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Effect of Solar-Reflective Glazing on Fuel Economy, Tailpipe Emissions, and Thermal Comfort

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ABSTRACT

Current air-conditioning systems can reduce the fuel economy of high fuel-economy vehicles by about 50% and reduce the fuel economy of today's mid-sized vehicles by more than 20% while increasing NOx by nearly 80% and CO by 70%. Automotive glazing has a significant impact on the peak and steady-state cooling loads of the vehicle. Glazing that reflects the infrared portion of the solar spectrum can reduce interior temperatures by 9°C and reject more than 500 W while the vehicle is parked. Such a windshield can improve the fuel economy of a compact car by about 0.3 km/L (0.7 mpg) over the SC03 drive cycle if the air-conditioning system is appropriately down-sized.

INTRODUCTION

The mission at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) is to lead the nation toward a sustainable energy future by developing renewable energy technologies, improving energy efficiency, advancing related science and engineering, and facilitating commercialization. The goal of the Cool Car Project is to work with the automotive industry to reduce the fuel used for vehicle climate control by 50% in the short-term and 75% in the long-term while maintaining or improving occupant thermal comfort and safety. We have considered a variety of technologies to reduce climate control loads[1] such heated/cooled seats, park car ventilation[2], recirculation strategies, and air cleaning. The focus of this paper is the impact of advanced glazings. All of our projects are conducted in collaboration with the automotive industry.

Until recently, there has been little motivation in the United States to reduce the impact of air-conditioning on fuel economy and emissions. However, a new U.S. emissions test, the Supplemental Federal Test Procedure[3] (SFTP), will measure tailpipe emissions with the air-conditioning system operating.

SUPPLEMENTAL FEDERAL TEST PROCEDURE

The SFTP consists of the current emissions test (called the Federal Test Procedure or FTP), an air-conditioning test (SC03), and a high-speed, high-acceleration test (US06). The air-conditioning portion of the SFTP will contribute 37% of the total tailpipe emissions. Details of the tests are shown in Table 1. The SFTP applies to vehicles with a gross vehicle weight under 2608 kg (5750 lb). The SC03 is conducted at 35°C (95°F), 850 W/m^2, and 100 grains of water per pound of dry air.

Table 1. Supplemental Federal Test Procedure Specifications

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

Although the SFTP is not used to measure fuel economy, reducing the weight of the air-conditioning system of a mid-size vehicle by 9.1 kg (20 lb) results in about a 0.04 km/L (0.1 mpg) increase in fuel economy on the current combined city/highway test.

The SC03 portion of the procedure can be either measured or simulated with an EPA-approved modeling tool. If measured, the EPA specifies that metal halide, quartz halogen with dichroic mirrors, and sodium iodide solar simulators are acceptable. The radiant energy must be uniform within ±15% over a 0.5 meter grid with an intensity of 850 ±45 W/m^2 averaged at the centerline of the vehicle at the base of the windshield and base of the rear window. The acceptable spectral distribution is shown in Table 2.

Table 2. SFTP Spectral Distribution

Band width (nanometers)	Percent of total spectrum	
	Lower Limit (Percent)	Upper limit (percent)
<320	0	0
320-400	0	7
400-780	45	55
>780	35	53

EPA Note: Filter the UV region between 280 and 320 nm

The Clean Air Vehicle Technology Center has measured the effect of the air-conditioning system on fuel economy and tailpipe emissions for a variety of vehicles[4]. The average impacts of seven vehicles ('95 Voyager, '97 Taurus, '95 Civic, '95 F-150, '97 Camry, '96 Camaro, and '95 Skylark) are shown in Table 3 for the A/C system on compared with the results with the air-conditioning system off. The tests conditions were as specified for the SC03 test.

