2001-01-3077

Effect of Solar Reflective Glazing on Ford Explorer Climate Control, Fuel Economy, and Emissions

John P. Rugh and Terry J. Hendricks
National Renewable Energy Laboratory

Kwaku Koram
PPG Industries

ABSTRACT

The energy used to air condition an automobile has a significant effect on vehicle fuel economy and tailpipe emissions. If a small reduction in energy use can be applied to many vehicles, the impact on national fuel consumption could be significant. The SCO3 is a new emissions test conducted with the air conditioner (A/C) operating that is part of the Supplemental Federal Test Procedure (SFTP). With the 100% phase-in of the SFTP in 2004 for passenger cars and light light-duty trucks, there is additional motivation to reduce the size of the A/C system. The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) is investigating ways to reduce the amount of energy consumed for automobile climate control.

If the peak soak temperature in an automobile can be reduced, the power consumed by the air conditioner may be decreased while passenger comfort is maintained or enhanced. Solar reflective glass is one way to reduce the peak soak temperature. 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. Test results showed a dramatic reduction in interior and glass temperatures. After the A/C system and its effect on the passenger compartment were modeled to assess the potential reduction in compressor power, the vehicle performance was predicted.

INTRODUCTION

The air conditioner (A/C) is the single largest auxiliary load on an automobile engine. Its impact on fuel economy and emissions can be significant. For vehicles driven over the SCO3 drive cycle, recent tests indicate A/C use increases emissions of NO_x by about 80% and of CO by about 70%. It also reduces fuel economy by about 20%.[1] At NREL, our goal is to work with the auto industry to reduce the fuel used for climate control while maintaining or improving occupant thermal comfort. For the driver, a reduction in fuel use for climate control would increase real world fuel economy. A small reduction in fuel use per vehicle would translate into a significant reduction in national fuel consumption.

The automobile industry is facing the implementation of a new emissions test, the Supplemental Federal Test Procedure[2] (SFTP). The SFTP consists of the three tests shown in Table 1: the current Federal Test Procedure (FTP), an A/C test (SC03), and a high-speed test (US06).

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%

The SC03 test measures the tailpipe emissions of vehicles with the A/C operating at maximum fan speed, 100% recirculation, 100 grains of moisture/lb of dry air, and 850 W/m^2 of solar radiation over a drive cycle of approximately 10 minutes. Reducing the A/C size effectively reduces emissions and the demands on the exhaust aftertreatment system during the SCO3 test.

The A/C system is sized to provide adequate cooling in a specified time period from a hot soak condition. To impact the fuel used for climate control, the power draw of the compressor from the engine must be reduced. A secondary benefit of a smaller compressor is lower weight. Reducing the peak soak temperatures in a vehicle is one way to reduce A/C system power use. This paper discusses the testing and modeling results of PPG Industries Sungate® solar reflective glazing installed in a Ford Explorer.

DESCRIPTION OF SUNGATE® SOLAR REFLECTIVE GLAZING

Absorbing glazings, such as high iron glasses, re-radiate the absorbed energy in the thermal infrared wavelength range into the vehicle passenger compartment. Reflecting the incident solar radiation more efficiently reduces the solar load on vehicles. Sungate® is a solar reflective coating consisting of a double stack of silver and dielectric layers. High volume deposition of this coating on flat glass is achieved in production by use of a dc magnetron sputtering process in a flat glass coater. The design of the stack is such that when heated, the coating remains stable at glass bending temperatures. The optical properties of the heated coating are also enhanced over those of the unheated coating. Figure 1 shows the decreased transmissivity of a Sungate® windshield in the infrared region.

