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Vehicle Ancillary Load Reduction Project Close-Out Report

An Overview of the Task and a Compilation of the Research Results

J. Rugh and R. Farrington

Technical Report
NREL/TP-540-42454
January 2008

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We also acknowledge our close collaboration with the automotive industry and the strong support provided by our industrial R&D partners. We benefited greatly from our many interactions with industry and appreciate the challenges they face in order to deliver high-quality products in increasingly shorter time frames.

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Finally, we want to acknowledge the significant contributions of ADAM, the sophisticated thermal manikin.

Executive Summary

The amount of fuel used for climate control in vehicles affects our nation's energy security significantly as it lowers the fuel economy of the 230 million light-duty conventional vehicles in use in the United States today. Researchers at the National Renewable Energy Laboratory (NREL), a U.S. Department of Energy (DOE) national laboratory, have estimated that the United States consumes about 7 billion gallons of fuel per year just to air-condition light-duty vehicles. Therefore, the primary mission of NREL's Vehicle Ancillary Load Reduction Task was to develop and evaluate technologies that reduce the amount of fuel used for automobile air-conditioning (A/C). This report summarizes the results of evaluations, conducted over the last 10 years, of technologies and techniques for reducing A/C fuel consumption.

NREL's researchers used a variety of tools to research and develop innovative techniques and technologies that reduce the amount of fuel needed for a vehicle's ancillary loads. Specifically, their efforts have led to the following:

- Development and testing of ancillary load reduction technologies for reducing A/C fuel consumption while keeping occupants comfortable
- Development of a passenger compartment cooling system using waste heat as an energy source.

In addition to its impact on the fuel economy of conventional vehicles, A/C can reduce the fuel economy of advanced vehicles by as much as 35%, which in turn can increase their fuel consumption as much as 50%. To address these issues, NREL worked closely with the automotive industry to develop techniques to reduce ancillary loads, such as climate control, in vehicles. We conducted research to improve vehicle efficiency and fuel economy by controlling the climate in the vehicle while keeping passengers comfortable. As part of this effort, we conducted research in integrated modeling, optimized techniques to deliver conditioned air to vehicle occupants, conducted thermophysiological modeling, and investigated waste-heat cooling and heating opportunities.

There is great potential to reduce A/C fuel consumption because A/C systems have traditionally been designed to maximize capacity, not efficiency. Therefore, among other modeling activities, we used an integrated vehicle thermal modeling process to estimate the potential reduction in A/C system size and fuel use resulting from the use of solar reflective glass and solar-powered parked-car ventilation (reducing capacity). Using a Cadillac STS as an example vehicle, we determined that the vehicle's A/C cooling capacity of 5.7 kW could be reduced by 30% to 4.0 kW while maintaining a cooldown performance of 30 minutes. A vehicle simulation showed that reducing the A/C load by 30% decreased A/C fuel consumption by 26%.

Reducing Thermal Loads

When a vehicle is parked, typically 50% to 75% of the thermal energy entering the passenger compartment is from the solar energy transmitted and absorbed by window glazing. Reflecting the solar radiation incident on the vehicle's glass is a critical step in making significant reductions in the thermal loads. Lower thermal loads make it possible to reduce the capacity of the A/C system.

As part of the Improved Mobile Air Conditioning Cooperative Research Program (I-MAC), NREL tested a new type of solar-reflective glass that improved the reflection of the near-infrared (IR) portion of the solar spectrum on a 2005 Cadillac STS. The Sungate EP automotive glass allowed only 3% of the IR energy to be transmitted through the glass. Using this technology at all glazing locations reduced the average air temperature by 7.1°C (12.8°F), the seat temperature by 8.7°C (15.7°F), the windshield temperature by 19.3°C (24.7°F), and the instrument panel surface temperature by 14.6°C (26.3°F).

Another way to assess these data is in terms of maximum possible temperature reductions, in other words, the difference between a baseline vehicle's average air temperature and ambient. Using solar-reflective glass in all locations reduced the average air temperature by 34% of the maximum possible, and the seat temperature by 35%. Using reflective shades and electrochromic switchable glazing are also effective techniques for reducing the solar energy entering the passenger compartment. We also found that solar-reflective coatings on exterior opaque surfaces and body insulation can reduce a vehicle's interior temperatures, but to a lesser extent than solar-reflective glazing, shades, and parked-car ventilation can. Heat pipes were found to significantly reduce instrument panel (IP), windshield, and air temperatures.

Improving Ventilation

Because solar energy entering a vehicle heats the interior mass of the passenger compartment, which in turn heats the air, venting the warm air and pulling in cooler ambient air can reduce the temperature of the vehicle's interior. Therefore, NREL tested various natural and forced ventilation techniques for parked cars on a 2000 Jeep Grand Cherokee. The data showed that using strategically located air inlets for natural convection induced flow can be nearly as effective as using forced convection ventilation with the heating, ventilating, and air-conditioning (HVAC) blower speed set to medium. With the sunroof open 6 cm and floor inlets, buoyancy induced flow reduced the cabin's air temperature by 5.7ºC, a reduction of 38% of the maximum possible. In contrast, operating the HVAC blower on the medium setting reduced the average air temperature by 6.9ºC.

We also tested a solar-powered ventilation system for a parked car as part of I-MAC thermal soak testing on the Cadillac STS. The average air temperature was reduced 5.6ºC, and the seat temperatures were reduced 5º-6ºC when air was exhausted from the vehicle. These represented 26% and 21% of the maximum possible temperature reductions, respectively. Using interior window shades to block solar radiation can result in a warm layer of air between the window and shade. So, we investigated ventilation strategies that exhaust this warm air and prevent it from mixing with the air in the cabin.

Using Innovative Cooling Technologies

Conventional vehicles generate waste heat typically equivalent to 60% to 80% of the chemical energy in the fuel. Therefore, we investigated capturing a vehicle's waste heat using thermoacoustics to power a cabin cooling system. We also developed a thermoelectric analysis tool to assess the feasibility and performance of thermoelectric waste heat recovery systems.

The A/C system control strategy used is an important factor in a vehicle's overall energy consumption. Overcooling and then reheating air to control the temperature of the cabin is a method commonly used in vehicles with automatic temperature control. But this is not an effective energy-conservation practice. Using recirculated cabin air reduces energy use by avoiding the need to cool hot and humid outside air, but the air quality must remain acceptable. To address these issues, we developed a photocatalytic oxidation technique that reduced volatile organic compounds and odors in a vehicle's cabin and increased air recirculation rates.

In addition, conventional automotive seats insulate the occupant thermally and reduce evaporative cooling by means of perspiration, thus increasing the temperature of the contact between the occupant and the seat. Both actively ventilated seats and mesh seats are potentially low-energy approaches to improving thermal comfort and achieving more efficient climate control. Using a ventilated seat resulted in an overall thermal sensation improvement of 0.28, on a scale of +4 to -4. We estimate that this technique could allow the capacity of the A/C system to be reduced by 7% and still maintain thermal comfort. This would reduce A/C fuel consumption by 7.5%.

Conclusions and Recommendations

The thermal load-reduction technologies that we tested are available for today's vehicles. If they are incorporated along with a smaller A/C system, or they result in less frequent use of air-conditioning, America's drivers will save money while remaining comfortable. In addition, fuel-use reductions translate directly to lower carbon dioxide (CO_2) emissions. Since this project's inception, concerns about global warming have increased. These concerns have prompted new legislation and requirements to use alternative refrigerants and include A/C in vehicle CO_2 calculations. While automotive manufacturers and suppliers are redesigning A/C systems, they have a unique opportunity to incorporate thermal load-reduction technologies and improved efficiency components in the new designs.

This project has been successful for many different reasons. For example, NREL developed several new tools that weren't available previously, such as VSOLE, the National A/C Fuel Use Model, a sophisticated thermal comfort manikin (ADAM) controlled by a high-resolution model of the human thermoregulatory system, and a transient thermal comfort model. NREL also conducted objective evaluations of advanced technologies in a vehicle context. And we provided a means of modeling and testing components in a systems context to determine their performance and impact on A/C fuel consumption. Based on the insights we have gained on significantly reducing A/C system fuel consumption, we recommend the following steps in this R&D pathway:

1. Reduce the thermal load by using solar-reflective glass or shades and parked-car ventilation.
2. Incorporate low-mass, naturally ventilated seating (or active climate-control seating).
3. Incorporate the most efficient A/C components available.
4. Increase the use of recirculated air to the maximum extent possible, considering air quality, dehumidification, and safety issues, while avoiding condensation on windows.
5. Eliminate the overcooling and subsequent reheating of air that occurs now to achieve the desired temperature in vehicles with automatic temperature control systems.

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1.0 Introduction

1.1 History

The Vehicle Ancillary Loads Reduction Project fostered a national effort to estimate automotive air-conditioning fuel consumption rationally and laid the groundwork for future thermal comfort models. It began as the "Cool Car Project" in 1996 and was first funded internally under a laboratory-directed research and development program at the National Renewable Energy Laboratory (NREL). The first two-year project included 19 researchers from five different NREL research centers focusing on research in transportation technologies, buildings, photovoltaics, wind, basic sciences, and analysis.

With initial funding of $391,468, the project quickly gained industry support. Industry partners such as Chrysler Corporation provided a Plymouth Breeze test bed, PPG Industries created several types of solar-reflective glazing for test vehicles, Webasto provided a sunroof, Optical Coating Laboratory Inc. (OCLI) fabricated electrochromic panels for a sunroof, Solarex sent a photovoltaic array for cabin ventilation, and Life Enhancement Technologies manufactured heated and cooled seat panels for research. Among the many technologies investigated were these:

- Advanced glazing to reduce the solar load
- Photovoltaics to power a cabin ventilation system in a parked vehicle
- Boundary layer control at windows to capture and exhaust heat (which led to an NREL patent)
- Photocatalytic oxidation to purify cabin air and reduce outside air requirements
- Advanced air-conditioning (A/C) concepts, such as ejector systems and desiccant cooling.

This internal project set the stage for a decade of U.S. Department of Energy (DOE) funding totaling $9.16 million. Close collaborations with industry included the test vehicles provided by Chrysler, Ford, and General Motors (GM). Researchers obtained solar reflective and absorbing glazing from 3M, Guardian Industries, PPG, Solutia, and Southwall Technologies. Reflecting and absorbing window shades were provided by BOS; climate control seats by Amerigon, Johnson Controls, and W.E.T.; solar reflective films and paint by 3M and PPG; and advanced body insulation by 3M.

Our work focused on light-duty vehicles but led to numerous spin-off projects. These included several Cool Cab projects for Class 8 sleeper cabs. The projects involved DOE, Guardian Industries, International Truck, Volvo Truck, and Schneider, as well as the U.S. Army, the U.S. Environmental Protection Agency (EPA), the Society of Automotive Engineers (SAE), and the National Aeronautics and Space Administration (NASA).

1.2 Approach

Traditionally, the automotive industry has emphasized efficient equipment. Suppliers must be able to assemble the hardware that automotive manufacturers purchase. To reduce the size of this equipment as much as possible, there must be an emphasis on reducing thermal loads while paying close attention to cost, volume, weight, reliability, and serviceability. Methods for reducing cooling thermal loads can include the following:

- Using reflective glazing, shades, and paint to reflect the infrared (IR) and (or) visible portion of the solar spectrum
- Capturing heat at the vehicle's boundary through absorbing glass and exhausting it through boundary layer control
- Minimizing conduction into the cabin through body insulation
- Rejecting heat to outside the vehicle using active or passive ventilation of the vehicle's cabin or through heat pipes while the vehicle is parked in the sun.

In winter, reducing heat loss from the cabin becomes increasingly important in advanced vehicles because waste heat is not always readily available. One example of this occurs when the downsized engine of a hybrid electric vehicle (HEV) is not operating because the vehicle is idling or coasting. Another example occurs when a plug-in hybrid vehicle (PHEV) is operating in all-electric mode. Options to reduce this heat loss include increasing the vehicle body's insulation or using advanced glazing with a low-emissivity coating or double-glazed windows.

In addition to having a reduced load, the vehicle must be able to warm or cool its occupants as efficiently as possible. Traditional technologies have been inefficient because they have conditioned the entire cabin even when there is only one occupant. More efficient technologies for single-occupant vehicles could include occupant sensors, body coolers, and conditioned seats.

Future work must, therefore, involve designing more efficient equipment. Whenever possible, waste heat should be used for cooling as well as heating. This can be accomplished through the use of thermoacoustic systems, absorption systems, or adsorption systems, such as those made of metal-hydride. Climate-control equipment must be able to operate without using the engine to minimize fuel use. An electric A/C compressor is one option, perhaps one that can operate in heat pump mode to provide heating. Although electric heating can be expensive, it could be an effective technique for direct-delivery systems, such as heated seats and windshields.

The options are many, but one of the top challenges is to meet fuels savings goals while keeping initial and operating costs at reasonable levels. Another challenge is to achieve greater fuel economy while avoiding several unintended consequences. For example, polycarbonate glazing can reduce a vehicle's weight but could cause greater thermal discomfort in winter, because polycarbonate's long-wave infrared (IR) transmissivity is higher than that of glass. Similarly, more efficient or smaller engines generate less heat to warm cabins than today's engines do.

Still, the potential is great to reduce fuel use for A/C and increase occupants' comfort levels at the same time. New technologies are needed that will meet both goals and still be cost effective. The best solutions will probably require the development of multiple technologies designed to provide energy-efficient seating, glazing, and vehicle bodies.

2.0 Significant Accomplishments

2.1 Modeling

2.1.1 A/C Fuel Use Analysis

We calculated the impacts of air-conditioning on fuel use in light-duty vehicles both nationwide and state by state. Our analysis used a bottom-up approach to estimate the amount of fuel used annually in vehicles for A/C. Using a thermal comfort model, researchers determined the percentage of time that drivers use A/C to improve their thermal environment. Environmental conditions were an important input to this model. Results for thermal comfort were then combined with statistics concerning when people drive (time of day); where they live (climate, including cloud cover); and how many miles they drive in one year. Finally, vehicle simulations were used to determine the fuel-use penalty associated with using A/C in cars and trucks. This algorithm allowed the researchers to determine the amount of fuel used for A/C in light-duty vehicles.

The analysis showed that, in 2001, U.S. drivers used approximately 7.0 billion gallons of gasoline each year to air-condition vehicles. This was the equivalent of 5.5% of domestic light-duty vehicle petroleum consumption, or 0.46 million barrels of crude per day, assuming a one-to-one displacement. It took 9.5% of U.S. imported crude oil to produce this much gasoline, assuming a 0.435 refining ratio.[1] Figure 1 shows U.S. A/C fuel use by state.

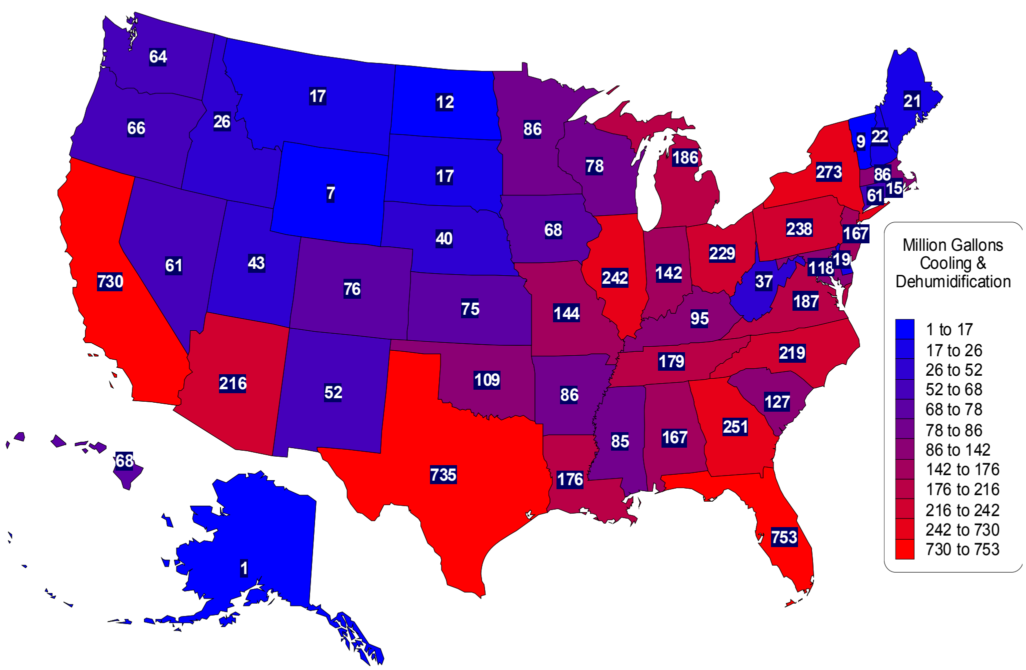

Figure 1. U.S. air-conditioning fuel use, by state

1. Total annual light-duty vehicle fuel use = 125.9 billion gal gasoline, in *Ward's 2001 Automotive Yearbook.* Southfield, MI: Ward's Communications, 2001; imported oil = 11.1 million barrels per day = 73 billion gal gasoline per year, according to the U.S. Department of Energy's Energy Information Administration, http://www.iea.doe.gov/cabs/usa.html, accessed April 2001.

2.1.2 Transient A/C Model

NREL developed a model that 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 was developed within SINDA/FLUINT analysis software environment and integrated with the ADVISOR vehicle systems analysis software first developed at NREL. The SINDA/FLUINT and ADVISOR software employ built-in optimization capabilities that are used to optimize a vehicle's A/C system within the overall vehicle design optimization process. An example of normalized compressor power output is shown in Figure 2.

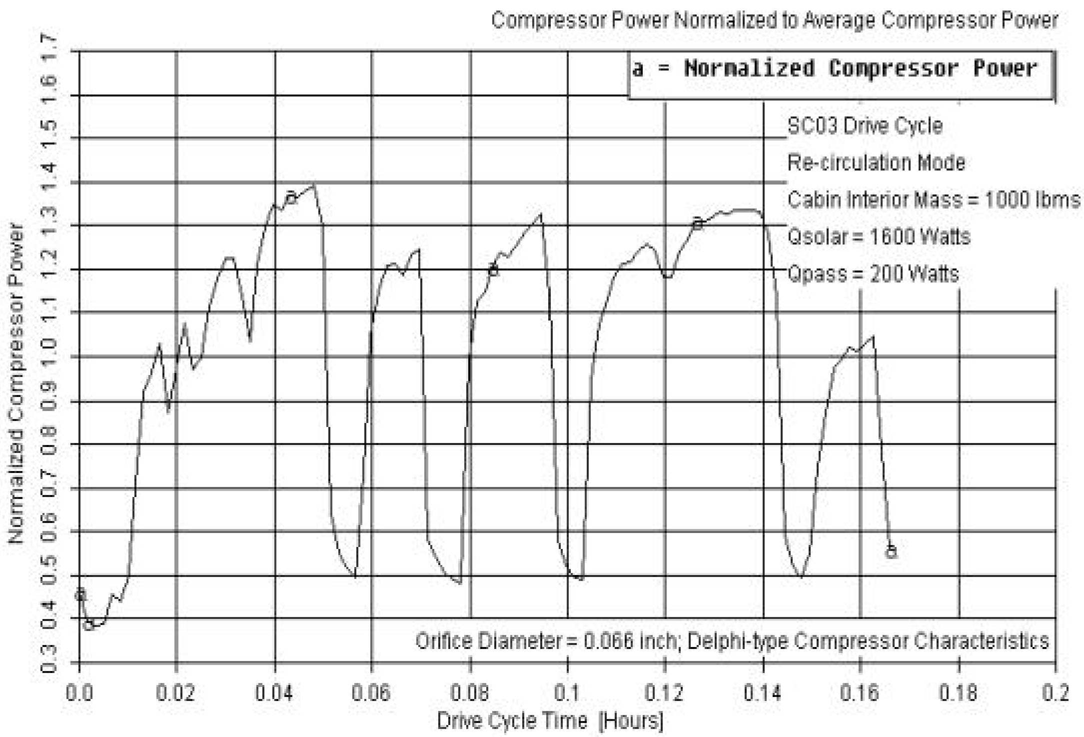

Figure 2. Normalized compressor power vs. time over the SC03 drive cycle

Researchers used NREL's transient A/C system model to perform multi-variable design optimization of electrically-driven compressor A/C systems. Five variables were considered: compressor displacement, capillary diameter, transfer line diameter, condenser tube diameter, and compressor speed. After 83 separate analyses, they determined that the optimum system has a system coefficient of performance (COP) = 3.42 at a compressor speed of 700 rpm, a compressor displacement of 120 cm^3, and an expansion device diameter of 0.191 cm.

The investigation then concentrated on optimizing the system design to maximize the evaporator cooling capacity over the SC03 drive cycle, which measures tailpipe emissions while the A/C is operating at maximum. The COP of this design was 0.856, far below that of the maximum COP system design. The optimum compressor speed of 2066 rpm and optimum compressor displacement of 276 cm^3 is much higher than that for maximizing COP (700 rpm and 120 cm^3, as noted above). This highlights the differences in systems that would be required to achieve DOE's goals to reduce A/C system power requirements in order to reduce vehicle fuel consumption, versus the automotive industry's need to maximize cooling capacity and cabin cooldown performance. Clearly, a systematic methodology that maximizes both COP and evaporator cooling capacity will require dynamic system operation.

We investigated A/C system design optimizations using a two-speed dynamic control strategy to quantify optimized A/C system performance and evaluate compromise A/C system designs that could partially, or simultaneously, satisfy the two diverse design objectives. A dual-compressor-speed strategy, coupled with the use of an electrically driven compressor, was found to be beneficial in developing system designs that improve system COP while maintaining a reasonable evaporator cooling capacity.

2.1.3 VSOLE

To better understand solar-reflective glazing and its impact on the heat load of passenger compartments, we developed the Vehicle Solar Load Estimator (VSOLE). VSOLE is a graphical user interface (GUI)-driven tool programmed in the MATLAB environment (see Figure 3). The model calculates solar radiation transmitted, absorbed, and reflected by glazing as a function of the optical properties of the glazing, the glazing's location, vehicle geometry, vehicle orientation, time, and source of radiation. The model accounts for the angular dependence of the optical properties of glass. The program can also display glazing properties and comparisons of different types of glazing under the same solar load and vehicle orientation as a function of time. (This software is available from the authors.)

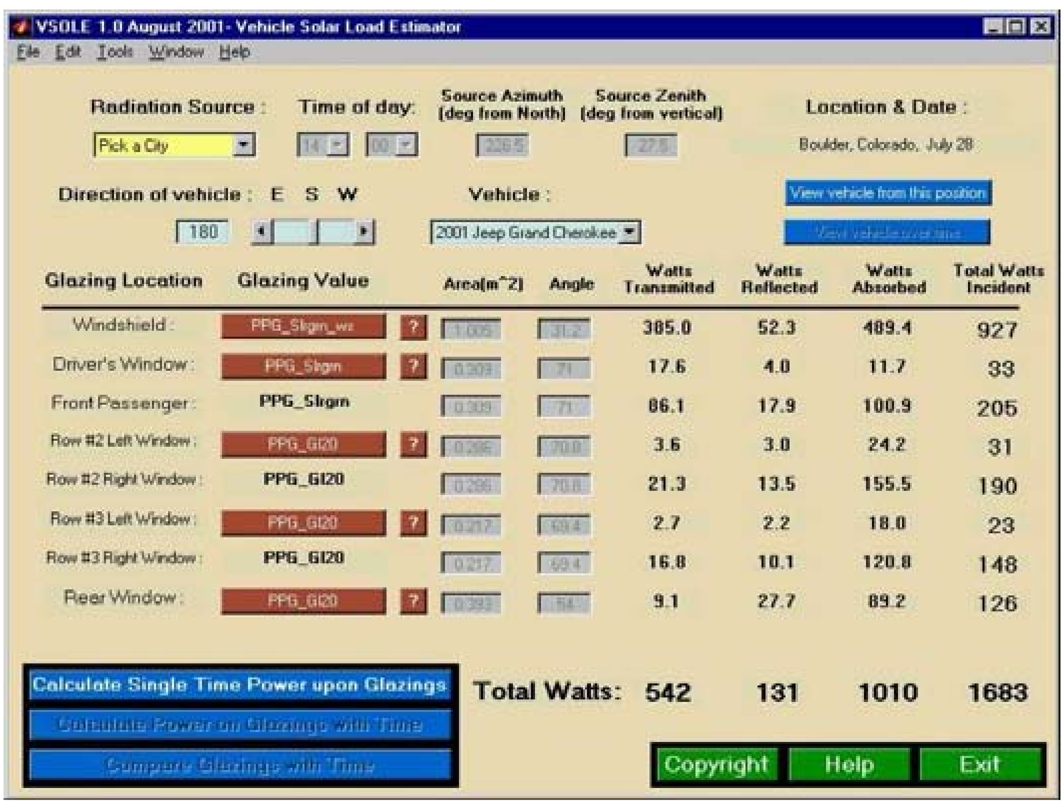

Figure 3. VSOLE interface

The solar radiation model developed at NREL provides radiation source data for VSOLE. The data are accessible from within the VSOLE GUI through the “pick a city” option in the radiation-source pull-down menu. The solar radiation model calculates the solar spectral irradiance incident on a vehicle as a function of location, weather, and vehicle orientation. Weather and sun position data for the model are available for 239 locations in the United States and U.S. territories. An example of the solar radiation model GUI is shown in Figure 4.

