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# Opportunities to Reduce Air-Conditioning Loads Through Lower Cabin Soak Temperatures

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**Abstract:** Air-conditioning loads can significantly reduce electric vehicle (EV) range and hybrid electric vehicle (HEV) fuel economy. In addition, a new U. S. emissions procedure, called the Supplemental Federal Test Procedure (SFTP), has provided the motivation for reducing the size of vehicle air-conditioning systems in the United States. The SFTP will measure tailpipe emissions with the air-conditioning system operating. If the size of the air-conditioning system is reduced, the cabin soak temperature must also be reduced, with no penalty in terms of passenger thermal comfort. This paper presents the impact of air-conditioning on EV range and HEV fuel economy, and compares the effectiveness of advanced glazing and cabin ventilation. Experimental and modeled results are presented.

**Keywords:** Air-conditioning, cooling, energy, heat exchange, solar energy, thermal management

## 1. Introduction

The power required to cool a vehicle's passenger compartment can significantly reduce the range of an electric vehicle (EV) and the fuel economy of a hybrid electric vehicle (HEV). The power necessary to operate the air-conditioning compressor can be greater than the engine power required to move a mid-sized vehicle 56 km/h (35 mph).

Until recently, little has motivated U.S. automakers to find ways to reduce the impact of air-conditioning on fuel economy and emissions But a new emissions regulation, the Supplemental Federal Test Procedure (SFTP), will include air-conditioning as part of the emissions testing procedure. Table 1 shows the SFTP implementation schedule and the specifications are given in Table 2. The test procedure consists of the current emissions test (called the Federal Test Procedure or FTP), an air-conditioning test (SCO3), and a high-speed, high-acceleration test (USO6). The SFTP applies to vehicles with a gross vehicle weight under 2608 kg (5750 lb). The air-conditioning portion of the SFTP will contribute 37% of the total tailpipe emissions.

**Table 1. SFTP implementation schedule**

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

*Model year

**Table 2. SFTP 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 | 35% | 37% | 28% |

Although there is no plan to expand the use of the SFTP to measure fuel economy, reducing the weight of the air conditioning system of a mid-size vehicle by 9.1 kg (20 lb) results in about a 0.04 km/L (0.1 mpg) increase in fuel economy.

## 2. Air-conditioning impacts on conventional and high fuel economy vehicles

Figure 1 shows the impacts of auxiliary loads on a conventional vehicle and on a high fuel economy vehicle for the SCO3 drive cycle. Using ADVISOR [1], the conventional vehicle is modeled as a 1406-kg (3100-lb), 3.0-L, spark-ignition engine, with an 800-W auxiliary load resulting in a combined city-highway fuel use of 8.78 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 metro-highway fuel use of 2.89-L/100 km (81.5 mpg). The fuel economy of a nominally 3.0-L/100 km (80-mpg) vehicle over the SCO3 cycle could drop from 37 km/L (87 mpg) with 400 W base electric load to about 21.1 km/L (50 mpg) if the auxiliary loads increase to 2000 W.

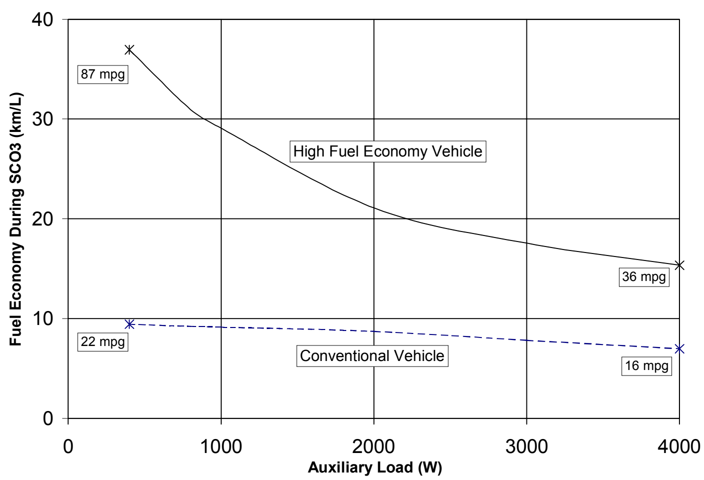


Figure 1. Fuel economy impacts of auxiliary loads

## 3. Air-conditioning impacts on near-term EV range and HEV fuel economy

To analyze the impacts of air-conditioning loads on the range of a near-term EV and on the fuel economy of a near-term HEV, we modeled two vehicles: a lightweight-chassis, five-passenger, NiMH battery EV (Table 3) and a lead-acid battery HEV (Table 4). Two engine manufacturers are listed for the HEV because two engines were scaled to the same maximum power and efficiency, separately modeled in the simulations, and the fuel economy results averaged.

