Opportunities to Reduce Vehicle Climate Control Loads

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Keywords

Air conditioning, cooling, energy, heat exchanger, hybrid electric vehicle, thermal management.

Abstract

The National Renewable Energy Laboratory (NREL), in cooperation with U.S. industrial partners, is developing innovative techniques to reduce vehicle climate control loads. This effort is aimed at one of the U.S. Department of Energy's (DOE) Office of Transportation Technologies goals—reducing the nation's dependence on oil. NREL uses a systems-level approach that examines climate control system performance, occupant thermal comfort, fuel consumption, and powertrain performance. Techniques include advanced glazings, ventilation, air cleaning, energy-efficient heating and cooling systems, and thermal comfort modeling. NREL, a DOE national laboratory, focuses its research and development on technologies that will increase the use of renewable energy, decrease the country's dependence on oil, and improve air quality.

Background

Reducing the climate control loads in a vehicle is important to improving a vehicle's fuel economy. Peak climate control thermal auxiliary loads, which can be as high as 6 kilowatts (kW), put a significant load on a vehicle's system. A vehicle that would consume 3 liters of fuel per 100 kilometers (3 L/100 km) or could be driven 80 miles per gallon (mpg) with no auxiliary loads may be able to achieve only 5.3 L/100 km (45 mpg) when typical auxiliary loads apply.

Figure 1 shows the increasing impact of auxiliary loads as vehicle fuel economy is increased. An auxiliary load increase of only 400 Watts (W) can decrease fuel economy of a 3-L/100 km (80-mpg) vehicle by 2.7 km/L (6.5 mpg). The same 400-W decrease results in a 0.4 km/L (1 mpg) decrease for a conventional 11.9-L/100 km (28-mpg) vehicle. If every vehicle in the United States were to save only 0.4 km/L (1 mpg), $4 billion (U.S. dollars [USD]) would be saved annually in gasoline and oil costs.

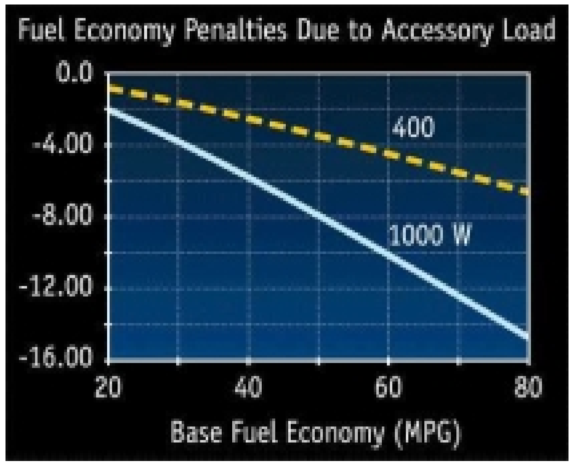

Figure 1: Fuel economy penalties resulting from auxiliary loads

In addition to saving money in oil and fuel costs, reducing automotive auxiliary loads will help auto manufacturers meet tough emissions and fuel economy standards. Today's regulations present a challenge for automakers. They must meet the standards while maintaining vehicle affordability, performance, cost, and safety. Soon, a new U.S. emissions test, the Supplemental Federal Test Procedure (SFTP), will begin measuring tail-pipe emissions with the air-conditioning (A/C) system operating. This additional requirement will make meeting emissions and fuel economy standards even more difficult.

Approach

The key for effective climate control is to make the occupants comfortable using as little energy as possible. Air conditioning, especially during the initial cool-down period following a hot soak in the sun, represents the biggest climate control load on a vehicle. The first step to reducing this peak load is to keep solar gains out of the vehicle through advanced glazings or shading devices. The second step is to reduce the build-up of heat in the vehicle by circulating ambient air to cool the vehicle's interior. Then, once the occupant enters the hot vehicle, the climate control system should cool the occupant, not the entire passenger compartment. This can be done with conductive or direct contact cooling. The cooling load for the outside air can also be significant. To maintain a pleasant and safe environment, the amount of outside air to be treated should be adequate for air quality and humidity control.

