Challenges and Potential Solutions for Reducing Climate Control Loads in Conventional and Hybrid Electric Vehicles

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Abstract
The National Renewable Energy Laboratory, a U.S. Department of Energy national laboratory, is collaborating with U.S. automotive manufacturers to develop innovative techniques to reduce national fuel consumption and vehicle tailpipe emissions by reducing vehicle climate control loads. A new U.S. emissions test, the Supplemental Federal Test Procedure (SFTP), will soon begin measuring tailpipe emissions with the air conditioning system operating. Modeled results show that emissions of oxides of nitrogen (NO_x) and carbon monoxide (CO) more than double during the air conditioning part of the SFTP. Reducing the transmittance of the glazing can have a greater impact on the cabin soak temperature than ventilating the vehicle during a hot soak. Reducing the amount of outside air can decrease cooling and heating loads but requires that the recirculated air be cleaned. We discuss a photocatalytic oxidation air-cleaning process for removing volatile organic compounds and bioareosols. We conclude with an example of modeling the thermal comfort of the occupants. An auxiliary load increase of only 400 Watts (W) 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) would be saved annually in gasoline and oil costs. Further information can be found at http://www.ctts.nrel.gov/auxload.html.

Keywords
Air conditioning, thermal comfort, energy efficiency, fuel economy, air cleaning

1 INTRODUCTION

Starting with model year 2001 (MY 2001) vehicles, U.S. automobile manufacturers face a new emissions standard. The procedure, called the Supplemental Federal Test Procedure (SFTP), adds two new drive cycles to the current Federal Test Procedure (FTP). The first additional test, the SC03 Air Conditioning Cycle, measures tailpipe emissions while the air conditioning is operating at maximum. The vehicle is thermally soaked for 10 minutes before the test and then operated in an environmental chamber at 35°C (95°F), 40% relative humidity, and a solar load of 850 W/m^2. The second additional test is the US06 High Speed, High Load Cycle. Table 1 shows the specifications for the drive cycles. The air conditioning test (SCO3) is the single largest contributor, 39%, to the total emissions results.

Table 1. Supplemental Federal Test Procedure specifications

	FTP	SCO3	US06
Time (s)	1877	594	600
Max. speed, km/h (mph)	91.2 (56.7)	88.2 (54.8)	129.2 (80.3)
Max. acceleration km/h/s, (mph/s)	5.8 (3.6)	8.2 (5.1)	12.9 (8)
Distance, km (miles)	17.8 (11.1)	5.8 (3.6)	12.9 (8)
Contribution to total emissions value	33%	39%	28%

Table 2 shows the current implementation schedule for vehicles with a gross vehicle weight (GVW) under 2608 kg (5750 lb). There is no plan to expand the use of the SFTP to measure fuel economy. However, reducing the weight of the air conditioning system results in a measurable impact on the fuel economy measurements. For a mid-size vehicle, every 9.1 kg (20 lb) reduction in vehicle weight results in about a 0.04 km/L (0.1 mpg) increase in fuel economy.

Table 2. SFTP implementation schedule

	Percent of vehicles subject to SFTP
MY 2001	25%
MY 2002	50%
MY 2003	85%
MY 2004	100%

Vehicle air conditioners in the United States are sized to provide sufficient cooling following a hot soak in such climates as Phoenix, Arizona, where the ambient temperature may be as high as 49°C (120°F). The cooling load in the cabin can be higher than 6 kW. This can add more than a 4 kW (5 hp) load to the engine, which is equivalent to the power required to move a mid-size vehicle at a constant speed of 56 km/h (35 mph). NREL's ADVISOR vehicle simulation tool has shown that although the impact of the additional load is significant for conventional vehicles, it is much more significant on high fuel economy vehicles (Figure 1, [1]). The conventional vehicle is modeled as a 1406-kg (3100-lb), 3.0-L, spark-ignition engine, with an 800-W base auxiliary load resulting in a combined city-highway fuel economy of 9 L/100 km

(26.8 mpg). The high fuel economy vehicle is modeled as a 907-kg (2000-lb), 1.3-L, direct-injection, compression-ignition engine, parallel hybrid with a base auxiliary load of 400 W and a resulting combined fuel economy of 3 L/100 km (81.5 mpg). The fuel economy of a nominally 80-mpg vehicle could drop to about 50 mpg if the auxiliary loads increase from 400 W to 2000 W. Clearly, a large auxiliary load is unacceptable for a high fuel economy vehicle.