Table 3. SC03 Test Results

	Change
CO	+71%
NOx	+81%
NMHC	+30%
Fuel Economy (km/L or mpg)	-22%

APPROACH

We developed a co-heating technique to measure the solar radiant energy rejected by solar-reflective glazing. We also measured soak temperatures in various vehicle types with different glazing types. We then estimated a reduced air-conditioning system size and modeled the fuel use using the simulation tool ADVISOR. We also predicted the impacts of advanced glazing on occupants in the vehicle.

ADVISOR

NREL's ADvanced VehIcle SimulatOR[5,6] is designed for quick analysis of the performance and fuel economy of conventional, electric, and hybrid vehicles. ADVISOR can be used to model vehicle efficiencies, to assess impacts of applying innovative technologies to existing vehicle configurations, to develop novel energy management strategies, and to integrate simulated and real-life assessments.

The analysis presented here illustrates the capability of ADVISOR. We used ADVISOR to model a conventional vehicle and a high-fuel-economy vehicle. We estimated the impact of auxiliary loads on the fuel economy of these vehicles during four driving cycles. The driving cycles used are those scheduled for use in U.S. EPA certification procedures: FUDS (an urban driving cycle), HWFET (a highway driving cycle), SC03 (an air-conditioning driving cycle), and US06 (a high-speed, high-acceleration driving cycle). The conventional vehicle is modeled as a 1406-kg (3100-lb), 3.0-L, spark-ignition engine, with an 800-W base auxiliary load resulting in a combined city/highway fuel economy of 11.4 km/L (26.8 mpg). The high-fuel-economy vehicle is modeled as a 907-kg (2000-lb), 1.3-L, direct-injection, compression-ignition engine, parallel hybrid with a base auxiliary load of 400 W and a resulting combined fuel economy of 34.6 km/L (81.5 mpg). Figure 1 shows the impact of auxiliary load on the fuel economy over the SCO3 cycle. The fuel economy of a nominally 33-km/L (80-mpg) vehicle could drop to about 21 km/L (50 mpg) if the auxiliary loads increase from 400 W to 2000 W. A large auxiliary load is unacceptable for a high-fuel-economy vehicle.

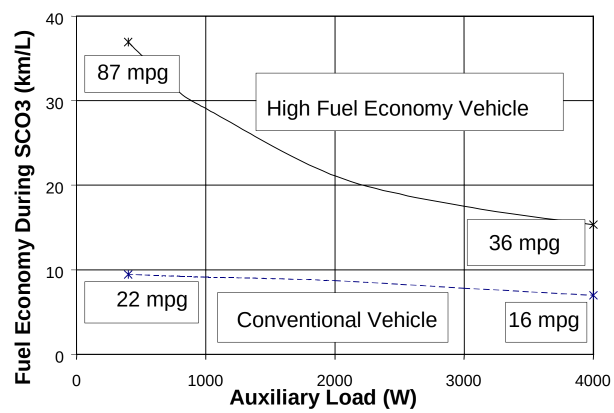

Figure 1. Auxiliary load impacts on fuel economy

THERMAL COMFORT MODEL

NREL has developed a transient thermal comfort model that estimates a person's comfort level in a vehicle during winter warm-up or summer cool-down. The current model[7] predicts an overall thermal sensation based on a variety of environmental parameters and thermal boundary conditions. It also has the capability to measure heat exchange by conduction such as from a heated or cooled seat. NREL is also developing a non-homogeneous, transient model that will predict thermal sensation variations over the body under highly non-uniform conditions.

Effective climate control makes the occupants comfortable using as little energy as possible while providing adequate window de-icing and defogging. Air-conditioning, especially during the initial cool-down period following a hot soak in the sun, represents the largest climate control load on a vehicle. Thermal comfort modeling focuses on providing thermal comfort to the occupant instead of attempting to achieve a uniform temperature within the passenger compartment.