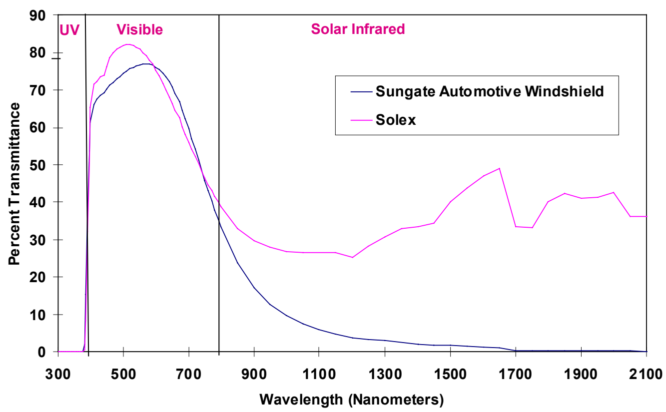

Figure 1 Transmissivity of Sungate® Windshield

Sungate® solar reflective glazings used in this study were glass/pvb/glass laminates with the coating on the inside surface of the outer clear glass. The inner glass was tinted. With this configuration, the coating is protected by lamination, and reflectance is not impaired by absorption in the pvb.

VEHICLE TEST PROCEDURE

A vehicle test procedure was developed to characterize the vehicle level thermal impact of solar reflective glazings. NREL uses outdoor testing to determine the behavior of solar reflective glazings under actual solar environmental conditions. Two vehicles are used in a test program: one has the production glazings and is the control vehicle; the other has modified glazings. The advantage of using two vehicles is that the effects of day to day environmental differences are minimized. Additionally, comparing a temperature difference between the baseline and test vehicles using the same data system reduces the impact of systematic errors. Theoretically, the same systematic error is incurred by both measurements and cancels out when the temperatures are subtracted.

Before testing the Sungate® solar reflective glazing, both Ford Explorers (see Figure 2) were tested with their production glazings to characterize any differences. Multiple soak and cooldown tests were then performed with each glazing configuration. In the soak test, the vehicles were heated by the sun and the peak soak temperatures of the baseline and test vehicle were measured. After the peak breath temperatures were attained, a cooldown test was performed. The vehicles were operated at idle with the air conditioner operating at maximum fan speed and 100% recirculation air.

Both vehicles were tested at DSET Laboratories in Phoenix, AZ, in November 2000, to determine the impact of the Sungate® solar reflective glazing. The vehicles had white exteriors, graphite interiors, and cloth seats, and faced south in a front-back configuration. As seen in Figure 2, the baseline vehicle (Vehicle A) was forward and the test vehicle with Sungate® glazings (Vehicle B) was in the rear. The vehicles were fully instrumented, including heat flux gauges between the headliner and roof and pyranometers on the instrument panel. Cabin air temperatures were measured at eight locations with type K thermocouples protected by radiation shields. The air temperatures at four heating, ventilation, and air-conditioning (HVAC) duct exits were also measured. Surface temperatures were measured on the glazing interior, door trim, seat, and instrument panel. During the soak test, the HVAC systems were in 0% recirculation mode, which allowed the passenger compartments to breathe through the HVAC system.

Figure 2. Ford Explorer Test Vehicles at DSET

VEHICLE TEST RESULTS

The baseline soak test revealed that the vehicles were approximately thermally equivalent with the breath and foot air temperatures within 0.1°C (0.2°F) and windshield and IP temperatures within 0.4°C (1°F). These differences were small enough that the comparative data did not need a correction. Figure 3 illustrates the similarities between the breath and foot air temperatures for the two vehicles.