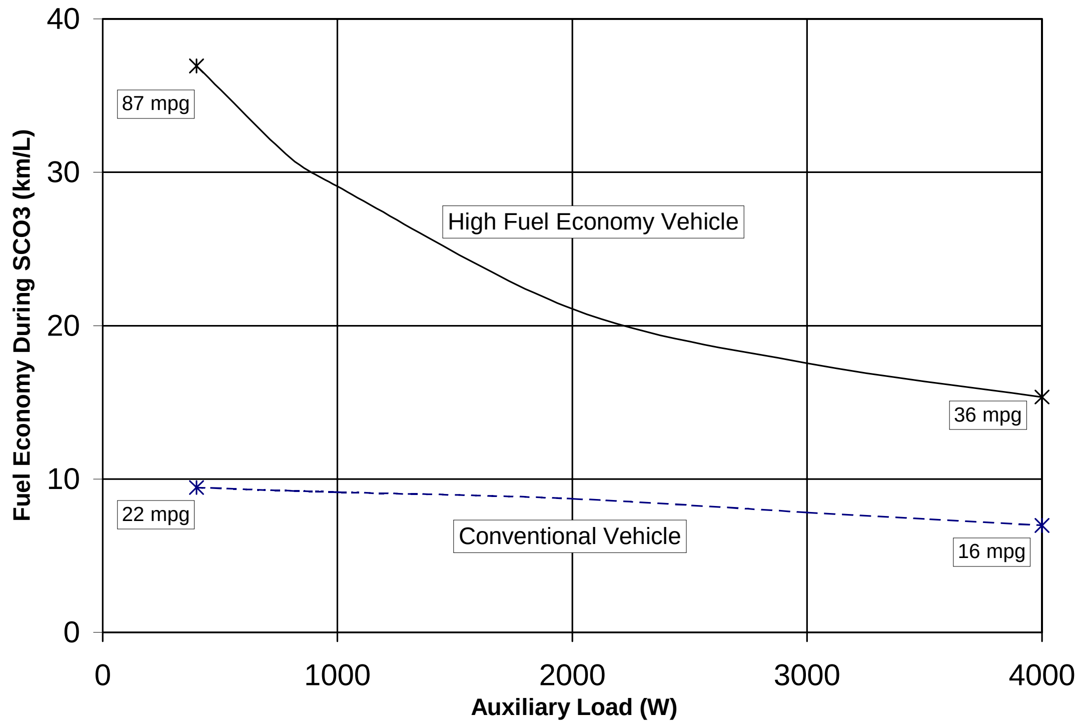

Figure 1. Auxiliary load impacts on fuel economy

A 400-W load on a conventional engine can decrease the fuel economy by about 0.4 km/L (1 mpg). The United States could save about $4 billion annually if all the light-duty vehicles in the country achieved a 0.4 km/L (1 mpg) increase in fuel economy. We seen, then, that the nation could realize significant fuel savings through only modest reductions in auxiliary loads.

Table 3 presents the modeled increase in tailpipe emissions for a conventional vehicle and the SC03 drive cycle that results from air conditioning use, where the net coefficient of performance (COP) is defined as the product of the air-conditioning system's COP and the compressor efficiency. The baseline without air conditioning assumed a 500-W auxiliary load. There is significant engine-to-engine variation for each pollutant as well as a dependence on the COP, which is not surprising. The results from the modeling show that the air conditioning system can increase tailpipe emissions significantly, more than doubling the CO and NO_x depending on the engine modeled. Notice the difference control strategies can have for the same size engine.

We are investigating a number of possible approaches to reduce peak and average air-conditioning loads on the engine. Reducing the cabin soak temperature, using advanced window glazings, and reducing the use of outside air, made possible by air cleaning techniques, are three such approaches. In addition, we are focusing on directing the thermal power where it matters—toward improving passenger comfort, among other things. Research in each of these areas is presented below.

Table 3. Predicted increase in tailpipe emissions resulting from air conditioning during SCO3 drive cycle

Engine	Net COP = 2.25			Net COP = 1.25		
	HC	CO	NO_x	HC	CO	NO_x
1.5-L Geo	31%	22%	52%	50%	50%	113%
1.9-L Saturn	4%	51%	39%	13%	125%	58%
3.0-L Dodge	24%	26%	29%	46%	68%	56%
3.0-L Toyota	18%	11%	31%	29%	20%	54%

2 CABIN ROOF SOLAR GAINS

A systematic design approach is needed to reduce fuel consumption and emissions that result from auxiliary loads such as air conditioning, which is the largest auxiliary load on a vehicle by an order of magnitude.

One common misconception is that insulating the cabin roof will reduce the cooling load in the cabin. Although this may be true in the steady-state mode, it may not be true when a typical vehicle is soaking in the sun. Insulating the roof can increase the cabin temperature as the cabin gains solar heat through the glass but can no longer reject it through the roof. Test data (Figure 2) show that the roof initially conducts heat into the cabin, but as the cabin temperature increases, it rejects heat from the cabin to the ambient. The peak temperature on the dash was 86°C (187°F) and the cabin air temperature peaked at 58°C (136°F). The variation in the roof heat flux data is caused by wind. Wind increases the convective heat loss coefficient, which makes the roof a more effective heat loss mechanism. The roof plays an even more important role on partly cloudy days (Figure 3), where the peak temperature on the dash was 80°C (176°F) and the cabin air temperature peaked at 56°C (133°F). As clouds pass in front of the sun, the roof becomes a significant heat loss mechanism. Insulating the roof can result in higher cabin temperatures.