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

Figures 2 and 3 show the results of two different initial cabin temperatures, 82°C (180°F) and 66°C (151°F), with a vehicle exposed to full sun and an ambient temperature of 38°C (100°F). The lower temperature could be achieved by a combination of advanced glazing and parked car ventilation. Thermal discomfort peaks after about 3 minutes as the core body temperature increases. Note that although it is possible to dissatisfy 100% of the population (at 3 minutes in the upper figure), it is not possible to satisfy 100% regardless of the allowable conditioning time.

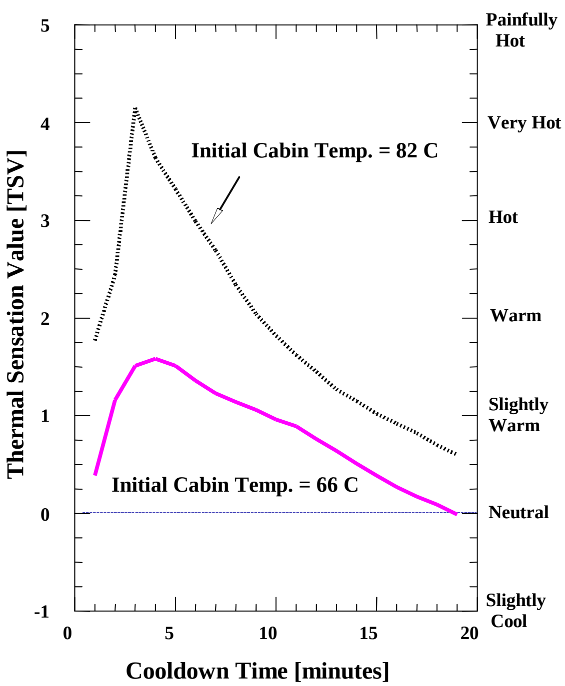

Figure 2. Example of TSV

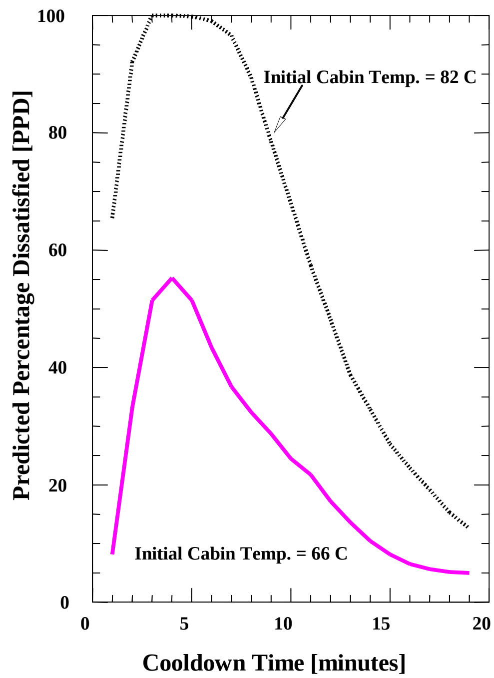

Figure 3. Example of PPD

ADVANCED GLAZINGS - DESCRIPTION

The first line of defense to prevent high cabin temperatures in a parked vehicle is to prevent the solar radiation from entering the vehicle. This is most easily accomplished by reflecting all of the solar radiation back into the ambient through the use of metallic coatings that reflect over the entire solar spectrum (300-4000 nm). Due to visibility requirements of windshields over the visible part of the solar spectrum (400-700 nm) and the necessity to see out of the sidelights and rear window, passive glazings of this type cannot be used. Thus glazing manufacturers try to minimize the amount of solar radiation entering the vehicle by either absorbing it or selectively reflecting the infrared part of the solar spectrum.