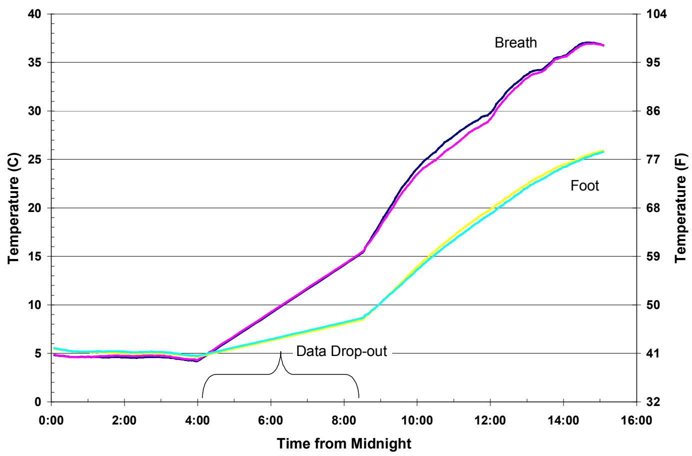

Figure 3. Breath and Foot Air Temperatures, Baseline Soak

The baseline cooldown test revealed that Vehicle B took longer to cool than Vehicle A (Figure 4). Although the A/C systems were fully charged before testing, some difference in the A/C system probably caused the variation. We considered this difference when comparing the cooldown data of the two vehicles during the comparative glazing tests.

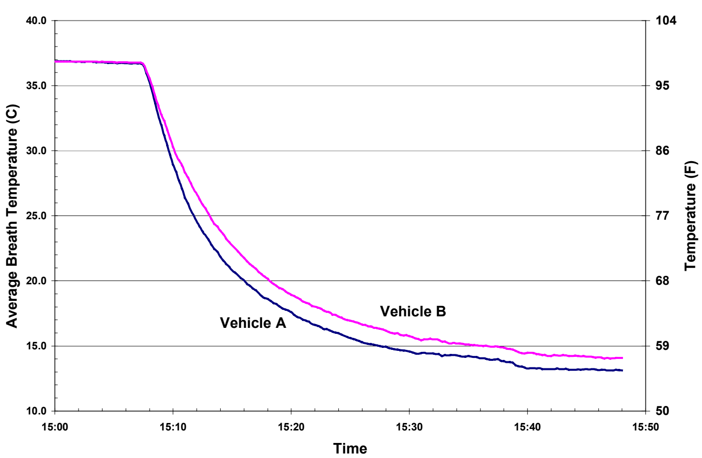

Figure 4. Breath Air Temperature, Baseline Cooldown

Three glazing configurations were tested in Vehicle B.

- All glazings with laminated Sungate®
- Sungate® windshield and two front laminated sidelites
- Sungate® windshield

Vehicle B, with all Sungate® glazings, had a maximum breath temperature 2.7°C (4.9°F) lower than Vehicle A; the Sungate® windshield by itself reduced the maximum breath temperature by 2.2°C (4.0°F). Table 2 shows the instrument panel (IP) and windshield were also cooler when Sungate® glazings were applied.

Table 2. Reduction in Maximum Temperature

Glazing Configuration	Breath Temp °C (°F)	IP Temp °C (°F)	Windshield Temp °C (°F)
Sungate®all glazings	2.7 (4.9)	7.6 (13.7)	10.5 (18.9)
Sungate® windshield and front sidelites	2.5 (4.5)	7.0 (12.6)	9.8 (17.6)
Sungate® windshield	2.2 (4.0)	8.0 (14.4)	12.2 (22.0)

In Figure 5, the breath air temperature for both vehicles are compared. Vehicle B experienced a reduced air temperature soon after the sun rose.