Thermal Comfort

Thermal comfort modeling is useful in ensuring comfort at a minimum level of energy use because it can provide an integrated, systems-level approach to evaluating energy-efficient alternatives to automotive climate control. It is insufficient to look only at cabin air temperature or heat added or removed from the cabin air, because alternatives such as heated or cooled seats affect the cabin air very little, but can have significant impacts on occupant thermal comfort. NREL has developed a transient thermal comfort model, called the Average Thermal Sensation Comfort Model, which estimates a passenger's comfort level in a vehicle during winter warm-up or summer cool-down [1].

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

Figure 2 shows an example of thermal comfort results from our model. The baseline results are without cabin air ventilation. The other curve demonstrates the effect of 47 L/s (100 cfm) of cabin ventilation continuously during hot soak conditions. The ventilation fan is powered by a small photovoltaic (PV) panel. Both vehicles are exposed to full sun and 38°C ambient air. After 2 hours, the baseline vehicle reaches a cabin air temperature of 83°C. The vehicle with ventilation, however, reaches only 66°C. This results in a significant difference in thermal comfort. Note that thermal discomfort peaks after about 3 minutes as the core body temperature increases.

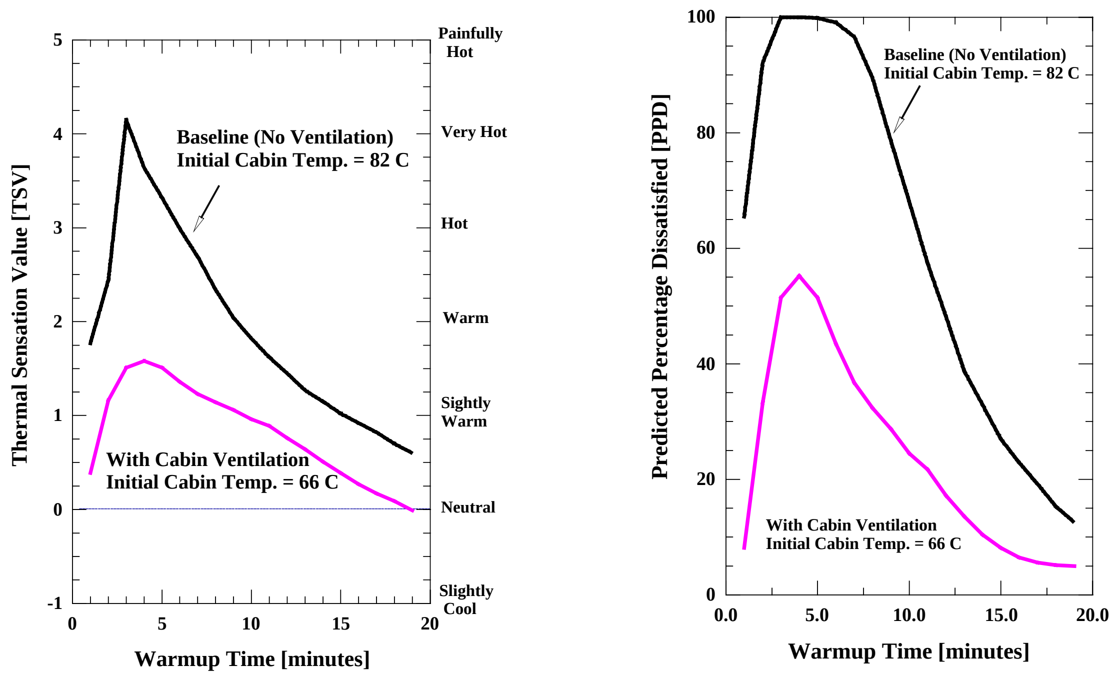

Figure 2: Example of thermal comfort modeling – the effect of cabin ventilation

Glazing

Advanced windshields, such as PPG's Sungate , effectively reduce transmission of ultraviolet (UV) and infrared (IR) solar radiation into the vehicle compartment. Figure 3 compares the transmissivity of the Sungate windshield (purple lower curve) with that of a conventional windshield (blue upper curve).