We estimated the impact of four auxiliary loads for four driving cycles on these vehicles. The driving cycles modeled 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 HEV had a combined metro-highway fuel economy of 5.19 L/100 km (45.4 mpg).

**Table 3. EV specifications**

| Parameter | Value |
|---|---|
| Test Mass | 1599 kg |
| $C_D$*A | 0.67 $m^2$ |
| Fixed Gear Ratio | 6.7 |
| Accessory Load | 500 W |
| **Motor** | |
| Max. Power | 75/135 kW (continuous/intermittent) |
| Max. Torque | 271/488 Nm (continuous/intermittent) |
| Max. Speed | 10,000 rpm |
| **Battery Pack** | |
| Type | NiMH |
| Manufacturer | Ovonic |
| Pack Voltage | 327 V |
| Pack Energy | 30.4 kWh |
| Pack Mass | 412 kg |

**Table 4. HEV specifications**

| Parameter | Value |
|---|---|
| Test Mass | 1136 kg |
| $C_D$*A | 0.67 $m^2$ |
| Number of gears | 5 |
| Accessory Load | 500 W |
| **Motor** | |
| Max. Power | 41/68 kW (continuous/intermittent) |
| Max. Torque | 171/284 Nm (continuous/intermittent) |
| Max. Speed | 7500 rpm |
| **Battery Pack** | |
| Type | Lead-acid |
| Manufacturer | Hawker |
| Pack Voltage | 144 V |
| Pack Energy | 3.7 kWh |
| Pack Mass | 132 kg |
| **Fuel Converter (Engine)** | |
| Manufacturer | Isuzu / Chrysler |
| Max. Power | 55 kW |
| Max. Efficiency | 38% (spark ignition) |

The maximum thermal cooling load was assumed to be 7 kW. The net coefficient of performance of the electrically driven air-conditioning system, including the efficiency of the compressor and the electric motor required to drive it, was assumed to be 2.33. This yielded a maximum electrical load (resulting from air-conditioning) of 3 kW, which was added to the baseline value of 500 W in increments of 1000 W to determine the impact of auxiliary loads.

NREL's advanced vehicle simulation code, ADVISOR, was used to predict EV range and HEV fuel economy for the defined vehicles on each of the four driving cycles, and at accessory loads of 500 W, 1500 W, 2500 W, and 3500 W. All simulated cycles for the HEV model started and ended at the same battery state-of-charge, to within 0.5% of the initial pack capacity.

Table 5 shows the results for the EV range and Table 6 presents the HEV fuel economy. The first row indicates that an increase of the accessory load from 500 W to 3500 W will cause the EV range on repeated FUDS cycle to decrease by 38%. The first 1000-W increase, taking the accessory load from 500 W to 1500 W, causes a greater percentage decrease in range than do the successive increases in accessory load.

**Table 5. Electric vehicle range simulation results**

| | 500 W | 1500 W | | 2500 W | | 3500 W | |
|---|---|---|---|---|---|---|---|
| | Range (km / mi) | Range (km / mi) | Change from 500 W Case | Range (km / mi) | Change from 500 W Case | Range (km / mi) | Change from 500 W Case |
| FUDS | 175.9 / 109.3 | 147.7 / 91.8 | -16% | 125.5 / 78.0 | -29% | 108.9 / 67.7 | -38% |
| HWFET | 183.6 / 114.1 | 167.5 / 104.1 | -9% | 154.0 / 95.7 | -16% | 142.1 / 88.3 | -23% |
| US06 | 116.0 / 72.1 | 107.6 / 66.9 | -7% | 102.5 / 63.7 | -12% | 95.3 / 59.2 | -18% |
| SC03 | 174.3 / 108.3 | 146.9 / 91.3 | -16% | 126.8 / 78.8 | -27% | 111.2 / 69.1 | -36% |

Peak air-conditioning load, 3000 W of electric power (in addition to the base 500 W electrical load), reduces SC03 EV range by 36%. An electrical A/C load of 1000 W, which might meet steady-state air-conditioning requirements for a small sedan, reduces SC03 range by 16%.

