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# EFFECTS OF IRR GLAZING ON RADIANT HEAT AND THERMAL COMFORT FOR ON-ROAD CONDITIONS

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16. Abstract

We tested the hypothesis that reducing radiant heat by the application of an infrared-reflective (IRR) treatment will allow occupants to maintain the same level of comfort in a warmer vehicle cabin. Participants were passengers in a mid-sized sedan that was driven for 46 minutes along a 41.5-mile route. Each participant experienced two drives: one with infrared-reflective (IRR) film applied to all glazing surfaces of the vehicle, and one with no IRR treatment applied. Every two minutes, participants were asked to rate their thermal sensation at five body locations and to indicate whether, overall, they felt too hot or too cold. Cabin air temperature in the vehicle was raised or lowered depending on participants' responses.

Although the IRR treatment did not have a statistically significant effect on the air temperature that participants found comfortable, the trend was in the expected direction, and a decrease in the average time required to reach thermal comfort was observed. IRR-treated drives were also associated with reductions in air conditioner compressor use and fuel consumption.

While the physical effects in this study confirmed findings of previous studies, data concerning the relationship between radiant heat and comfortable air temperature were more complicated and inconclusive and would benefit from further research.

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# CONTENTS

# INTRODUCTION

Based upon geographical location, time of year, and ambient weather conditions, the air temperature inside a car that has been sitting in the sun often exceeds 100° F (37.8° C), and in many cases can reach as high as 140° F (60° C) (Hymore, Tweadey, & Wozniak, 1991; Moyer, 1995; Young & Van Esso, 1989). This greenhouse-like phenomenon carries implications not only for occupant comfort, but also for issues such as fuel economy and engine size—higher temperatures result in increased demands on the vehicle's air conditioning (A/C) system. Because as much as 70% of the total solar heat load in a vehicle arises from sunlight incident through glazing areas (Kai & Kawasaki, 1985, as cited in Roessler & Heckmann, 1992), automotive glazing manufacturers have sought to develop materials that can reduce solar heat load. One such material is infrared-reflective (IRR) glazing, which, as the name suggests, reflects the infrared portion of solar radiation while still transmitting most visible light.

The application of IRR treatment on automotive glazing has been associated with decreases in cabin air temperature and surface temperatures during soak-tests (prolonged stationary exposure to the sun), but less is known about how to quantify potential improvements in occupant thermal comfort and fuel economy (Devonshire & Sayer, 2002). In the first of a series of related studies, Devonshire and Sayer (2003a) examined the effect of IRR treatment on occupant thermal comfort during a stationary vehicle cool-down. Four otherwise identical sedans had an IRR film applied to differing sections of the vehicles' glazing. Two independent variables were manipulated: A/C output (two levels) and IRR film placement (four levels–windshield and front side windows, windshield only, front side windows only, and no IRR film applied). Consistent with past research, the IRR film significantly decreased interior air temperatures. As expected, the magnitude of this effect was greatest in those conditions in which larger surface areas of film were applied. Presence of the film was also associated with a significant increase in subjective assessments of thermal comfort during vehicle cool-down, an increase that appeared at least partly independent of the air temperature inside the vehicle. That is, for any given air temperature, subjective ratings of thermal comfort were better in those conditions in which the IRR film was applied.

This last finding is consistent with established thermal comfort models that include additional factors other than air temperature (e.g., Fanger, 1970; Gagge, Nishi, & Gonzalez, 1972 as cited in Parsons, 2003; Hodder & Parsons, 2001a, 2001b as cited in Parsons, 2003), and points in particular to the possible role of radiant heat in influencing thermal comfort. However, Devonshire and Sayer (2003a) included no direct measure of radiant energy, making it difficult to quantify a relationship between air temperature and radiant heat. Further, the study examined subjective comfort ratings in transient cool-down conditions (in which participants entered a hot vehicle and immediately turned on the A/C), but not in steady-state conditions (i.e., conditions more closely resembling driving on the road, in which the climate remains relatively unchanged).

In a follow-up study, IRR films were systematically applied to the driver-side window of an outdoor stationary vehicle (Devonshire and Sayer, 2003b). In this study, solar irradiance was measured in addition to cabin air temperature. In Phase 1, air temperature was controlled (at one of two steady-state levels) while participants rated their thermal comfort under different levels of IRR treatment exposure. In Phase 2, air temperature was adjusted according to participants' responses. Results in Phase 1 showed that the IRR treatment improved thermal comfort on the left forearm, which was exposed to direct solar irradiance, but its effect on whole body thermal comfort did not reach statistical significance. In Phase 2, participants indicated that they were comfortable at a higher air temperature (mean of 2.5° F [1.4° C]) with the IRR treatment than in the untreated condition. The results supported the conclusion that IRR treatment's effect on direct radiant heating of the skin affects subjective ratings of comfort and allows occupants to maintain the same level of comfort in a warmer vehicle cabin.