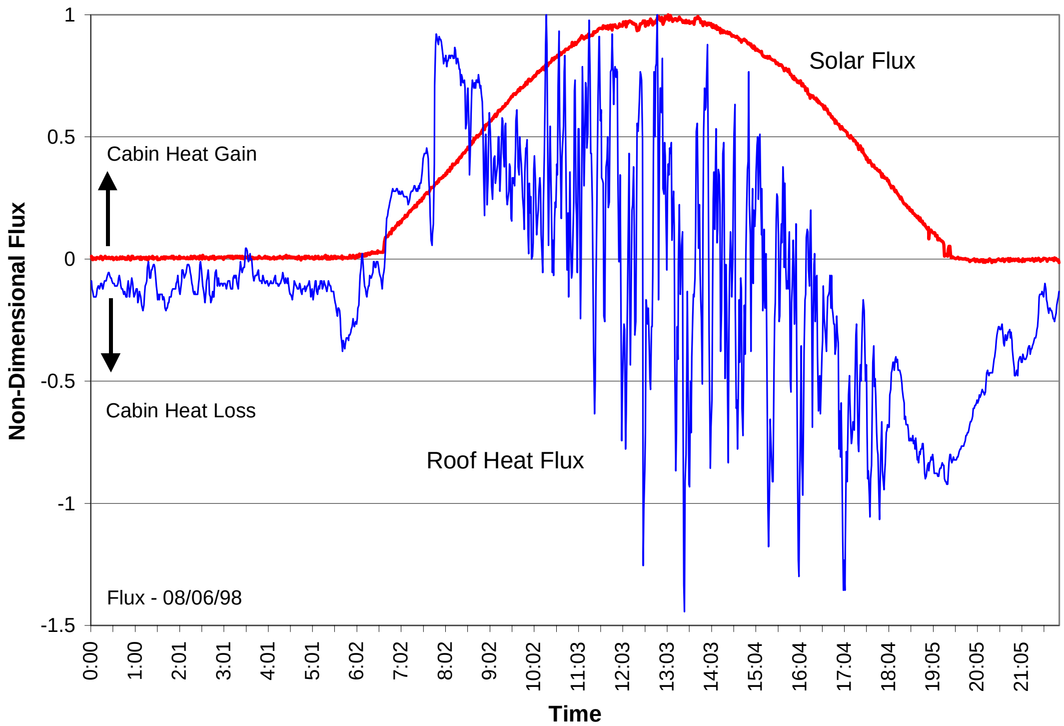

Figure 2. Cabin roof heat gain and loss test results, clear day

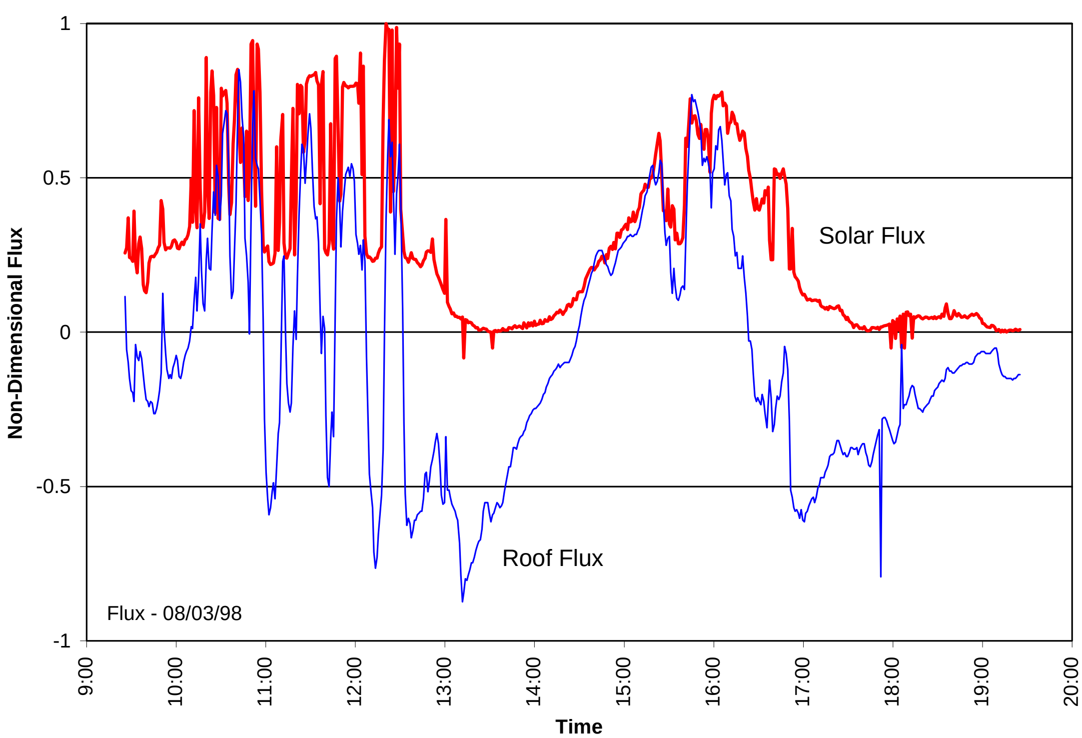

Figure 3. Cabin roof heat gain and loss test results, partly cloudy day

3 ADVANCED GLAZINGS

Modeling results show that it is much more effective to reduce the cabin soak temperature by preventing the solar radiation from entering the vehicle than it is to ventilate the vehicle with outside air. Ventilation during a hot soak can be an effective technique to cool the vehicle once the solar gain has been minimized. Figure 4 shows modeled results of the effect of increasing the ventilation rate from 10 to 20 air changes per hour (ACH) with an ambient temperature of 49°C (120°F). Doubling the ventilation rate has a smaller effect than reducing the solar transmittance of the windows.

Baseline measurements, using tracer gases, of natural ventilation in a parked vehicle soaking in the sun range from about 0.5 ACH for a 1997 Dodge Neon to 1.5 ACH for a 1996 Ford Aerostar. Better door and window seals, used to reduce noise inside the passenger compartment, have led to tighter vehicles with lower natural ventilation rates. The lower rates result in higher cabin stagnation temperatures. Interior temperatures in a 1997 Plymouth Breeze were measured at 113°C (235°F) on the dash and 71°C (160°F) air temperature in the shade of the instrument panel with an ambient temperature of 32°C (90°F) and horizontal solar radiation of about 900 W/m^2.