**Table 6. Hybrid electric vehicle fuel economy simulation results**

| | 500 W | 1500 W | | 2500 W | | 3500 W | |
|---|---|---|---|---|---|---|---|
| | Fuel Use (L/100 km) Fuel Economy [mpg] | Fuel Use (L/100 km) Fuel Economy [mpg] | Change from 500 W Case | Fuel Use (L/100 km) Fuel Economy [mpg] | Change from 500 W Case | Fuel Use (L/100 km) Fuel Economy [mpg] | Change from 500 W Case |
| FUDS | 5.45 [43.2] | 6.51 [36.1] | 19% [-16%] | 7.69 [30.6] | 41% [-29%] | 9.03 [26.0] | 66% [-40%] |
| HWFET | 4.88 [48.3] | 5.18 [45.4] | 6% [-6%] | 5.48 [42.9] | 12% [-11%] | 5.84 [40.3] | 20% [-16%] |
| US06 | 6.64 [35.4] | 6.94 [33.9] | 5% [-4%] | 7.30 [32.2] | 10% [-8%] | 7.70 [30.6] | 16% [-12%] |
| SC03 | 5.96 [39.5] | 6.91 [34.1] | 16% [-10%] | 7.96 [29.5] | 34% [-19%] | 9.38 [25.1] | 57% [-28%] |

Peak air-conditioning load, 3000 W of electric power, increases SC03 HEV fuel use by 57%. An electrical air-conditioning load of 1000 W, which might meet steady-state air-conditioning requirements for a small HEV sedan, increases SC03 fuel use by 16%.

## 4. Opportunities to reduce air-conditioning loads

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

The peak load should be reduced first by reducing the solar gain into the vehicle and second by using ambient air to cool the hot vehicle cabin. The solar gain enters the vehicle 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. As the soak temperature is reduced using advanced glazings, the cabin temperature is lowered, and roof insulation may be beneficial.

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. A 1997 Plymouth Breeze served as the test vehicle.

The effectiveness of the advanced glazings was determined using a co-heating technique. We measured the power of a ceramic heater required to maintain the cabin interior air temperature at a constant 60°C (140°F), eliminating the effect of the thermal capacitance of the vehicle interior. As the solar gains increased, the heater power decreased. An energy balance on the vehicle for this steady-state condition is:

[Heater power] + [Solar gain] = [Vehicle heat loss] (1)

where

[Solar gain] = [Window gain] + [Opaque gain] (2)

The vehicle heat loss includes heat loss through the windows when they were opened 1.9 cm (0.75 in.). The vehicle heat loss with the windows closed was estimated from the nighttime conditions when there was no solar radiation. The opaque gains represent the body gain and were measured with 2.5 cm (1 in.) of foam insulation on the outside of all of the vehicle windows. Hence, the solar gain through the windows can be estimated as

[Window gain] = [Vehicle heat loss] – [Heater power] – [Opaque gain] (3)

An assumption implicit in this approach is that the vehicle heat loss during the day is approximately the same as during the night.

Figure 2 shows the measured heater power for four cases with or without solar reflective film and with the windows slightly opened or closed.