THE SOLAR SPECTRUM

The solar radiation at ground level varies with location, time of day, time of year, and humidity, dust, and aerosols in the air. Because of this variation, standards such as ASTM E-891 and ASTM E-892 were developed so that different solar glazings can be compared. The direct normal incident solar radiation as a function of wavelength for air mass 1.5 (AM 1.5) from 0.300 to 2.5 µm is shown in Figure 4 (ASTM E-891).[8] Under these conditions, the solar radiation peaks at 525 nm at an irradiance of 1102.20 W/m2-µm and the integrated power density over this wavelength range is approximately 756.50 W/m^2.[8] The ultraviolet (300-400 nm), visible (400-700 nm), and the infrared (700-2500 nm) regions of the direct, normal solar spectrum (ASTM E-891) contain approximately 3%, 38%, and 57% of the integrated power density respectively. Thus a significant portion of the solar load in a vehicle is in the non-visible part of the spectrum. This radiation provides unnecessary heating to a vehicle passenger compartment.

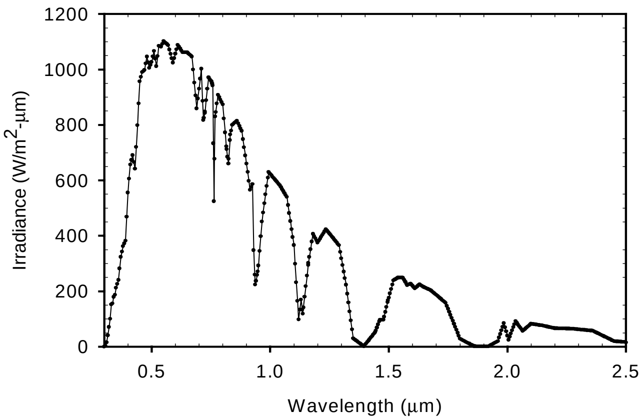

Figure 4. Direct normal incident radiation received from the sun under air mass (AM) 1.5 conditions (ASTM E-891).[8]

ABSORPTIVE GLAZINGS

Absorption of the solar radiation occurs through the use of glass that absorbs the solar radiation either in selective parts of the solar spectrum while leaving the visible wavelengths intact or over visible wavelengths as well. An example of a selective solar absorption glazing would be ferrous oxide (FeO) doped glass. FeO-modified silica glass broadly absorbs over the 800-1100 nm range.[9] This part of the solar spectrum contains ~ 25% of the energy density that a vehicle would receive under AM 1.5 conditions. Tinted glass or privacy glass are examples of solar control glazings that absorb over the visible part of the spectrum. The problem with these glazings is that after the photon is absorbed (and the momentum is picked up with a lattice phonon), the radiant energy is re-radiated at longer wavelengths and has about a 50% probability of being re-emitted into the vehicle. Although these glazings do reduce the incident solar load, much of the radiation is still transmitted into the vehicle through re-radiation and convection. However, an advantage of these glazings is that they are fabricated by conventional glass processing techniques thereby reducing processing costs.

REFLECTIVE GLAZINGS

Selective reflection of the infrared part of the solar spectrum can be accomplished via two different methods. The first is based on the principle that as light/radiation goes from one medium with index of refraction n_1 (air n_1~1) to another medium of index of refraction n_2 (glass n_2~1.55), a certain percentage of the radiation will be reflected. Assuming lossless media and normally incident radiation, the intensity of reflected radiation or reflectance is the square of the difference in indices divided by the square of the sum of the indices. By combining a series of layers of the appropriate indices of refraction and of the appropriate thickness', it is possible to create a dielectric filter that transmits in the visible and reflects in the infrared (as well as vice-versa and any combination in between). A non-optimized example of this type of glazing can be seen in Figure 5. Although the glazing does a good job of selectively transmitting over the 400-700 nm range, interference effects can be seen over this range as well as in the infrared. More layers would have to be added to this optical stack to produce smaller interference effects over the visible part of the spectrum.

