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Comparison of Indoor Vehicle Thermal Soak Tests to Outdoor Tests

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ABSTRACT

Researchers at the National Renewable Energy Laboratory conducted outdoor vehicle thermal soak tests in Golden, Colorado, in September 2002. The same environmental conditions and vehicle were then tested indoors in two DaimlerChrysler test cells, one with metal halide lamps and one with infrared lamps. Results show that the vehicle's shaded interior temperatures correlated well with the outdoor data, while temperatures in the direct sun did not. The large lamp array situated over the vehicle caused the roof to be significantly hotter indoors. Yet, inside the vehicle, the instrument panel was cooler due to the geometry of the lamp array and the spectral difference between the lamps and sun. Results indicate that solar lamps effectively heat the cabin interior in indoor vehicle soak tests for climate control evaluation and SCO3 emissions tests. However, such lamps do not effectively assess vehicle skin temperatures and glazing temperatures.

INTRODUCTION

At the National Renewable Energy Laboratory (NREL), we have conducted outdoor tests of advanced technologies in vehicles to reduce solar loads and possibly the size of vehicle mobile air conditioning systems (MACS). We periodically ask the question: Must a vehicle be tested outside, or can indoor tests using solar lamps accurately simulate the sun? We partnered with DaimlerChrysler to address this question.

We gathered a large database of outdoor thermal soak data on a Jeep® Grand Cherokee, then selected and simulated environmental conditions from two test days (09/02/02 and 09/15/02) in two DaimlerChrysler test cells, one with metal halide lamps and one with infrared (IR) lamps. The resulting temperatures were then compared to those measured during the outdoor tests to assess the performance of the lamps and test cell.

Repeatability issues are common in cooldown tests because hot outdoor temperatures are not always available and outdoor conditions vary from day to day. This presents challenges for testing new vehicle technologies in outdoor conditions. To enable testing anytime during the year and reduce vehicle development times, solar lamps are used in climate control chambers to test vehicle MACS. The SCO3 emissions test, part of the Supplemental Federal Test Procedure[1], is also performed indoors with a vehicle driven over a 10-min cycle with the air conditioner operating and a solar load of 850 W/m^2. In addition to running the SCO3 procedure in the emissions test chambers, DaimlerChrysler uses environmental wind tunnels with solar lamps to soak vehicle interiors for cooldown tests and provide a cabin heat load during MACS performance testing.

Solar lamps are used to simulate the sun (represented in Figure 1 by ASTM-E-892[2]). IR lamps are commonly used because they are cost effective; however, a disadvantage is that the energy is shifted toward the IR portion of the spectrum. Solar load-reducing technologies such as solar reflective glass reflect in the IR region, so test results with IR lamps can artificially improve performance. Metal halide lamps simulate the sun better, but are more expensive. A few references in the literature discuss solar simulator design, but vehicle

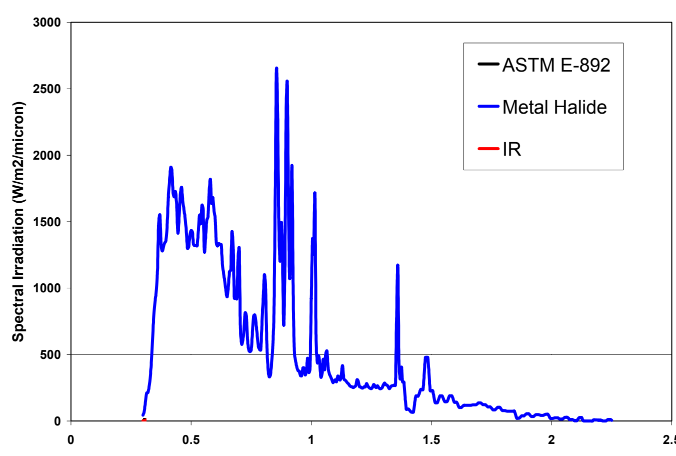

Figure 1. Sun Compared to Metal Halide and IR Lamps

data comparing indoor and outdoor testing are not available[3,4].

TEST SETUP

A tan Jeep Grand Cherokee with standard original equipment manufacturer glazings was used for the thermal soak tests (Figure 2). Thermocouples were placed in the middle of the seat cushions and seat backs in the front and back seats, embedded approximately ¼ in. into the seat material. Thermocouples were attached to the door trim, sidelites, instrument panel (IP), windshield, headliner, and roof with small amounts of thermal epoxy. The air temperatures were measured with a thermocouple protected by a 2-layer radiation shield at the foot and breath levels. Ambient air temperature, wind speed, and solar radiation (global horizontal) were measured approximately 6 ft from the ground.