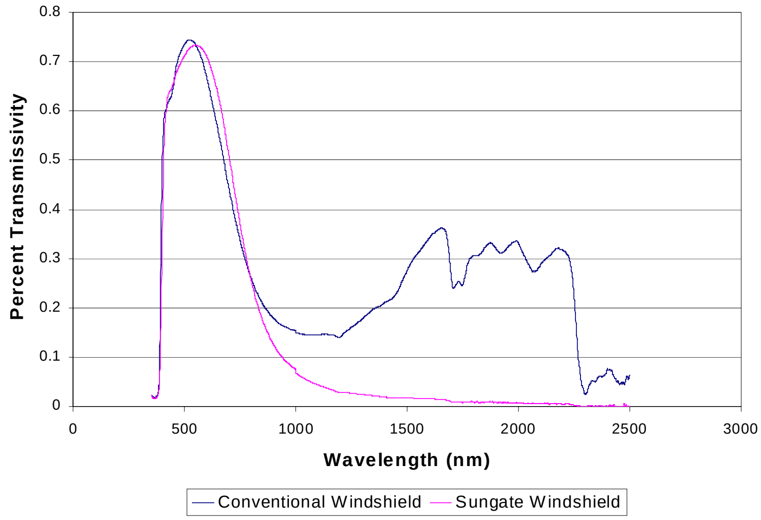

Figure 3: Spectral properties of solar reflective windshield

By reducing the solar gain, we can reduce the vehicle's interior temperature and thus the cooling load. We performed co-heating tests were on a Chrysler Breeze vehicle to determine the performance of three separate PPG windshields. The temperature inside the vehicle was kept at a 60°C (140°F) during the co-heating tests. We monitored the inside and outside air temperatures as well as the heater power and the front and rear dash temperatures.

The three windshields tested were the Solex (used for vehicles produced in the United States), the Solargreen (used for vehicles produced in Europe), and the Sungate. Figure 4 shows the heater power for the three different windshields and for the opaque case. At 13:00, the heater requires no power to maintain an interior temperature of 60°C when the Solex windshield is used. However, the heater requires 160 W of power to maintain an interior temperature of 60°C when the Solex windshield is used. The solar incident radiation between tests was within 5%. Table 1 shows the ratio of solar gain seen by each windshield over the base case or opaque case.

Table I: Relative Solar Gain of Windshields

Test Condition	Solar Gain
Opaque	1
Sungate	1.66
Solargreen	1.81
Solex	1.93

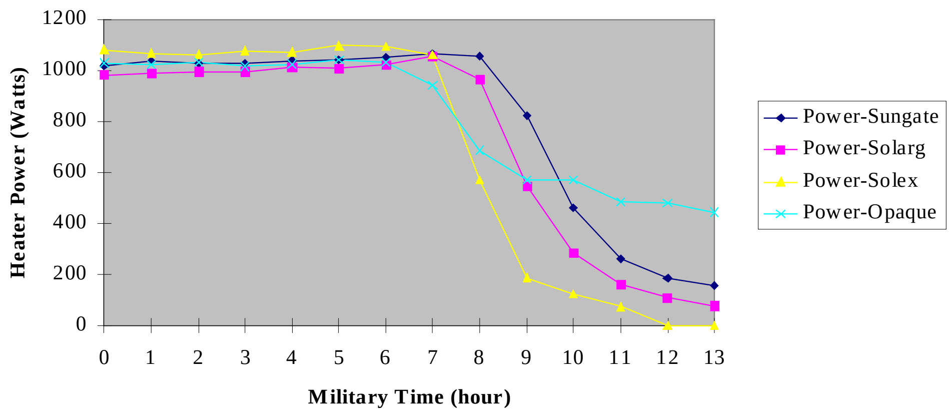

Figure 4: Co-heating tests performed for the Sungate, Solex, and SolarGreen windshields

The solar gains in the vehicle are decreased by 27% if the standard front windshield (Solex) is replaced with the Sungate windshield. If the compressor is proportionally downsized, the Sungate windshield can increase the fuel economy of the Breeze by about 1.5% over the SFTP and by about 3.5% over the SCO3 drive cycle.