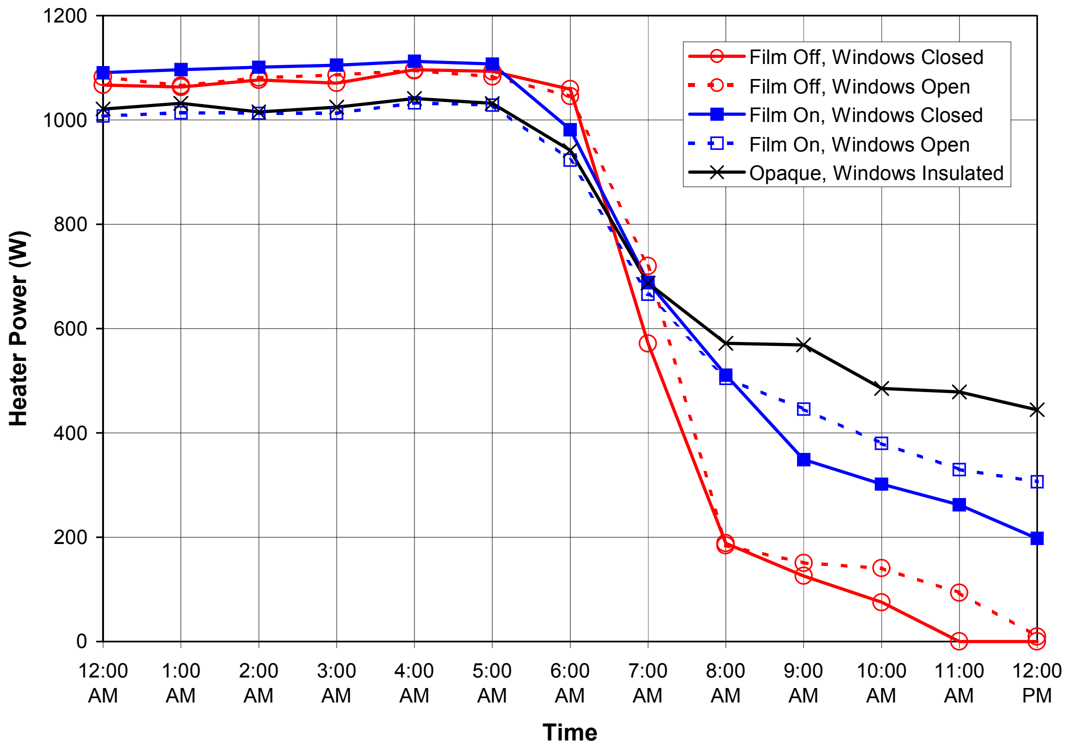


Figure 2. Measured heater power for solar reflective films

The graph indicates that greater heater power is required to maintain the cabin temperature as the solar gain into the cabin is reduced. 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 had the greatest solar gain. 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. Figure 3 shows the ratios of the net solar gain (through the windows plus the opaque gains less heat lost by ventilation, in the cases where the windows are open) to the opaque test for the test configurations.

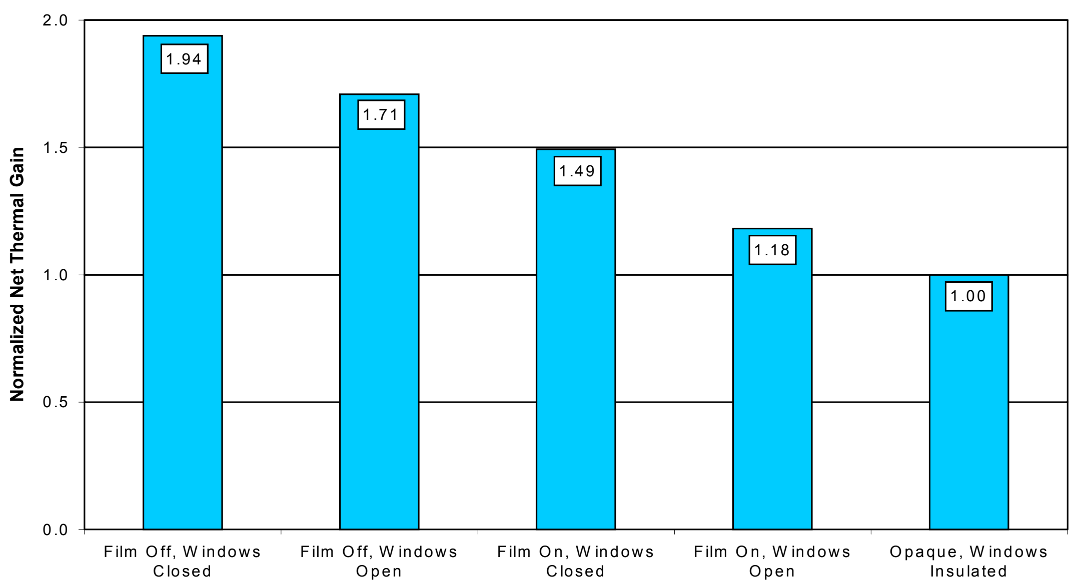


Figure 3. Window film results

The use of advanced glazings plus cabin ventilation can significantly reduce the solar gain into the vehicle as can be seen in the "Film On, Windows Open" case. The "Film Off, Windows Closed" has 64% more thermal gain than the "Film On, Windows Open" case.