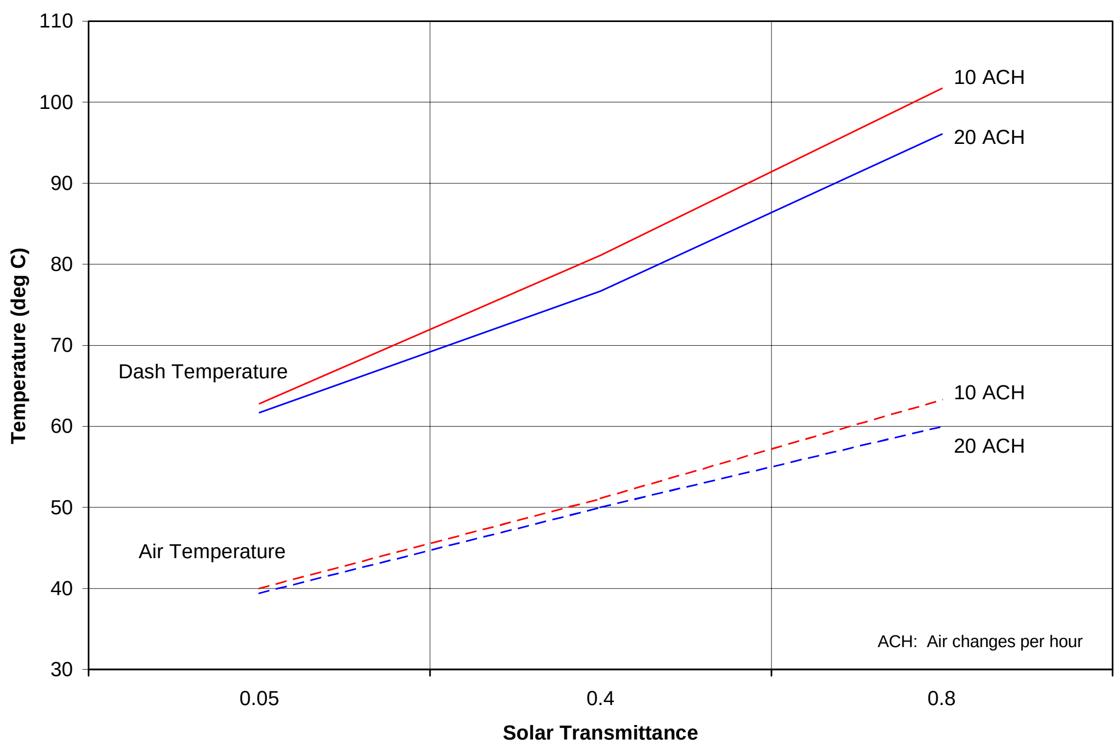

Figure 4. Effect of ventilation and glazing properties

3.1 Solar reflective glazing

Advanced windshields, such as PPG's Sungate™, effectively reduce the transmission of ultraviolet (UV) and infrared (IR) solar radiation into the vehicle compartment. Figure 5 compares the transmittance of the Sungate™ windshield with that of a conventional windshield. The Sungate™ windshield uses a multi-layer silver coating deposited on the glass between the inner and outer glass of the windshield to reflect infrared radiation. The electrically conductive coating can serve as the radio antenna and can also be used to electrically de-ice the windshield. The transmittance of visible light through the windshield must be at least 70% in the United States and 75% in Europe to comply with safety regulations.

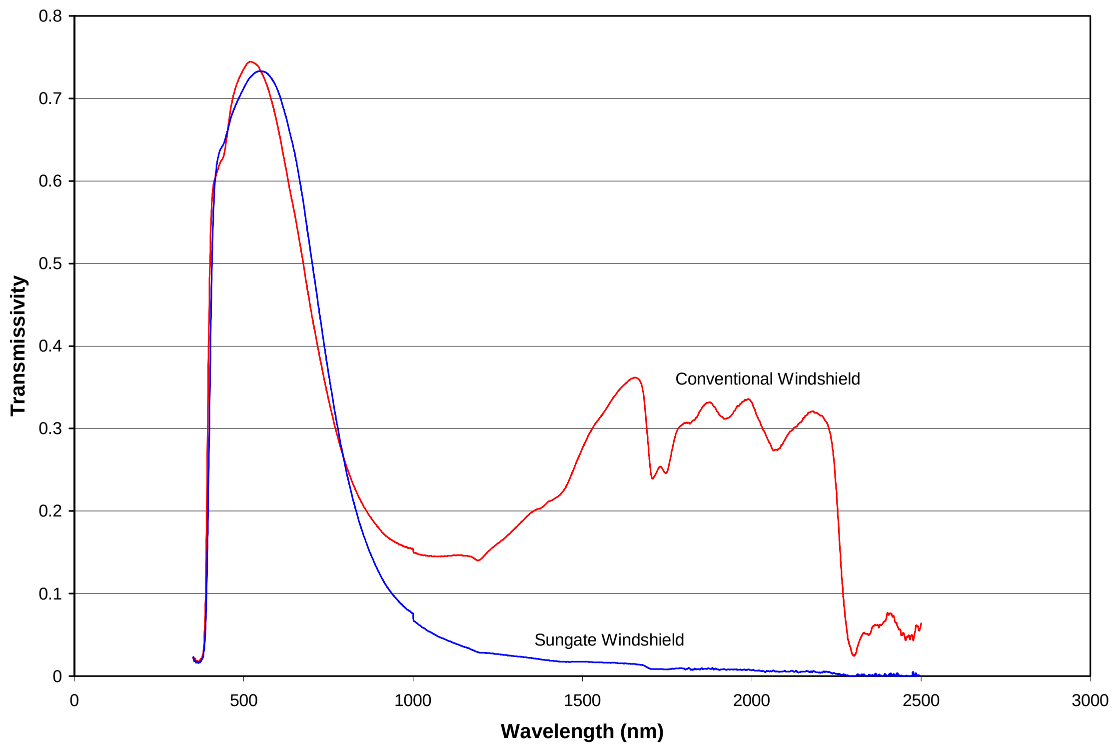

Figure 5. Transmittance of solar-reflecting windshield

We measured the relative performance of three different windshields provided by PPG in a Plymouth Breeze vehicle. The temperature inside the vehicle was maintained at 60°C (140°F) with a combination of solar and electric heating. This test, called a co-heating test, is a useful technique to measure the change in solar radiation entering the cabin. We monitored the inside and outside air temperatures as well as the heater power and the front and rear dash temperatures.