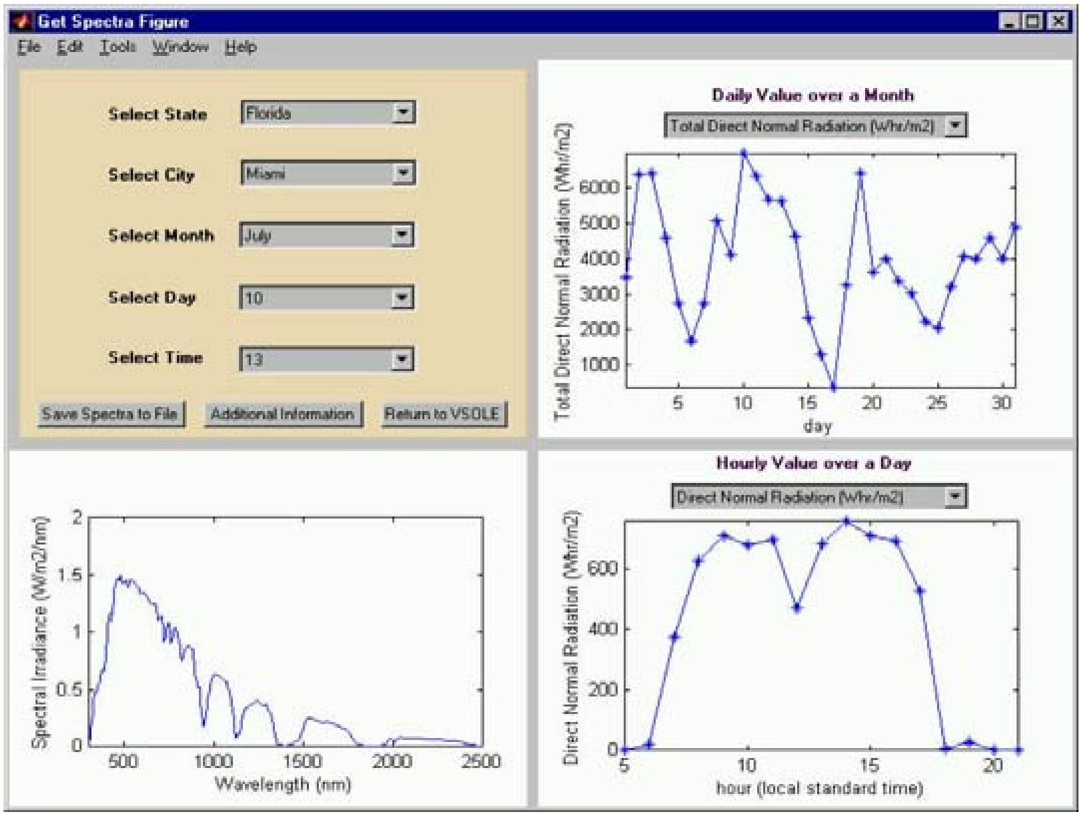

Figure 4. Solar radiation model GUI

2.1.4 Integrated Vehicle Thermal Modeling Process

We developed the numerical modeling process shown in Figure 5 to assess the impact of reducing the thermal load on A/C system capacity and the amount of vehicle fuel used for A/C. A vehicle’s interior geometry is typically defined by computer-aided design (CAD) data or, as is the case for vehicles under development, it is not defined.

We followed two approaches to develop a computational fluid dynamics (CFD) mesh. One approach was to use a parametric modeling tool developed by ICEM CFD to modify a generic vehicle to one with the appropriate dimensions and generate a mesh in preparation for cabin thermal and fluid modeling using CFD software. A second approach was to import the CAD data into BETA CAE Systems ANSA software where it was cleaned up, details were removed, and the surface was meshed.

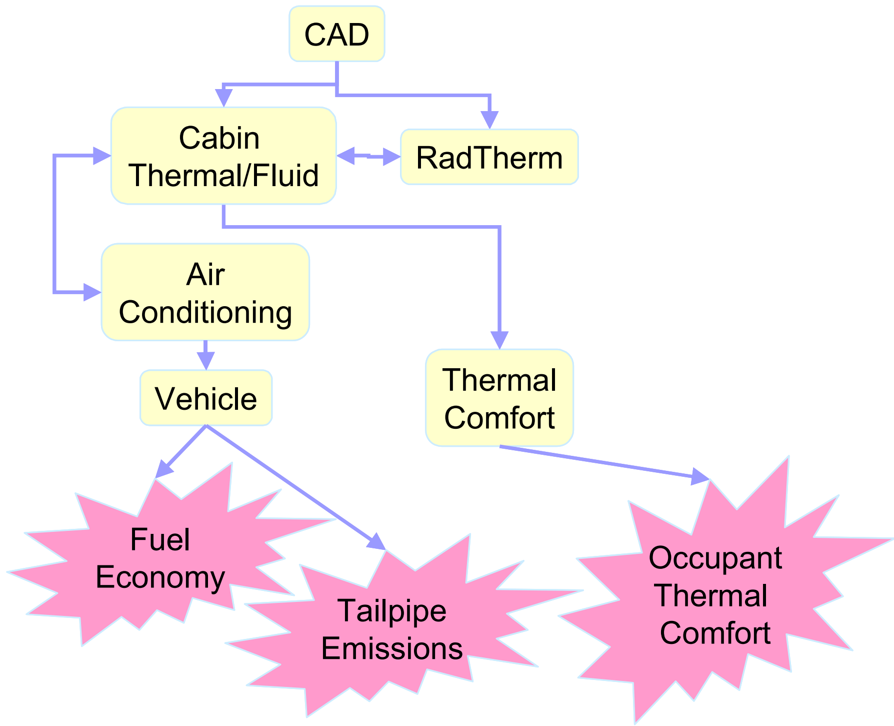

Figure 5. Vehicle integrated thermal modeling process

RadTherm was used to model the solar load on the vehicle, convection losses on exterior surfaces, and conduction through the surfaces. FLUENT CFD software was used to model the convective heat transfer and fluid flow in the cabin. We compared the model results with quasi-steady-state vehicle soak data to gain confidence in the model. Before we used the RadTherm software, we used VSOLE to provide the solar radiation boundary conditions and the FLUENT Discrete Ordinates radiation solver.

We found that excessive run times were needed to achieve a cooldown simulation using the full CFD/RadTherm model. Therefore, a simplified model was created for the cooldown simulations, which used only RadTherm. This simplified RadTherm model was compared with cooldown data for the vehicle.

Next, the vehicle was simulated using the ADVISOR vehicle simulator to determine the effect of the reduced A/C load on fuel use. We used two approaches for calculating the A/C power requirement on the engine, depending on the data available. In some cases, we used the transient A/C model described in section 2.1.2. When only bench data were available, we used a compressor power-versus-rpm curve. For a reduced thermal load case, we reduced the compressor power by the same percent reduction as the calculated percent reduction in capacity. We are assuming the reduced thermal load A/C system has the same COP as that of the baseline case.

We applied the integrated modeling process to a climate control system proposed by Johnson Controls Inc. The design consists of under-seat heating and cooling of air for the front and rear passengers and an air recirculation system in the instrument panel (IP). Instead of blowing conditioned air directly on the body, the system creates an envelope of conditioned air around the occupants in the front of the vehicle. The flow path lines from the CFD analysis are shown in Figure 6.

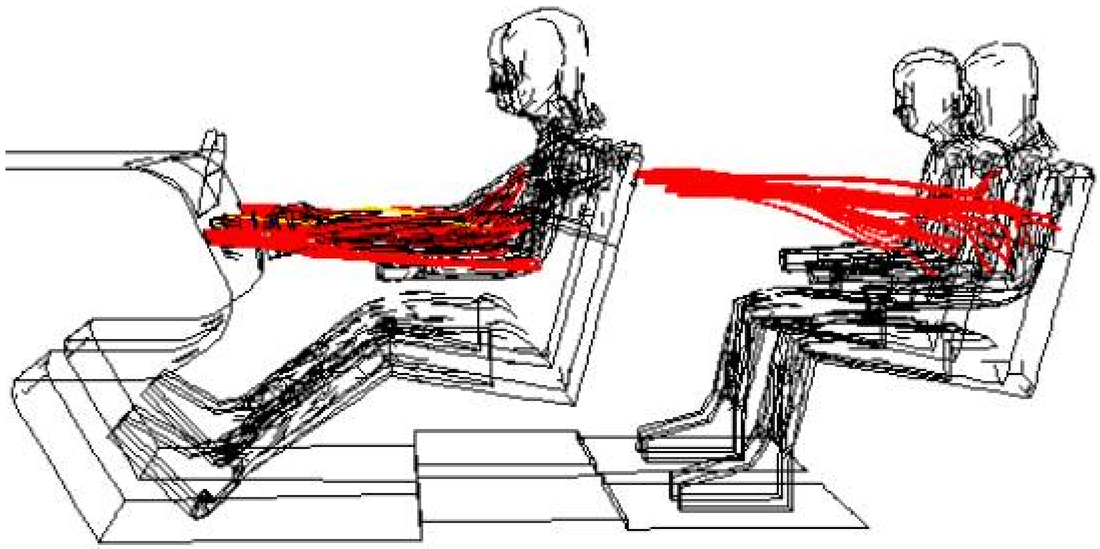

Figure 6. Flow path lines from body coolers

This distributed heating, ventilating, and air-conditioning (HVAC) system improves the driver and front passenger's comfort levels compared with those of a baseline vehicle. The overall equivalent homogeneous temperature (EHT) of the driver was reduced by 1.9°C, while the overall passenger EHT was 1.3°C lower. Since comfort is enhanced, there is potential to use a smaller A/C system compressor while maintaining comfort. Another benefit of a distributed HVAC system is that the passenger side of the system can be turned off if that seat is not occupied. Both actions would reduce A/C fuel use.

As part of SAE's Improved Mobile Air Conditioning Cooperative Research Program (I-MAC), the integrated modeling process was applied to a Cadillac STS vehicle with thermal load-reduction technologies that included solar-reflective glass, solar-powered parked-car ventilation, and solar-reflective paint. A combination of these technologies reduced breath air temperature by 12°C (22°F), seat temperatures by 11°C (20°F), the windshield temperature by 20.4°C (37°F), and the instrument panel surface temperature by 16.8°C (30°F). The vehicle simulation showed that reducing the A/C load by 30% resulted in a 26% reduction in A/C fuel use. Figure 7 shows the CFD mesh of the Cadillac STS, and Figure 8 shows the air temperatures in the baseline Cadillac STS.

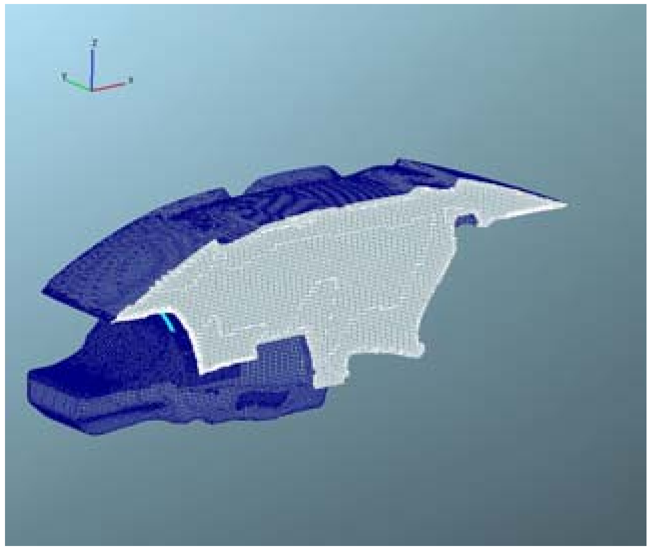

Figure 7. CFD mesh of Cadillac STS

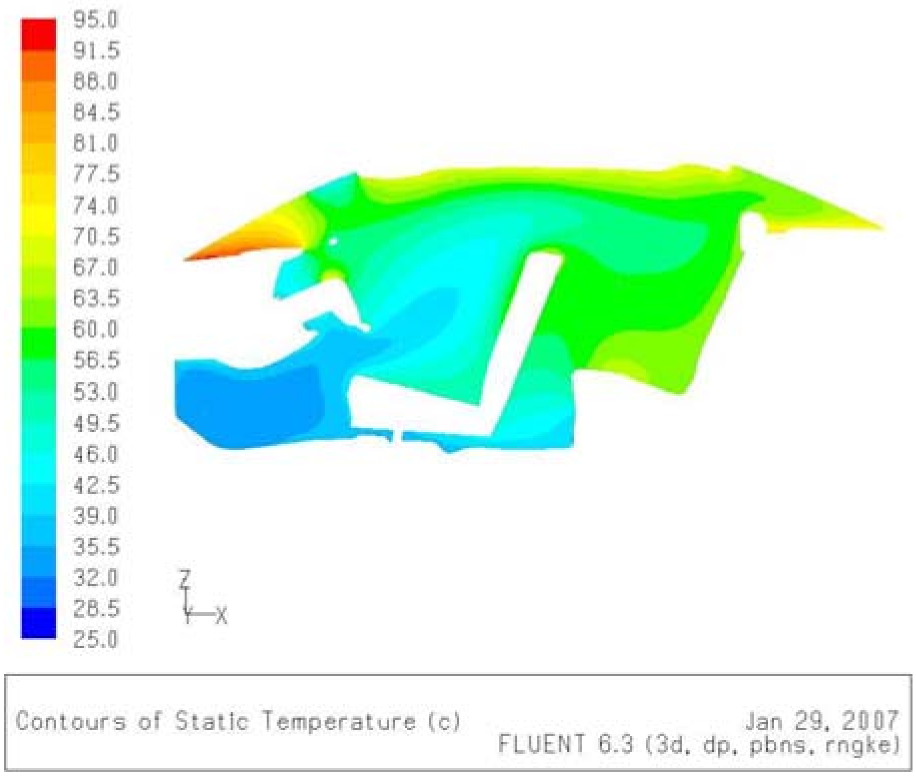

Figure 8. Air temperature contours in a baseline Cadillac STS

2.1.5 Integrated Heat Exchanger/Thermoelectric Power Generation Analysis Tool

NREL investigated the use of thermoelectric (TE) devices to capture energy from a vehicle's waste heat. Researchers developed an integrated heat exchanger/thermoelectric power generation system analysis tool in the MATLAB/Simulink environment. The tool's capabilities are as follows:

- Simultaneously analyzes heat exchanger and TE device performance
- Optimizes the performance of each to obtain the highest system efficiency and power output
- Outputs the optimum design parameters as a function of hot-side and cold-side temperatures
- Integrated with NREL's ADVISOR software.

The integrated system analysis approach allowed NREL to simultaneously quantify the effects of important system design parameters on system performance and to maximize power output in a waste heat recovery system. The flexible TE property input format allowed NREL to analyze segmented-TE and single-TE material designs, including quantum-well and thin-film superlattice TE material designs. The tool was used to investigate potential TE system power output at various locations in the exhaust streams in light-duty and heavy-duty vehicles for a variety of thermal conditions.

Figure 9 shows the results of a 2-p/2-n segmented-leg TE design analysis. Peak powers of 333, 626, and 843 W are shown for various exhaust gas flow rates. Figure 10 shows the respective cold-side mass flow required. Power generation levels as high as 0.9 kW appear to be possible in light-duty vehicle exhaust flow streams; power generation levels as high as 6 kW appear to be possible in heavy-duty vehicle exhaust streams.

The interaction between heat exchanger and TE device performance creates critical system impacts that maximize TE system power outputs and define preferred hot-side and cold-side heat exchanger performance regimes. System power is strongly impacted by interface thermal resistances. Selecting superior TE materials can reduce system cold-side mass flow requirements significantly. Heat exchanger performance requirements to maintain stable TE system operation are much higher in heavy-duty vehicle exhaust stream applications (by a factor of 15-20) than in light-duty vehicle applications.

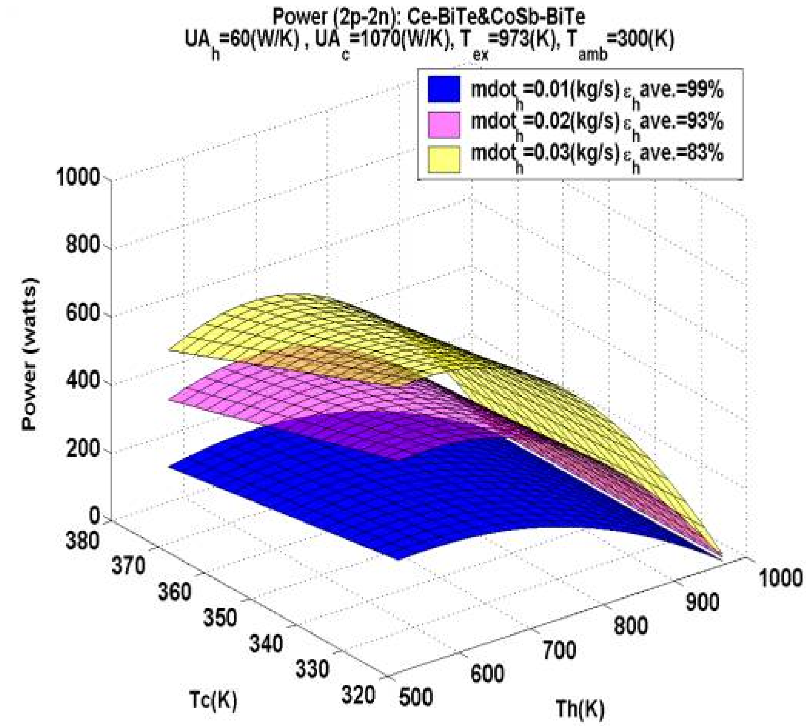

Figure 9. Thermoelectric power output vs. hot-side and cold-side temperature

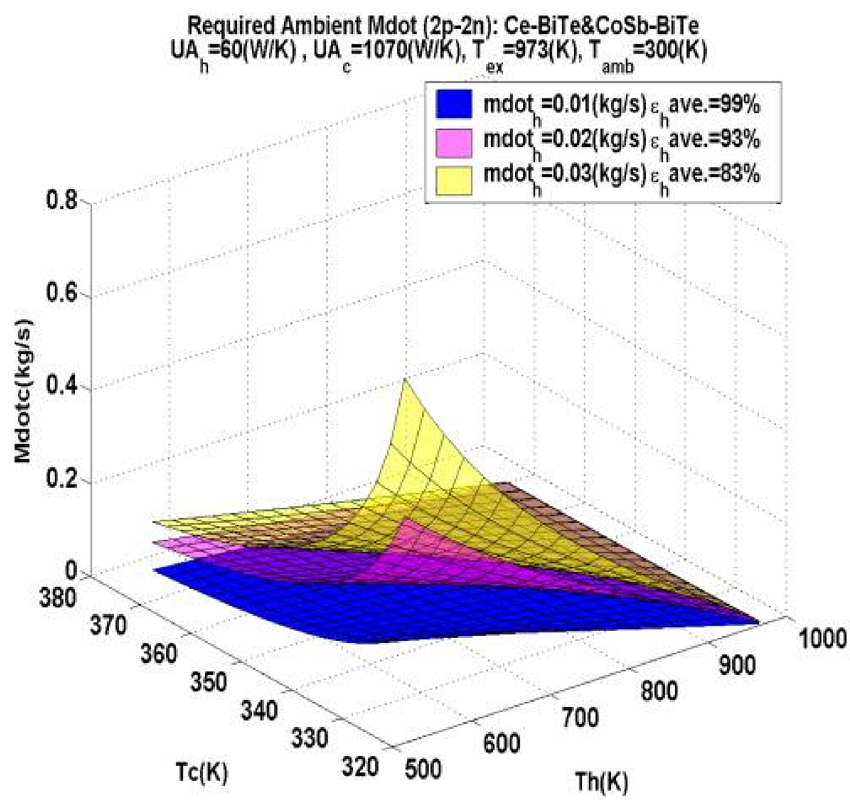

Figure 10. Required cold-side mass flow vs. hot-side and cold-side temperature

2.2 Vehicle and Component Testing

2.2.1 Solar-Reflective Glazing

When a vehicle is parked, typically 50% to 75% of the thermal energy entering the passenger compartment is from transmitted and absorbed solar energy at the glazings. Transmitted energy is primarily absorbed directly by the interior mass. The absorbed energy at the glazing is transferred to the interior by convection and reradiation in the thermal IR wavelength range. Reflecting incident solar radiation at the vehicle glazing is a critical step in achieving significant reductions in thermal loads.

A 3M nonmetallic solar-reflective film was soak-tested in two tan Dodge Grand Caravan minivans and two black Ford Explorer sport utility vehicles. The configuration with solar-reflective film on all the glazings had the best thermal performance, showing a 1.8°C (3.2°F) reduction in maximum breath temperature. The maximum instrument panel temperature was reduced by 3.4°C (6.1°F) in this case. These results were not as good as those for other solar-reflective technologies, but an advantage of the nonmetallic construction is that it does not attenuate electromagnetic transmission or reception from cell phones and other communication devices.

NREL and PPG Industries conducted a test program with Sungate laminated solar-reflective glass installed in a Ford Explorer to quantify improvements in fuel economy and reductions in tailpipe emissions. Sungate is a solar-reflective coating consisting of a double stack of silver and dielectric layers. The vehicle with the solar-reflective glazing at all locations had a maximum breath temperature 2.7°C (4.9°F) lower than that of the baseline vehicle, and the instrument panel was 7.6°C (13.7°F) lower.

NREL later tested a new type of solar-reflective glass on a 2005 Cadillac STS as part of the I-MAC program. The glass improves reflection of the near-IR portion of the solar spectrum. The test setup is shown in Figure 11.

Figure 11. Side-by-side Cadillac STS test for the I-MAC program

The Sungate EP allows only 3% of the infrared energy to be transmitted through the glass. Figure 12 shows that this technology at all glazing locations reduced the average air temperature by 7.1°C (12.8°F), seat temperatures by 8.7°C (15.7°F), the windshield temperature by 19.3°C (24.7°F), and the instrument panel surface temperature by 14.6°C (26.3°F). Another way to assess these data is in terms of the maximum possible temperature reduction. The solar-reflective glass in all locations reduced the average air temperature by 34% of the maximum possible and the seat temperature by 35%. Solar-reflective glass also reduces steady-state thermal loads when a vehicle is being driven with A/C on.