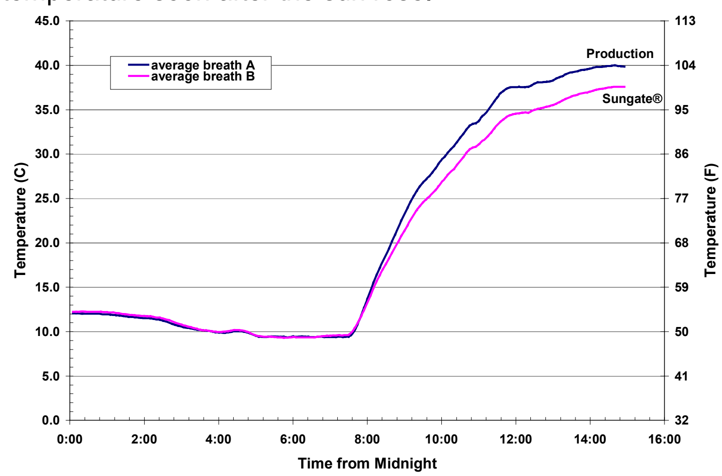

Figure 5. Breath Air Temperatures, All Sungate®

The impact of the Sungate® glazing on the IP and windshield was dramatic. Figure 6 shows Vehicle B had a significantly cooler windshield surface temperature because the solar energy was reflected instead of absorbed. The production windshield was solar management glass, which absorbs energy to reduce the transmitted energy. This increases the windshield temperature and radiant load at face level with a corresponding decrease in passenger comfort until the windshield cools due to increased convection heat transfer as the vehicle speed increases during driving.

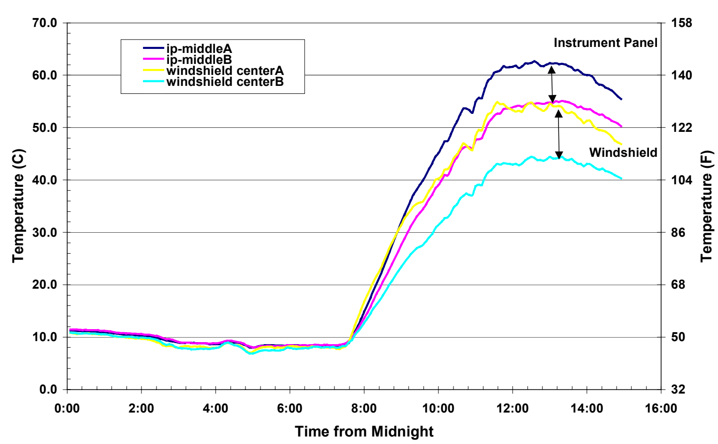

Figure 6. Surface Temperatures

Figure 7 shows the reduction in average temperature of the seats and door trim. Less energy in the internal mass will result in a quicker cooldown and enhanced passenger comfort.

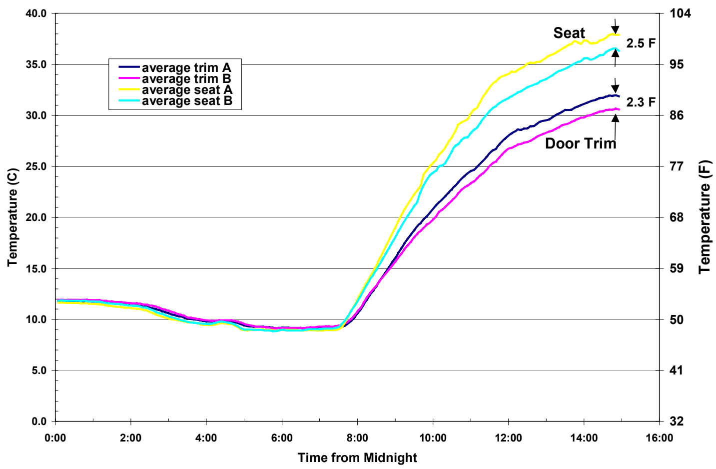

Figure 7. Trim and Seat Temperatures

The pyranometers on the instrument panel provided a good indication of the transmitted solar radiation. Figure 8 shows that the Sungate® windshield reduced the measured solar radiation on the IP. The ambient pyranometer is included to document the solar environment for the test day. Integrating the solar data from 10:00 to 14:00, the Sungate® windshield reduced the solar radiation by 14%. This is consistent with calculations based on the transmissivity data.