Figure 2. Jeep Grand Cherokee at Outdoor Test Site

OUTDOOR

The vehicle was oriented due south on a flat section of ground covered with crushed rock with no shading by buildings or trees.

INDOOR: EMISSIONS TEST CELL (METAL HALIDE LAMPS)

The vehicle was loaded in DaimlerChrysler's Emissions Test Chamber #7 and centered under a bank of Venture metal halide lamps. The solar lamps were arranged in a flat plane on the ceiling (Figure 3). The lamp intensities can be adjusted individually to account for the vehicle's profile. The wind velocity was simulated using a pop-up road speed fan in front of the vehicle. The maximum fan speed is 95000 cfm. The wind direction was from the front to rear of the vehicle.

INDOOR: ENVIRONMENTAL TEST CELL (IR LAMPS)

The vehicle was loaded in DaimlerChrysler's Environmental Test Chamber #3 and centered under a bank of tungsten filament quartz tubes (GE T3). Only the overhead and front banks were used to be comparable to the emissions test cell (Figure 4). The wind velocity was simulated using the permanent, external wind tunnel fan drive system, which is capable of 100 mph. The air flows from a 50-ft^2 nozzle at the front of the vehicle and travels to the back. The air is collected at the rear of the test chamber and vertically recycled back to the front.

Figure 3. Test Cell with Metal Halide Lamps

Figure 4. Test Cell with IR Lamps

TEST CONDITIONS

The indoor tests required a constant ambient temperature, solar radiation, and wind speed. Since the outdoor environment is not constant, selecting the steady state set points for the indoor tests was challenging. After reviewing the weather data from all the test days, 9/2/02 and 9/15/02 were selected because they were sunny and the wind was calm. The environmental conditions and vehicle temperatures were reasonably constant between 13:00 and 14:00; therefore, ambient temperature, solar radiation, and wind speed set points were averages of the readings during that time period. Tables 1 and 2 show the set points and conditions in the tunnel.

Table 1. Ambient and Test Cell Conditions for 9/15/02

9/15/02 Conditions	Outdoor	Metal Halide	IR
Wind speed (mph)	6.5	5.3	7.2
Solar Flux (W/m2)	878.4	864.7	873.7
Ext. Air Temperature (°C)	26.7	27.3	28.2

Table 2. Ambient and Test Cell Conditions for 9/02/02

9/2/02 Conditions	Outdoor	Metal Halide
Wind speed (mph)	5.8	4.9
Solar Flux (W/m2)	899.1	889.6
Ext. Air Temperature (°C)	25.0	25.3

RESULTS

The vehicle's roof temperature was 24.5°C hotter in the indoor tests with IR and 20.1°C hotter with metal halide lamps, compared to outdoor temperatures (Figure 5). This is because outdoors, the roof loses thermal radiant heat energy to the sky, which is reasonably close to ambient air temperature. Indoors the roof is surrounded by the hot lamp array and associated structure. The roof gains heat energy by thermal radiation exchange with the array, and therefore attains temperatures hotter than those measured outdoors.

The indoor incident radiation on the roof is also higher than the outdoor test. The test radiation levels were determined by a pyranometer located 12 in. above the

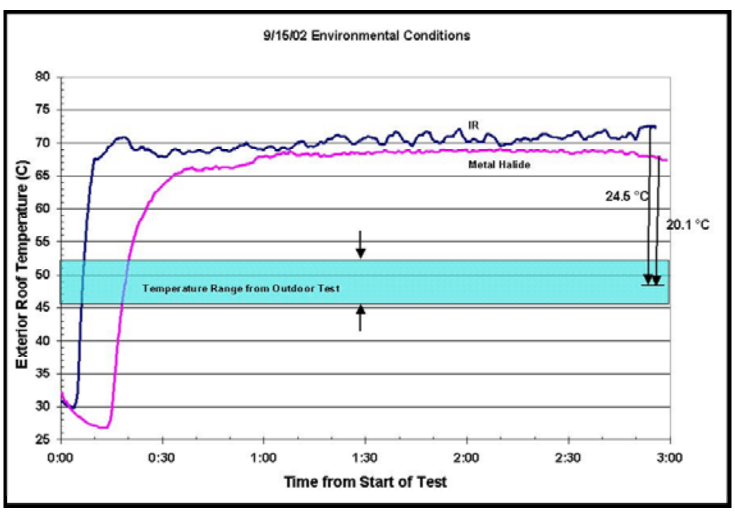

Figure 5. Exterior Roof Temperature

hood at the vehicle centerline. At the location where the roof temperature was measured, the solar flux was 15% higher than the set point for the metal halide lamps. This is because the radiant load is a strong function of the distance away from the lamp and the roof is closer than the pyranometer to the lamps.