The three windshields were the Solex™ (used for vehicles sold in the United States), the Solargreen™ (used for vehicles sold in Europe), and the Sungate™. Figure 6 shows the power required for the heater to maintain a cabin air temperature of 60°C for the three different windshields and for the case of windows covered with opaque insulation. At 1:00 p.m. (13:00), the heater required no power to maintain the interior temperature with the Solex™ windshield. However, the heater required 160 W to maintain it with the Sungate™ windshield, indicating that under those conditions the Sungate™ windshield reduced the solar gain by 160 W. The hourly solar incident radiation, after mid-morning, varied less than 5% between tests. Table 4 shows the ratio of solar gain with each windshield to the opaque case.

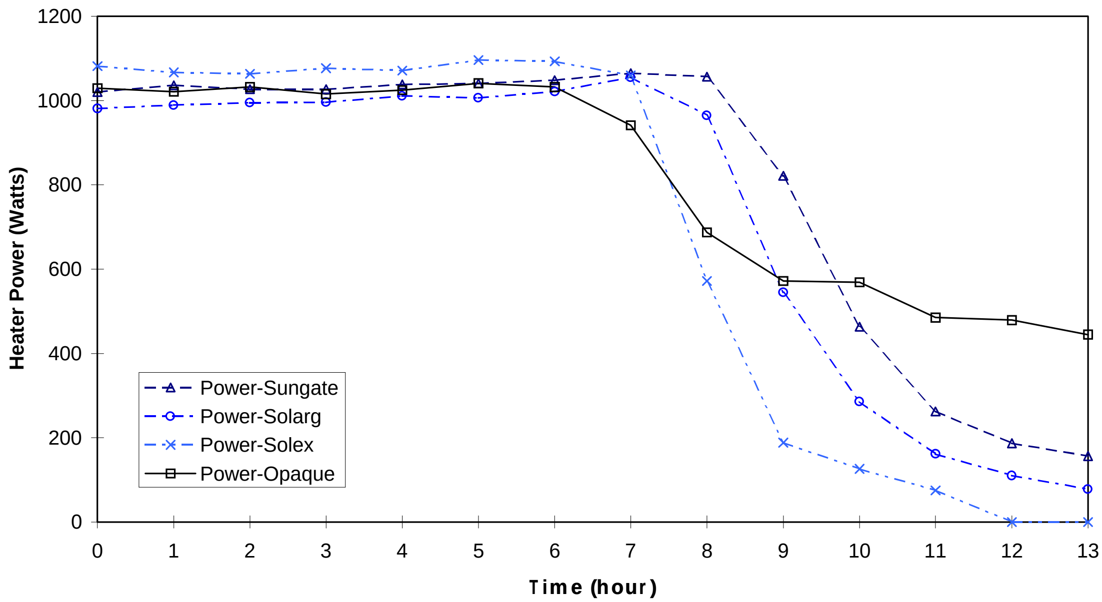

Figure 6. Co-heating tests performed for the Sungate, Solex, and SolarGreen windshields

Table 4. Relative solar gain of windshields

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

The solar gains in the vehicle decreased by 27% when the standard front windshield (Solex™) was replaced with the Sungate™ windshield. If the compressor is proportionally downsized, the Sungate windshield can increase the fuel economy of the Breeze by about 1.9% or 0.2 km/L (0.5 mpg) over the SFTP, and by about 3.5% or 0.3 km/L (0.7 mpg) over the SCO3 drive cycle.

4 AIR CLEANING

After reducing the peak thermal load and the solar gain, the next most important approach to minimizing air conditioning 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 cold or very hot air from outside. Increased recirculation of air leads to two additional challenges: (1) removing odors, bioaerosols, and harmful volatile organic compounds (VOCs), and (2) controlling humidity levels to avoid condensation on cold surfaces in either the heating mode (such as cold windows) or the cooling mode (such as cooled seats, pipes, or ducts).

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

Using advanced heating and cooling techniques and alternative means of de-icing and defogging glazings makes high air flow rates unnecessary for achieving thermal comfort. Typically 0.0084 kg/s (15 cfm) per person is needed in building applications. However, with potentially higher concentrations of VOCs in newer vehicles, higher fresh airflow rates may be desirable unless the contaminant levels are reduced. With four adults in a vehicle, approximately 0.034 kg/s (60 cfm) of outside air may be needed. This corresponds to 70% recirculated air for vehicle heating in Figure 7 and 80% recirculated air for vehicle cooling. Intelligent sensors may be used to control the amount of outdoor air as a function of the number of occupants, ambient conditions, or the contaminant concentration levels in the passenger compartment.