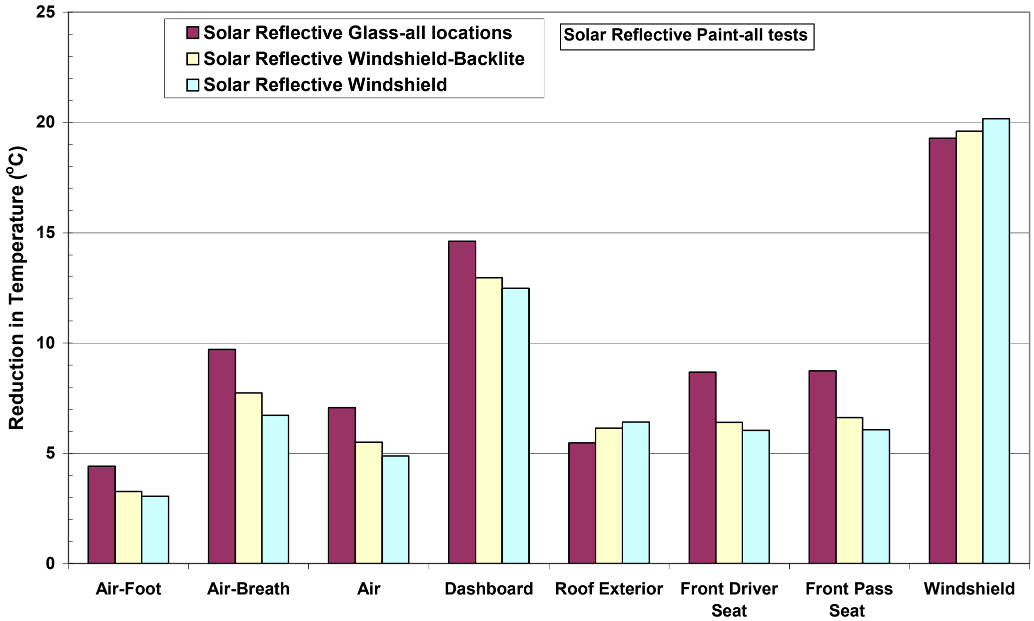

Figure 12. Temperature reductions from use of solar-reflective glass in a Cadillac STS

In cold environments, solar-reflective glass would also cause the temperature of a vehicle's interior to be lower than it would be with traditional glazing. In most of today's vehicles, drivers are used to a warmer than ambient passenger compartment when the sun is shining even if it is cold outside. With solar-reflective glazing, drivers will have to adjust their expectations to a cooler interior in the winter. However, interior temperatures would not be lower than ambient or than those already encountered in a vehicle after sunset.

2.2.2 Parked-Car Ventilation

When solar energy does enter the vehicle, it heats the interior mass of the passenger compartment and the air. Venting the warm air and pulling in cooler, ambient air can reduce the temperature of the interior. Therefore, NREL tested various natural and forced parked-car ventilation techniques on a 2000 Jeep Grand Cherokee (see Figure 13).

Figure 13. Jeep Grand Cherokee ventilation test setup

The results showed that natural-convection-induced flow can be effective with strategically located air inlets and that this technique was nearly as effective as forced convection ventilation with the HVAC blower running on medium speed. Figure 14 shows that having the sunroof open 6 cm and using floor inlets reduced the cabin's air temperature by 5.7ºC, 38% of the maximum possible temperature reduction, while running the HVAC blower on medium reduced the breath air temperature by 6.9ºC. Although having air enter the vehicle at the foot level enhances natural convection flow, implementation challenges for this technique include preventing moisture and contamination (such as exhaust products, dirt, and animals) from entering the vehicle through the inlets.

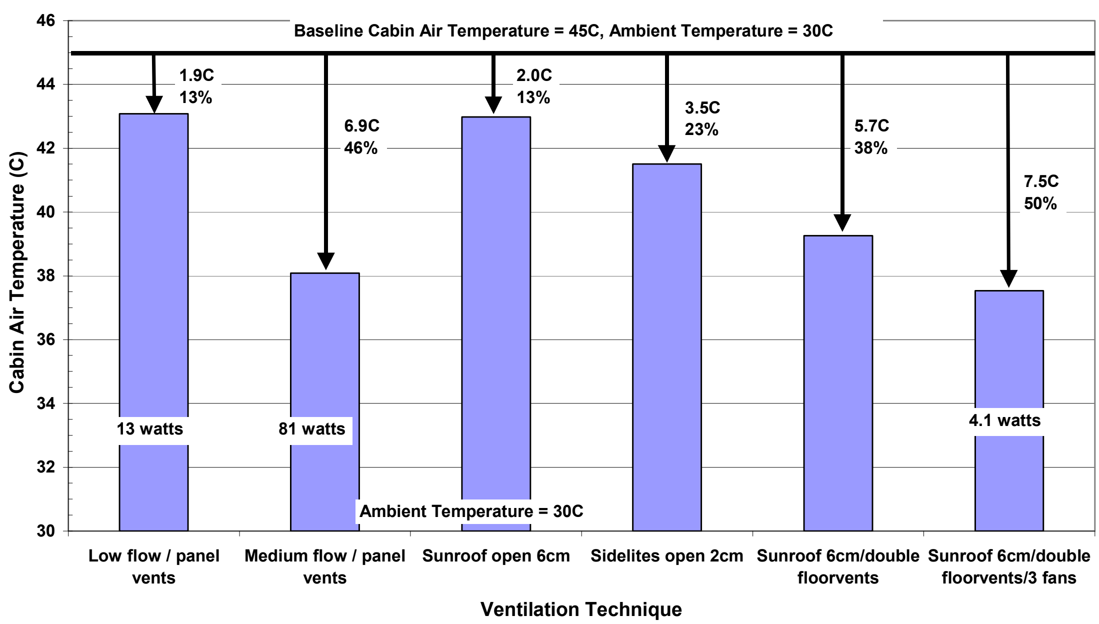

Figure 14. Parked-car ventilation in a Jeep Cherokee

As part of I-MAC thermal soak testing on the Cadillac STS, we also tested a solar-powered parked-car ventilation system. When air was pulled out of the vehicle, the average air temperature was reduced by 5.6ºC and seat temperatures were reduced by 5º-6ºC. These were 26% and 21% of the maximum possible temperature reductions, respectively. Air was pulled in through the HVAC heater/defroster ducts and natural vehicle body leakage areas. Even though they do not reduce temperatures as much as solar-reflective glass does, parked-car ventilation technologies can be used in conjunction with solar-reflective technologies to reduce interior temperatures significantly. Combining these technologies in the Cadillac STS reduced the average air temperature by 46% and the seat temperature by 44% of the maximum possible. The temperature reductions for the Sungate EP in all glazing locations and for solar-powered ventilation are shown in Figure 15.

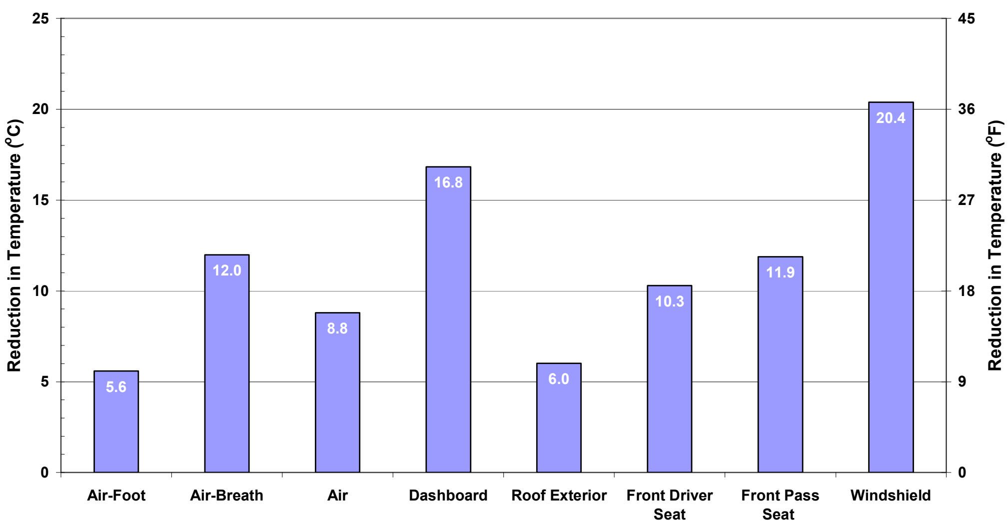

Figure 15. Sungate EP and ventilation temperature reductions in a Cadillac STS

2.2.3 Solar-Reflective Opaque Surface Coatings

If the exterior vehicle skin temperature is warmer than the interior surfaces, the resulting conduction heat transfer will warm the vehicle's interior. This is more likely to occur when solar-reflective glazing and (or) parked-car ventilation are used and the interior is cooler. Using a 2001 Lincoln Navigator, NREL investigated the impact of solar-reflective coatings on interior cabin temperatures on a parked vehicle.

We used two identical vehicles: one baseline and the other modified. A visibly reflecting roof film from 3M reduced breath air temperature by 12% of the maximum possible temperature reduction, which is defined as the difference between the baseline vehicle breath air temperature and ambient. The exterior surfaces were covered with aluminum foil to determine the largest potential reduction. The breath air temperature was reduced 28% relative to the maximum possible reduction for this case.

As part of the I-MAC project, we soak-tested a solar-reflective film on the roof of a stationary Cadillac STS in 2005. The film was an infrared reflecting product (CI-100T) manufactured by 3M. The baseline gray paint had a solar absorptance of 0.78, and the paint with the film had a solar absorptance of 0.55. The 6.7ºC cooler roof temperature resulted in less than a 1ºC reduction in the breath air temperature (Figure 16).

In the summer of 2006, we tested a prototype solar-reflective paint on the Cadillac STS. The new baseline paint had a solar absorptance of 0.89, and the solar-reflective paint had a solar absorptance of 0.82. The exterior surface temperature was 6.0ºC cooler than that of the baseline. The impact of paint by itself was not tested, but we estimate that the results would have been similar to the 2005 data. Table 1 summarizes NREL solar reflective coating data as well as data in the literature.

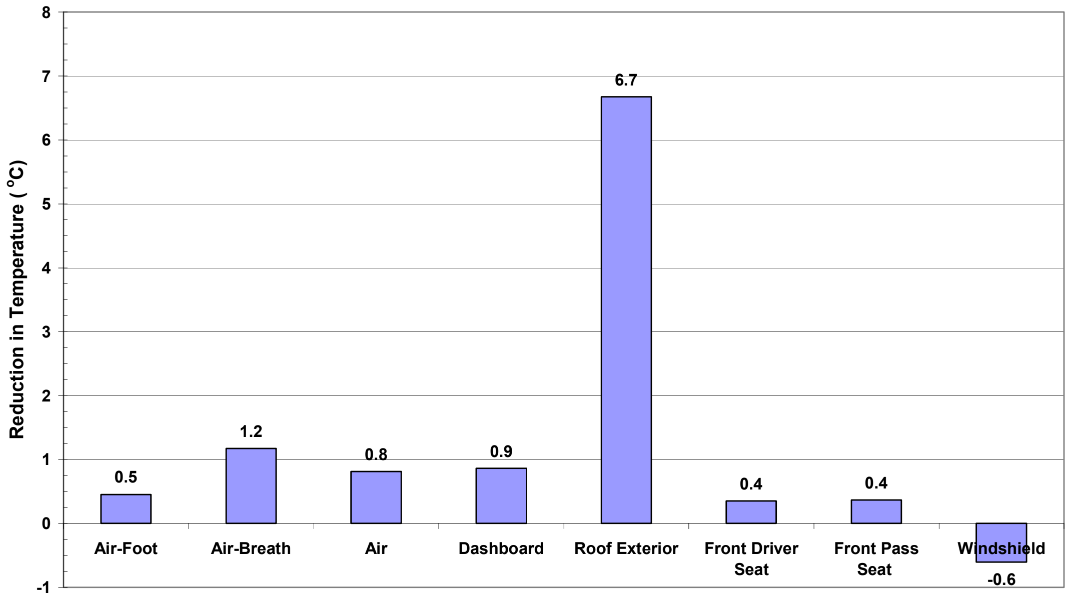

Figure 16. Solar-reflective roof temperature reductions in a Cadillac STS

While vehicle skin temperatures can be significantly reduced with these technologies, the impact on interior temperatures is not that large because 1) the majority of thermal load is entering though the windows, 2) the roof is typically insulated, and 3) wind reduces the advantage of the lower temperature skin by cooling the hot skin. If the vehicle is moving, the increased convective heat loss further reduces the thermal impact of the solar-reflective coatings on opaque surfaces.

Table 1. Overview of Solar Reflective Coating Data from NREL and the Literature

Vehicle	Source	Test Configuration	absorptance baseline	absorptance reflective coating	exterior surface temeprature reduction (C)	breath air temeprature reduction (C)	Comments
Ford Explorer	NREL internal test data	black vs white vehicle	est. 0.96	est. 0.4	-20	-2.1	
Lincoln Navigator	NREL VTMS8 paper, 20-24, May 2007, Nottingham, UK	red vs aluminum foil	est. 0.7	est. 0.15		-5.6	Used foil to assess the maximum possible roof temperature reduction
full sized SUV	Ford SAE paper 2005-01-1880	black vs solar reflective black	0.95	0.75		-2.7	Assumed breath temperature, location not clearly stated in paper
full sized SUV	Ford SAE paper 2005-01-1881	red vs solar reflective red	0.78	0.64		-1.3	Assumed breath temperature, location not clearly stated in paper
full sized SUV	Ford SAE paper 2005-01-1882	black vs white	0.95	0.5		-4.6	Assumed breath temperature, location not clearly stated in paper
Cadillac STS	NREL SAE paper 2007-01-1194	Metallic silver vs 3M solar reflective film over silver	0.79	0.55	-6.7	-1.2	film on roof only
Cadillac STS	I-MAC final report	Baseline gray paint vs PPG solar reflective gray paint	0.89	0.82	-6		paint not tested by itself, no data for breath air
B Class vehicle	Ihara presentation, IEA Workshop "Cooling Cars with Less Fuel", Oct 24, 2006	dark blue mica vs solar reflective dark blue mica	not reported	reduction of .04 to .44	-5 to -10	-1.6 to -3.9	Unclear what is meant by "anterior heading compartments", assumed breath for now

2.2.4 Window Shades

NREL assessed the impact of the use of window shades in the 2001 Lincoln Navigator thermal soak test program. Reflective shades manufactured by BOS were placed inside the cabin against the windows (Figure 17). Hooks near the windows held them in place, and a small air gap separated the shades from the windows. The reflective shades on all windows showed a temperature reduction of roughly 20% of the maximum possible reduction, based on the difference between the baseline vehicle's average air temperature and ambient. The upper instrument panel showed a reduction of 43%. Black shades manufactured by BOS were also tested in the Navigators. The average cabin air temperature increased in comparison to that of the baseline vehicle. Even though the shades block transmitted radiation, their higher temperature along with convection to the air in the cabin caused a net heat gain in the cabin.

Figure 17. Solar-reflective shades in a Lincoln Navigator

As part of the I-MAC project, we soak-tested a common, manually installed reflective shade behind the windshield and backlite of a stationary Cadillac STS in 2005. Although the test day was not completely cloudless, we were able to measure impacts during sunny periods.

The IP and breath air temperatures were reduced by 25ºC and 4ºC, respectively. The seat temperatures were reduced 5ºC, while the windshield temperature increased 8ºC.

Exterior mounted shades would be better than interior shades, but durability concerns are a barrier. Using shades would eliminate the need for solar reflective glass to reduce the solar load during a soak. However, reducing the solar load while the A/C is operating would improve comfort and reduce steady-state A/C fuel use. Note that using interior shades results in a hotter window after a soak and during the initial phase of a cooldown.

One technology that could be particularly beneficial is switchable, diffusely reflecting glazing. We are not aware of a functional prototype in existence, but some suppliers are conducting research in this area. In theory, it would work as follows: the car is parked in the sun and the glazing is activated to park mode, becoming reflecting. When the driver returns, the glazing goes back to its driving state. The power required would have to be low to allow for long periods of time when the vehicle is parked, and a fail-clear logic would be needed to mitigate safety concerns.

2.2.5 Insulation

The benefit of headliner insulation depends on exterior surfaces and interior temperatures. If the interior is warmer than the exterior, then increasing the insulation in the headliner will make the car warmer. However, if solar-reflective glazing and (or) parked-car ventilation are used to cool the car, headliner insulation may reduce the heat gain of a parked car.

A CFD analysis of a Jeep Grand Cherokee resulted in only a 0.2ºC reduction in the average cabin air temperature due to the insulation in the roof. Advanced technology insulation on the roof of the Lincoln Navigator reduced the cabin breath air temperature by 5% of the maximum possible. In a Cadillac STS, adding insulation based on today's technology had little impact on interior soak temperatures.

Insulation was not very effective in reducing parked-car thermal loads in conventional vehicles. If the thermal loads are reduced first with solar-reflective glass or ventilation, insulation could become more important. When the A/C of a vehicle in use is operating in a warm outdoor environment (e.g., in summer), added insulation would reduce thermal loads. In winter, when the interior is warm and the outdoor environment is cold, insulation would help to reduce the heating load. In the United States, cabin heating is not an issue with today's vehicles because waste heat is available. But this will be a challenge for advanced vehicles and small diesels that have less (or no) waste heat available to warm the cabin.

2.2.6 Climate-Control and Low-Mass Seats

Increasing delivery efficiency means providing climate control more effectively to each vehicle occupant, thereby increasing thermal comfort with a net decrease in energy consumption. Automotive seats have the potential to improve delivery efficiency because of their large contact area with, and proximity to, occupants. A standard automotive seat thermally insulates the occupant and reduces evaporative cooling of perspiration, thus increasing the occupant/seat contact temperature. Both actively ventilated seats and meshed seats are potentially low-energy approaches to improving both thermal comfort and climate control delivery efficiency.

The NREL Vehicle Climate Control Laboratory was developed to simulate thermal soaking and cooldown of a vehicle passenger compartment (Figure 18). A compact car passenger compartment was thermally soaked for 3.5 hours using a 963 W/m^2 ± 23% full spectrum solar simulator. The average room environment was controlled to 31.6°C ± 0.4°C and 30% ± 5% relative humidity. Both the ADvanced Automotive Manikin (ADAM), which will be discussed in a later section, and human subjects were first conditioned in an office environment. ADAM (see Figure 19) and a subject then entered the heat-soaked room, and the subject stood for 30 seconds before doing step exercises for 1 minute. The cooldown began 45 seconds after cabin entry, allowing time for pre-cooldown evaluations to be made.

Figure 18. Vehicle Climate Control Laboratory with solar lamps

ADAM was also used to test ventilated seats provided by W.E.T. Automotive Systems. ADAM recorded a seat contact temperature reduction of ~4.7°C when the ventilated seat was on and an increase in heat loss from the back and the bottom of ~60 W/m^2 when the ventilated seat was on in comparison to when it was off. This resulted in an overall thermal sensation improvement of 0.28 (on a +4 to -4 scale where positive values indicate that one is feeling hot, and negative values indicate that one is feeling cold.). The average evaluation of thermal comfort over the cooldown is shown in Figure 20. We estimate that using ventilated seats could allow the A/C system capacity to be reduced by 7%. NREL's A/C fuel use model indicated this could result in an estimated 522 million gallon/year reduction (7.5%) in U.S. A/C fuel use.

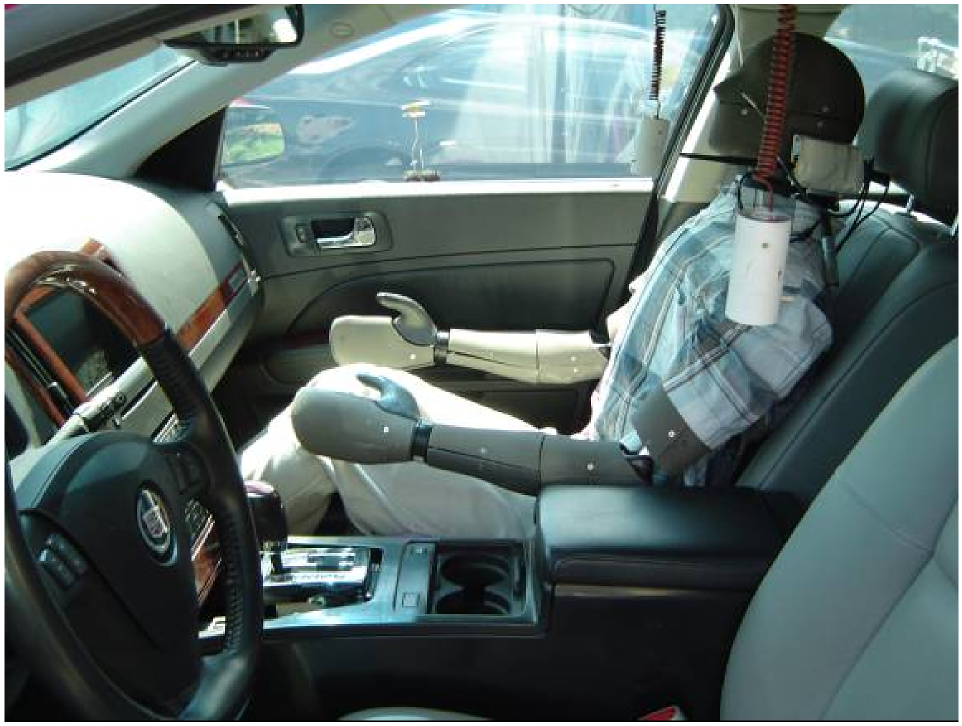

Figure 19. ADAM testing a W.E.T. ventilated seat

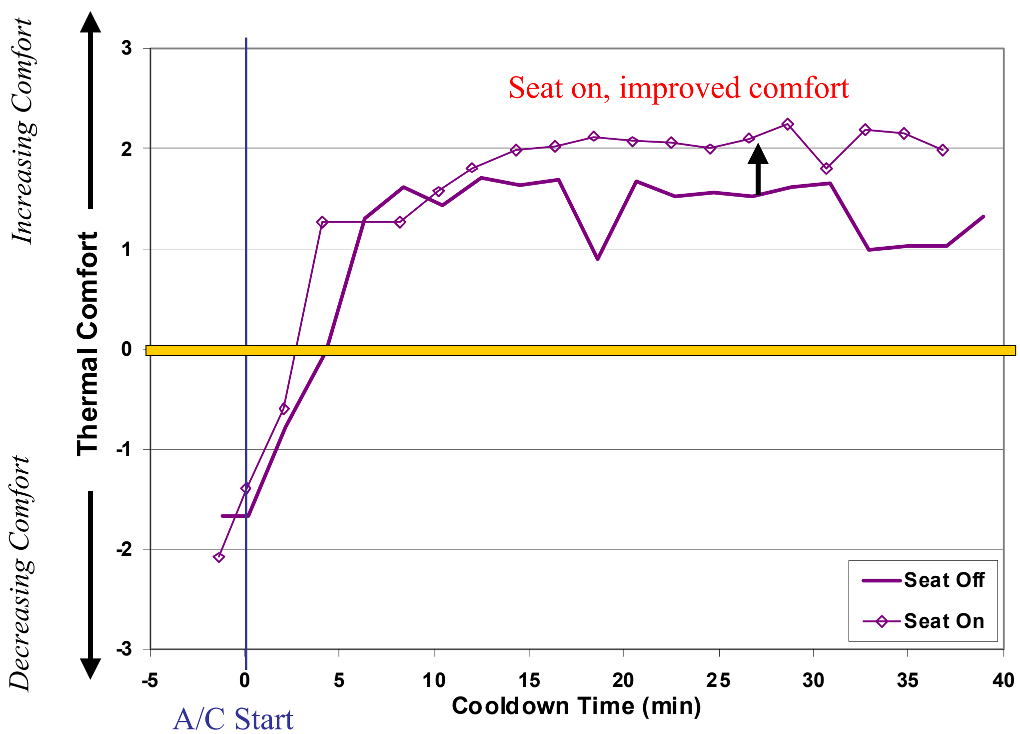

Figure 20. Thermal comfort with the ventilated seat off and on

A prototype seat with a meshed back was also tested, with encouraging results. Using a reduced, 96% heat capacity A/C system, we observed an average seat back and bottom temperature reduction of 4° and 0.6°C, respectively. Assuming that using a meshed bottom would provide results similar to those for the meshed back, much of the thermal benefit gained through ventilation could be achieved using low-mass meshed seats, and energy costs would not increase. One disadvantage of mesh seats, however, is that they increase body cooling during cold-weather driving. Traditional seats insulate the back, but a low-mass seat would cause heat loss from the back during winter. Occupants might find this heat loss uncomfortable, especially if they are expecting an insulated seat. So, the lack of thermal control, physical ergonomics, and safety are some remaining challenges for mesh seat technologies.