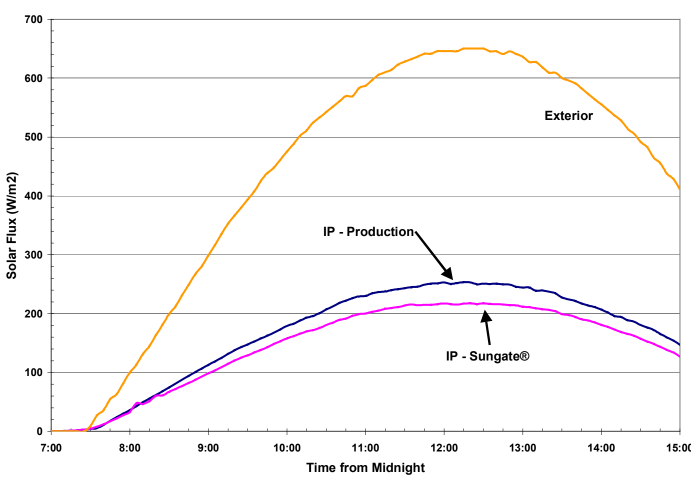

Figure 8. Transmitted Solar Energy

Figure 9 shows data from a cooldown test of both vehicles. The initial temperature is lower for Vehicle B since more solar radiation was reflected. Vehicle B now has a similar cooldown to Vehicle A, where before in the baseline test (Figure 4), Vehicle B's cooldown lagged. Translating this improved cooldown performance into a potential reduction in A/C compressor size is challenging but necessary to determine the potential impact on fuel economy.

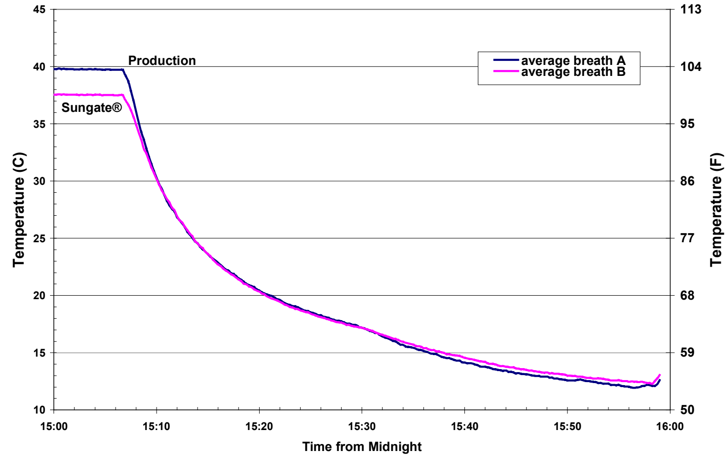

Figure 9. Breath Air Temperature, Cooldown

VEHICLE MODELING

TRANSIENT A/C MODEL – NREL has developed a detailed transient air conditioning system/simplified cabin model[5] that was used to estimate A/C compressor power reductions possible from cabin temperature reductions. NREL developed this model using SINDA/FLUNT analysis software and integrated it with the Advanced VehIcle SimulatOR (ADVISOR)[3,4] vehicle systems analysis software. This transient one-dimensional, thermal-hydraulic model 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. It predicts typical transient A/C compressor power requirements, system pressures and temperatures, system mass flow rates, and two-phase/single-phase flow conditions throughout the A/C system flow circuit, as well as transient cabin temperature conditions during a user-defined drive cycle.

The transient A/C model was used by modeling the Ford Explorer A/C system and cabin thermal environment, and then comparing its cabin air temperature test data with model-predicted cabin air temperature versus time profiles. In this study, we did not have access to specific Explorer A/C system design parameters in the project timeframe and schedule. Consequently, the A/C system model was estimated, using nominal A/C system design parameters to approximate the Explorer A/C system. The A/C system/cabin thermal model was then calibrated by adjusting model design parameters so cabin air temperature predictions matched as closely as possible to actual cabin air temperature test data in the baseline case. Figure 10 shows the model prediction/test data comparison achieved for cabin air temperature and panel outlet temperature in this baseline model calibration for the production glazing case. The initial cabin temperature was taken from the baseline cabin experimental data for the Ford Explorer with production glazings in Figure 9.