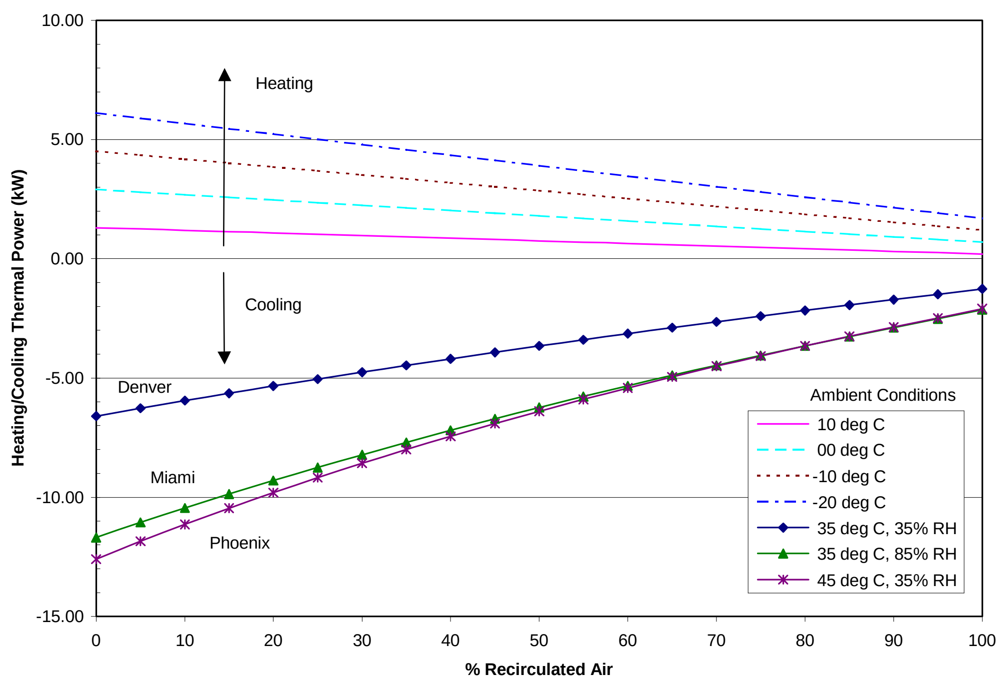

Figure 7. Heating/cooling thermal power as a function of percent recirculated air and ambient conditions

4.1 Contaminants

Particle filters used to clean ventilation air are available in an increasing number of vehicle models. Activated carbon filter units for removing odor compounds are available for some vehicles. Activated carbon filters use an adsorption process in which VOCs and bioaerosols attach to the surface of the carbon. Once the surface is saturated, the filter must be replaced. The adsorption process for some VOCs on carbon filters is reversible, so under some conditions, very clean air can be contaminated by desorption of compounds from the filter. There is some concern that aged carbon filters may become incubators for microorganisms, and we are beginning to test for such evidence.

The combination of condensate in a recently operated air conditioning system and the heat from a vehicle soaking in the sun provides ideal conditions for growing microorganisms in the heating, ventilating, and air conditioning (HVAC) system. We have obtained cultures for organisms growing on surfaces in the HVAC unit and carried by air from cabin vents. Figure 8 shows the result for a 10-minute exposure to the flow from an air conditioning vent of a 1996 model vehicle. This sample was collected from a vehicle in Denver, Colorado, which is in a semi-arid climate. Similar cultures were grown from samples taken at various locations within the HVAC system [2].

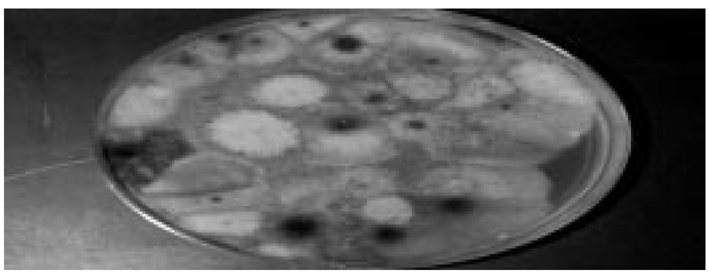

Figure 8. Fungal culture grown from air samples taken from a vehicle's HVAC system

4.2 Photocatalytic oxidation

NREL and others are developing an alternative to adsorption systems for controlling odor and VOCs. Photocatalysis uses light at wavelengths below 385 nm (near ultraviolet light) and a photo-sensitive titanium dioxide catalyst to kill microorganisms and oxidize VOCs to harmless substances.

The photocatalytic oxidation (PCO) process separates and immobilizes VOCs and bioaerosols on the catalytic surface, kills the microorganisms, and then oxidizes the organic matter and VOCs to carbon dioxide and water. The net effect is that of a self-cleaning filter for removal of odors, VOCs, and bioaerosols. Inorganic compounds, such as dust, must be filtered upstream of the catalytic surface to prevent fouling of the surface by mineral matter.

We have completed an initial analysis of VOC concentrations in several closed cars soaking in the sun in July 1998 in Denver. The results are shown in Table 5 [3]. The results for the Camry show the effect of increasing temperature on the generation of

VOCs. Figure 9 shows the effectiveness of removing these compounds using a PCO unit [4].

The goal for the PCO air cleaning system is an operating power less than 10 W with a cost less than $10.

Table 5. Measured VOC concentrations

	Formaldehyde (ppbv)*	Acetaldehyde (ppbv)*	Acetone (ppbv)*
’87 Camry (morning)	81	71	20
’87 Camry (afternoon)	171	204	39
’98 Subaru (afternoon)	86	47	28
’91 4Runner (morning)	17	13	5