2.2.7 Instrument Panel Heat Pipe Cooling

When a vehicle is parked, the instrument panel can absorb a large amount of heat, attain temperatures approaching 100ºC, and impact drivers' thermal comfort and cooldown performance. Researchers constructed a mock-up of a passenger compartment and instrument panel to assess the impact of using heat pipes to cool the instrument panel (Figure 21). Experimental results demonstrated IP surface temperature reductions of 20° to 30°C during maximum solar intensity environments of 525 to 800 W/m^2 (which are typical of Golden, Colorado, from January to April), in comparison to un-cooled conditions.

The heat pipe's cooling effect in the IP also reduced windshield temperatures by 9° to 12°C compared with those of the non-cooled configuration in the April 2001 testing. A cooler IP and windshield would significantly improve the thermal comfort of the driver and passengers in a typical vehicle cabin. In addition, Figure 22 shows how IP cooling reduced cabin air temperature by 4° to 10°C during long-term vehicle thermal soak conditions in these tests. Figure 23 provides a summary of the temperature reductions for the various tests.

Freeze/thaw tests were also conducted on the heat pipe systems in the IP cooling demonstration at NREL. All the heat pipes survived the freezing event, and all but one heat pipe demonstrated the ability to start up and operate normally in both an evaporator-led and a condenser-led thaw process. Besides having lower surface temperatures, the electronic components in the IP would also benefit from the lower temperatures as well as the reduced heat pickup of the airflow in the A/C ducts. However, there are barriers to incorporating heat pipes in the IP. These include the need for increased mass, volume, and cost for the pipes as well as the best place to locate the condensing section outside the cabin.

Figure 21. Mockup of passenger compartment for testing heat-pipe IP cooling

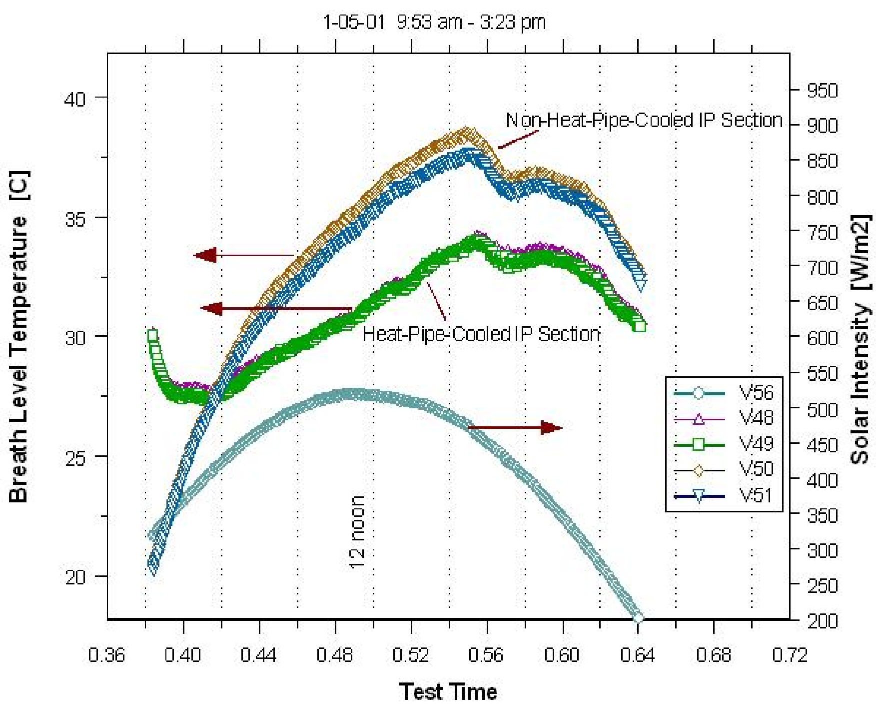

Figure 22. Temperatures of a heat-pipe-cooled and non-cooled IP

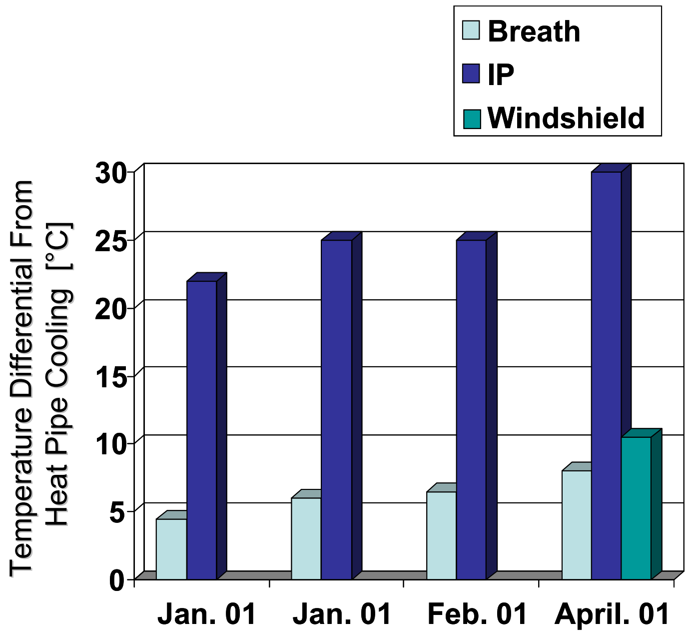

Figure 23. Temperature reductions resulting from heat-pipe cooling

2.2.8 Waste Heat Utilization: Thermoacoustics

Thermoacoustics is an innovative technology that uses sound to provide cooling or produce electricity. Thermoacoustic effects, which convert heat energy to sound, have been well understood for more than 100 years. However, substantial design improvements been made only over the past two decades in regard to thermoacoustic engines and refrigeration cycles. Recently, thermoacoustic refrigerators have flown on the space shuttle, cooled electronics in a U.S. Navy destroyer, and cooled Ben and Jerry's ice cream.

Thermoacoustics has many potential advantages over a conventional A/C system to cool a vehicle cabin. For example, it uses waste heat, is reliable and inexpensive, does not place an extra energy load on the engine, relies on gases that are environmentally benign, has no moving parts (thus a device should last a long time), and requires no lubrication. The downside is that, because of its low energy density, a thermoacoustic device could take up significant volume. If we can overcome that barrier, it could be one of the cooling technologies in your next-generation car.

During the last quarter of 2004, NREL designed and developed a standing-wave thermoacoustic device that pumps heat using a standing sound wave to take the working fluid (helium) through a thermodynamic cycle. We relied on the heating and cooling that accompany the compression and expansion of a gas in a sound wave to produce cooling for the interior of a vehicle. The device was modular and allowed different stack designs and heat exchangers to be used in order to assess the most cost-efficient and best-performing components.

Modeling showed that a thermoacoustic standing-wave engine and heat pump has a heat efficiency of approximately 15% and a heat pump COP of approximately 1. An NREL research team finished testing a standing-wave thermoacoustic engine and heat pump in early

2005. The thermoacoustic engine performed within 10% of the modeled results. However, the heat pump provided only 20 W of cooling. The poor performance of the heat pump was attributed to combining the room temperature heat exchanger for both the engine and heat pump into a single unit. Researchers determined that the pressure wave from the engine has to be fully developed before it can be used in cooling. This problem can be rectified easily by separating the heat engine from the heat pump and incorporating two ambient heat exchangers. Although the standing-wave thermoacoustic system works, it has to be too large to generate sufficient cooling power for a light-duty vehicle. Therefore, NREL researchers concentrated their efforts on developing a smaller, traveling-wave thermoacoustic system.

In 2006, the NREL team assembled and tested a traveling-wave thermoacoustic engine (Figure 24). Like the standing-wave prototype, the traveling-wave system was modular, allowing different components (such as heat exchangers and regenerators) to be tested. We were particularly interested in testing a microchannel regenerator and copper foam heat exchanger.

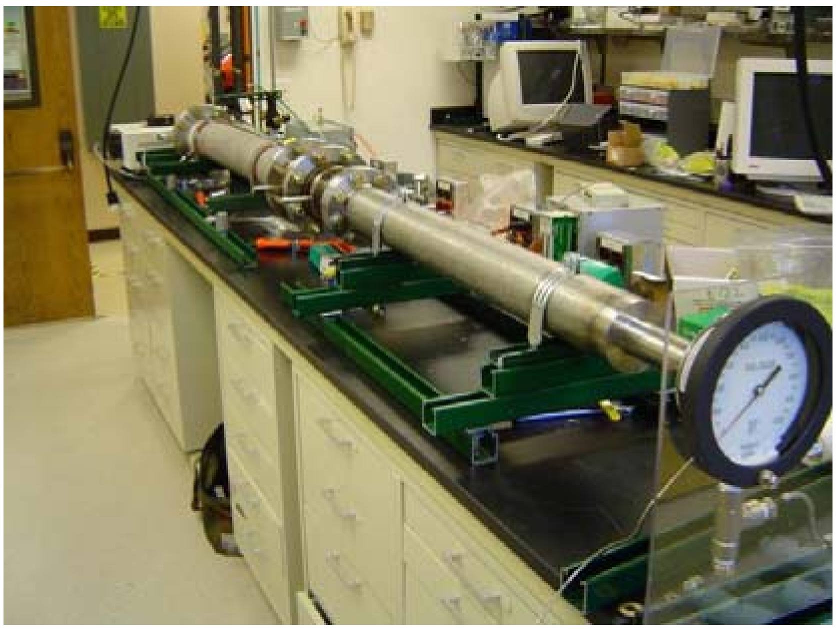

Figure 24. Traveling-wave thermoacoustic test setup

The regenerator is an important component in a traveling-wave system because it amplifies the sound. Our modeling indicated that the microchannel regenerator would approximately double the total acoustic power output and increase the conversion efficiency of heat to acoustic power by 15% in comparison to traditional wire mesh regenerators. Figure 25 shows a microchannel regenerator with rectangular flow passages measuring 1 mm by 0.075 mm. This microchannel regenerator did not perform as expected, however. Rather than reducing viscous losses, the soldering technique and the method used to trim the shims increased the viscous losses in the regenerator. Furthermore, the spacing between plates within the regenerator was uneven, which led to further losses in efficiency.

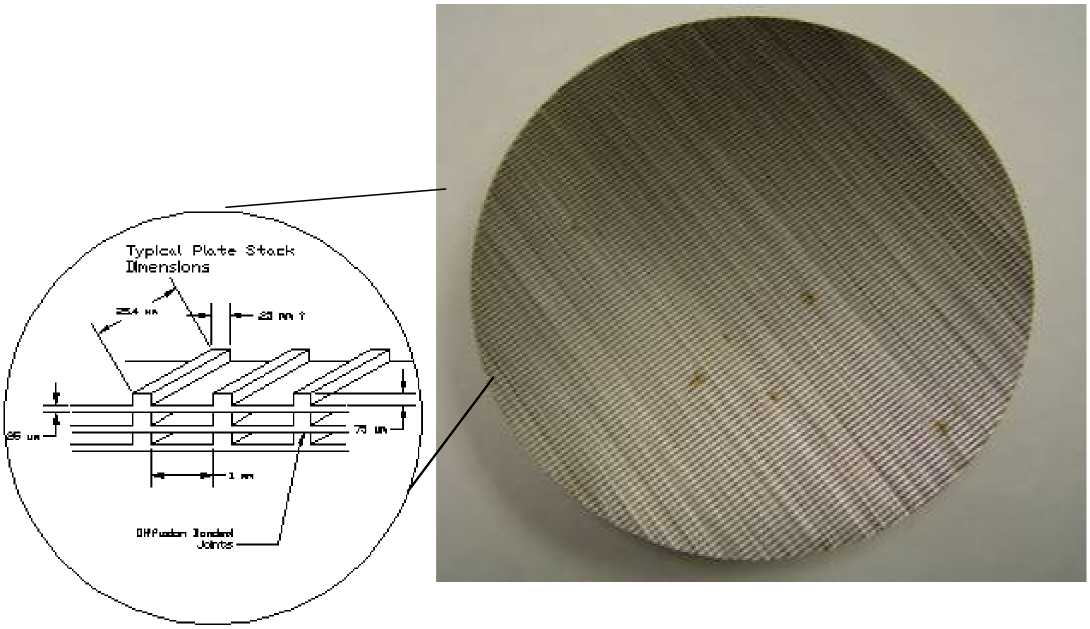

Figure 25. Microchannel regenerator prototype for a thermoacoustic generator

The copper foam heat exchanger shown in Figure 26 was used in hope of eliminating the hundreds of welds used in traditional shell-and-tube heat exchangers for thermoacoustic systems. The copper foam heat exchanger design also eliminated the need for penetrations into the pressure vessel. Instead, it relied on heat conduction through the pressure vessel walls and the copper foam to exchange the hot vehicle exhaust gas with the thermoacoustic working fluid.

Unfortunately, there was a very large temperature difference across the surface of the copper foam heat exchanger. That large temperature difference resulted in non-uniform amplification of the incoming sound. It also has the potential to cause jet or convective streaming, reducing the overall efficiency of the thermoacoustic device.

Figure 26. Copper foam heat exchanger for a thermoacoustic system

NREL researchers determined from the modeling and test results that a traveling-wave thermoacoustic system for direct vehicle cooling will not be viable for light-duty vehicles because the resonant cavity needed is too large. To decrease the cavity's size, a new combination of gases and working fluid is needed that will lower the resonant frequency of the device without reducing the power-per-unit volume.

One way to reduce the length of the resonant cavity is to combine a heavier gas with a lighter gas. Unfortunately, combining gases precipitously reduces the power-per-unit volume, and the result is an unrealistically large device diameter to provide the cooling needed. However, we determined that a traveling-wave thermoacoustic system could in fact be used in light-duty vehicles for electricity generation. Electrical power could be produced through the use of a flexible membrane, which would also determine the resonant frequency of the thermoacoustic system and, therefore, its size. Future work should focus on reducing the cyclical fatigue of such a membrane for eventual integration into light-duty vehicles.

2.2.9 Indoor Air Quality

After reducing the peak thermal load and solar gain, the next most important approach to minimizing A/C loads is to reduce the amount of outside air brought in for ventilation. It is more effective to condition recirculated cabin air than to treat very hot air brought in from outside (or very cold air in the case of cabin heating). Increasing the 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 found when the vehicle is either in heating mode (e.g., cold windows) or in cooling mode (e.g., cooled seats, pipes, or ducts). In addition, a microbial examination of the A/C system of a 1996 Chevrolet Lumina provided an example of what comes out of a vehicle's vents. Figure 27 shows the resulting bacterial growth and Figure 28 shows the fungal growth that occurred after a 10-minute exposure to the A/C vent flow.

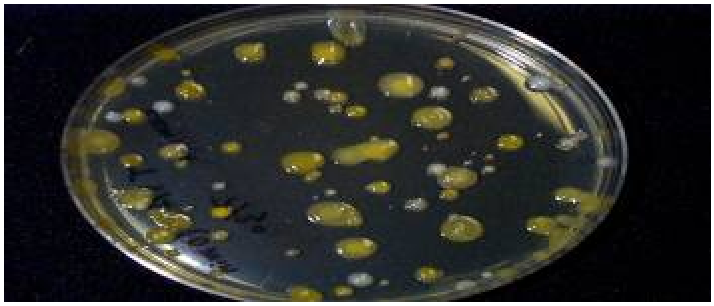

Figure 27. Bacterial growth from a 10-minute A/C vent outflow

Figure 28. Fungal growth from a 10-minute A/C vent outflow

Techniques such as photocatalytic oxidation (PCO) can reduce VOCs and odors in a vehicle's cabin. NREL's PCO device uses a room-temperature, low-pressure-drop process that traps and oxidizes VOCs and bioaerosols in the vehicle. The system, shown in Figure 29, operates with ultraviolet light and a titanium dioxide catalyst. It is inexpensive and requires minimal maintenance. We measured significant reductions in formaldehyde, acetaldehyde, and acetone while testing this device.

Figure 29. A prototype photocatalytic air-cleaning system

2.2.10 Boundary Layer Capture

Section 2.2.4 described the Lincoln Navigator test data that showed interior window shades can trap warm air and result in warmer cabin air temperatures. One way to avoid this situation is to vent the warm air layer between the window and shade. Small fans were integrated with low-flow exhaust plenums to extract thermal boundary layers from window shading devices. A mockup of a boundary layer capture system is shown in Figure 30. 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% to 50% less airflow than strategies that ventilate the entire interior of the vehicle. Removing hot boundary layers is more effective than letting heat mix within the vehicle and then trying to bulk-ventilate the entire interior.

Figure 30. Boundary layer capture mockup

2.2.11 Electrochromic Sunroof

An electrochromic window is an example of a shading technology that is built into the glazing. We built an electrochromic sunroof using samples from OCLI. The transmissivity of electrochromic glazing can be controlled to be clear, opaque, or partially clear with separate driver and passenger controls to adjust solar gains while the vehicle is parked or being driven. Electrochromic windows, which change transmissivity with an applied voltage of as little as 2 V and only a few milliwatts, can be made in various colors. In principle, electrochromic windows can be applied to the side glazing and backlite to control solar gains, match a vehicle's color for aesthetic purposes, and enhance security. Photovoltaics can be integrated into the electrochromic window to provide power needed to change the state of the window.

2.3 Thermal Comfort Tools

NREL developed a suite of thermal comfort tools to help develop smaller and more efficient climate control systems in automobiles. These tools consist of the thermal comfort manikin described earlier, a physiological model, and a psychological model linked together to assess comfort in a transient, nonhomogeneous environment. The manikin and models have been validated by comparison with physiological data that are available in the literature and with test subject data used to develop the psychological model.

The integrated human thermal comfort system consists of a thermal manikin controlled by a finite-element physiological model of the human body. The thermal manikin is a surface sensor that measures the rate of heat loss at 120 independently controlled zones. The skin heat transfer rates are sent to the physiological model, which computes the skin and internal temperature distribution and surface sweat rates. This information is then sent back to the manikin, which generates the prescribed skin temperatures, surface sweat rates, and breathing rates. As the model steps forward in time, this loop provides a transient measurement tool. The psychological comfort model uses temperature data from the physiological model to predict local and global thermal comfort as a function of local skin and core temperatures and their rates of change. Using this manikin as a sensor simplifies the complexities of heat transfer from clothing and the environment into local heat loss measurements from the skin.

2.3.1 ADvanced Automotive Manikin

The thermal manikin is approximately 175 cm tall and was sized to represent dimensions of a western person in the 50th percentile (Figure 31). ADAM weighs approximately 61 kg, which is heavy enough to compress an automotive seat and provide a realistic contact area. The manikin's skeleton is composed of laminated carbon fiber, which supports its structure, houses all internal components, and provides mounting locations for surface zones.

The manikin's fundamental components are the 126 individual surface segments, each with a typical surface area of 120 cm^2. Each segment (Figure 32) is a stand-alone device with integrated heating, temperature sensing, sweat distribution and dispensing, a heat flux gauge, and a local controller to manage the closed-loop operation of the zone. The high thermal conductivity of the all-metal sweating surface increases thermal uniformity and speed of response. A high-porosity layer within the surface provides lateral sweat distribution, while the lower porosity of the exterior promotes uniform sweat across the surface.

Distributed resistance wire provides uniform heating across the zone surface. Six segments are controlled in pairs, for 120 separately controlled zones. A single zone controller, including flow control, is mounted directly on the back of each segment. The skin temperature of each zone is determined by an array of thermistors (typically, four) on each zone. A heat flux gauge integrated onto the internal surface of each zone measures heat transfer between the surface zones and the internal body cavity.

Figure 31. ADAM, the ADvanced Automotive Manikin

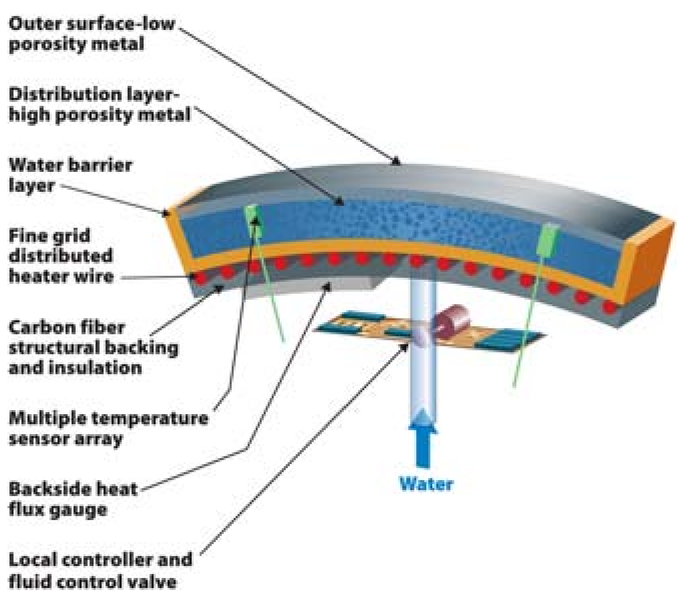

Figure 32. Cross section of a segment of the manikin

ADAM was built by Measurement Technology Northwest, Seattle, Washington. The characteristics that make ADAM a unique thermal manikin are as follows:

- High spatial resolution (120 zones)
- Self-contained
- Uniform sweating and heating over the entire area of the manikin
- Finite-element physiological model control.

2.3.2 Human Thermal Physiological Model

The NREL Human Thermal Physiological Model is a three-dimensional transient finite-element model of the human body. The model simulates human internal thermal physiological systems, such as muscles, blood, and thermoregulatory responses. The model was developed using ANSYS commercially available finite-element software. This software computes heat flow by conduction, convection, and mass transport of blood. The arms and legs consist of bone, muscle, fat, and skin. There are additional lung and abdominal tissues in the torso and brain tissues in the head. The finite element mesh is shown in Figure 33.

Blood flow is modeled with a network of supply and return pipe elements within each body zone (Figure 34). The diameter of the pipes decreases from the center of each zone outward, toward the skin and extremities. The thermoregulatory system controls physiological responses, such as vasoconstriction/dilation, sweating, shivering, and metabolic changes.