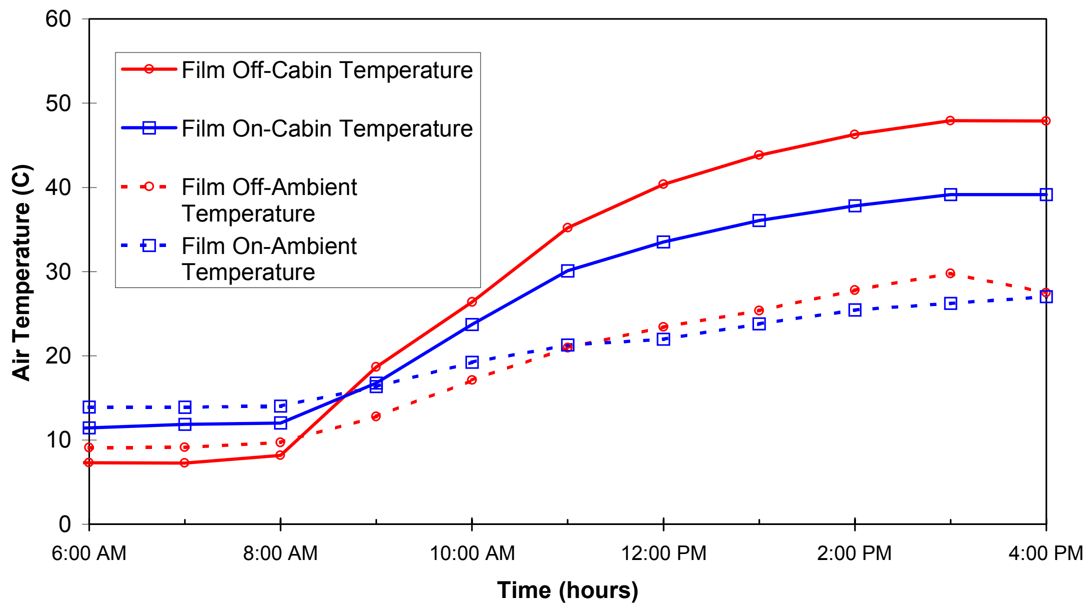


Figure 4. Vehicle soak temperature

We also conducted a series of soak tests using only solar heating with the windows closed. Figure 4 presents a comparison of the cabin soak temperature for the vehicle with and without the film, along with the ambient temperatures during the test. The film kept the cabin about 9°C (16°F) cooler for these conditions.

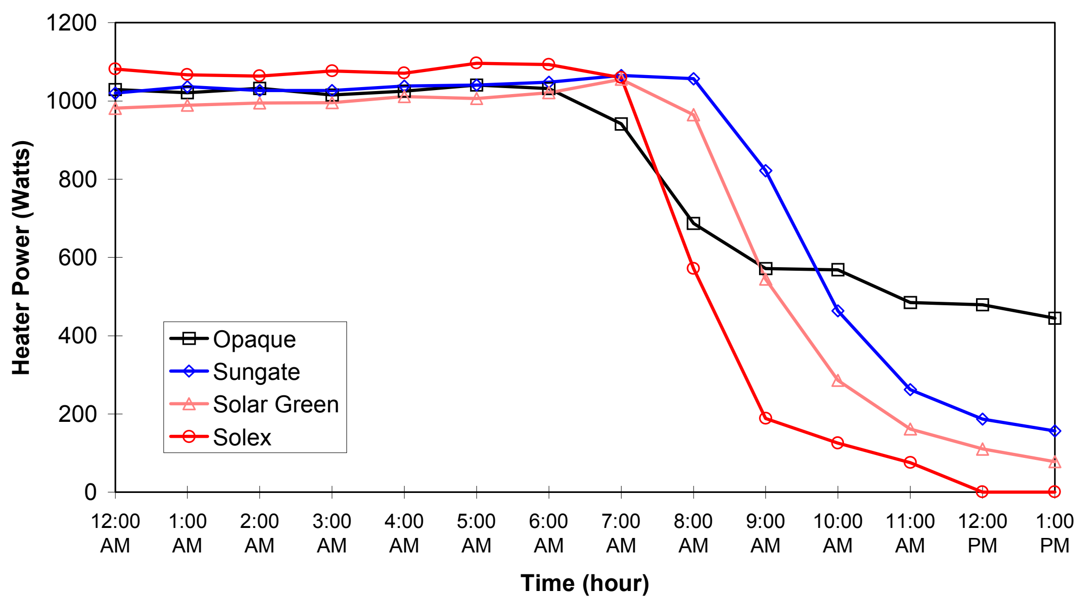


Figure 5. Heater power for windshield tests

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 results from the co-heating test are shown in Figure 5.