The second method involves the use of metal and dielectric thin films. Typically, these materials are in a dielectric-metal-dielectric-metal-dielectric construction. The outer dielectrics are added to a Fabry-Perot etalon (metal-dielectric-metal) for several reasons including increased admittance of the filter, to provide a barrier layer against corrosive agents to the metals, and provide a more mechanically robust outer surface that can be handled. The transmission spectrum of a silver-based filter is shown in Figure 6. These filters are very good at suppressing transmission in the infrared while maintaining good transmission in the visible part of the spectrum and are probably the most widely used solar selective automotive glazing used today. A drawback of these filters is that they are produced by vacuum processing techniques and have relatively low tolerances. These restrictions increase the cost of these glazings. However, their performance is superior to absorptive glazings and thus the higher premiums may be justified.

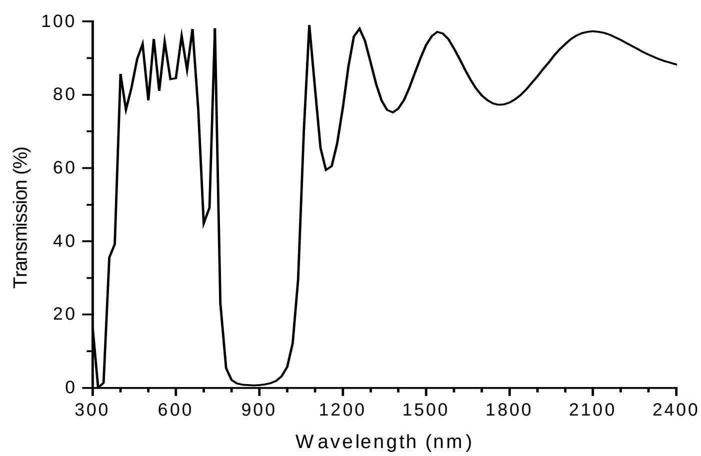

Figure 5. Plot of an all dielectric visible transmission (near infrared reflection) filter. The reflected radiation between 800-1100 nm corresponds to about 25% of the incident solar power.

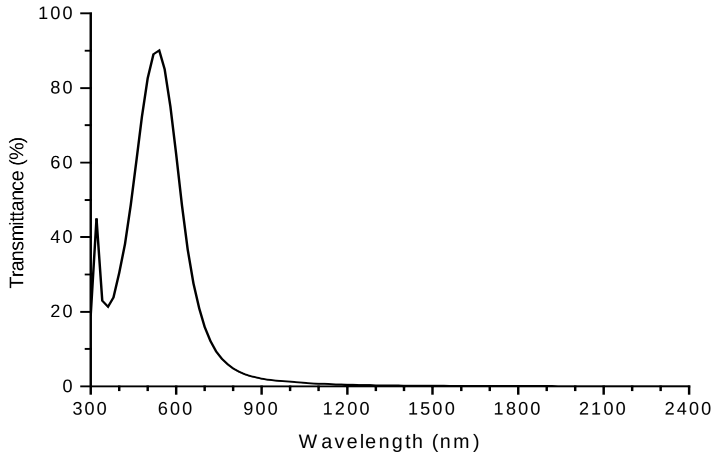

Figure 6. Plot of a Fabry-Perot style Ag-based infrared reflecting solar control glazing. The reflected radiation between 800-2500 nm corresponds to about 55% of the incident solar power.

ADVANCED GLAZINGS - TESTING

Vehicle air-conditioning systems in the United States are typically sized for adequate cool-down time for a peak cooling load in Phoenix, Arizona, with a solar load of 1 kW/m2 and 49°C (120°F) ambient temperature. Such conditions lead to surface temperatures of more than 121°C (250°F) and cabin air temperatures of more than 82°C (180°F). The peak load can be two to four times greater than the steady-state cooling load. To reduce the size of the air-conditioning system, we must reduce the cabin soak temperature.

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

To determine the effectiveness of the advanced glazings, we used a co-heating technique as shown in Figure 7. We measured the power of a ceramic heater required to maintain the cabin interior air temperature at a constant 60°C (140°F), eliminating the effect of the thermal capacitance of the vehicle interior. As the solar gains increased, the heater power decreased. The vehicle heat loss with the windows closed was estimated from the nighttime conditions when there was no solar radiation. An assumption implicit in this approach is that the vehicle heat loss during the day is approximately the same as during the night. The opaque gains were measured with 2.5 cm (1 in.) of foam insulation on the outside of all of the vehicle windows.