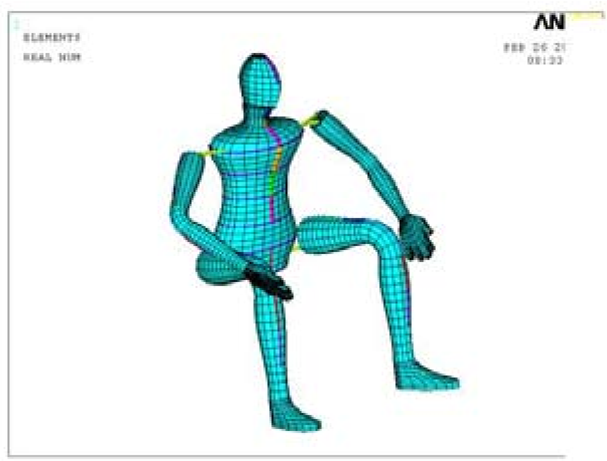

Figure 33. Physiological model finite-element mesh

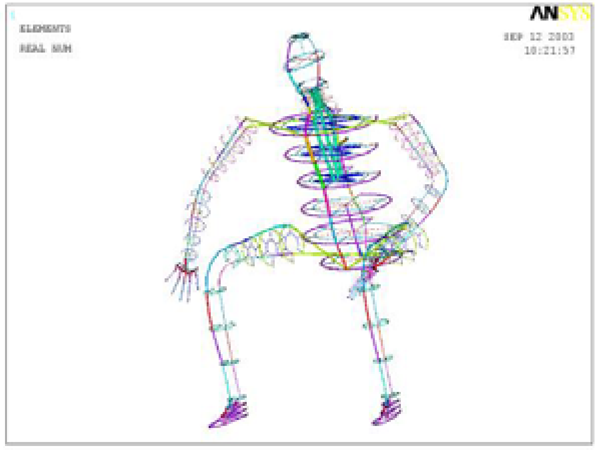

Figure 34. Physiological model depiction of circulatory system

2.3.3 Human Thermal Comfort Empirical Model

Under a subcontract to NREL, a researcher at the University of California, Berkeley, performed 109 human subject tests in its Controlled Environmental Chamber under a range of steady-state and transient thermal conditions. The tests were conducted to explore the relationship between local thermal conditions and the perception of local and overall thermal comfort. Core and local skin temperature data and subjective data were used to develop a predictive model of thermal sensation and perception. The relationship between the model's inputs and outputs is shown in Figure 35.

The researcher concluded that overall comfort is not an additive function of all local perceptions but is instead "complaint"-driven. This means that the most uncomfortable body parts drive the overall perception of thermal comfort. However, we encountered some difficulties in using this approach. Using the data available, we found a straight average to be a better predictor of subjective responses.

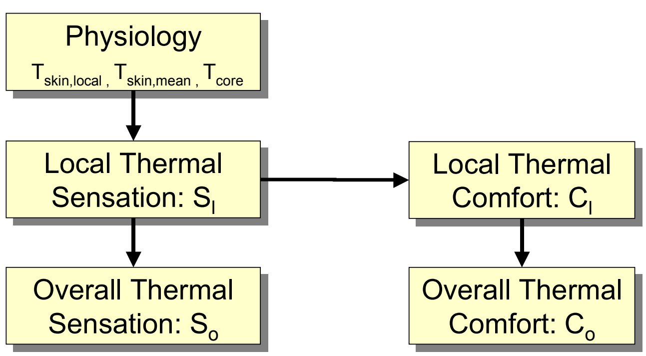

Figure 35. Thermal comfort correlation data flow

2.3.4 Nonautomotive Applications for Thermal Comfort Tools

NASA currently uses liquid cooling garments (LCGs) under spacesuits to remove heat from the human body during a spacewalk. Thermally conditioned liquid is circulated through small tubes distributed around the suit. We used ADAM to assess a Shuttle LCG (Figure 36) as well as an Orlan LCG, a Russian-designed cooling garment. NASA uses a comfort curve to determine the inlet flow temperature as a function of metabolic rate for the Shuttle LCG. We tested three points on the curve and two points off the curve.

Figure 36. ADAM in a NASA Liquid Cooling Garment

The core temperature for the Orlan LCG was an average of 0.06ºC lower than that of the Shuttle LCG in all tests. Since the sweat rate is a function of core temperature in the model, the Orlan LCG also had lower sweat rates. Heat transfer to the LCG fluid was, on average, 15 W greater for the Orlan suit, indicating better heat transfer in comparison to that of the Shuttle LCG. This resulted in lower core and skin temperatures. The less-than-perfect fit on the upper back of the Shuttle LCG prevented a good comparison of thermal sensation and comfort.

Constant skin temperature tests showed that sweat impacts the performance of LCGs through increased thermal conductivity resulting from moisture between the skin and the tubes and condensation on the tubes. A comparison of skin temperatures from a model control run with NASA subject data showed reasonably good correlation. ADAM may have overestimated the leg temperature because he did not walk like the subjects did.

We also used NREL's thermal comfort tools to assess technologies to maintain the thermal state of a patient during a medical evacuation, as part of a test program funded by the U.S. Army Aeromedical Research Laboratory (USAARL). Injured persons arriving at a field hospital may be hypothermic. Environmental conditions during medical transport, along with a traumatic injury, can make it difficult for human bodies to maintain thermal balance. We used our thermal manikin and Manikin Environmental Chamber to evaluate current and proposed thermal blankets to reduce or prevent hypothermia in patients during transport.

A wool blanket was used as the baseline, and the manikin was controlled with the physiological model (Figure 37). The electrical and chemical blankets generally resulted in warmer skin and core temperatures, although one of the electric blanket configurations resulted in a lower core temperature. This demonstrates the value of testing using a manikin and the risk of assuming that even an expensive electric blanket will reduce heat loss. With constant temperature control, using a chemical blanket with a radiation shield wrap resulted in the lowest heat loss. The electric blanket with the lower core temperature had a correspondingly higher heat loss compared with that of the wool blanket. Supplemental testing showed that heat loss can be significantly reduced in any configuration by placing a wool blanket between the patient and the mesh stretcher.

Figure 37. ADAM testing an army blanket

2.4 Test Facilities

2.4.1 Vehicle Climate Control Laboratory

The Vehicle Climate Control Laboratory (VCCL) at NREL was developed to simulate the thermal soak and cooldown of a vehicle passenger compartment. The test setup shown in

Figure 38 consisted of a compact car passenger compartment from A to C pillar, and an automobile A/C system. Environmental conditions were supplied by a full-spectrum solar simulator and room temperature and humidity control. The VCCL was used to assess the thermal comfort and fuel-use impacts of climate control seats (Section 2.2.6)

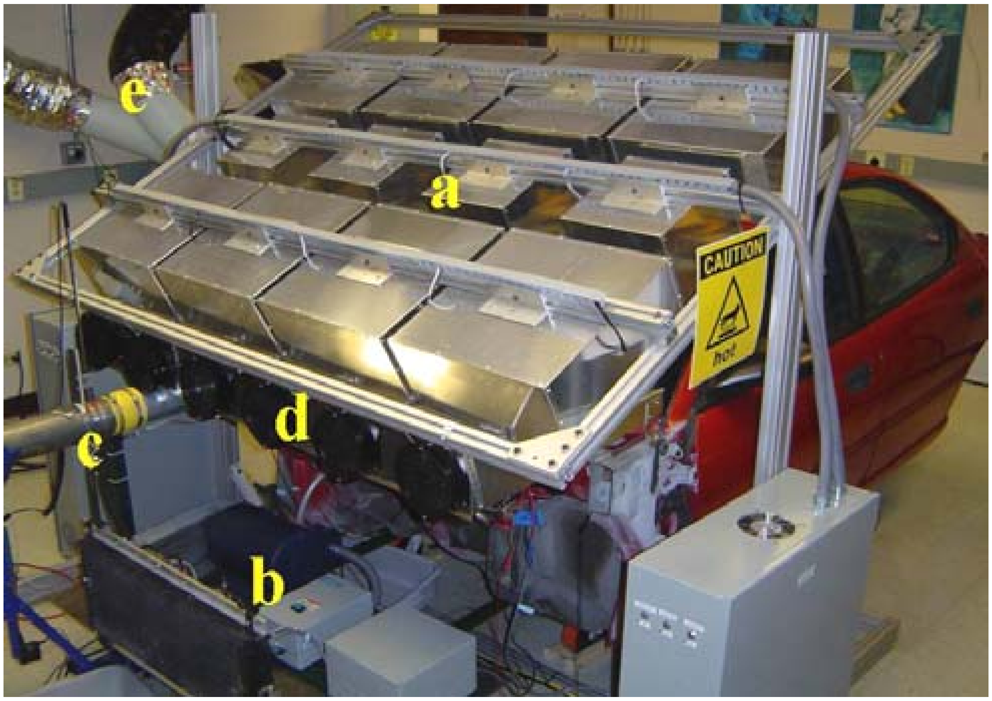

Figure 38. Vehicle Climate Control Laboratory

The solar simulator, “a” in Figure 38, had a mean irradiance of 963 $W/m^2 \pm 23\%$. Metal halide lamps were used to approximate the solar spectrum. The front of the car was illuminated because it was the area of primary interest in this study. Collimation of the light was not addressed because the simulator’s primary purpose was thermal loading.

Air-conditioning was simulated using an actual system with a belt driven by an electric motor, “b” in Figure 38. The change in the thermodynamic state was measured across the air side of the evaporator to allow calculations of heat removal to be made. To prevent the evaporator from overcooling or freezing, researchers used dead-band control of the evaporator’s exit temperature. This resulted in an average steady-state vent exit temperature.

A wind-flow simulator, “d” in Figure 38, was designed and built to blow air across the windshield and correct for the overheating resulting from the lack of reradiation and ambient air movement.

The temperatures in the test setup were taken at more than 80 locations, measuring both room and passenger cabin conditions. Concentric cylinder radiation shields were used to measure passenger compartment air temperatures.

To simplify the recording of a subject's evaluation of thermal comfort, the Vehicle Ancillary Load Reduction (VALR) team built a heads-up voting and driving simulation interface (Figure 39). This enabled computer aided data acquisition of votes on thermal comfort while improving accuracy and reducing data entry time. When prompted, the subjects selected their thermal sensation and comfort level by changing the position of the steering wheel; they recorded their votes by toggling the headlight high beam lever. The interface improved thermal comfort testing by using a driving simulation between voting periods to maintain a realistic metabolism and keep the evaluator's attention.

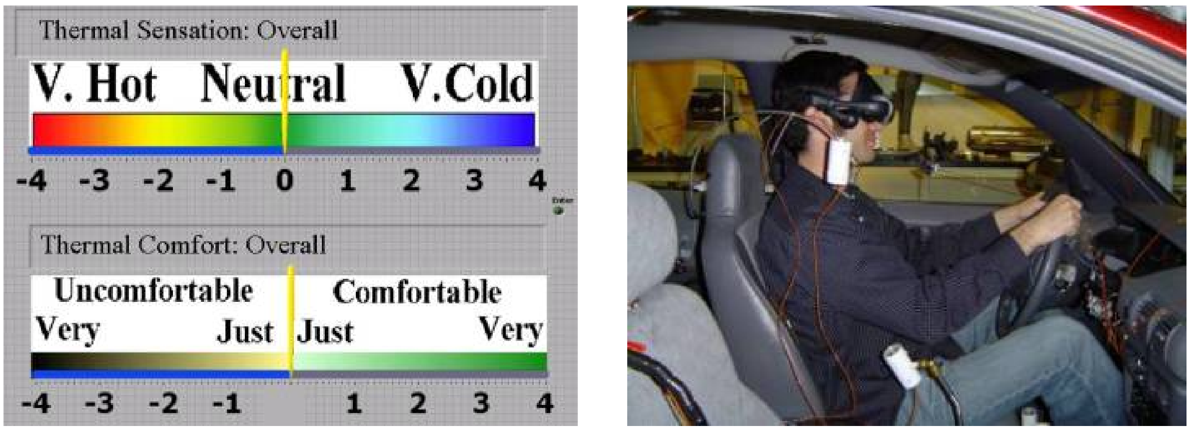

Figure 39. Heads-up thermal sensation and comfort voting screen; system in use

2.4.2 Manikin Environmental Chamber

The Manikin Environmental Chamber provides a controlled environment for preconditioning ADAM for tests inside the VCCL. The chamber was also used for calibration and validation tests for ADAM and for tests of a liquid cooling garment with NASA and of a thermal blanket with the U.S. Army (Section 2.3.4).

Measuring approximately 2.5 m by 2.5 m, the room shown in Figure 40 has a dedicated HVAC system installed to provide humidity, temperature control, and air recirculation. The windows, walls, and floor are insulated to reduce heat transfer to surrounding rooms. The control system maintains temperatures between 15°C and 38°C. The humidity can be controlled between approximately 20% and 100%, depending on the room temperature set points. A portable dehumidifier is available when high humidity in the building makes it difficult to achieve lower humidity levels. Typical airflow velocity in the middle of the room where the manikin is positioned is approximately 0.1 m/s. Portable fans are used to provide higher air flows when desired.

Relative humidity can be controlled to ±1%, and temperature surveys have shown variations of less than 0.4°C from floor to ceiling in the center of the room. The air temperature is measured with type K thermocouples located at head, waist, and foot level. The wall, ceiling, and floor temperature are also measured. A Neslab water chiller was installed to provide a source of chilled water to the chamber.

Figure 40. NREL's Manikin Environmental Chamber

2.4.3 Waste Heat Utilization Laboratory

NREL's Waste Heat Utilization laboratory houses thermoacoustic component development, a high-vacuum capability, cryogenic tank development, and hydride and getter evaluations. The equipment for the lab is as follows:

- High-vacuum hardware
- Helium leak detection
- Signal processing
- Acoustic system analysis (see Figure 41).

In this laboratory, we have demonstrated an ammonia/water absorption cycle, a thermoelectric cooling demonstration unit, a desiccant cooling loop, a heat-driven standing-wave thermoacoustic cooler (Figure 42), and a traveling-wave thermoacoustic prototype.

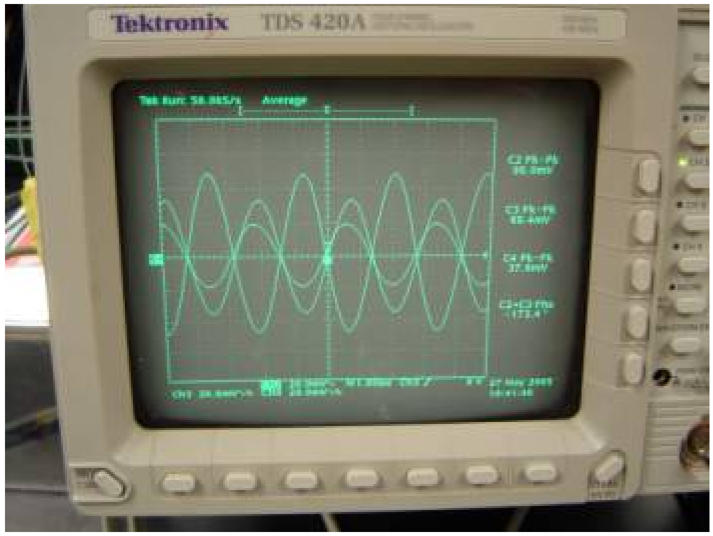

Figure 41. Real-time thermoacoustic data evaluation using an oscilloscope

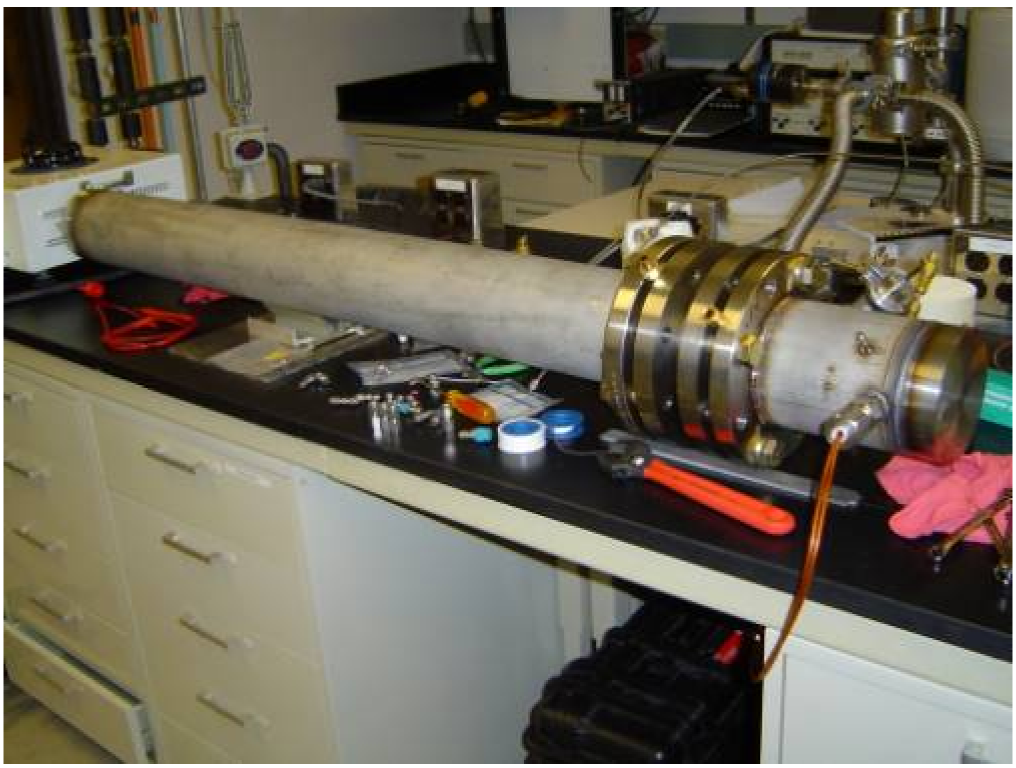

Figure 42. Standing-wave thermoacoustic prototype in the Waste Heat Utilization Lab

2.4.4 Outdoor Testing

NREL researchers have conducted outdoor tests of advanced technologies in vehicles to investigate reducing solar loads and possibly the size of vehicle mobile air-conditioning systems (MACS). A typical thermal soak test consists of two vehicles and a central data acquisition system (Figure 11). We have access to high-quality weather data from NREL's Solar Radiation Research Laboratory.

For one test program, we gathered a large body of data on a Jeep Grand Cherokee (Figure 13). We then tested the vehicle in two Chrysler test cells, one with metal halide lamps (Figure 43) and one with IR lamps (Figure 44) to find out if a vehicle must be tested outside or if indoor tests using solar lamps can be used to accurately simulate the sun.

Figure 43. Chrysler Emissions Test Cell with metal halide lamps

Figure 44. Chrysler Environmental Test Cell with IR lamps

Steady-state vehicle thermal soak tests were performed indoors using data from actual outdoor test conditions. Vehicle temperature measurements from indoor test cells were then compared with measurements taken outdoors. Indoor test results show that the windshield was 3.4°C cooler and the IP was 4.8°C cooler when metal halide lamps were used. In addition, the driver's seat was 1.4°C cooler and the roof was 20.1°C hotter. Trim temperatures were approximately the same.

The differences were thought to be caused by the use of a large array of lamps (a planar source) versus the sun (a point source). Specifically, in an outdoor test, the roof exchanges radiant heat energy with the cool sky; in the test cell, it exchanges radiation with hot lamp bulbs and the associated structure. In the outdoor test, the location of the sun and the vehicle's geometry determine the solar radiation incident on each window. Some windows are completely shaded from incident solar radiation because of the position of the sun. In the indoor test, using the overhead planar lamp array results in a different amount of incident radiation on all the windows, even though the global horizontal flux on the hood matches that of the outdoor test.

The difference between the spectral irradiance characteristics of the sun and of the test cell lamps also causes temperature differences. The vehicle glass absorbs more energy from the IR lamps, resulting in higher windshield temperatures and lower IP temperatures. Although the spectral irradiance of the metal halide lamps approximates that of the sun more closely than that of the IR lamps, significant differences between vehicle temperatures were recorded in the test cell and outdoors.

These results indicate that a vehicle thermal soak can be performed in a test cell to heat the passenger compartment in preparation for a cooldown test or SCO3 emissions test. However, a test cell should not be used to determine a vehicle's skin temperatures or maximum component temperatures. Also, caution should be taken in using test cell solar lamps to assess advanced solar reflective glazing, because the incident angle, projected area, and spectral characteristics will not represent actual solar conditions

3.0 Application to Heavy-Duty Vehicles

Many of the thermal load reduction and improved comfort technologies investigated for light-duty vehicles can be applied to heavy-duty vehicles as well. Light-duty vehicles, used intermittently throughout the day, average 12,000 miles per year. They are often driven after being parked in the sun for an extended period of time; therefore, the A/C system is designed to cool the passenger compartment rapidly after a heat soak. Heavy-duty vehicles are different; typically, they are used continuously throughout the day and average 120,000 miles per year. Thus, heavy-duty vehicle owners and operators can be sensitive to operating costs.

For example, truck drivers are often inside the vehicle's cab during loading or unloading of the vehicle or during regulated rest periods; at those times, climate control is usually needed. When the engine is operating, the interior is cool; minimizing heat gain from the environment in summer is thus critical to reduce steady-state A/C fuel use. The main engine is typically idling to provide power to the A/C system unless an auxiliary power unit is used. A study by Argonne National Laboratory estimates that long-haul trucks idle an average of 1830 hours per year (see www.transportation.anl.gov/research/technology_analysis/idling.html).

As our awareness of the emissions resulting from idling trucks increases, regulations are being created to ban idling in metropolitan areas. Reducing the thermal load and targeting cooling and heating to occupants can eliminate the need for idling the main engine while the vehicle is stopped. A smaller auxiliary-powered A/C system can then provide climate control, or comfortable conditions can be maintained without active heating and cooling. Drivers' comfort is also important; fleet operators want to create a comfortable environment in the cab to retain trained and experienced drivers.

The activities discussed in this section were funded by DOE through NREL's VALR task as well as ongoing Advanced Vehicle Testing Activity work under NREL's CoolCab task. The goal of CoolCab work is to evaluate advanced vehicle thermal management technologies for light-duty vehicles in heavy-duty vehicles application.

3.1 International Truck/Guardian Industries Infrared Reflective Glazing

In 2001, NREL, International Truck, and Guardian Industries conducted a joint medium-duty truck project to examine the potential fuel economy impacts of improving the thermal management of the driver cab using infrared reflective (IRR) laminated glass. The project's objective was to characterize the thermal performance of the cabins of Class 6 Series 4300 "Next-Generation Vehicle" (NGV) trucks, test the effect of Guardian Industries' IRR window glazing on the cabin's thermal environment and performance, and quantify any potential effects on the sizing and fuel economy of a truck's A/C system.

The cabin's thermal performance was characterized using a side-by-side test of two International Class 6 NGV trucks exposed to the same hot ambient thermal environments, as defined by ambient temperature, humidity, and direct/indirect solar flux conditions. The test was carried out at Atlas DSET test facilities in Phoenix, Arizona (Figure 45).