The comparison was reasonable given our limited access to Explorer A/C system design information and specific cabin design information. Specific limitations of the modeling were our lack of data on system ducting thermal mass and dimensions, evaporator heat exchanger data, condenser heat exchanger data, compressor performance data, and cabin thermal mass. This calibrated model gave us a reference production-glazing-case baseline that we could then use to compare modified compressor power requirements as cabin initial temperature conditions varied due to different glazing configurations.

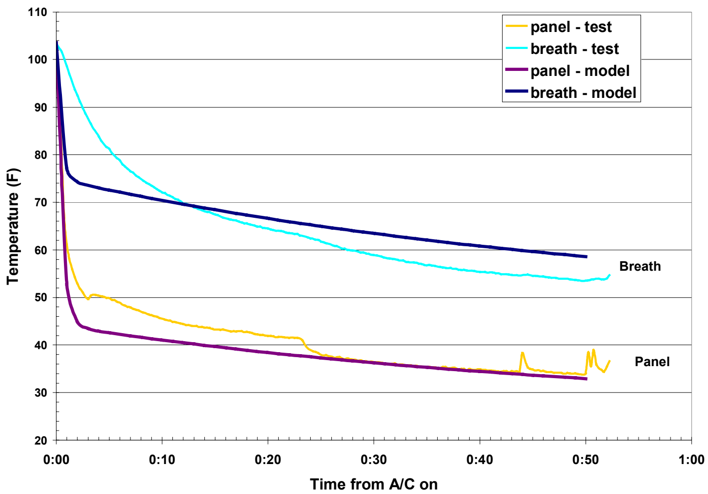

Figure 10 Model Compared to Test Data

A major effect of the Sungate® glazings was to reduce the cabin soak temperature and initial cabin temperature before cooldown, as shown in Figure 9. The calibrated model was modified for the change in cabin initial temperature and reduced solar load caused by the Sungate® glazings. Figure 11 shows the transient cabin temperature profile for the reference production glazing baseline (blue line) and the Sungate® glazings case with no compensating adjustments to compressor power (yellow line). With no decrease in compressor power, the cabin temperature profile was lower than the baseline case, which would enhance passenger comfort. Compressor power was then reduced to decrease the cooling capacity of the A/C system and match the cabin temperature profile of the reference baseline at 30-50 minutes into the cabin cooldown to maintain the baseline passenger comfort. The resulting compressor power was 11.3% lower than in the reference baseline (production glazing) case. Figure 11 shows this new cabin temperature profile for the 11.3% lower compressor power case (pink line).