The present study was designed to further explore the relationships of radiant heat, air temperature, and thermal comfort under a wider range of conditions. Whereas the authors' previous studies used stationary vehicles and were limited to relatively short radiant heat exposure, a dynamic driving scenario was employed for the present study. Participants were passengers in a mid-sized sedan that was driven along a 46-minute, 41.5-mile route. Each participant experienced two drives: one with IRR treatment applied to all of the vehicle's glazing, and one with no IRR treatment applied. It was hypothesized that in order to maintain the same level of comfort, participants would require a lower air temperature in the untreated condition than in the treated condition. It was also hypothesized that the IRR treatment would result in decreases of A/C compressor usage and fuel consumption.

# METHOD

## Participants

There were 12 paid participants.  Six were in a younger age group (between 20 and 35 years old with a mean age of 27.8 years) and six were in an older age group (between 55 and 70 years old with a mean age of 64.1 years).  The groups were balanced for gender, and all participants were licensed drivers.  Participants were required to wear shorts, a white T-shirt, socks, and shoes (no open-toed shoes or sandals).  During their pre-test instruction, participants were not told which aspects of the vehicle environment would be manipulated.

## Independent variables

The independent variable was IRR treatment.  The vehicle was either untreated (no film applied) or treated (IRR film applied to the inside surface of all glazing areas).  Specifications of the film and the method of application are described later in this section.

## Dependent variables

### *Objective measures.*

*Solar irradiance*.  Solar irradiance was measured at three sites: the roof of the vehicle, the passenger-side interior window ledge, and the dashboard (passenger-side).  The sensor on the vehicle's roof measured "ambient irradiance," or the sum of direct solar irradiance and diffuse sky irradiance.  The sensors inside the vehicle measured "net irradiance," or irradiance reaching the participant (after reductions from the vehicle's glazing and the IRR treatment).  Throughout the remainder of this article, net irradiance measured from the dashboard is referred to as "net irradiance-front," while net irradiance measured from the side window is referred to as "net irradiance-side."  Ambient and net irradiance were measured at a rate of 1 Hz.

*Air temperature*.  Air temperature was also measured at 1 Hz and consisted of an average measurement of eight sites within the vehicle cabin: on the ceiling directly above the passenger, two sites on each side of the passenger seat, directly behind the participant's head, near the brake pedal, and on the passenger-side dashboard trim.  The air temperature was raised or lowered every two minutes in response to the participants' indicated thermal comfort.

*A/C compressor state*. The on/off state of the vehicle's A/C compressor was measured at 1 Hz.

*Subjective measures.*

*Thermal comfort.* Participants were asked to give periodic ratings of their thermal comfort. Thermal comfort was measured with a modified version of a numerical rating scale suggested in ISO 10551 (1993). The scale ranged from negative four ("very cold") to positive four ("very hot"), with a midpoint of zero ("comfortable"). Each participant was shown a copy of the scale during his or her instruction, and an additional copy was mounted inside of the vehicle for participants to reference. Participants used this scale to give five thermal comfort ratings: right forearm, left forearm, right upper leg, left upper leg, and feet.

*Hot/cold response.* In addition to comfort ratings, participants were asked at two-minute intervals to indicate whether they were too hot or too cold.

## Materials and setup

One four-door sedan was used in the experiment. The vehicle's glazing and A/C system were original equipment. The vehicle's A/C system included two control mechanisms: a 20-position detented control for the temperature of the output air and a four-position detented control for fan speed. All A/C vents were directed away from the passenger seat. The passenger-side headrest was removed (to simplify air temperature measurement).

In addition to a copy of the subjective rating scale (mounted to hide the A/C controls from the participant's view), a wooden bar was installed near the front of the passenger-seat so that participants could extend both arms while in the vehicle (to experience direct radiant heating of the skin). The participants' arm positions were thus roughly similar to those of a driver gripping a steering wheel. This is illustrated in Figures 1 and 2, which also show how the interior of the vehicle was instrumented. The figures show the location of air temperature and solar irradiance sensors inside the vehicle. Insulated type-T thermocouples (shielded from radiation) were used to measure air temperature while silicon pyranometer sensors were used to measure solar irradiance. All pyranometers were level to gravity. The relative spectral response of the pyranometer sensors (as compared to the total solar spectrum) is reported in Devonshire and Sayer (2003b). A data logger and laptop computer were used to collect and store all objective measurements.