We have also built an electrochromic sunroof using samples from OCLI, as shown in Figure 5. The transmissivity of electrochromic glazing can be controlled to be either clear or opaque, or at a state of partially clear, with separate driver and passenger controls to adjust solar gains while parked or driving. Electrochromic windows, which change transmissivity with an applied voltage as little as 2 volts 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 vehicle color for aesthetic purposes, and enhance security. Photovoltaics can be integrated into the electrochromic window to provide the power to change the state of the window.

Figure 5: Electrochromic sunroof

Ventilation Control

NREL has developed a unique way of ventilating parked vehicles to reduce the peak cooling load. The technique reduces surface temperatures, which will allow less expensive materials to be used during manufacture. High interior temperatures reduce the service life of plastics and fabrics used inside vehicles, increase the energy used for air conditioning, reduce occupant comfort, increase material costs, and reduce vehicle mileage.

Modern vehicles have large windows to increase the driver's visibility and improve the vehicle's appearance. However, while a vehicle is parked, these large windows turn the vehicle into a very efficient solar collector. Sunlight entering through the windows is converted to thermal energy that becomes trapped inside the vehicle (glass is transparent to short wavelength radiation and opaque to long wavelength radiation).

Typically, vehicle interior stagnation temperatures range between 71°-82°C (160°-180°F) during the summer in many U.S. cities. Under severe summer conditions, vehicle interior stagnation temperatures can approach 104°C (220°F). The objective of this work was to develop techniques to limit vehicle stagnation interior temperatures to 66°C (150°F) under 49°C (120°F) ambient conditions. We studied performance tradeoffs associated with reducing solar gains and facilitating the removal of thermal energy from the vehicle's interior. The study focused on full-scale measurements in a 1996 Neon and a 1997 Breeze.

We measured solar gains to peak at about 1.4 kW with standard glazing, and measured infiltration rates at stagnation at about 4.7 L/s (10 cfm). By adding "intentional" infiltration while the vehicle is parked (by opening low and high dampers or "cracking" the windows or sunroof), the infiltration level can be increased to 9.4 L/s (20 cfm). Small fans coupled to the vehicle's pressure relief dampers can provide ventilation during peak solar gain hours at a power cost of about 1 W per 235 L/s (50 cfm).

Small fans were integrated with low-flow exhaust plenums to extract thermal boundary layers from window shading devices. We found that boundary layer thermal control required about 0.8 L/s per linear meter (0.5 cfm per linear foot) of window. Because of the increased temperature of the boundary layer relative to the bulk air temperature in the vehicle, we found that boundary layer control required 30%-50% less airflow than strategies that ventilate the entire interior of the vehicle. Figure 6 shows an infrared image of the effectiveness of the technique that removes the boundary layer near a hot surface. Removing hot boundary layers is more effective than letting the heat mix within the vehicle and then trying to bulk ventilate the entire interior of the vehicle.