Figure 45. International Class 6 Series 4300 truck test outside Phoenix, Arizona

A non-dimensional thermal analysis was conducted to establish the important cabin design and environmental parameters governing the cabin's thermal behavior and response and to lay the foundation for interpreting test data and future testing. An additional thermal analysis of the test data was performed to estimate the thermal conductance of the cabin's ceiling, left and right doors, and rear wall. Using the temperature differential and heat flux data gathered during the testing, researchers estimated the effective cabin thermal conductance (the inverse of thermal resistance) as follows, for a Class 6 NGV truck cabin:

Left door:	4.2 W/m^2-°C
Right door:	3.6 W/m^2-°C
Ceiling:	10.0-11.0 W/m^2-°C
Rear wall:	1.2 W/m^2-°C

Vehicle experimental results showed that IRR glazing had strong impacts on many interior cabin component and air temperatures. The difference between the breath air temperatures is highlighted in Figure 46, showing a reduction of 4.7ºC when the maximum ambient temperature was attained. The IRR windshield/sidelight combination reduced maximum component and cabin air temperatures by the following values:

Cabin air temperature:	4.7°C
Interior windshield temperature:	7.2°C
Door interior window temperature:	2.3-5.8°C
Instrument panel temperature:	6.6°C
Inside door temperature:	1-1.5°C

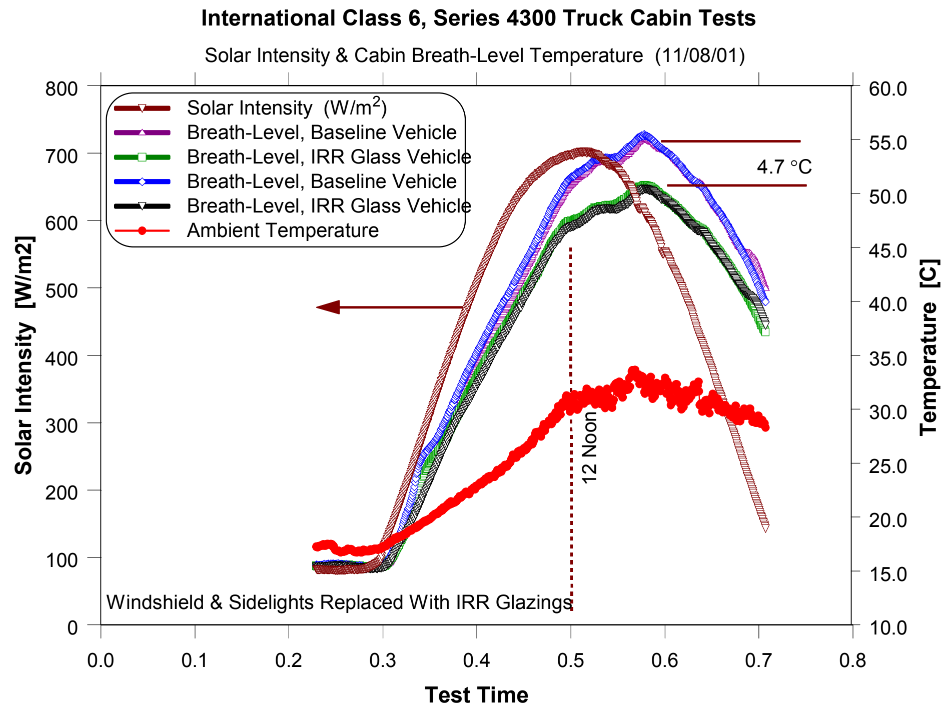

Figure 46. Cabin breath-level air temperature with IRR windshield and sidelights

A combined A/C system/vehicle modeling analysis yielded best estimates for fuel economy improvements resulting from the lower cabin air temperatures in the International Class 6 NGV truck as follows:

SC03/CSHVR drive cycles:	0.2 to 0.3 mpg increase over a baseline of 11.3 mpg
Constant 65-mph cycle:	0.0 mpg increase over a baseline of 11.8 mpg

Fuel economy increases of about 2% in the SC03 and City-Suburban Heavy Vehicle Route (CSHVR) drive cycles are believed to be associated with the stop-start nature and acceleration/deceleration characteristics of the drive cycles, as well as the associated accelerations/decelerations of the A/C compressor during these drive cycles.

3.2 Schneider/Freightliner IR Imaging

NREL conducted an IR imaging test with Schneider National and Freightliner. The main objective was to perform a qualitative comparison of two different truck cab insulation packages (standard vs. “super”) using infrared imaging. Schneider National is a large truckload carrier headquartered in Green Bay, Wisconsin. Schneider uses 15,000 drivers to operate more than 11,000 trucks and each truck averages about 120,000 miles per year. Freightliner LLC manufactures the majority of trucks operated by Schneider. Two Freightliner Century Class truck cabs were the subjects of this field test.

Freightliner, recognizing the need for improved cab insulation to meet cooling requirements during summer months, provided Schneider with 25 evaluation truck cabs equipped with an upgraded or super insulation package. Schneider provided two truck cabs (one standard and one super-insulated) for IR testing to evaluate the impact of the upgraded insulation package on heat loss.

The two test truck cabs were parked for testing in a vacant area of Schneider's Green Bay Operating Center parking lot. Both cab interiors were heated to similar temperatures. Initially, the truck cabs were parked apart to allow sufficient space between to capture individual images of each truck cab. As the test progressed, one truck cab (super-insulated) was moved closer to the other truck cab to allow images that contained both truck cabs together (Figure 47). The ambient temperature was approximately 0ºC and the imaging was conducted at night. These were good conditions in which to evaluate the differences in insulation packages.

Figure 47. IR imaging test setup at Schneider's Green Bay facility

Several areas, identified through differences in surface temperatures, show the potential of improving insulation to further reduce heat loss. These areas were evident in both the standard and super-insulated truck cabs and include the following:

- Driver and passenger foot wells
- Front overhead storage support
- Optional sunroof area and ceiling pad
- Rear of upper bunk
- Underneath auxiliary heater.

A difference of about 2°C was observed in comparing exterior surface temperatures of the baseline and super-insulated truck cabs (Figure 48). This difference indicates the performance improvement found in the super-insulated truck cab.

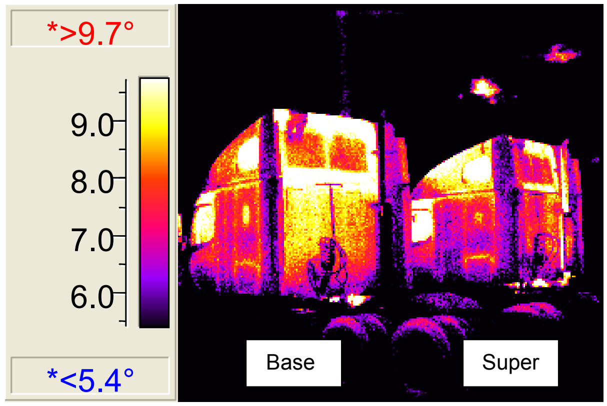

Figure 48. IR image of the baseline and super-insulated truck cabs

The test results established a baseline for typical truck cab insulation while identifying the potential for reducing heating and cooling loads. The testing also identified the high-heat-loss areas within the truck cab that may have the greatest potential for improvement.

3.3 Volvo Truck Test

Volvo provided a Class 8 truck cab to NREL to help investigate potential reductions in the truck cab's thermal load as part of the CoolCab project (Figure 49). The main objective of this testing was to identify opportunities to reduce the thermal load inside the truck cab in order to reduce fuel consumption by improving system efficiency.

Figure 49. Volvo truck cab test setup

Testing began with establishing a baseline for typical truck cab insulation. Simple modifications (such as adding window insulation and applying a sleeper isolation curtain) were made to the Volvo truck cab to help understand heat loss paths. Using an NREL Freightliner Century Class truck cab for reference, tests were performed to quantify the overall heat transfer coefficient (UA) in both the Volvo and Freightliner truck cabs:

$$Q = UA\left(T_{interior} - T_{ambient}\right).$$

We measured a UA of 65 W/K for the Volvo truck cab. Closing the sleeper curtain reduced the UA by 15%, which indicates reduced heat transfer between the interior and environment. The UA was reduced 20% by installing shades in all the windows. We measured an average air temperature rise above ambient of 10ºC for the baseline Volvo case and an average air temperature rise above ambient of 5ºC with windows covered under soak conditions. The white Freightliner truck cab had an average air temperature rise above ambient of 7ºC.

Reducing the load could reduce the size, cost, and weight of idle reduction technologies. Working with industry, the CoolCab task is applying a systems approach to improving truck efficiency and reducing fuel use.

3.4 International Truck Test and CFD Analysis

International Truck and Engine, a manufacturer of over-the-road truck cabs, approached NREL to investigate improving cab insulation to help reduce idling and overall fuel consumption. International wants to reduce the HVAC load during drivers' rest periods because of battery energy storage constraints. The company lent NREL a ProStar sleeper cab to help investigate potential reductions in the truck cab thermal load as part of the CoolCab project (Figure 50). International also partially funded this test and analysis program.

Figure 50. International truck cab test setup

NREL's Freightliner Century Class truck cab was used for comparison and baseline data. UA tests were performed to quantify the overall heat transfer coefficient in both the International and Freightliner truck cabs. Solar heat soak tests were performed to quantify interior temperatures. The data obtained in the heat soak tests were also used to validate a FLUENT CFD model of the cab that NREL had developed previously for International. Once the baseline testing of both truck cabs was completed, simple modifications (such as insulating windows and applying a sleeper isolation curtain) could be made to the International truck cab to help understand heat loss paths.

Table 2 shows results for UA and average air temperature above ambient for the baseline and modified configurations. The baseline white Freightliner truck cab had an average cabin interior air temperature of ~8ºC above ambient.

Table 2. Results from the International Truck Cab Tests

	Base or Unmodified Case	Sleeper Curtain Closed (change from base)	Arctic Curtain Closed (change from base)	Windows Insulated (change from base)
UA	50 W/K	-20%	-25%	-13%
Avg. cab T_{air} above ambient	11ºC	-1ºC	-3ºC	-4ºC

The magnitude of the UA and temperature rise above ambient were similar to those of the Volvo tests described in Section 3.3. The use of sleeper and window shades can significantly reduce heat transfer between the cab and the environment.

3.5 Sage Electrochromics

Sage Electrochromics, Inc. was involved in a program to evaluate means of reducing cabin temperatures in a Family of Medium Tactical Vehicles (FMTVs) operating in hot climates. One method for reducing cabin temperatures is to reduce the thermal load on the compartment. To that end, Sage Electrochromics developed an electrochromic technology that can be integrated into the windshield of FMTVs. The project involved evaluating the impact on interior temperatures of Sage Electrochromics glass installed on an FMTV under steady-state driving conditions with the A/C operating.

We applied our experience in evaluating the thermal load on passenger cars to determine the impact of the electrochromic glass on interior temperatures and heat transfer into an FMTV cab (Figures 51 and 52). Sage Electrochromics funded this work.

NREL prepared a model of an FMTV using a surface mesh and generated a final volume mesh. The next step involves collecting boundary conditions and running the model.

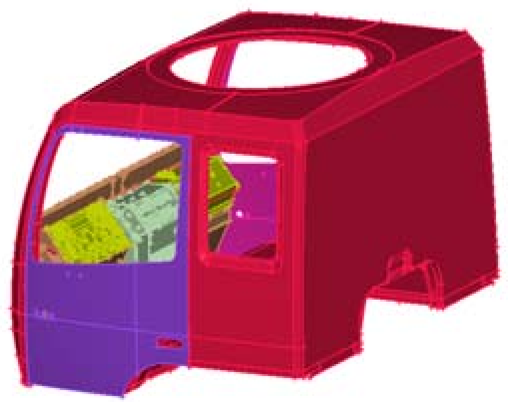

Figure 51. FMTV geometry

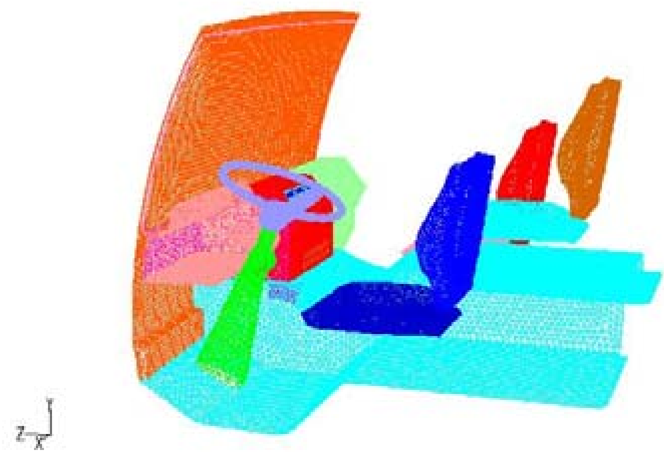

Figure 52. Surface mesh of the FMTV

3.6 New York City Transit Fleet

In a recent test of hybrid buses in a New York City Transit fleet sponsored by DOE's Advance Vehicle Testing Activity, researchers found that fuel economy dropped during summer months. The Orion 7 buses, which incorporated BAE Systems hybrid technology, experienced up to a 26% reduction in fuel economy in summer (Figure 53), and the use of A/C is the most likely cause. Technologies that reduce fuel use in light-duty vehicles could also be applied to buses to reduce fuel consumption and improve fuel economy.

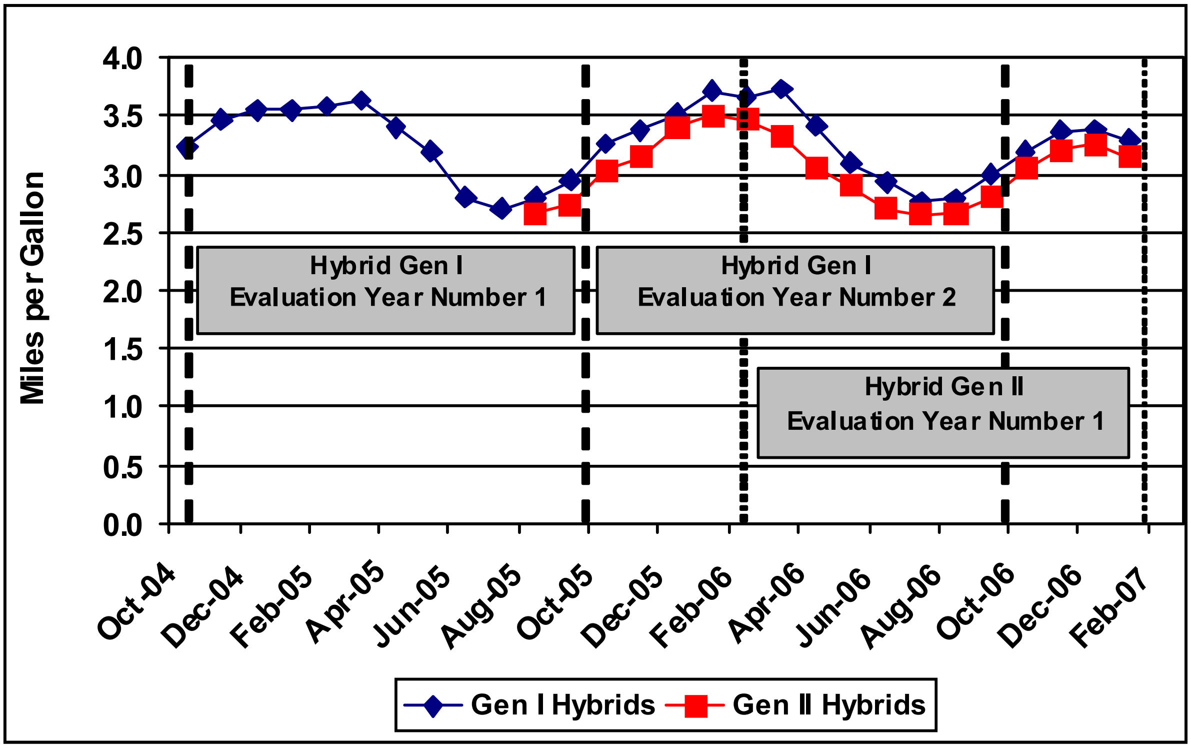

Figure 53. Seasonal variation in mpg for hybrid buses shows impact of A/C

4.0 Implementation Barriers

A critical barrier to the incorporation of advanced climate-control technologies is the increased cost. If consumers were to demand better climate control along with lower fuel use, automobile manufacturers would have a financial incentive to incorporate technologies like those discussed in this report. However, consumers often do not know that such technologies exist. Besides reduced fuel use, additional benefits of advanced climate-control systems include improved comfort for drivers and passengers, which could increase consumer demand.

Another thermal load reduction benefit that has great potential to motivate consumer demand is child safety. In the United States, approximately 30 children per year die from heat-related injuries caused by entrapment in the passenger compartment. Lower cabin interior temperatures would provide trapped children with a better chance of survival. In a related issue, the deaths of approximately 10 children per year prompted the National Highway Traffic Safety Administration to require release latches inside trunks (49 CFR Part 571).

Since the A/C system is not operating during corporate average fuel economy (CAFE) tests, there has not been a motivation regarding fuel economy to reduce fuel use for mobile A/C systems. Some have suggested adding an A/C test to CAFE tests, but a barrier is the potential added complexity of such a test to properly account for thermal load reduction. If A/C is included in fuel economy tests, we strongly recommend developing a procedure that will take into account all technologies than can reduce A/C fuel use. This is needed to motivate original equipment manufacturers (OEMs) to incorporate such technologies in their products.

In addition to cost, volume, weight, and serviceability are important considerations. The increased risk of recalls is a factor when automotive manufacturers are considering a new technology with no track record.

Also, thermal management crosses multiple disciplines for automotive OEMs, which sometimes makes system-level decisions difficult. The thermal environment and comfort of the cabin are impacted by the design choices and requirements of multiple groups (such as the body, glass, interior, HVAC, and seating). Beyond that for the cabin, thermal management of the engine, energy storage system, and power electronics add still more challenges.

Barriers to using waste heat for cabin cooling include relatively low and variable temperatures, weight, volume, corrosion, and engine back-pressure requirements. In particular, cabin cooling is required in stop-and-go traffic when engine waste heat is at a minimum. Furthermore, HEVs and PHEVs will generate even less waste heat. However, waste-heat utilization technology may be well suited for long-haul commercial vehicles.

It is often difficult to assess the performance of advanced technologies. Vehicle-level testing of thermal-load-reducing technologies such as solar-reflective glass or paints in indoor test chambers has provided incorrect results. While outdoor soak-testing yields real performance data, several vehicles and longer test times are needed.

Additional barriers to incorporating advanced climate-control technologies include these:

- A/C is often considered toward the end of the vehicle design process
- Some suppliers do not have tools for estimating fuel economy benefits
- International standards vary, for example, between the European Union (EU) and the United States, for such things as the choice of refrigerant and glass transmissivity requirements, among others
- Having multiple powertrains poses its own challenges (for example, for gasoline, diesel, hybrid, and plug-in hybrid vehicles).

5.0 Conclusions and Recommendations

NREL pursued a variety of avenues in efforts to improve vehicle efficiency and fuel economy by controlling the climate in a vehicle while keeping passengers comfortable. Because climate control loads can significantly impact the fuel economy and tailpipe emissions of conventional and hybrid electric vehicles, NREL worked closely with industry to develop techniques to reduce auxiliary loads, such as climate control, in vehicles.

One critical benefit of reducing thermal loads is that occupants experience lower temperatures upon entering a heat-soaked vehicle and thus feel less uncomfortable. Our research has shown that certain technologies can significantly reduce thermal loads and thus fuel consumption, such as solar-reflective glass and parked-car ventilation. In comparison, solar-reflective coatings and insulation had a lesser impact on interior temperatures. But they could become increasingly important as both cabin thermal loads and the waste heat from engines decrease in advanced vehicles. Cooling occupants through ventilated, cooled, or low-mass seats can also yield energy savings.

Using waste heat to generate cooling with thermoacoustics was not feasible for light-duty vehicles. But a thermoacoustic system has potential for generating electricity in vehicles with an abundance of waste heat, like today's typical U.S. vehicles. In advanced vehicles like PHEVs and small diesels, there will be periods of time when there is little or no waste heat. In those cases, heat-generated electricity would not make sense.

In fact, we found that reducing fuel use is not by itself a sufficient motivation for automotive OEMs to incorporate advanced A/C technologies in U.S. vehicles. Although the price of fuel has risen in recent years, consumers are not demanding fuel-efficient A/C systems. To gain greater acceptance in this country, fuel-efficient A/C systems will have to be combined with a benefit such as improved thermal comfort. We have shown that several thermal load reduction technologies for vehicles provide this benefit while reducing fuel consumption.

Another incentive for using fuel-efficient A/C systems in U.S. vehicles could come from new regulations addressing the need to reduce all vehicle-related air emissions. Automotive A/C is gaining more attention abroad as a result of the EU F-gas regulation banning refrigerants with a global warming potential (GWP) > 150. The EU has been discussing how to deal with the carbon dioxide emissions caused by the fuel used to power A/C systems, and the California Air Resources Board (CARB) in our country has been doing the same. While increased attention is being paid to MACs, this also represents a unique opportunity to change the technology to reduce A/C fuel use and carbon dioxide emissions at the same time.

Because operating automobile A/C systems uses 0.46 million barrels per day of gasoline, reducing A/C fuel consumption also enhances our national energy security by enabling us to reduce oil imports. To significantly reduce fuel consumption in A/C systems, therefore, we recommend following the steps in this R&D pathway:

1. Reduce the thermal load by using solar-reflective glass or shades and parked-car ventilation.
2. Incorporate low-mass, naturally ventilated seating (or active climate-control seating).
3. Incorporate the most efficient A/C components available.
4. Increase the use of re-circulated air to the maximum extent possible, considering air quality, dehumidification, and safety issues, while avoiding condensation on windows.
5. Eliminate the overcooling and subsequent reheating of air that occurs now to achieve the desired temperature in vehicles with automatic temperature control systems.

Many of the load-reduction technologies we tested, as well as climate-control seating, are already available for today's vehicles. In addition, interest in making A/C systems more fuel-efficient is growing in the automotive industry. And, as HEVs and PHEVs become more widespread, A/C loads will become increasingly important. Operating an A/C system during electric-powered driving will reduce the vehicle's range and have negative impacts on the design and cost of the energy storage system. Reducing the cooling load allows the stored electrical energy to be used for propulsion. This load reduction also enables a vehicle to be designed that can use a smaller and less expensive energy storage system while maintaining the same range.

This work was, and is, worthy of federal support and funding for the following reasons:

- The national energy security benefit resulting from reducing the 0.46 million barrels of gasoline used per day to power A/C systems.
- The risk of developing some advanced technologies (such as thermoacoustics and thermoelectrics) is more than the automotive industry can readily incur.
- Because vehicle cabin thermal management involves multiple disciplines and technologies, automobile manufacturers can benefit from the systems perspective provided by projects carried out at a national laboratory.
- National laboratories can provide objective, unbiased analyses.
- The tools, modeling capabilities, and experimental methods needed to develop these technologies are often beyond the capabilities of the suppliers who will need to produce the technologies for the automotive industry.
- Fuel-efficient A/C systems and reduced thermal loads will help advanced vehicles to operate more efficiently while reducing greenhouse gas emissions.

Appendix A. Project Partners

We would like to acknowledge all the partners that have supported our work during the past 12 years. Without their support and contributions, our research would have not have been as successful.

Automotive industry partners were Chrysler Corporation, Ford Motor Company, and General Motors.

Automotive parts and equipment project partners and suppliers included 3M, Amerigon, BOS, BSST, Delphi, Guardian International, Johnson Controls, Measurement Technology Northwest, Modine, PPG, Sage Electrochromics, Solutia, Southwall, Thermacore, Valeo, Visteon, W.E.T. Automotive Systems, and Webasto.

Software companies and tools that enabled us to conduct this research included ANSYS, AVL, BETA CAE Systems (ANSI), Cullimore and Ring Technologies (SINDA/FLUINT), FLUENT, ICEM CFD, and ThermoAnalytics (RadTherm).

Several government groups have also contributed to this work, including CARB, NASA, the U.S. Army, the U.S. Department of Energy, and the U.S. EPA. Other organizations that have contributed include the Society of Automotive Engineers and the University of California, Berkeley.

Appendix B. Chronology and Project Summaries

Figure 54 shows an overview of NREL's Vehicle Ancillary Load Reduction task. The top arrows indicate the major R&D tools that were developed; the horizontal bars show key industry partners for different phases of the overall project.

In addition, the following pages summarize the work of each year of the task, including the budget, key activities, technical papers, and significant presentations. To access a document, simply click on the title.