Figure 1. Interior of the vehicle as viewed from the passenger seat.

Figure 2. Interior of the vehicle. Circles highlight thermocouple and pyranometer positions.

The treatment consisted of two different grades of aftermarket IRR film (one grade of film had a higher IR rejection and slightly lower visible light transmission than the other grade). Table 1 lists the specifications of both grades of film. The specifications were provided by the manufacturer and represent the films as applied to the inside of double-strength 1/8 in. (3.17 mm) clear monolithic annealed glass. The Grade A film was applied only to the windshield of the vehicle, while the Grade B film was applied to the remainder of the vehicle's glazing. All film was professionally applied to the interior surfaces of the vehicle's glazing.

Table 1
IRR film specifications.

| | Grade A | Grade B |
|---|---|---|
| Visible light transmittance: | 77.0% | 70.0% |
| IR rejection: | 77.1% | 94.0% |
| UV rejection: | 99.0% | 98.0% |

### Procedure

The experiment was performed outdoors on freeways and local roads around the city of Ann Arbor, Michigan. Experimental sessions were conducted on sunny to mostly sunny days between July 29 and September 11, 2004. Each session consisted of a 45-minute drive, during which the participant sat in the passenger seat and periodically rated his/her thermal comfort. For each session, two experimenters were required: one to drive the vehicle and adjust the vehicle's A/C output temperature, and one who sat in the back seat of the vehicle to record subjective responses and monitor objective data collection. With the exception of three individual sessions, the driver of the vehicle was always the same person. This was done to minimize any possible effects that differences in driving style between drives (e.g., acceleration, speed, etc.) may have on parameters such as fuel consumption or cabin air temperature.

Each participant experienced two drives conducted on separate days: one in which the vehicle was treated with IRR film on all glazing surfaces, and one in which the vehicle was untreated (no IRR film). There was an average of 24 days between the first and second drives, and each participant began their respective drives at the same time of day (10:00 a.m., 11:15 a.m., or 12:30 p.m., balanced across subjects). The order of drives (untreated followed by treated or vice versa) was balanced between subjects with one exception: An extra participant was run to replace a participant whose drives had been characterized by low ambient irradiance. Because the film could not be removed and reapplied, the replacement participant experienced the opposite presentation order from the person he replaced.

Approximately 15 minutes before each drive, the vehicle cabin was heated to the desired air temperature range (95° to 100° F [35° to 37.8° C]) by using two portable electric heaters. The average starting air temperature for the treated condition was 97.2° F (36.2° C) with a standard deviation of 2.7° F, while the average starting air temperature for the untreated condition was 98.9° F (37.2° C) with a standard deviation of 4.7° F. Although the treated condition began at a slightly lower air temperature, a paired-samples t-test showed no significant difference between the two conditions.

When the vehicle had reached the desired air temperature range, the first experimenter remained in the back seat of the vehicle with all doors closed while the second experimenter (the driver) led the participant from the UMTRI building (a controlled climate) to the vehicle. The participant was instructed to approach the passenger-side door, but to wait for the driver to signal before entering the vehicle. When the driver signaled, both the participant and the driver entered the vehicle simultaneously and closed the doors as quickly as possible. This procedure was performed in order to minimize climate change inside the vehicle.

Once inside the vehicle, the participant was asked to fasten the seat belt and to place his/her hands at predefined locations on the wooden bar in front of him/her. The participant was then asked to give an initial set of five thermal comfort ratings before the vehicle was started (right forearm, left forearm, right upper leg, left upper leg, and feet). After the initial ratings, the driver started the vehicle and began to drive. (The vehicle’s A/C was always “on” so that it would start as soon as the vehicle was started; the fan speed was always at the highest setting.)