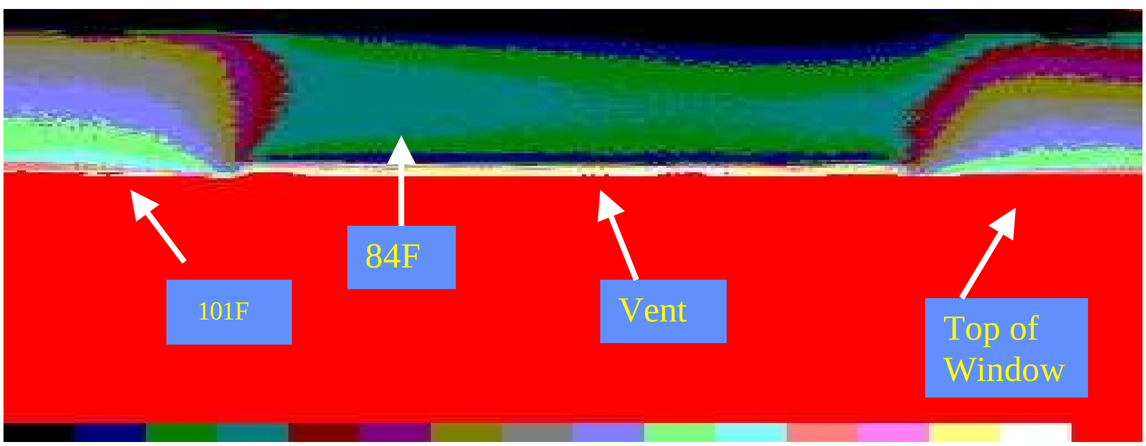

Figure 6: Boundary layer control

Photocatalytic Oxidation for Air Cleaning

Increasing the percentage of recirculated air can reduce steady-state climate control loads. However, passenger comfort and health dictate that odors be removed from recirculated air. Techniques such as photocatalytic oxidation (PCO) reduce volatile organic compounds (VOCs) and odors in a vehicle 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 7, operates with ultraviolet light and a titanium dioxide catalyst. It is inexpensive and requires minimal maintenance. Figure 8 shows the ambient indoor air quality with and without the PCO reactor. We measured significant reductions in formaldehyde, acetaldehyde, and acetone.

Figure 7: A prototype photocatalytic air cleaning system

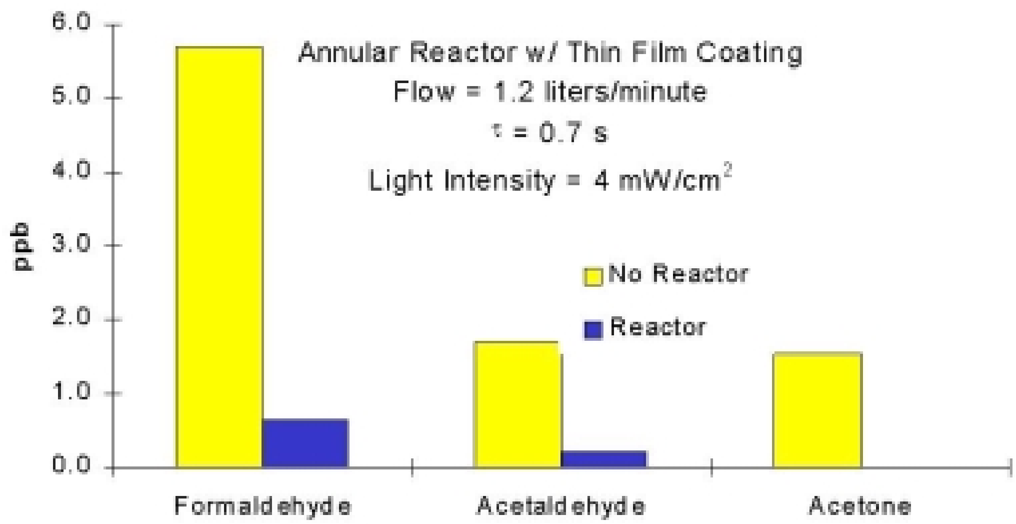

Figure 8: Ambient indoor air quality

Liquid Heated and Cooled Seats

We are testing a liquid heated and cooled seat developed by Life Enhancement Technologies. Using these seats, NREL hopes to reduce the need for the air-conditioning and heating systems. The seat is unique because it is in direct contact with the passenger, providing warmth and cooling via thermal conduction. With this approach, the passengers become comfortable more quickly than with traditional air-conditioning and heating alone. Each seat has individual controls so that each occupant can adjust the seat for individual comfort. Figure 9 shows an infrared image of the liquid heated/cooled seat.