*Parts per billion by volume

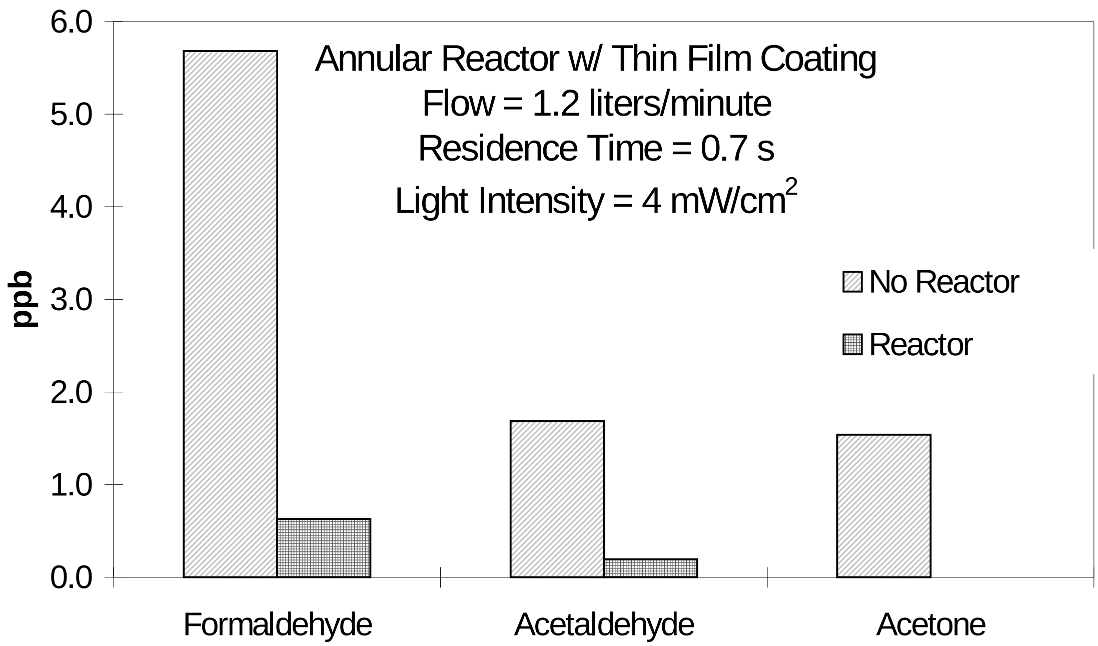

Figure 9. Effectiveness of PCO

5 THERMAL COMFORT

The goal of the climate control system is two-fold. First, the system must provide sufficient visibility to the driver; ice and condensation must be removed quickly and then prevented from forming on the windows when the vehicle is being driven. Typically this has been accomplished by blowing hot air over the inside surface of the windshield and into the cabin compartment. Some vehicles automatically use the evaporator to dehumidify the air when in the defrost mode. Second, the system must provide thermal comfort to the occupants. Blowing large amounts of conditioned air into the cabin has been the typical solution, but alternative techniques, such as conductive heating and cooling and radiant heating, can be considered. Radiative, convective, and conductive heating and cooling can be combined into an effective climate control system. However, a tool is needed to evaluate and predict the thermal comfort provided by these alternative approaches. Such a tool allows an acceptable climate control system to be designed and minimizes the fuel used.

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 [5]. The model goes beyond considering only air temperature as a function of time.

NREL's thermal comfort model starts 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.

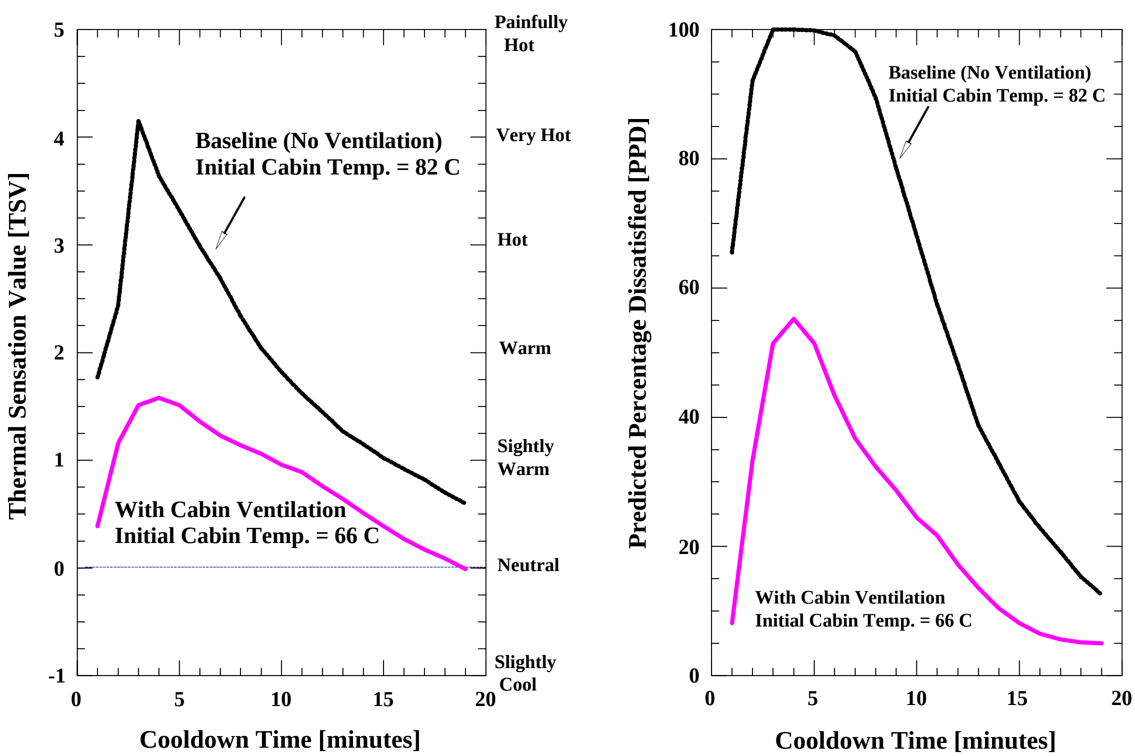

Figure 10. Example of thermal comfort modeling – the effect of cabin ventilation

5.1 Cooling

The initial cabin temperature significantly affects thermal comfort. Figure 10 shows two cases that compare the temporal thermal sensation value for two different initial cabin temperatures. Lowering the cabin soak temperature from 82°C (180°F) to 66°C (151°F) greatly increases the comfort of the passengers. Using advanced glazings and cabin ventilation, perhaps powered by a small photovoltaic panel, can reduce the cabin soak temperature. Note that thermal discomfort peaks after about 3 minutes as the core body temperature increases. The initial cabin temperature following a hot soak must be reduced to provide higher levels of thermal comfort to the occupants. Reducing the thermal mass of the cabin interior will not change the peak cabin temperature during a hot or cold soak but it will decrease the response time.