Figure 6 shows the soak temperatures at various locations on the vehicle for the outdoor test, indoor test with metal halide lamps, and indoor test with IR lamps. Indoors, the windshield and IP temperatures were lower than the outdoor test, which was surprising since metal halide lamps are generally thought to simulate the sun well. The windshield was 3.4°C cooler with metal halide lamps and the IP was 4.8°C cooler than outdoors. The deviation is thought to be mostly due to the geometry difference between a point source sun and a lamp array radiation source.

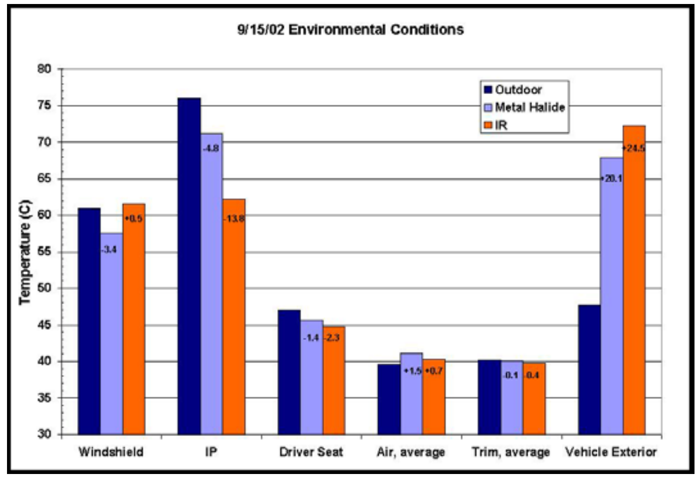

Figure 6. Comparison of Outdoor to Test Cell Data

VSOLE Simulation Results

We used a computer program developed at NREL called the Vehicle Solar Load Estimator (VSOLE) to calculate the reflected, transmitted, and absorbed energy at each window of the vehicle. We input the solar azimuth and zenith from the 9/15/02 outdoor test to determine the vehicle's position relative to the sun (see Figure 7). A visual comparison of the vehicle position with respect to overhead lamps indicates the energy into the vehicle will be different. For an ASTM-E-892 incident radiation source, VSOLE predicts the indoor transmitted power to be 13% less than outdoors at the windshield. The transmitted and absorbed powers are shown in Table 3. The absorbed power is 9% less for the indoor case. The windshield area normal to the source determines the amount of incident radiation, and in the case of the indoor lamps, there is less area normal to the source. The IP and windshield are cooler because less energy is transmitted and absorbed indoors. Other factors that may affect the windshield temperature are the characteristic of the wind (varying magnitude-random direction outdoor versus constant velocity-constant direction indoor) and the uniformity of the lamp radiant flux on the windshield.

Table 3. Windshield Transmitted and Absorbed Power with an ASTM-E-892 Source at Outdoor and Indoor Solar Source Positions

	Azimuth (deg)	Zenith (deg)	Transmitted (W)	Absorbed (W)
Outdoors	205	41	400	498
Indoors	180	0	349	453

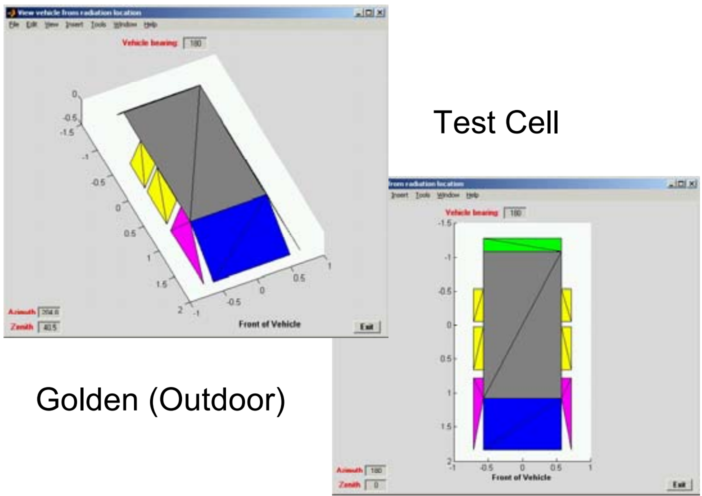

Figure 7. Vehicle Position Relative to Solar Source

The IR lamps result in cooler windshield temperatures and hotter IP temperatures than metal halide lamps (Figure 6). Under IR lamps, the windshield is 0.5°C warmer than the outdoor test; the IP is 13.8°C cooler. The spectral characteristics of the lamps account for this. The solar management glass in the windshield is designed to absorb in the IR region. The IR lamps have more energy in the IR region (Figure 1), so the windshield will absorb more energy. This results in higher glass temperatures and lower IP temperatures.