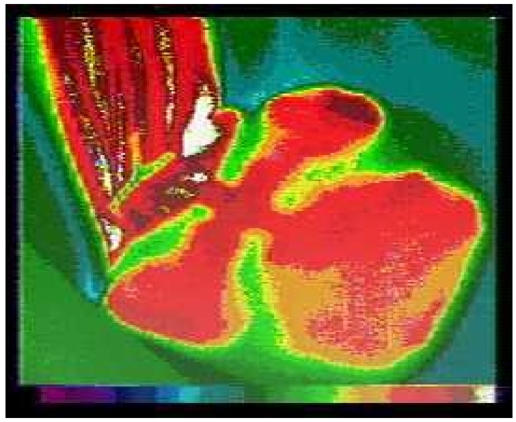

Figure 9: Infra-red thermography image of a liquid heated seat

Cabin Warm-up Alternatives

We have also examined ways to provide sufficient heat for vehicle cabins with small efficient engines. Cabin heating systems must attain acceptable comfort under extreme design conditions in reasonably short periods of time (< ~10 minutes). Conventional gasoline-powered automotive heating systems use coolant heat and achieve acceptable comfort partly because waste heat is abundant. In gasoline engines, engine efficiency averages about 25%, with about two-thirds of the waste heat going to the coolant.

Hybrid electric vehicles have significantly less coolant waste heat available, for two reasons. First, the fuel use is reduced by about 50%. The warm-up problem is further exacerbated by the reduction in the fraction of waste heat that goes to coolant, which drops from two-thirds for a gasoline engine to about one-fourth for a small diesel engine. Hence, small diesel engines, such as those that may be used in HEVs, may provide only 25% to 35% of the required peaking heating needs in a cold climate.

For our analysis, we chose a base-case HEV with a city driving case and fuel input of 27 kW. The waste heat (65% of the fuel input) was divided 3:1 between exhaust and coolant fluids. Cabin air flow was set to .07 kg/s (180 cfm), with 20% recirculated and 80% outdoor air (70 air changes per hour).

We used the SINDA/FLUINT™ finite difference analyzer to simulate the vehicle heat transfer and modeled thermal comfort with the NREL Average Thermal Sensation comfort model previously discussed. Two of the methods investigated for enhancing warmup were exhaust heat recovery and heated seats. Figure 10 shows the cabin air temperature for the baseline and for exhaust heat recovery. The exhaust heat recovery method performs better because exhaust air warms up quickly and also because of low mass in the heating system. We added a 100-W heated seat to the exhaust-heat-enhanced system. Figure 11 shows the seat temperature (with occupant) versus time for a heated and unheated seat .

Figure 12 shows occupant thermal sensation value (neutral = 0, cold<0) for these three cases. The baseline case does not result in comfort after 30 minutes of driving. Adding exhaust heat recovery results in thermal comfort within 16 minutes, and combining exhaust heat recovery with heated seats achieves thermal neutrality in about 8 minutes.