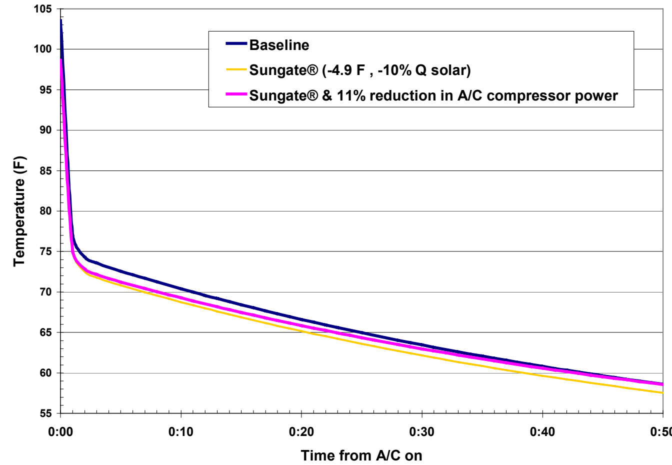

Figure 11 Temperatures with Reduced A/C Compressor and Sungate®

The 11.3% reduction in compressor power in the Sungate® glazing case translates to a 2.3% compressor power reduction for every degree Fahrenheit reduction in cabin soak temperature. This was the compressor power reduction at cabin temperatures of about 100°F. Additional analyses were performed for more severe conditions of cabin temperatures of about 150°F and a cabin solar thermal load of 1000 watts (this case was more typical of Phoenix, AZ, summer conditions). A 5°F reduction in cabin temperature and corresponding 10% reduction in cabin solar thermal load in this case produced a 2.2% compressor power reduction for every degree Fahrenheit reduction in cabin soak temperature. Several auxiliary load reduction concepts/projects at NREL are projecting cabin soak temperature reductions of 6-10°C (11-18°F). These projects could dramatically reduce (about 25-41%) required vehicle A/C compressor power in advanced and hybrid electric vehicles.

ADVISOR - After we estimated the reduction in A/C compressor size, we modeled the fuel use with ADVISOR, which is designed to quickly analyze the performance and fuel economy of conventional, electric, and hybrid vehicles. ADVISOR can be used to model vehicle efficiencies, assess the impacts of applying innovative technologies to vehicle configurations, develop novel energy management strategies, and integrate simulated and real-life assessments.

The impact of the reduced A/C system was estimated for an Explorer driven over the SCO3 drive cycle. NREL was provided with details of the engine, transmission, and vehicle geometry. These data were used to generate an ADVISOR model. Initial simulations over the UDDS and HWFET drive cycles showed that the transmission and auxiliary losses were low and the fuel economy was high. After a small adjustment to the loss coefficients, the fuel economy for the city (UDDS) matched to within 0.05% and highway (HWFET) matched to within 0.5%.

The A/C load of 4000 W was then added to the baseline auxiliary load of 1000 W and the vehicle operation was simulated over the SCO3 drive cycle. This was defined as the baseline vehicle simulation from which the percentage differences were calculated. Then the A/C load was reduced incrementally and Figure 12 was generated. Assuming an 11% decrease in A/C power caused by Sungate® on all glazings, the fuel economy is increased 2.2% or approximately 0.35 mpg. Figure 13 shows that NO_x emissions were reduced by 4.4%. Since Figures 12 and 13 are not directly related to Sungate® glazings, they can be used to assess the impact of a reduction in the A/C compressor regardless of the method used to reduce the peak soak temperature.

