objective of this work is to develop techniques to limit vehicle stagnation interior temperatures to 66°C (150°F) under 49°C (120°F) ambient conditions.

NREL has developed a unique way of removing the hot boundary layer of air that forms against the windshield when the vehicle is parked. The technique uses innovative ducting and fans to exhaust the heat while the vehicle is parked. This technique will also help reduce surface temperatures, which will allow the materials to have a longer life.

We studied performance tradeoffs associated with reducing solar gains and facilitating the removal of thermal energy from the vehicle's interior. The study focused on full-scale measurements in a 1996 Neon and a 1997 Breeze. We measured solar gains to peak at about 1.4 kW with standard glazing and measured infiltration rates at stagnation of about 4.7 L/s (10 cfm). By adding "intentional" infiltration while the vehicle is parked (by opening low and high dampers or "cracking" the windows or sunroof), the infiltration level can be increased to 9.4 L/s (20 cfm). Small fans coupled to the vehicle's pressure relief dampers can provide ventilation during peak solar gain hours at a power cost of about 1W per 235 L/s (50 cfm).

Small fans were integrated with low-flow exhaust plenums to extract thermal boundary layers from window shading devices. We found that boundary layer thermal control required about 0.8 L/s per linear meter (0.5 cfm per linear foot) of window. Because of the increased temperature of the boundary layer relative to the bulk air temperature in the vehicle, we found that boundary layer control required 30%–50% less airflow than strategies that ventilate the entire interior of the vehicle. Removing hot boundary layers is more effective than letting the heated air mix within the vehicle and then trying to bulk ventilate the entire interior of the vehicle.

AIR QUALITY (PHOTOCATALYTIC OXIDATION)

Rather than treating very cold or very hot air from outside, it is more efficient to utilize recirculated passenger compartment air. As the percentage of recirculated air is increased, the corresponding heating or cooling thermal power required is reduced. Figure 7 shows that only 1.2 kW is needed to maintain the cabin air at 30°C (54°F) above ambient using 100% recirculated air, while 4.5 kW is needed if only outside air is used. The vehicle skin heat transfer coefficient was 50 W/K and the air flow rate for climate control was 0.167 kg/s (300 cfm) for cooling and 0.111 kg/s (200 cfm) for heating. The thermal power required is a function of the ambient temperature, total air flow rate, percentage of recirculated air, humidity (cooling only), and the heat gain/loss of the passenger compartment. Humidity can dramatically increase the cooling load, which can be seen by comparing the cooling load in Denver to that in Miami.

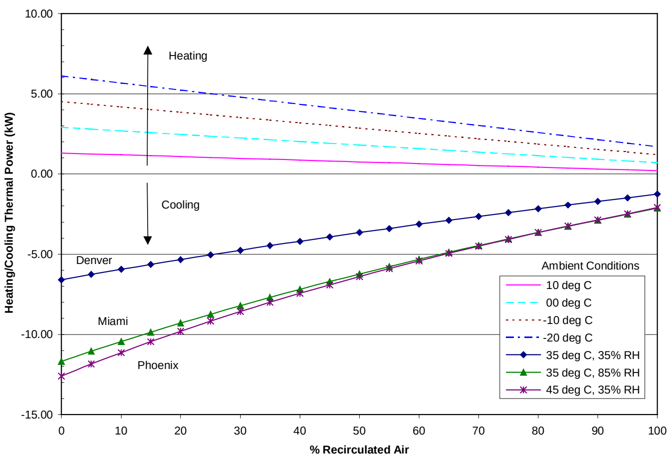

Figure 7. Heating/cooling thermal power as a function of percent recirculated air

Increased recirculation of air leads to two additional challenges: (1) removing odors, bioaerosols, and harmful volatile organic compounds (VOCs), and (2) controlling humidity levels to avoid condensation on cold surfaces in either the heating mode (such as cold windows) or the cooling mode (such as cooled seats, pipes, or ducts). Conventional active air-cleaning techniques, such as carbon beds and HEPA filters, rely on separating the pollutants from the air matrix and concentrating them in another matrix. The equipment is difficult to maintain and energy consumption is high, primarily because of pressure drop. The air treatment modules can also provide a breeding ground in which micro-organisms can multiply and become a source of contamination. We are evaluating a novel photocatalytic oxidation (PCO) air-cleaning process for removing volatile organic compounds and bioaerosols, which are the two most problematic pollutants in passenger compartments. Figure 8 shows the effectiveness of removing these compounds using a PCO unit [4]. PCO is a room-temperature, low-pressure-drop process that is particularly effective in treating pollutants in dilute matrices. Active cleaning of passenger compartment air will provide enhanced comfort while allowing an increase in the ratio of recycled to fresh air. This can significantly lower auxiliary loads for air conditioning and heating.