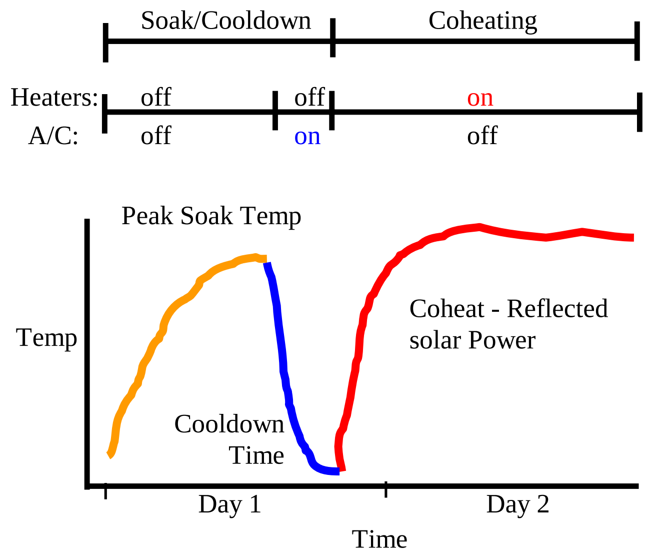

Figure 7. Test procedure.

Using a Plymouth Breeze as the test vehicle, we measured the effect of advanced glazings by (1) applying a solar reflective film to all of the vehicle windows and (2) using a commercially available ultraviolet and infrared reflecting windshield. We tested three windshields supplied by PPG: Solex®, a standard windshield in the United States; Solar Green®, a windshield used in European vehicles; and Sungate®, an advanced ultraviolet and infrared reflecting windshield. The windows were either closed or open 1.9 cm (0.75 in.)

A cabin soak test was performed without heaters, and the results are presented in Figure 8. A comparison of the temperature for the vehicle with and without the film, and with the windows closed showed that the film kept the cabin about 9°C (16°F) cooler for these particular conditions.

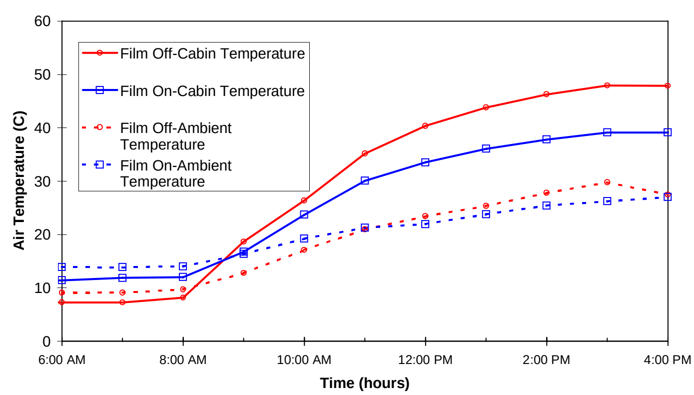

Figure 8. Vehicle soak temperature

For the co-heat test, the opaque case required the greatest heater power, and the case with the film off and windows closed required the least because the latter case has the greatest solar gain. To calculate the normalized net thermal gain (see Figure 9), the heater power was integrated from sunrise to noon and normalized to the integrated solar radiation during the test, which fell within 4% of the solar radiation during the opaque test. The reflective characteristic of the film resulted in a thermal gain of 1.49 compared to 1.94 for the vehicle without film.