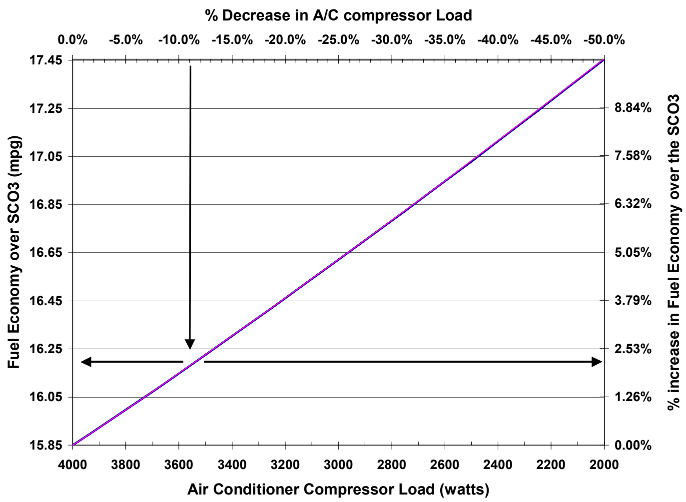

Figure 12. Impact of Sungate® on Ford Explorer Fuel Economy over the SCO3

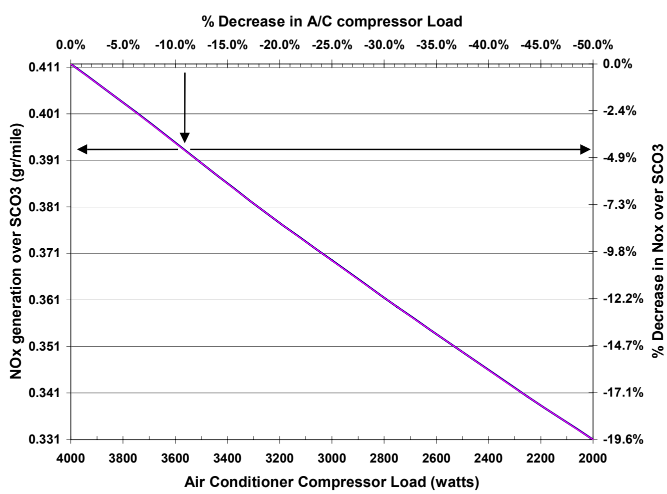

Figure 13. Impact of Sungate® on Ford Explorer NO_x over the SCO3

CONCLUSION

With the development of high fuel economy vehicles and hybrid electric vehicles, the energy consumed by the A/C system will become increasingly important. With the large number of vehicles in the United States, the energy consumed nationally for vehicle air conditioning is significant (11 billion gallons per year)[6]. The goal at NREL's Center for Transportation Technologies and Systems is to work with industry to reduce the amount of fuel used for climate control. A small change in today's vehicles can make a large impact on national fuel consumption.

Using solar reflective glazings such as Sungate®, the peak soak temperature can be decreased, thus reducing the A/C compressor size. Testing has demonstrated that interior temperatures are reduced when the sun's energy is reflected. This reduces the A/C compressor size by 11% on the Ford Explorer, which reduces fuel use and emissions. When solar reflective glazings are combined with other technologies (such as ventilation and insulation) to reduce the peak soak temperature, the resulting reduction in interior temperatures and the corresponding vehicle impacts will be enhanced. Solar reflective glazing is an important part of the system solution for reducing the fuel used for climate control.

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, DOE program managers; Terry Penney, NREL's HEV technology manager; and Barbara Goodman, director of the Center for Transportation Technologies and Systems. The authors would like to acknowledge the significant contributions provided by PPG and by our colleagues at NREL. PPG provided the glazing systems, vehicles, and technical support. In addition, we recognize the significant contribution of Valerie Johnson, who assisted with the ADVISOR analysis.

REFERENCES

1. Clean Air Vehicle Technology Center; October 1999. "Effect of Air-conditioning on Regulated Emissions for In-Use Vehicles, Phase I, Final Report." Prepared for Coordinating Research Council, Inc. CRC Project E-37. Also available at http://www.crcao.com.
2. Federal Register, October 22, 1996. "Part II Environmental Protection Agency. Motor Vehicle Emissions Federal Test Procedure Revisions: Final Regulations." 40 CFR Part 86.
3. Wipke, K.; Cuddy, M.; Burch, S.; 1999. "ADVISOR 2.1: A User-Friendly Advanced Powertrain Simulation Using a Combined Backward/Forward Approach." 14 pp.; NREL Report No. JA-540-26839, Golden, CO: NREL.
4. Wipke, K.; Cuddy, M.; Bharathan, D.; Burch, S.; Johnson, V.; Markel, A.; and Sprik, S. 1999. ADVISOR 2.0: A Second-Generation Advanced Vehicle Simulatory for Systems Analysis. 14 pp.; NREL Report No. TP-540-25928, Golden, CO: NREL.

5. Hendricks, T.J., 2001, "Optimization of Vehicle Air Conditioning Systems Using Transient Air Conditioning Performance Analysis." *Proceedings of VTMS 5 Vehicle Thermal Management Systems Conference*, Paper # 2001-01-1734, Society of Automotive Engineers, Nashville, TN.
6. Farrington, R.; and Rugh, J.; October 2000, "Impact of Vehicle Air Conditioning on Fuel economy, Tailpipe Emissions, and Electric Vehicle Range." NREL Report No. CP-540-28960, Golden, CO: NREL.

CONTACT

http://www.nrel.gov
http://www.ott.doe.gov/coolcar
john_rugh@nrel.gov
terry_hendricks@nrel.gov
koram@ppg.com