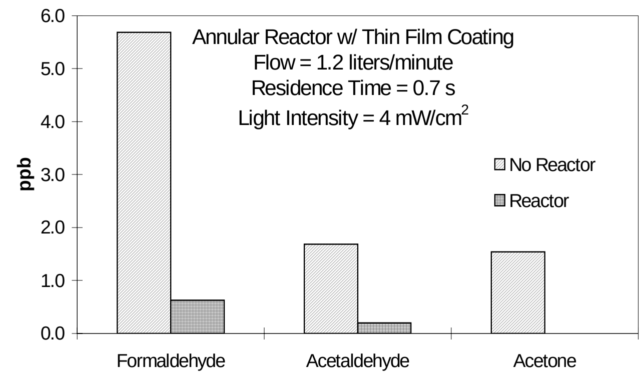

Figure 8. Ambient indoor air quality

HEATED AND COOLED SEATS

Because the smaller engine size reduces the engine heat available to heat the passenger compartment in low-emission vehicles, we are looking at various ways to provide heat directly to the passenger. NREL has received an electrically heated seat from Johnson Controls and a liquid heated and cooled seat from Life Enhancement Systems. Heated and cooled seats can allow vehicle passengers to quickly become comfortable and may reduce the need for using the air conditioning or heating systems at peak load for extended periods of time. We plan to perform jury and/or thermal manikin testing of the thermal seats to assess the ability of the seats to provide thermal comfort. These seats fit into NREL's vehicle systems approach quite nicely and will help improve passenger comfort and reduce the use of vehicle auxiliary loads.

CONCLUSION

Fuel efficiency, air quality, and energy security concerns, along with ever-tightening emissions regulations, are some of the driving forces automakers face as they design the vehicles of the future. It is clear that significant reductions in automotive auxiliary loads are needed for these vehicles, making tomorrow's vehicles more fuel efficient, quiet, and safe, while making passengers comfortable more quickly. Vehicle climate control loads can be reduced in many ways—some can be readily implemented in today's vehicles, and others will require more development. The techniques we describe here appear promising for reducing vehicle climate control loads, and we have seen that even small changes in climate control loads can result in increased vehicle efficiencies. Increasing vehicle efficiencies and decreasing polluting emissions will go a long way toward achieving the national and global goals of reduced dependency on foreign oil and improved air quality.

ACKNOWLEDGMENTS

This work was supported by DOE's Hybrid Vehicle Propulsion Program, which is managed by the Office of Advanced Transportation Technologies. The authors appreciate the support of Robert Kost and Roland Gravel, the DOE Program Managers; Terry Penney, NREL's HEV Technology Manager; and Barbara Goodman, the Director of the Center for Transportation Technologies and Systems. The authors would like to acknowledge the significant contributions provided by both industry and our colleagues at NREL. Our industry partners in this project provided significant hardware and feedback. Chrysler provided the Plymouth Breeze, and PPG provided the windshields. In addition, we recognize the significant contribution of Tom Thoensen who assisted with the construction and operation of many of the experiments.

BIBLIOGRAPHY

1. Farrington, R.; Anderson, R.; Blake, D.; Burch, S.; Cuddy, M.; Keyser, M.; and Rugh, J., 1999, "Challenges and Potential Solutions for Reducing Climate Control Loads in Conventional and Hybrid Electric Vehicles," presented at the VTMS4.
2. Burch, S.; Ramadhyani, S.; and Pearson, J. 1991, "Analysis of Passenger Compartment Thermal Comfort in an Automobile Under Severe Winter Conditions," *ASHRAE Transaction*s, Vol. 97, Part 1.
3. Farrington, R.; Cuddy, M.; Keyser, M.; and Rugh, J.; 1999, "Opportunities to Reduce Air Conditioning Loads through Lower Cabin Soak Temperatures." 11 pp.; NREL Report No. CP-540-26615, Golden, CO: NREL.
4. Wipke, K.; Cuddy, M.; Bharathan, D.; Burch, S.; Johnson, V.; Markel, A.; and Sprik, S. 1999. *ADVISOR 2.0: A Second-Generation Advanced Vehicle Simulatory for Systems Analysis*. 14 pp.; NREL Report No. TP-540-25928, Golden, CO: NREL.
5. Wipke, K..; Cuddy, M.; Burch, S. 1999. "ADVISOR 2.1: A User-Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach." 14 pp.; NREL Report No. JA-540-26839, Golden, CO: NREL.
6. Farrington, R.; Brodt, D.; Burch, S.; Keyser, M., 1998, "Opportunities to Reduce Vehicle Climate Control Loads," presented at the EVS15.