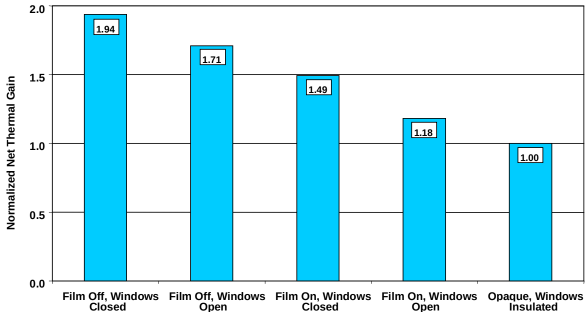

Figure 9. Normalized net thermal gain for window film and window open

The tests of commercially available windshields used the same standard automotive glass on the side and back windows. Hence, the difference in heater power is directly related to the change in windshield properties. At noon, Figure 10 shows the Sungate® windshield required 187 W more than the Solex® windshield, meaning that the Sungate® reduced the solar gain by 187 W under those conditions. The Solex® windshield had 17% more thermal gain than the Sungate® windshield.

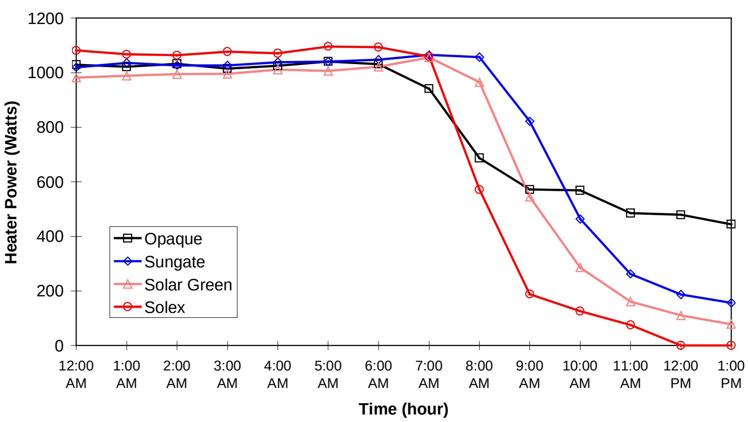

Figure 10. Measured heater power for windshield tests

The potential impact on fuel economy for a conventional vehicle such as a Neon using the Sungate® windshield compared with the standard Solex® windshield, shown in Table 4, is significant. The advanced windshield without any treatment on the side windows permits a compressor reduction of about 400 W which could reduce fuel consumption by 3.4%, or about 0.3 km/L (0.7 mpg), over the SCO3 drive cycle according to ADVISOR simulations performed at NREL.

Table 4. Modeled Sungate fuel economy impacts

Wind-shield	Load, kW (hp)	SFTP		SCO3	
		Fuel Economy, km/L (mpg)	% Change from Solex	Fuel Economy, km/L (mpg)	% Change from Solex
Solex®	3.9 (5.2)	10.88 (26.2)	-	8.47 (20.4)	-
Sungate®	3.5 (4.7)	11.09 (26.7)	1.7%	8.76 (21.1)	3.4%

ADVANCED GLAZINGS – CABIN CFD MODELING

We used computational fluid dynamics (CFD) modeling to predict air velocities and air temperatures in the cabin for a different glazing configurations. STAR CD was used to model the cabin, with the sun's position from the front passenger corner of the vehicle. The orientation permitted four different solar radiant loads on the vehicle occupants. The driver-side rear passenger received no solar load while the front-passenger received solar radiation from the front and right side. Providing comfort under such diverse environmental conditions is challenging. Minimizing the solar load into the cabin has a significant impact on the occupants. Figure 11 shows transient cooldown at 10, 610, and 1190 seconds for a vehicle moving at a constant speed of 80 kph (50 mph) after soaking in the sun. The ambient temperature was set at 38°C (100°F). The solar reflective glazing cases use an air-conditioning system with only half of the volumetric output of each register, but with the same velocity accomplished by reducing the cross-sectional area of the diffuser.