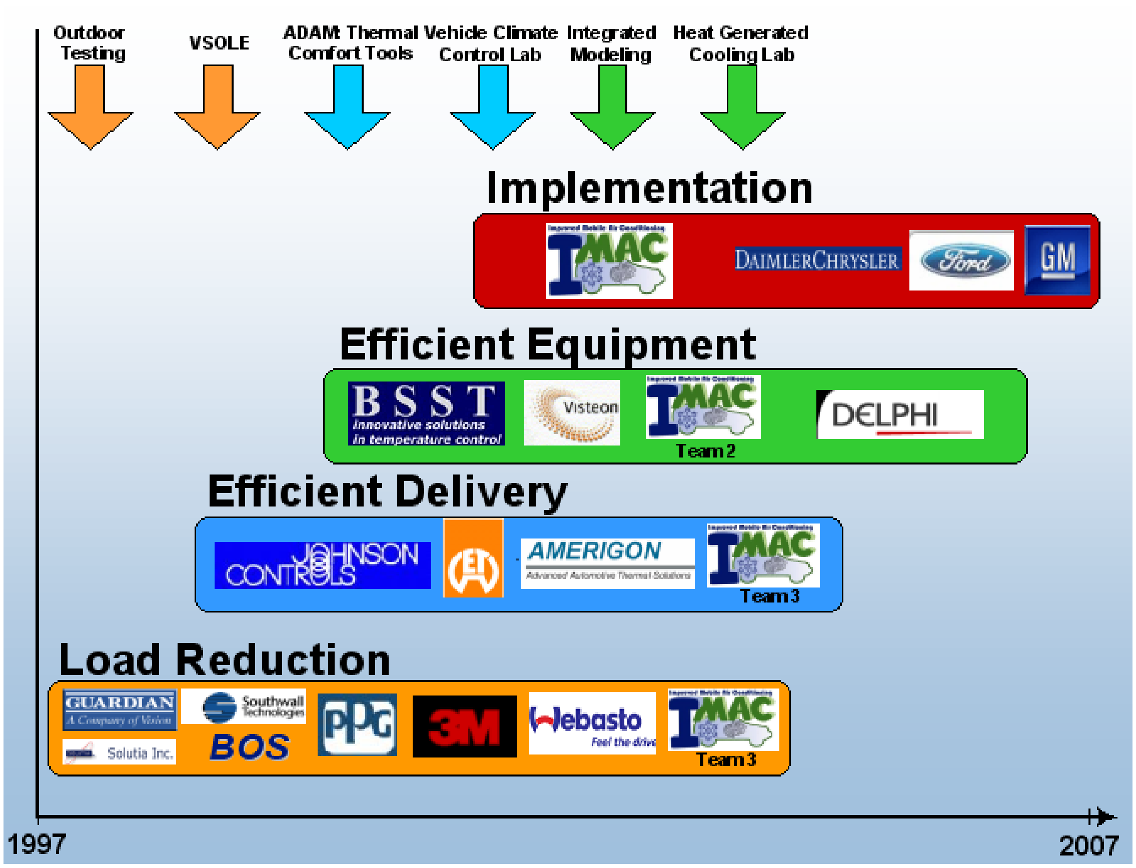

Figure 54. Vehicle Ancillary Load Reduction project timeline

Vehicle Ancillary Load Reduction Project, FY 1996 and FY 1997

Funding

NREL: $391K

Key Accomplishments

Modeling and Analysis

1. Completed ADVISOR modeling to show A/C fuel use for selected vehicles over various drive cycles.
2. Completed preliminary estimate of national A/C fuel use.
3. Wrote ejector cooling system model.

Testing

1. Outfitted a Plymouth Breeze with electrochromic sunroof, PV cabin ventilation, and liquid cooled/heated seats.
2. Completed modeling and testing of automotive window boundary layer control.

Significant Presentations

1. Presented results to automotive manufacturers and suppliers and to DOE.

Other

1. Filed patent application "Vehicle Cabin Cooling System for Capturing and Exhausting Heated Boundary Layer Air from Inner Surfaces of Solar Heated Windows," leading to U.S. Patent No. 6,186,886.
2. Exhibited technologies for reducing vehicle ancillary loads at the Third International Vehicle Thermal Management Systems Conference; May, 1997, Indianapolis, Indiana.

Vehicle Ancillary Load Reduction Project, FY 1998

Funding

DOE: $500K

Key Accomplishments

Modeling and Analysis

1. Model results showed that a 400W ancillary load changes fuel economy of a 28-mpg vehicle by 1 mpg and an 80-mpg vehicle by 6.5 mpg.
2. Model results showed significant reduction of volatile organic components in new and aged vehicles.
3. Modeled benefits of cabin ventilation on occupant thermal comfort.
4. Completed transient 16-segment thermal comfort model that predicts thermal sensation and predicted percent dissatisfied as a function of time and cabin conditions (temperature, humidity, air velocity, and solar load).

Testing

1. Grew and characterized bacteria collected from vehicle climate control systems. Completed prototype photocatalytic oxidation air cleaner to reduce outside air requirements. Test results showed reductions of 90 to 100% of formaldehyde, acetaldehyde, and acetone.
2. Measured optical properties of industry solar reflective coating
3. Experimental results showed that boundary layer control with 0.5 cfm/liner foot of window removed as much heat as active cabin ventilation but with 30 to 50% less power.

Technical Papers

1. Farrington, R. B.; Brodt, D. L.; Burch, S. D.; Keyser, M. A. "Opportunities to Reduce Vehicle Climate Control Loads." *International Electric Vehicle Symposium and Exposition Proceedings, EVS-15*; *October, 1998, Brussels, Belgium*.

Significant Presentations

1. Farrington, R. B.; Brodt, D. L.; Burch, S. D.; Keyser, M. A. "Opportunities to Reduce Vehicle Climate Control Loads." Presented at the International Electric Vehicle Symposium and Exposition, EVS-15, October, 1998, Brussels, Belgium.

Other

1. Sponsored NREL/Industry Meeting titled "Partnering to Enhance Vehicle Climate Control Systems." August, 1998.

Vehicle Ancillary Load Reduction Project, FY 1999

Funding

DOE: $1,108K

Key Accomplishments

Modeling and Analysis

1. Completed drive cycle assessment of A/C contributions to tailpipe emissions and impacts of A/C on fuel economy over the SC03 drive cycle used in the supplemental test procedure (SFTP).
2. Completed prediction of air and dash temperatures for a range of glazing optical properties and cabin ventilation rates.
3. Completed model of reductions of heating and cooling power requirements as a function of recirculation rates and ambient conditions (temperature and humidity).

Testing

1. Developed co-heating test method to measure impacts of solar reflective glazings on solar loads.
2. Modified Dodge Neon test bed to evaluate passive cabin ventilation.
3. Measured A/C fan power consumption.
4. Documented Dodge Neon cabin soak conditions. Heat flux sensors showed that roof insulation can increase cabin soak temperatures.
5. Testing of cooled seats showed necessity for thermal comfort model. Cold surfaces cause vasoconstriction, unlike heated seats, which lead to vasodilation and muscle relaxation.

Technical Papers

1. Farrington, R. B.; Anderson, R.; Blake, D. M.; Burch, S. D.; Cuddy, M. R.; Keyser, M. A.; Rugh, J. P. “Challenges and Potential Solutions for Reducing Climate Control Loads in Conventional and Hybrid Electric Vehicles.” *Fourth International Vehicle Thermal Management Systems Conference Proceedings; May, 1999, London, United Kingdom*.
2. Farrington, R.; Cuddy, M.; Keyser, M.; Rugh, J. "Opportunities to Reduce Air-Conditioning Loads Through Lower Cabin Soak Temperatures." *International Electric Vehicle Symposium and Exposition Proceedings, EVS-16*; *October, 1999, Beijing, China*. NREL Report No. CP-540-25975.

Significant Presentations

1. Farrington, R. B.; Anderson, R.; Blake, D. M.; Burch, S. D.; Cuddy, M. R.; Keyser, M. A.; Rugh, J. P. “Challenges and Potential Solutions for Reducing Climate Control Loads in Conventional and Hybrid Electric Vehicles.” Presented at the Fourth International Vehicle Thermal Management Systems Conference Proceedings; May, 1999, London, United Kingdom.
2. Farrington, R.; Cuddy, M.; Keyser, M.; Rugh, J. "Opportunities to Reduce Air-Conditioning Loads Through Lower Cabin Soak Temperatures." Presented at the International Electric Vehicle Symposium and Exposition, EVS-16. October 17, 1999, Beijing, China.

Other

1. Technical Monitor of DOE Cooperative Automotive Research for Advanced Technology Program (CARAT).
    a. New Higher Performance Low Cost Selective Solar Radiation Control Coatings
    Energy Conversion Devices
    b. Development of Vehicle Magnetic Air Conditioner (VMAC) Technology
    Iowa State University/Astronautics Corporation of America
    c. High-Efficiency Motor for Vehicle Power Accessories
    Visual Computing Systems, Kentucky
    d. Climate Control Seating
    Life Enhancement Technologies
2. Participated in Third International Meeting on Thermal Manikin Testing, October 1999, Stockholm, Sweden.

Vehicle Ancillary Load Reduction Project, FY 2000

Funding

DOE: $1,108K

Key Accomplishments

Modeling and Analysis

1. Demonstrated the first stage of the vehicle integrated modeling process on the Chrysler ESX3 hybrid vehicle. Completed a steady state thermal model using FLUENT and the ICEM CFD cabin modeler.
2. Hosted Automotive Glazing R&D Panel (May, 2000) with participation by 3M, Chrysler, DOE, Ford, PPG, SAE, Southwall, and Visteon Glass.
3. Developed a SINDA/FLUINT air-conditioning model with an integrated lump-capacitance cabin model to predict cabin cooldown including evaluation of heat-pipe instrument panel thermal rejection system.

Testing

1. Assessed the impact of a 3M non-metallic solar reflective film in a Chrysler minivan thermal soak test in Golden and Phoenix.
2. Completed a vehicle thermal soak test using black Ford Explorers in Golden and Phoenix (3M prototype non-metalic solar reflective film).
3. Completed conceptual design of a thermal manikin and experimentally evaluated various skin heating and sweating concepts.

Technical Papers

1. Rugh, J.P.; Howard, R.S.; Farrington, R.B.; Cuddy, M.R.; Blake, D.M. "Innovative Techniques for Decreasing Advanced Vehicle Auxiliary Loads." *Future Car Congress 2000 Proceedings; April, 2000, Arlington, Virginia*. SAE Document No. 2000-01-1562. NREL Report No. JA-540-27225.
2. Farrington, R.B.; Rugh, J.P.; Barber, G.D. "Effect of Solar-Reflective Glazing on Fuel Economy, Tailpipe Emissions, and Thermal Comfort." *2000 International Body Engineering Conference Proceedings; October 3-5, 1999, Detroit, Michigan*. SAE Document No. 2000-01-2694. NREL Report No. 28779.
3. Farrington, R.; Rugh, J. "Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range." *Earth Technologies Forum Proceedings; October 31, 2000, Washington, D.C.* NREL Report No. CP-540-28960.
4. Huang, Z.; Maness, P. C.; Blake, D. M.; Wolfrum, E. J.; Smolinski, S. L.; Jacoby, W. A. (2000). Bactericidal Mode of Titanium Dioxide Photocatalysis. *Journal of Photochemistry and Photobiology A: Chemistry*. Vol. 130, January 2000; pp. 163-170; NREL Report No. JA-590-27085.
5. Huang, J.; Farrington, R.; Maness, P. C.; Huang, Z.; Blake, D.; Wolfrum, E.; Manvi, R.; Kern, R. (2000). Effect of Titanium Dioxide Photocatalytic Oxidation on Fungal Spore Germination. Abstract Q-110. *Abstracts of the American Society for Microbiology 100th General Meeting*, 21-25 May 2000, Los Angeles, California. Washington, DC: American Society for Microbiology (ASM) p. 565; NREL Report No. AB-510-35823.

Significant Presentations

1. Rugh, J.; Howard, R.; Farrington, R.; Cuddy, M.; Blake, D. "Innovative Techniques for Decreasing Advanced Vehicle Auxiliary Loads." Presented at the Future Car Congress 2000. April, 2000, Arlington, Virginia. SAE Paper No. 2000-01-1562.
2. Farrington, R.; Rugh, J.; Barber, G. "Effect of Solar-Reflective Glazing on Fuel Economy, Tailpipe Emissions, and Thermal Comfort." Presented at the International Body Engineering Conference. October, 2000. SAE Paper No. 2000-01-2694.
3. Farrington, R. "Vehicle Testing to Determine the Benefits of 3M Solar Reflective Film." Presented to Chrysler. February 29, 2000.
4. Rugh, J. "Vehicle Testing to Determine the Benefits of 3M Solar Reflective Film." Presented to Ford. October 25, 2000.

5. Rugh, J. "Integrated Vehicle Systems Analysis - ESX3 Final Analysis - Glazing Update." Presented to the Department of Energy. August 30, 2000.
6. Farrington, R.; Rugh, J. "Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range." Presented at the Earth Technologies Forum. October 31, 2000, Washington, D.C.

Vehicle Ancillary Load Reduction Project, FY 2001

Funding

DOE: $1,586K

Key Accomplishments

Modeling and Analysis

1. Assessed heat-generated cooling opportunities, including absorption, metal hydride absorption, desiccant, and thermoacoustic systems.
2. Wrote optimization software for heat-generated electricity with thermoelectric devices.
3. Developed a solar radiation model that calculates the solar spectral irradiance incident on the vehicle for 239 locations in the U.S.
4. 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 locations, including parametric analysis.
5. Developed a detailed transient, two-phase A/C model in SINDA/FLUiNT analysis software with optimization capability.

Testing

1. 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.
2. Completed vehicle testing of Jeep Grand Cherokee in a collaborative effort with Chrysler to validate integrated modeling techniques.
3. Developed and tested passively cooled instrument panel using heat pipes demonstrating significantly lower peak IP and air temperatures.
4. Evaluated PPG solar reflective glazing with two white Ford Explorers in Phoenix.
5. Built a prototype thermal manikin leg with sweating, heated segments.

Technical Papers

1. Farrington, R.; Barber, G.; Hendricks, T.; Marion, W.; Markel, T.; McGuffin, R.; Rugh, J. "Integrated Modeling to Predict Occupant Thermal Comfort." *7th International Automotive Technologies Association Conference Proceedings; May, 2001*, Florence, Italy. NREL Report No. 29898.
2. Hendricks, T.J. "Milestone Report - Vehicle Transient Air Conditioning Analysis: Model Development & System Optimization Investigations." *June, 2001*. NREL Report No. TP-540-30715.
3. Cullimore, B.A.; Hendricks, T.J. "Design and Transient Simulation of Vehicle Air Conditioning Systems." Fifth *Vehicle Thermal Management Systems Conference &Exhibition Proceedings*; *May, 2001, Nashville, Tennessee*.
4. Rugh, J.; Hendricks, T.; Koram, K. "Effect of Solar Reflective Glazing on Ford Explorer Climate Control, Fuel Economy, and Emissions." *International Body Engineering Conference & Exposition Proceedings; October, 2001*.
5. Rugh, J.; Farrington, R.; Boettcher, J. "The Impact of Metal-Free Solar Reflective Film on Vehicle Climate Control." *Fifth Vehicle Thermal Management Systems Conference &Exhibition Proceedings*; *May, 2001, Nashville, Tennessee*.
6. McGuffin, R. "Modeling of Human Thermal Comfort." *SAE 5th Vehicle Thermal Management Conference Proceedings; July, 2001*.
7. Burke, R.; McGuffin, R. "Development of an Advanced Thermal Manikin for Vehicle Climate Evaluation." *4IMM Conference Proceedings; September, 2001.*
8. Hendricks, T.J. "Optimization of Vehicle Air Conditioning Systems Using Transient Air Conditioning Performance Analysis." *Fifth Vehicle Thermal Management Systems Conference & Exhibition Proceedings; May, 2001, Nashville, Tennessee.* Paper No. 2001-01-1734.

9. Hendricks, T.J.; Thoensen, T. "Experimental Demonstration of Heat Pipe/Two-Phase Flow Systems for Vehicle Passenger Cabin Cooling." *2001 ASME International Mechanical Engineering Congress and Exposition (IMECE2001) Proceedings*; November 11-16, 2001, New York, New York. Heat Transfer Division Vol. 369-7. NREL Paper No. 30741.

Significant Presentations

1. Farrington, R.; Barber, G.; Hendricks, T.; Marion, W.; Markel, T.; McGuffin, R.; Rugh, J. "Integrated Modeling to Predict Occupant Thermal Comfort." Presented at the Seventh International Automotive Technologies Association Conference. May, 2001, Florence, Italy.
2. Hendricks, T. "Vehicle Air Conditioning Systems: Transient Analysis, Optimization & MATLAB Integration." Presented at the International SINDA/FLUINT User's Conference. February 9, 2001, Keystone, Colorado.
3. Rugh, J.; Farrington, R.; Boettcher, J. "The Impact of Metal-Free Solar Reflective Film on Vehicle Climate Control." Presented at the Fifth International Vehicle Thermal Management Systems Conference, May, 2001, Nashville, Tennessee.
4. McGuffin, R. "Modeling of Human Thermal Comfort." Presented at the SAE Vehicle Thermal Management Conference. July, 2001.
5. Hendricks, T. J. "Optimization of Vehicle Air Conditioning Systems Using Transient Air Conditioning Performance Analysis." Presented at the Fifth Vehicle Thermal Management Systems Conference & Exhibition. May, 2001.
6. Rugh, J. "Analysis of Advanced Solar Reflective Glazings using the Vehicle Solar Load Estimator (VSOLE)." Presented to the Department of Energy. August 31, 2001.Rugh, J. "Vehicle Testing to Determine the Benefits of PPG Sungate® Glazing." Presented to PPG. February 13, 2001.
7. Rugh, J. "Reduction in A/C Fuel Use Milestone Presentation." Presented to the Department of Energy. September 29, 2001.
8. Rugh, J. "Integrated Vehicle Modeling Milestone Presentation." Presented to the Department of Energy. September 29, 2001.
9. Hendricks, T. J.; Thoensen, T. "Experimental Demonstration of Heat Pipe/Two-Phase Flow Systems for Vehicle Passenger Cabin Cooling." Presented at the ASME International Mechanical Engineering Congress and Exposition (IMECE2001). November 11-16, 2001, New York, New York. Heat Transfer Division Vol. 369-7.

Other

1. Marion, W. "Solar Radiation Model for Vehicle Simulation Tools." Presented to the Department of Energy. May 29, 2001.
2. McGuffin, R. "Examination of Technologies to Reduce Cabin Solar Loads and Peak Soak Temperatures in Lincoln Navigators." Presented to Ford Motor Company.
3. Farrington, R. et al., Patent No. 6,186,886, awarded February 13, 2001.
4. Hendricks, T. J. et al., U.S. Patent No. 6,964,294 B2, filed May, 5, 2001.
5. Hendricks, T.; Johnson, V.; Keyser, M. "Heat-Generated Cooling Opportunities." White Paper to DOE.

Vehicle Ancillary Load Reduction Project, FY 2002

Funding

DOE: $1,182K

Key Accomplishments

Modeling and Analysis

1. Integrated the transient A/C model with the ADVISOR vehicle systems analysis software.
2. Optimized an electric-driven air conditioning system for a light-duty vehicle using the transient A/C model.
3. Analyzed and designed a metal hydride heat pump for a fuel cell vehicle.
4. Developed an A/C fuel use analysis methodology. Calculated first thermal-comfort-based A/C fuel use analysis of U.S. as a function of local ambient conditions using monthly data for 116 metropolitan areas.

Testing

1. Performed vehicle soak tests of ventilation techniques to reduce the peak soak temperature using a Jeep Grand Cherokee provided by Chrysler.
2. Tested Guardian solar reflective glazings in a Class 6 International truck in Phoenix.
3. Completed human subject tests at UC Berkeley to assess human thermal sensation and comfort in transient asymmetric thermal environments

Technical Papers

1. Hendricks, T.J.; Lustbader, J.A. (2002) "Advanced Thermoelectric Power System Investigations for Light-duty and Heavy-duty Applications: Part I." and "Advanced Thermoelectric Power System Investigations for Light-duty and Heavy-duty Applications: Part II." *ICT '02: XXI International Conference on Thermoelectrics Proceedings; August 25-29, 2002, Long Beach, California.* Piscataway, NJ: Institute of Electrical and Electronics Engineers (IEE) pp. 381- 394; NREL Report No. CP-540-32756 and CP-540-35510.
2. Johnson, V. "Fuel Used for Vehicle Air Conditioning: A State-by-State Thermal Comfort-Based Approach." *Future Car Congress 2002 Proceedings; June, 2002, Arlington, Virginia*. SAE Paper No. 2002-01-1957.
3. Farrington, R.; Johnson, V. "The Impact of Vehicle Air-Conditioning Fuel Use and What Can Be Done to Reduce It." *Fourth Annual Earth Technology Forum Proceedings*; *March 25-27, 2002, Washington*, *D.C.*
4. Johnson, V. "Heat-Generated Cooling Opportunities in Vehicles." *Future Car Congress 2002 Proceedings; June, 2002, Arlington, Virginia.* SAE Paper No. 2002-01-1969.
5. Hovland, V. "Integrated Cabin and Fuel Cell System Thermal Management with a Metal Hydride Heat Pump." *International Symposium on Metal Hydrogen Systems: Fundamentals and Applications Proceedings; September 2-6, 2002, Annecy, France.*
6. Rugh, J.P. "Integrated Numerical Modeling Process for Evaluating Automobile Climate Control Systems." *Future Car Congress 2002 Proceedings; June, 2002, Arlington, Virginia*. SAE Paper No. 2002-01-1956.
7. McGuffin, R; Burke, R.; Huizenga, C.; Zhang, H.; Vlahinos, A.; Fu, G. "Human Thermal Comfort Model and Manikin." *Future Car Congress 2002 Proceedings; June, 2002, Arlington, Virginia*. SAE Paper No. 2002-01-1955.
8. Hendricks, T. "Heat Pipe/Two-Phase Flow Systems For Vehicle Passenger Cabin Cooling." *Future Car Congress 2002 Proceedings; June, 2002, Arlington, Virginia*. SAE Paper No. 2002-01-1970.
9. Farrington, R. "Advanced Automotive Glazings: A Cool Idea for Hot Cars." *The Society of Vacuum Coaters 45th Technical Conference Proceedings; April 13-18, 2002, Lake Buena Vista, Florida.*

Significant Presentations

1. Hendricks, T.J.; Lustbader, J.A. "Advanced Thermoelectric Power System Investigations for Light-duty and Heavy-duty Applications." Presented at the ICT '02: XXI International Conference on Thermoelectrics. August 25-29, 2002, Long Beach, California.
2. Johnson, V. "Fuel Used for Vehicle Air Conditioning: A State-by-State Thermal Comfort-Based Approach." Presented at the Future Car Congress 2002. June, 2002, Arlington, Virginia. SAE Paper No. 2002-01-1957.
3. Farrington, R.; Johnson, V. "The Impact of Vehicle Air-Conditioning Fuel Use And What Can Be Done to Reduce It." Presented at the Fourth Annual Earth Technology Forum. March 25-27, 2002, Washington, D.C.
4. Johnson, V. "Heat-Generated Cooling Opportunities in Vehicles." Presented at the Future Car Congress 2002. June 5, 2002, Arlington, Virginia. SAE Paper No. 2002-01-1969.
5. Hovland, V. "Integrated Cabin and Fuel Cell System Thermal Management with a Metal Hydride Heat Pump." Presented at the International Symposium on Metal Hydrogen Systems: Fundamentals and Applications. September 2-6, 2002, Annecy, France.
6. Rugh, J.P. "Integrated Numerical Modeling Process for Evaluating Automobile Climate Control Systems." Presented at the Future Car Congress 2002. June, 2002, Arlington, Virginia. SAE Paper No. 2002-01-1956.
7. McGuffin, R. Burke, R.; Huizenga, C.; Zhang, H.; Vlahinos, A.; Fu, G. "Thermal Comfort Modeling and Manikin." Presented at the Future Car Congress 2002. June, 2002, Arlington, Virginia. SAE Paper No. 2002-01-1955.
8. Rugh, J. "Jeep Grand Cherokee Project: Test Program and Thermal/Fluid Modeling." Presented at a meeting with Chrysler. November 30, 2001.
9. Farrington, R. "Advanced Automotive Glazings: A Cool Idea for Hot Cars." Presented at the Society of Vacuum Coaters 45th Technical Conference. April 13-18, 2002, Lake Buena Vista, Florida.
10. Hendricks, T. "Class 6 Truck Cabin Thermal Characterization." March 6, 2002.
11. Hovland, V. "An Application: A Metal Hydride Heat Pump for a Fuel Cell Vehicle." Presented to the Department of Energy. September 5, 2002.
12. Hendricks, T. “Heat Pipe/Two-Phase Flow Systems for Vehicle System Cooling.” Presented at the Future Car Congress 2002. June 5, 2002, Arlington, Virginia. SAE Paper No. 2002-01-1970.