5.2 Heating

We have also examined ways to provide sufficient heat for passenger compartments in vehicles 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 used may be reduced by about 50% if a small diesel engine is used. Second, the fraction of waste heat that goes to the engine coolant may drop from two-thirds for a gasoline engine to as low as one-fourth for a small diesel engine. Most waste heat from a diesel goes out the exhaust. So small diesel engines, such as those that may be used in HEVs, may provide only 25% of the required peak heating needs under low loads in a cold climate if they depend solely on heat from the engine coolant. HEVs can face an additional challenge if the control system turns off the engine while the vehicle is operating and heat is required for the passenger compartment.

For our analysis, we modeled a base-case HEV in city driving with a 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 0.07 kg/s (180 cfm), with 20% recirculated and 80% outdoor air (70 air changes per hour) and -10°C (14°F) ambient air temperature.

We used the SINDA/FLUINT™ finite difference analyzer to simulate the vehicle cabin and coolant heat transfer and modeled thermal comfort with the NREL Average Thermal Sensation Comfort Model previously discussed. For enhancing occupant warming, we investigated two methods: exhaust heat recovery and heated seats. Figure 11 shows thermal sensation value (neutral = 0, cold<0) for three cases: the baseline (BL), exhaust heat recovery, and a 100-W heated seat added to the exhaust-heat-enhanced system. The exhaust heat recovery method performs better because exhaust air warms up quickly and also because of low mass in the heating system. 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.

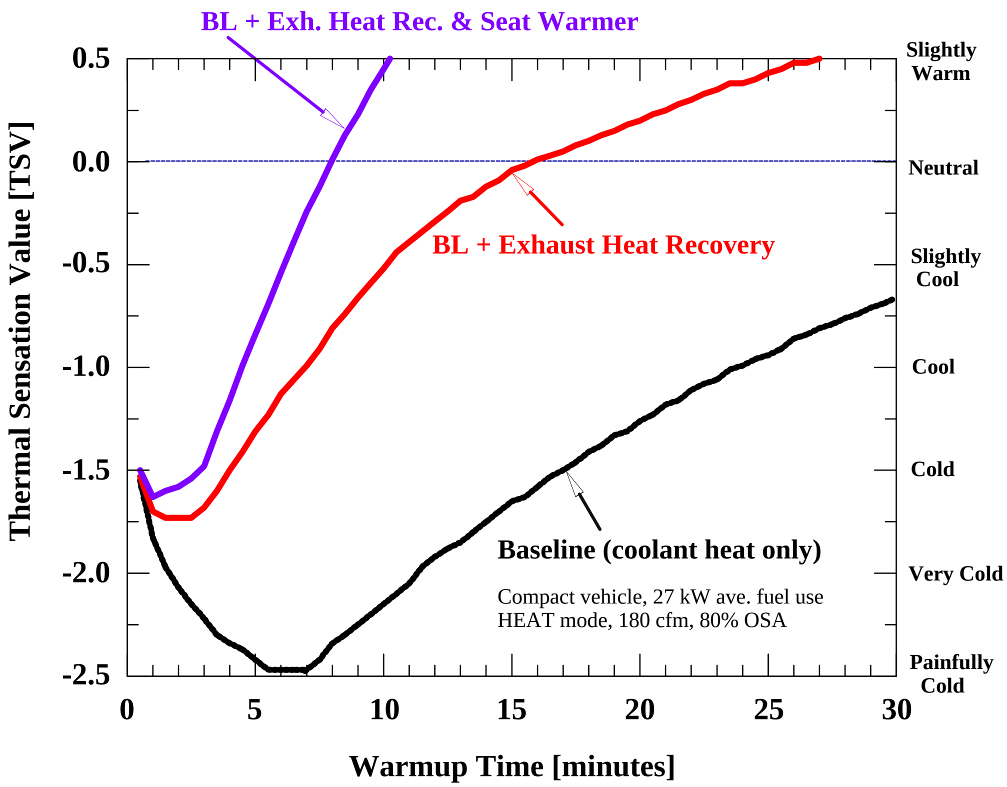

Figure 11. Example of thermal comfort modeling: the effect of cabin ventilation

6 CONCLUSIONS

The air conditioning system is the single largest auxiliary load on a vehicle by nearly an order of magnitude. Current air conditioning systems reduce the fuel economy of conventional vehicles and are completely unacceptable for high fuel economy vehicles. New U.S. emissions standards are providing the impetus for evaluating new climate control designs and approaches.

Significant opportunities for reducing the size of the climate control system lie in the glazing system and in advanced techniques for delivering heating and cooling directly to the occupants. Thermal comfort models are essential for evaluating the impacts of new concepts. Air cleaning becomes necessary as the amount of outside air is reduced. Photocatalysis can be an effective option to provide low-cost, low-maintenance, reliable removal of VOCs and bioaerosols.

Climate control systems of the future will likely bear little resemblance to those of today. There are great opportunities to develop fuel-efficient, low-emission, quiet, light, and comfortable climate control systems.

7 ACKNOWLEDGMENTS

This work was supported by DOE's Hybrid Vehicle Propulsion Program, which is managed by the Office of Advanced Transportation Technologies. The authors appreciate the support of Robert Kost and Roland Gravel, the DOE Program Managers, Terry Penney, NREL's HEV Technology Manager, and Barbara Goodman, the Director of the Center for Transportation Technologies and Systems. The authors would like to acknowledge the significant contributions provided by both industry and our colleagues at NREL. Our industry partners in this project provided both significant hardware and feedback. Chrysler provided the Plymouth Breeze, PPG provided the windshields, Webasto provided a sunroof, OCLI provided electrochromic samples, Solarex provided a photovoltaic sunroof, and Life Enhancement Technologies and Orisa both provided liquid heated and cooled seats. In addition, we recognize the significant contributions of Dave Benson, Deborah L. Brodt-Giles, Jay Burch, Nick Chornet, Ahmad Pesaran, Loreno Roybal, and Tom Thoensen.

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