Figure 8 shows the vehicle's interior average air temperature (an average of the air temperatures at the foot and breath levels for the driver, passenger, left rear, and right rear) from the outdoor and indoor tests. The temperatures compared well, but were slowly increasing at the end of the test. Running the test until steady state was attained would have been preferable, but time constraints precluded this. The vehicle heated with IR lamps had an air temperature 0.7°C hotter than the outdoor vehicle and the metal halide lamps resulted in air temperatures 1.5°C hotter than outdoors because the overhead lamps radiated all the windows. Outdoors, the left side and rear windows were shaded from the incident radiation by the roof. The overall solar power transmitted through all the windows was 556 W outdoors and 607 W indoors according to a VSOLE simulation. This results in 9% more energy entering the vehicle cabin and higher air temperatures indoors. The interior measurement locations that were shaded compared well to the respective outdoor test data. The driver seat temperature is the average of the seat cushion and back; the average trim temperature is the average of the door trim at the driver, passenger, left rear, and right rear locations. The driver seat was 1.4°C cooler with the metal halide lamps and 2.3°C cooler with the IR lamps than the outdoor test. The average trim temperatures were slightly warmer indoors.

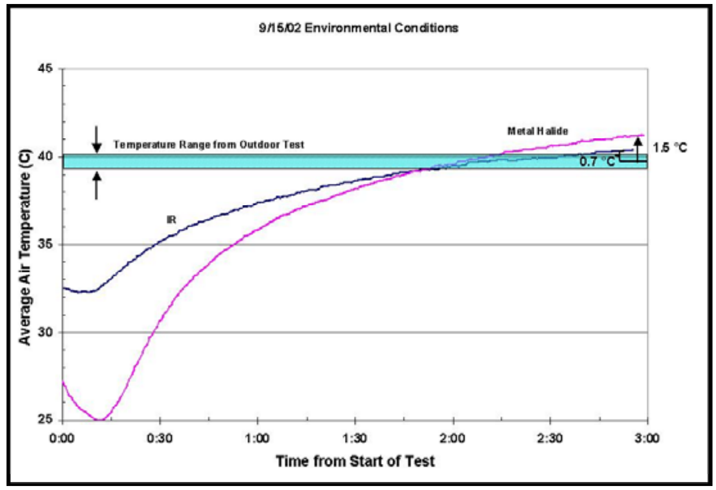

Figure 8. Average Air Temperature

The data from the metal halide lamps compared with 9/2/02 outdoor testing data show similar trends and are not presented here.

CONCLUSION

Steady state indoor vehicle thermal soak tests were performed using data from actual outdoor test conditions. Vehicle temperature measurements from indoor test cells were compared to measurements taken outdoors. Indoor test results show that the windshield was 3.4°C cooler and the IP was 4.8°C cooler using metal halide lamps. Additionally, the driver seat was 1.4°C cooler and the roof 20.1°C hotter. The trim temperatures were approximately the same. The differences are thought to be due to the use of a large array of lamps (a planar source) versus the sun (a point source). Specifically, in the outdoor test, the roof exchanges radiant heat energy with the cool sky; in the test cell, it exchanges radiation with hot lamp bulbs and associated structure. In the outdoor test, the sun location and vehicle geometry determine the incident solar radiation on each window. Some windows are completely shaded from incident solar radiation due to the position of the sun. In the indoor test, the overhead planar lamp array results in a different amount of incident radiation on all the windows even though the global horizontal flux on the hood matches the outdoor test.

The difference between the spectral irradiance characteristics of the sun and test cell lamps also causes temperature differences. The vehicle glass absorbs more energy from the IR lamps, resulting in higher windshield temperatures and lower IP temperatures. Although the spectral irradiance of the metal halide lamps approximates the sun more closely than the IR lamps, there were significant deviations between vehicle temperatures recorded in the test cell and outdoors.

Based on these results, a vehicle thermal soak can be performed in a test cell to heat the passenger compartment in preparation for a cooldown test or SCO3 emissions test. However, a test cell should not be used to determine vehicle skin temperatures or maximum component temperatures. Also, caution should be taken in using test cell solar lamps to assess advanced solar reflective glazings because the incident angle, projected area, and spectral characteristics will not represent actual solar conditions.

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