Other

1. Hendricks, T. "Class 6 Next Generation Vehicle Cabin Thermal Characterization Investigations." Joint Project by National Renewable Energy Laboratory / International Truck & Engine Corporation / Guardian Industries Automotive Products. May, 2002.

Vehicle Ancillary Load Reduction Project, FY 2003

Funding

DOE: $500K

Key Accomplishments

Modeling and Analysis

1. Improved A/C fuel use analysis for the U.S. Applied methodology on the EU and Japan.
2. Applied an integrated modeling process to a collaborative project with Johnson Controls to assess the impact of a new distributed HVAC concept based on human thermal comfort.
3. Developed a the Human Thermal Physiological Model (a three-dimensional, finite-element model of the human thermal physiological and thermoregulatory systems to control the thermal manikin).

Testing

1. Completed fabrication and developmental testing of ADAM (the ADvanced Automotive Manikin). Compared outdoor thermal soak of a Jeep Grand Cherokee with indoor testing at Chrysler's environmental test cell (IR lamps) and the emissions cell (metal halide lamps) showed significant errors with indoor testing including much higher surface temperatures due to lamp spectrum, lack of breezes, and significantly different radiation view factors between the heat source and the vehicle.

Technical Papers

1. Rugh, J.P. "Application of an Integrated Modeling Process to Evaluate an Automotive Climate Control System." *Vehicle Thermal Management Systems 6 Proceedings; May 18-21, 2003, Brighton, United Kingdom.* London, UK: Institution of Mechanical Engineers pp. 303-312. NREL Report No. CP-540-33370.
2. Hendricks, T.J. "Optimization of Vehicle Air Conditioning Systems Using Transient Air Conditioning Performance Analysis." *Vehicle Thermal Management Systems 6 Proceedings; May 18-21, 2003, Brighton, United Kingdom.* NREL Report No. 29930.
3. Rugh, J.; Farrington R.; Bharathan, D.; Vlahinos, A.; Burke, R.; Huizenga, C.; Zhang, H. "Predicting Human Thermal Comfort in a Transient Non-Uniform Thermal Environment." *European Journal of Applied Physiology*; Vol. 92; 2004, Number 6; pp. 721-727.
4. Burke, R.; Rugh, J.; Farrington R. "ADAM – the Advanced Automotive Manikin." *Fifth International Meeting on Thermal Manikins and Modeling Proceedings; Strasbourg, France*.
5. Zhang, H.; Huizenga, C.; Arens E.; Wang, D. "Thermal Sensation and Comfort in Transient Non-Uniform Thermal Environments." *European Journal of Applied Physiology*; Vol. 92; 2004, Number 6; pp. 728-733.
6. Hendricks, T.; Lustbader, J. "Thermoelectric Energy Recovery Systems in Future Advanced Vehicle Systems." *The 6th ASME-JSME Thermal Engineering Joint Conference Proceedings*; *March 16-20, 2003, Hawaii*.
7. Farrington, R.; Rugh, J. "Stay Cool with Advanced Automotive Glazings." *Glass Processing Days Proceedings; June 15-28, 2003, Tampere, Finland*.

Significant Presentations

1. Farrington, R.; Coroller, P.; Malvicino, C.; Gense, R.; Clodic, D.; Hrnjak, P.; Kruse, P.; Mager, R.; Harte, S.; Hovland, V. "Fuel Consumption and Associated CO_2 Emissions due to MACs." Presented at the Mac Summit 2003. February 10, 2003, Brussels, Belgium.
2. Rugh, J; Hovland, V. "National and World Fuel Savings and CO_2 Emission Reductions by Increasing Vehicle Air Conditioning COP." Presented at the 2003 Automotive Alternate Refrigerant Systems Symposium. July 17, 2003.
3. Rugh, J. "Parked Car Ventilation WJ Test Program." Presented at meeting with Chrysler. December 12, 2002.
4. Farrington, R.; Rugh, J. "Stay Cool with Advanced Automotive Glazings." Presented at Glass Processing Days. June 15-28, 2003, Tampere, Finland.

5. Rugh, J.P. "Application of an Integrated Modeling Process to Evaluate an Automotive Climate Control System." Presented at Vehicle Thermal Management Systems 6. May 18-21, 2003, Brighton, United Kingdom. London, UK: Institution of Mechanical Engineers pp. 303-312. NREL Report No. CP-540-33370.
6. Hendricks, T.J. "Optimization of Vehicle Air Conditioning Systems Using Transient Air Conditioning Performance Analysis." Presented at Vehicle Thermal Management Systems 6. May 18-21, 2003, Brighton, United Kingdom. NREL Report No. 29930.
7. Rugh, J.; Farrington R.; Bharathan, D.; Vlahinos, A.; Burke, R.; Huizenga, C.; Zhang, H. "Predicting Human Thermal Comfort in a Transient Non-Uniform Thermal Environment." *European Journal of Applied Physiology*; Vol. 92, Number 6; pp. 721-727.
8. Burke, R.; Rugh, J.; Farrington R. "ADAM – the Advanced Automotive Manikin." Presented at the Fifth International Meeting on Thermal Manikins and Modeling. Strasbourg, France.
9. Zhang, H.; Huizenga, C.; Arens, E.; Wang, D. "Thermal Sensation and Comfort in Transient Non-Uniform Thermal Environments." *European Journal of Applied Physiology*; Vol. 92, Number 6; pp. 728-733.
10. Hendricks, T.; Lustbader, J. "Thermoelectric Energy Recovery Systems in Future Advanced Vehicle Systems." Presented at the 6th ASME-JSME Thermal Engineering Joint Conference. March 16-20, 2003, Hawaii.
11. Farrington, R. "Fuel Savings from Efficient Mobile Air Conditioners." Presented at the 2003 Earth Technologies Forum. April 22-24, 2003, Washington, D.C.
12. Farrington, R.; Rugh, J. "Reducing Fuel Used for Mobil Air-Conditioners Through Solar Reflective Glazing." Presented at the ITB Group Above-The-Bent Line Modules and Systems. November, 6, 2003, Dearborn, Michigan.

Vehicle Ancillary Load Reduction Project, FY 2004

Funding

DOE: $964K ***WFO:*** US EPA $70K

Key Accomplishments

Modeling and Analysis

1. Modeled standing wave thermoacoustic devices capable of using waste heat to generate cooling.
2. At the request of SAE, compared GM and EU Life Cycle Climate Performance analyses of mobile air conditioning systems.
3. Completed the Human Thermal Physiological Model.
4. Completed the Human Thermal Comfort Empirical Model.

Testing

1. Completed fabrication of the thermal manikin (ADAM) and used the improved human thermal physiological model to simulate skin temperatures within approximately +3/-1ºC of published results.
2. Thermal soak tested a prototype Chrysler HEV with advanced thermal management technologies.
3. Designed and demonstrated a standing wave thermoacoustic device capable of using waste heat to generate cooling.
4. Measured a 2.8 to 4.5% reduction in automotive air-conditioning fuel use by improving thermal comfort with a ventilated seat prototype.

Technical Papers

1. Farrington, R; Rugh, J.; Bharathan, D. "Use of a Thermal Manikin to Evaluate Human Thermoregulatory Responses in Transient, Non-Uniform, Thermal Environments." *International Conference on Environmental Systems Proceedings; July 19-22, 2004, Colorado Springs, Colorado*. SAE Paper No. 2004-01-2345.
2. Rugh, J.; Malaney, V. "Comparison of Indoor Vehicle Thermal Soak Tests to Outdoor Tests." *2004 SAE Congress Proceedings; Detroit, Michigan*. SAE Paper No. 2004-01-1376.
3. Rugh, J.; Hovland, V. Andersen, S. "Significant Fuel Savings and Emission Reductions by Improving Vehicle Air Conditioning." *Mobile Air Conditioning Summit Proceedings*; *April 14-15, 2004*, *Washington, D.C.*

Significant Presentations

1. Farrington, R; Rugh, J.; Bharathan, D. (2004) "Use of a Thermal Manikin to Evaluate Human Thermoregulatory Responses in Transient, Non-Uniform, Thermal Environments." Presented at the 2004 International Conference on Environmental Systems. July 19-22, 2004, Colorado Springs, Colorado. SAE Paper No. 2004-01-2345.
2. Rugh, J.; Malaney, V. "Comparison of Indoor Vehicle Thermal Soak Tests to Outdoor Tests." Presented at the 2004 SAE Congress. Detroit, Michigan. SAE Paper No. 2004-01-1376.
3. Rugh, J.; Hovland, V.; Andersen, S. "Significant Fuel Savings and Emission Reductions by Improving Vehicle Air Conditioning." Presented at the Mobile Air Conditioning Summit, April 14-15, 2004, Washington, D.C.
4. Rugh, J. "Comparison of Two Mobile A/C LCCP Analyses." Presented at the 2004 Alternate Refrigerant Systems Symposium. June 28-July 1, 2004, Scottsdale, Arizona.
5. Rugh, J.; Gooding, S. "Vehicle Soak Testing of Lightweight Vehicle with Advanced Thermal Management Technologies." Presented to Chrysler. November 17, 2004.
6. Keyser, M.; King, C. "FY04 Milestone 6.2 Report Light Vehicle Ancillary Systems Heat Generated Cooling Using A Standing Wave Thermoacoustic Engine/Heat Pump." Presented to the Department of Energy. September 30, 2004.

Other

1. Established CRADA with AVL to investigate integrated modeling concepts based on thermal comfort.
2. Built the Waste Heat Utilization Laboratory.
3. Completed Vehicle Climate Control Laboratory (VCCL) including an automobile passenger compartment (Dodge Neon), heated with solar lamps, temperature measurement, and automotive A/C cooldown.

Vehicle Ancillary Load Reduction Project, FY 2005

Funding

DOE: $1141K ***WFO:*** US EPA $250K

Key Accomplishment

Modeling and Analysis

1. Applied NREL's A/C fuel use analysis methodology to the country of India under EPA funding.
2. Started applying the integrated modeling process to a Cadillac STS.
3. Improved the Human Thermal Comfort Empirical Model.

Testing

1. Completed validation/calibration testing of ADAM with jury test results in the literature. Assessed thermal load reduction in a thermal soak test using two Cadillac STSs as part of the industry/government/SAE I-MAC Cooperative Research Program.
2. Evaluated two types of advanced seating technology with W.E.T. and Amerigon. Determined the potential to reduce A/C fuel use.
3. Completed testing of the standing wave thermoacoustic engine/heat pump and designed a modular standing/traveling wave thermoacoustic engine.

Technical Papers

1. Rugh, J.; Bharathan, D. "Predicting Human Thermal Comfort in Automobiles." *Seventh Vehicle Thermal Management Systems Conference Proceedings; May 10-12, 2005, Toronto, Canada*. SAE Paper No. 2005-01-2008.
2. Wolfahrt, J.; Baier, W.; Wiesler, B.; Raulot, A.; Rugh, J.; Bharathan, D.; Kußmann, C. "Aspects of Cabin Fluid Dynamics, Heat Transfer, and Thermal Comfort in Vehicle Thermal Management Simulations." *Seventh Vehicle Thermal Management Systems Conference Proceedings; May 10-12, 2005, Toronto, Canada.* SAE Paper No. 2005-01-2000.
3. Lustbader, J. "Evaluation of Advanced Automotive Seats to Improve Thermal Comfort and Fuel Economy." *Seventh Vehicle Thermal Management Systems Conference Proceedings; May 10-12, 2005, Toronto, Canada*. SAE Paper No. 2005-01-2056.
4. Farrington, R.; Rugh, J.; Bharathan, D.; Paul, H.; Bue, G.; Trevino, L. "Using a Sweating Manikin, Controlled by a Human Physiological Model, to Evaluate Liquid Cooling Garments." *35th International Conference on Environmental Systems Proceedings; July 11-14, 2005, Rome, Italy*. SAE Paper No. 2005-01-2971.

Significant Presentations

1. Rugh, J.; Bharathan, D. "Predicting Human Thermal Comfort in Automobiles." Presented at the 7th Vehicle Thermal Management Systems Conference. May 10-12, 2005, Toronto, Canada. SAE Paper No. 2005-01-2008.
2. Lustbader, J. "Evaluation of Advanced Automotive Seats to Improve Thermal Comfort and Fuel Economy." Presented at the 7th Vehicle Thermal Management Systems Conference. May 10-12, 2005, Toronto, Canada. SAE Paper No. 2005-01-2056.
3. Farrington, R.; Rugh, J.; Bharathan, D.; Paul, H.; Bue, G.; Trevino, L. "Using a Sweating Manikin, Controlled by a Human Physiological Model, to Evaluate Liquid Cooling Garments." Presented at the 35th International Conference on Environmental Systems. July 11-14, 2005, Rome, Italy. SAE Paper No. 2005-01-2971.
4. John Rugh, J.; Bharathan, D; Chaney, L. "Predicting Human Thermal Comfort in Automobiles." Presented at the AVL Advanced Simulation Technologies User Meeting 2005. June 13, 2005, Graz, Austria.
5. Rugh, J. "How Diverse Powertrains Affect Thermal Management." Presented during a Research Forum Panel, 7th Vehicle Thermal Management Systems Conference. May 11, 2005, Toronto, Canada.

6. Rugh, J. "SAE Improved Mobile Air Conditioning Cooperative Research Program." Presented at the 2005 Mobile Air Conditioning Summit. March 15-16, 2005, Sacramento, California.
7. Rugh, J. "Measuring Indirect Emissions of MACs." Presented at Session 3 – Research Activities and Panel Discussion at the 2005 Mobile Air Conditioning Summit. March 15-16, 2005, Sacramento, California.
8. Keyser, M.; King, C. "Ancillary Loads Milestone 6.3.2 Investigate and Research New Heat Exchangers and Regenerators for a Traveling Wave Thermoacoustic System." Delivered to the Department of Energy. August 31, 2005.

Other

1. Invited participation at SAE's VTMS7 Conference research forum panel entitled "How Diverse Powertrains Affect Thermal Management."

Vehicle Ancillary Load Reduction Project, FY 2006

Funding

DOE:	$892K	***WFO:***	NASA	$76K	US EPA	$50K
			US Army (USAARL)	$10K	Sage Electrochromics	$20K
			SAE	$54K	BSST	$30K

Key Accomplishments

Modeling and Analysis

1. Used AVL software in the Cadillac STS thermal analysis (Improved Mobile Air Conditioning Cooperative Research Program) to model the thermal/fluid environment in the passenger compartment during soak and cooldown.
2. Determined the A/C fuel use impact of Cadillac STS thermal load reduction technologies tested in the summer of 2005.
3. Performed an A/C fuel use analysis of Mexico City with EPA funding.

Testing

1. Tested the best load reduction technologies in a thermal soak test using Cadillac STSs (Sungate EP, solar-powered parked car ventilation, solar reflective paint).
2. Completed NASA Liquid Cooling Garment testing using ADAM and the Manikin Environmental Chamber.
3. Completed thermoacoustic traveling wave prototype component testing.
4. Assessed an Amerigon Thermoelectric cooled seat using ADAM to determine improvement in thermal comfort and potential to reduce A/C fuel use.

Technical Papers

1. Rugh, J.; King, C.; Paul, H.; Bue, G.; Trevino, L. "Phase II Testing of Liquid Cooling Garments Using a Sweating Manikin, Controlled by a Human Physiological Model." *36th International Conference on Environmental Systems Proceedings; July 17-20, 2006, Norfolk, Virginia*. SAE Paper No. 2006-01-2239.

Significant Presentations

1. Rugh, J.; King, C.; Paul, H.; Bue, G.; and Trevino, L. "Phase II Testing of Liquid Cooling Garments Using a Sweating Manikin, Controlled by a Human Physiological Model." Presented at the 6th International Conference on Environmental Systems. July 17-20, 2006, Norfolk, Virginia. Paper No. 2006-01-2239.
2. Rugh, J.; Gooding, S. "I-MAC Vehicle Testing of Advanced Thermal Management Technologies." Presented to the I-MAC Core Team. October 27, 2005, Troy, Michigan.
3. Rugh, J. "Impact of Cadillac STS Ventilated Seat on Fuel Use and Thermal Comfort." Presented to the I-MAC Core Team. March 7, 2006, Troy, Michigan.
4. Chaney, L. "Analysis of the Impact of Reduced Vehicle Thermal Load on AC Fuel Use." Presented at the 2006 Alternate Refrigerant Systems Symposium. June 27-29, 2006, Scottsdale, Arizona.
5. Meyer, J.; Chaney, L.; Rugh, J. "SAE Improved Mobile Air Conditioning Cooperative Research Program - Reduced Thermal Load." Presented at the I-MAC Sponsors Meeting. June 26, 2006, Scottsdale, Arizona.
6. Rugh, J.; Chaney, L.; Lustbader J. "Vehicle Thermal Management Integrated Modeling of the 2005 I-MAC Test Vehicle." Presented at the 1st European Mobile Air Conditioning Workshop. November 29-30, 2005, Orbassano, Italy.
7. Rugh, J. "Indirect Emissions from MACs." Presented to the California Air Resources Board. December 20, 2005, Sacramento, California.
8. Lustbader, J. "W.E.T. Automotive Systems MTNW & NREL Meeting." Presented at a meeting at NREL. November 17, 2005.
9. Keyser, M.; King, C. "Ancillary Loads Milestone 8.1 - Heat Generated Cooling Investigation and Research Into Thermoacoustic Systems." Presented to the Department of Energy. September 30, 2006.

10. Thundiyl, K.; Chaney, L. "Mexico City Fuel Savings and Emission Reductions by Improving Vehicle Air Conditioning." Presented at the First International Conference on Carbon Management at Urban and Regional Levels: Connecting Development Decisions to Global Issues. September 7, 2006. NREL Report No. PR-540-40550.

Other

1. 2006 Environmental Protection Agency (EPA) Climate Protection Award (NREL is the first DOE laboratory to earn this honor).
2. Completed Manikin Environmental Chamber (temperature and humidity control).

Vehicle Ancillary Load Reduction Project, FY 2007

Funding

DOE:	$270K	***WFO:***	3M	$48K	Sage Electrochromics	$20K
			Delphi	$14K	SAE	$46K
			EPA	$25K		

Key Accomplishments

Modeling and Analysis

1. Converted the integrated vehicle thermal analysis process to use FLUENT CFD software.
2. Estimated the impact of reducing the thermal load on A/C thermal load on A/C system capacity of a Cadillac STS as part of the improved Mobile Air Conditioning Cooperative Research Program (summer 2006 vehicle data).
3. Updated the NREL A/C fuel use analysis methodology of India with improved boundary conditions and assumptions from Indian automobile experts with EPA funding.
4. Generated a CFD mesh of a HMMWV and FMTV.
5. Calculated the A/C fuel use of a secondary loop HFC-152a A/C system.

Testing

1. Thermal soak tested a 3M solar reflective film on a Class 8 truck in Phoenix.
2. Used ADAM and Manikin Environmental Chamber to evaluate current and proposed thermal blankets to reduce or prevent hypothermia in patients during transport - collaboration with the U.S. Army Aeromedical Research Laboratory (USAARL).

Technical Papers

1. Chaney, L.; Thundiyil, K.; Chidambaram, S.; Abbi, Y.P.; Andersen, S. "Fuel Savings and Emission Reductions from Next-Generation Mobile Air Conditioning Technology in India." *Eighth Vehicle Thermal Management Systems Conference Proceedings; May 20-24, 2007*. Paper No. C640/085/2007. NREL Paper No. CP-540-41154.
2. Rugh, J.; Chaney, L.; Lustbader, J.; Meyer, J.; Rustagi, M.; Olson, K.; Kogler, R. "Reduction in Vehicle Temperatures and Fuel Use from Cabin Ventilation, Solar-Reflective Paint, and a New Solar-Reflective Glazing." *2007 SAE World Congress Proceedings; April 16-19, 2007*. Paper No. 2007-01-1194.
3. Rugh, J.; Lustbader, J. "Application of a Sweating Manikin Controlled by a Human Physiological Model and Lessons Learned." *Sixth International Meeting on Thermal Manikins and Modeling (613M) Proceedings; October 17-18, 2006*.
4. Bharathan, D.; Chaney, L.; Farrington, R.; Lustbader, J.; Keyser, M.; Rugh, J. "An Overview of Vehicle Test and Analysis Results from NREL's A/C Fuel Use Reduction Research." *Eighth Vehicle Thermal Management Systems Conference Proceedings*; Paper No. C640/050/2007.

Significant Presentations

1. Rugh, J. "I-MAC CRP Team 3 Advanced Thermal Management Technologies 2006 Vehicle Test Status." Presented at the I-MAC Core Meeting. December 6, 2006.
2. Rugh, J.; Chaney, L.; Meyer, J. "I-MAC Team 3 Thermal Load Reduction." Presented at the I-MAC Final Meeting. July 20, 2007.
3. Rugh, J. "Assessing the Vehicle Level and National A/C Fuel Use Impact of Advanced Climate Control Technologies." Presented at the Cooling Cars with Less Fuel – IEA Workshop. October 23, 2006.
4. Chaney, L; Thundiyil, K.; Chidambaram, S.; Abbi, Y.P.; Andersen, S. "Fuel Savings and Emission Reductions from Next-Generation Mobile Air Conditioning Technology in India." Presented at the Eighth Vehicle Thermal Management Systems Conference. May 20-24, 2007. Paper No. C640/085/2007.
5. Rugh, J.; Chaney, L.; Lustbader, J.; Meyer, J.; Rustagi, M.; Olson, K.; Kogler, R. "Reduction in Vehicle Temperatures and Fuel Use from Cabin Ventilation, Solar-Reflective Paint, and a New Solar-Reflective Glazing." Presented at the 2007 SAE World Congress. April 16-19, 2007. Paper No. 2007-01-1194.

6. Rugh, J.; Lustbader, J. "Application of a Sweating Manikin Controlled by a Human Physiological Model and Lessons Learned." Presented at the Sixth International Meeting on Thermal Manikins and Modeling (613M). October 17-18, 2006.
7. Bharathan, D.; Chaney, L.; Farrington, R.; Lustbader, J.; Keyser, M.; Rugh, J. "An Overview of Vehicle Test and Analysis Results from NREL's A/C Fuel Use Reduction Research." Presented at the Eighth Vehicle Thermal Management Systems Conference. Paper No. C640/050/2007.
8. Baker, J.; Ghodbane, M.; Rugh, J.; Hill, W. "Alternative Refrigerant Demonstration Vehicles." Presented at the 2007 SAE Alternative Refrigerant Systems Symposium. July 17, 2007, Scottsdale, Arizona.
9. Rugh, J. "SL R-152a MAC: Updated Vehicle Analysis, Impact of Increased Mass, and Impact on Idle Time." Presented at the US EPA's HFC-152a Workshop. August 14-15, 2007, Washington, D.C.

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14. ABSTRACT *(Maximum 200 Words)*
The amount of fuel used for climate control in U.S. vehicles reduces the fuel economy of more than 200 million light-duty conventional vehicles and thus affects U.S. energy security. Researchers at the DOE National Renewable Energy Laboratory estimated that the United States consumes about 7 billion gallons of fuel per year for air-conditioning (A/C) light-duty vehicles. Using a variety of tools, NREL researchers developed innovative techniques and technologies to reduce the amount of fuel needed for these vehicles' ancillary loads. For example, they found that the A/C cooling capacity of 5.7 kW in a Cadillac STS could be reduced by 30% while maintaining a cooldown performance of 30 minutes. A simulation showed that reducing the A/C load by 30% decreased A/C fuel consumption by 26%. Other simulations supported the great potential for improving fuel economy by using new technologies and techniques developed to reduce ancillary loads.

15. SUBJECT TERMS
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