In the opaque case, all the windows were covered with foam insulation. The test used different windshields but 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, 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. Figure 6 shows the total solar gains (windows plus opaque gains) from sunrise to 1 p.m. compared with the results from the opaque gains test, normalized to the total solar radiation during each test. The Solex® windshield had 17% more thermal gain than the Sungate® windshield.

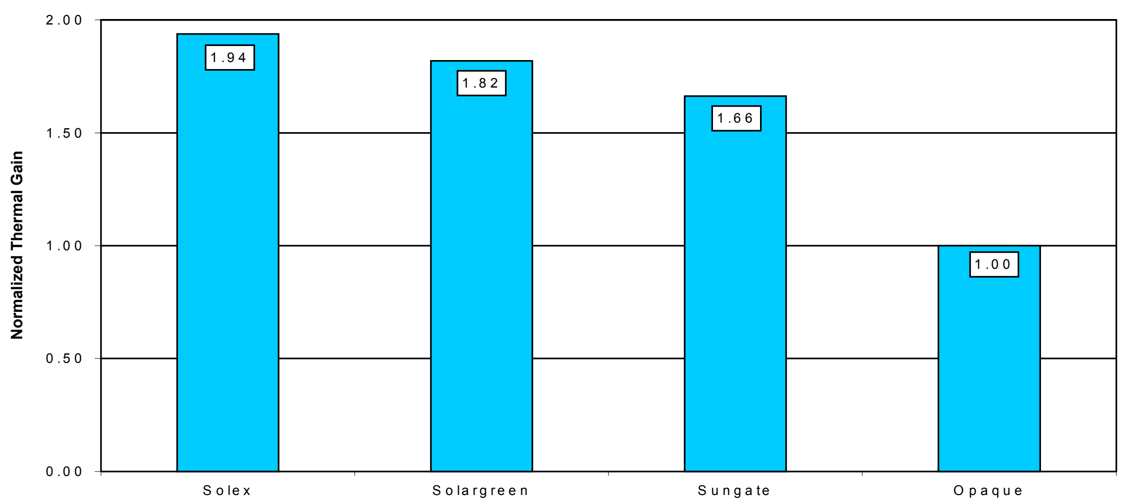


Figure 6. Windshield thermal gains

Table 7 shows the potential impact on fuel economy for a conventional mid-sized vehicle using the Sungate® windshield compared with the standard Solex® windshield. The advanced windshield without any treatment on the side windows can reduce fuel consumption by 3.4% over the SCO3 drive cycle.

**Table 7. Sungate fuel economy impacts**

| Windshield | Mechanical 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% |

## 5. Conclusions

Conventional air-conditioning loads can reduce EV range and HEV fuel economy by nearly 40% depending on the size of the air-conditioner and the driving cycle. The peak cabin soak temperature must be reduced if a smaller air-conditioning system is to be used. Advanced glazings and cabin ventilation during soak conditions are effective ways to reduce the peak cabin temperature. To avoid exacerbating the problem, effective modeling and testing must be conducted, which might be done by insulating the cabin roof without first reducing the peak cabin temperature. We are continuing to investigate advanced glazing and ventilation techniques, but it is apparent that great opportunities exist to improve EV and HEV performance while reducing fuel consumption and improving air quality.

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## References

[1] Wipke, K., Cuddy, M., Bharathan, D., Burch, S., Johnson, V., Markel, T., and Sprik, S., "ADVISOR 2.0: A Second-Generation Advanced Vehicle Simulator for Systems Analysis," presented at the North American EV & Infrastructure Conference and Exposition (NAEVI 98), December 3-4, 1998, Phoenix, Arizona. For more information, see http://www.ctts.nrel.gov/analysis/