CONCLUSION

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

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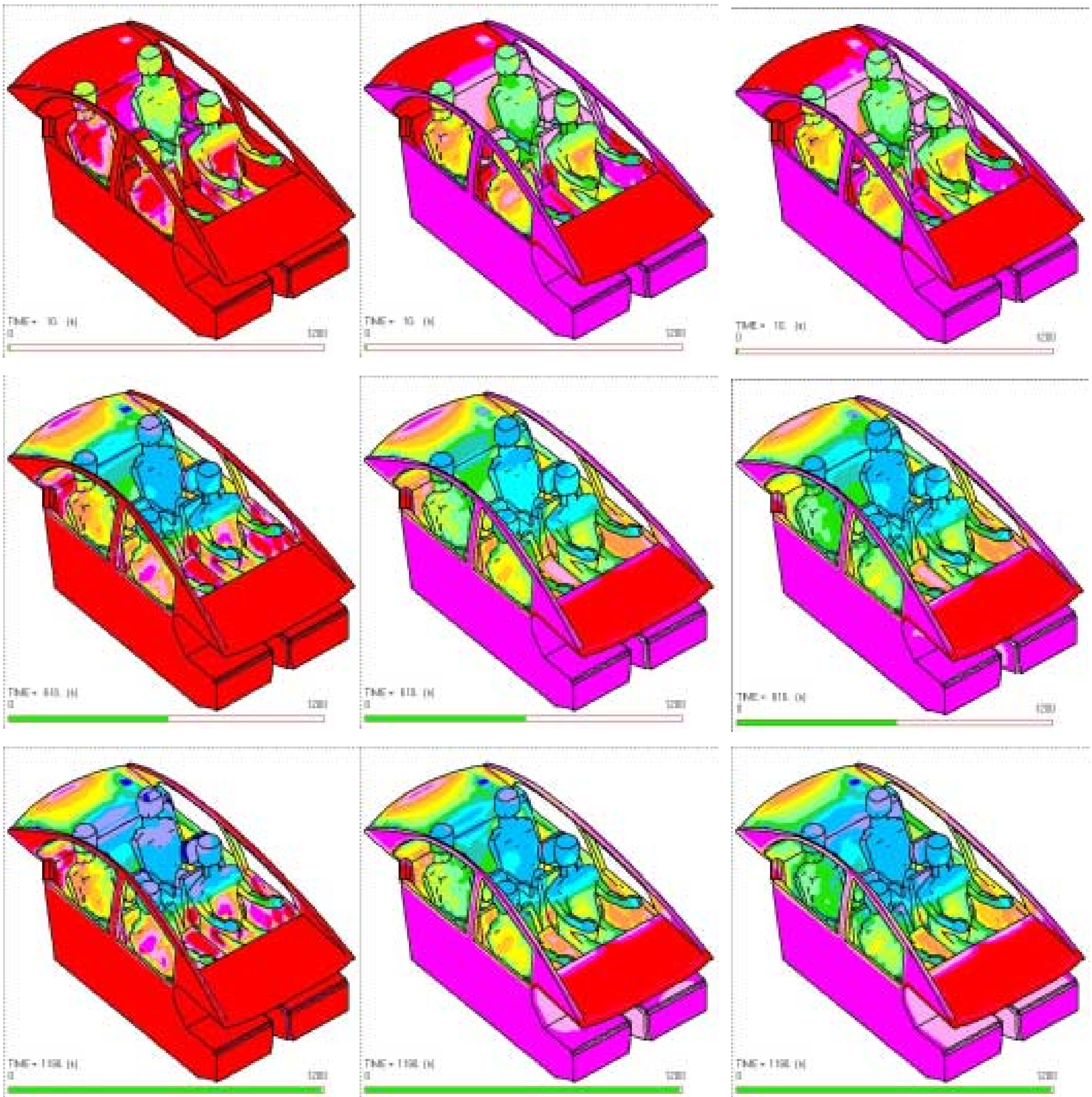

Conventional Glass | Solar Windshield Reduced A/C | All Solar Glass Reduced A/C

Figure 11. Cabin Temperature Profiles