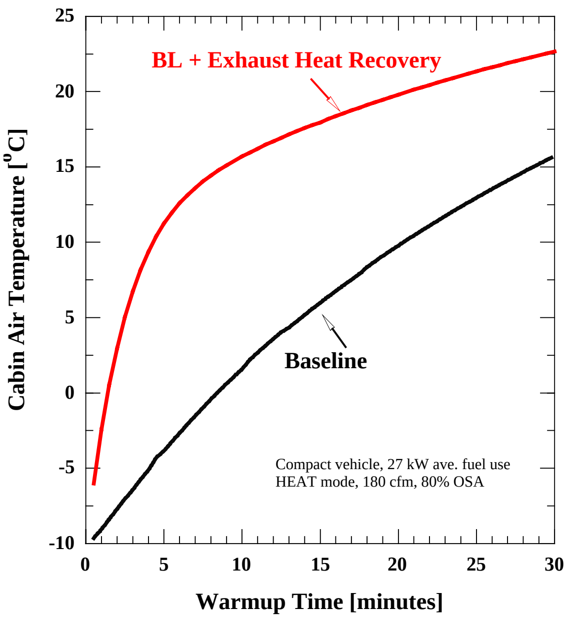

Figure 10: Cabin air temperature with exhaust heat

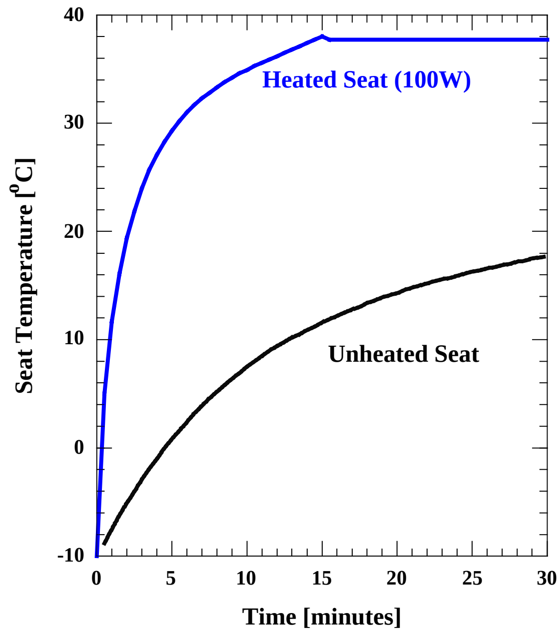

Figure 11: Heated versus unheated seat

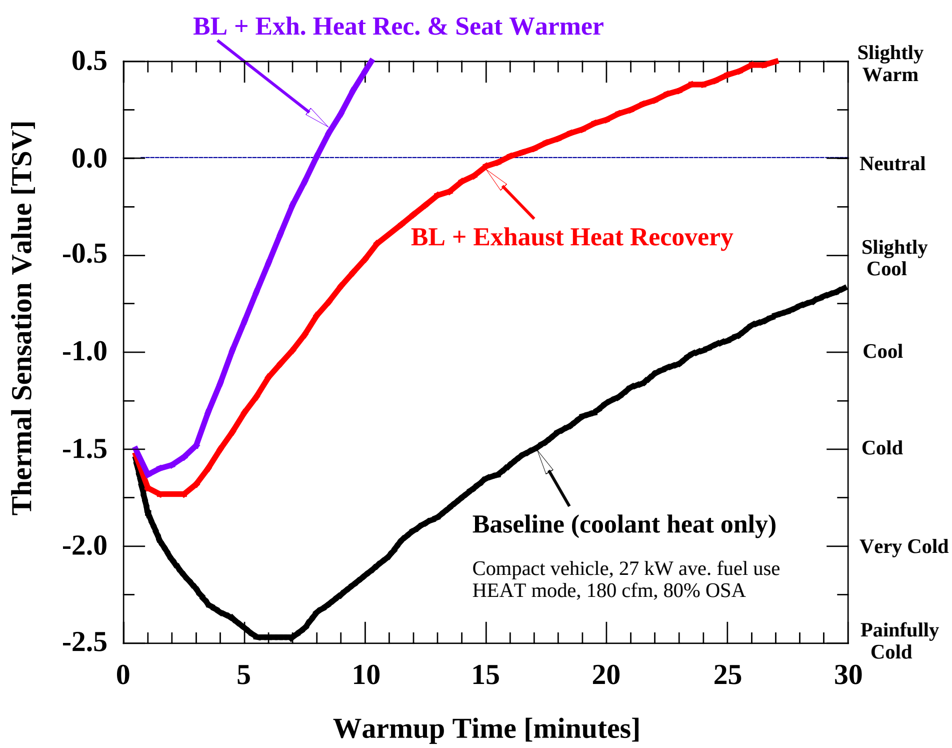

Figure 12: Predicted passenger thermal comfort during cabin warmup

Conclusions

Significant reductions in automotive auxiliary loads are needed for vehicles of the future, making passengers more comfortable, more quickly, and the vehicles themselves more fuel efficient, quiet, and safe. Vehicle climate control loads can be reduced in many ways—some can be readily implemented in today's vehicles, and others will require more development. The techniques we describe here appear promising for reducing vehicle climate control loads, and we have seen that even small changes in climate control loads can result in increased vehicle efficiencies. This, in turn, can have large national and global impacts in terms of reduced dependency on foreign oil and improved air quality.

References

1. S. Burch, S. Ramadhyani, and J. Pearson, "Analysis of Passenger Compartment Thermal Comfort in an Automobile Under Severe Winter Conditions," *ASHRAE Transactions*, Vol. 97, Part 1, 1991.