Throughout the drive, the same set of five thermal comfort ratings was taken every two minutes. In addition, after each set of ratings the participant was asked to indicate whether he/she was “too hot” or “too cold.” This was a forced-choice task; the participant was not allowed to give answers such as “perfect” or “comfortable.” If the participant indicated that he/she was too hot, the driver lowered the air temperature by adjusting the vehicle’s A/C output temperature. If the participant indicated that he/she was too cold, the experimenter raised the air temperature using the same method. Each drive began with an A/C output temperature setting of 10 (the midpoint out of 20 possible control positions), and adjustments were always made in one-unit steps. This resulted in an average temperature change across all participants of 1.5° F between each two-minute interval (with a standard deviation of 1.2° F). The specific adjustment to the A/C controls could not be detected by the participant, who could only see the driver reaching toward the instrument panel after each set of ratings.

The route was identical across all participants and treatment conditions (a map of the route is in the appendix). For the first half of the route, the vehicle was driven primarily north along a along a local two-lane freeway, with a four-minute portion traveling west and two or three minutes on local roads. While the vehicle was driven north, the sun was generally in the northeast (i.e., facing the passenger side of the vehicle). Halfway through the drive, the vehicle exited and re-entered the freeway, traveling south along the same stretch of road. During this half of the drive, the sun was primarily facing the driver side of the vehicle.

The driver was instructed to drive as consistently as possible (i.e., similar acceleration, speed, and lane changes across all drives). The driver used a stopwatch to time each drive as close to 46 minutes as possible; occasionally the driver needed to adjust his speed in order to achieve the correct timing. Although the speed of the vehicle was not measured, freeway speeds ranged from an average of 60 to 70 mph (96.6 to 112.6 km/hr).

At the end of each drive, the vehicle was returned to its starting position and the participant was asked to give one final set of thermal comfort and hot/cold ratings. The engine was then turned off, and the participant was led back to the building.

## RESULTS

### Objective measures

#### *Ambient irradiance*

The average ambient irradiance across all conditions was 661.1 W/m$^2$ with a standard deviation of 170.7 W/m$^2$. This represents a relatively low average (solar irradiance on clear days often exceeds 1000 W/m$^2$) and high variability. This most likely resulted from a combination of the geographic location, times of day, and unique uncontrolled seasonal conditions during the experiment. For example, although sessions were run on sunny, to mostly sunny, days, the months of July through September were unusually mild and cloudy. Consequently, there were some instances of scattered cloud cover and/or haze during the experiment.

Variability in ambient irradiance was not associated with whether the vehicle had IRR treatment applied; the average ambient irradiance over all untreated drives was 660.5 W/m$^2$ (*SD* = 156.8) while the average over treated drives was 661.6 W/m$^2$ (*SD* = 183.8).

### *Net irradiance*

Recall that net irradiance was a measure of the intensity of solar radiation that the participant actually was exposed to, after reductions from either the vehicle's glazing alone (untreated) or the combination of glazing and IRR treatment. In part because the average ambient irradiance was relatively low, net irradiance never rose above 400 W/m$^2$. The average net irradiance-front over all untreated drives was 317.2 W/m$^2$ (*SD* = 99.2), while the average net-irradiance-front over all treated drives was 240.1 W/m$^2$ (*SD* = 88.7), a reduction of 24.3%. The average net irradiance-side over all untreated drives was 238.7 W/m$^2$ (*SD* = 130.6), compared to 137.9 W/m$^2$ (*SD* = 72.6) over all treated drives, a reduction of 42.2%. To determine whether the reduction of irradiance caused by the IRR treatment was statistically reliable, a linear mixed-effects models analysis was performed on net irradiance-front and net irradiance-side, controlling for any differences in ambient irradiance. Factors included IRR treatment and time. The effect of IRR treatment on irradiance was significant, $F(1, 91.8) = 90.6$, $p < .001$ for net irradiance-front, and $F(1, 116.8) = 147.9$, $p < .001$ for net irradiance-side.

One would expect net irradiance to change as a function of both ambient irradiance and angle of incidence (i.e., whether, and at what angle, the glazing surface in question was facing the sun, and how intense solar radiation was at any given moment). Figures 3 and 4 help illustrate these relationships. Both figures compare the average (collapsed across all participants) ambient and net irradiance between the untreated and treated conditions over time. Net irradiance-front measures are shown in Figure 3 while net irradiance-side measures are displayed in Figure 4. The vertical line near the Y-axis represents the point in time at which the vehicle was started and the drive began.

The effect of the direction of travel can be seen particularly in Figure 4. Vertical lines were added in this figure to indicate when the vehicle began facing in a new direction. Note the larger effect of the IRR treatment on irradiance reduction during the first half of the drive, when the vehicle was traveling primarily north. During the second half of the drive, the passenger side was generally facing away from the sun, and the effect of the IRR treatment was smaller.

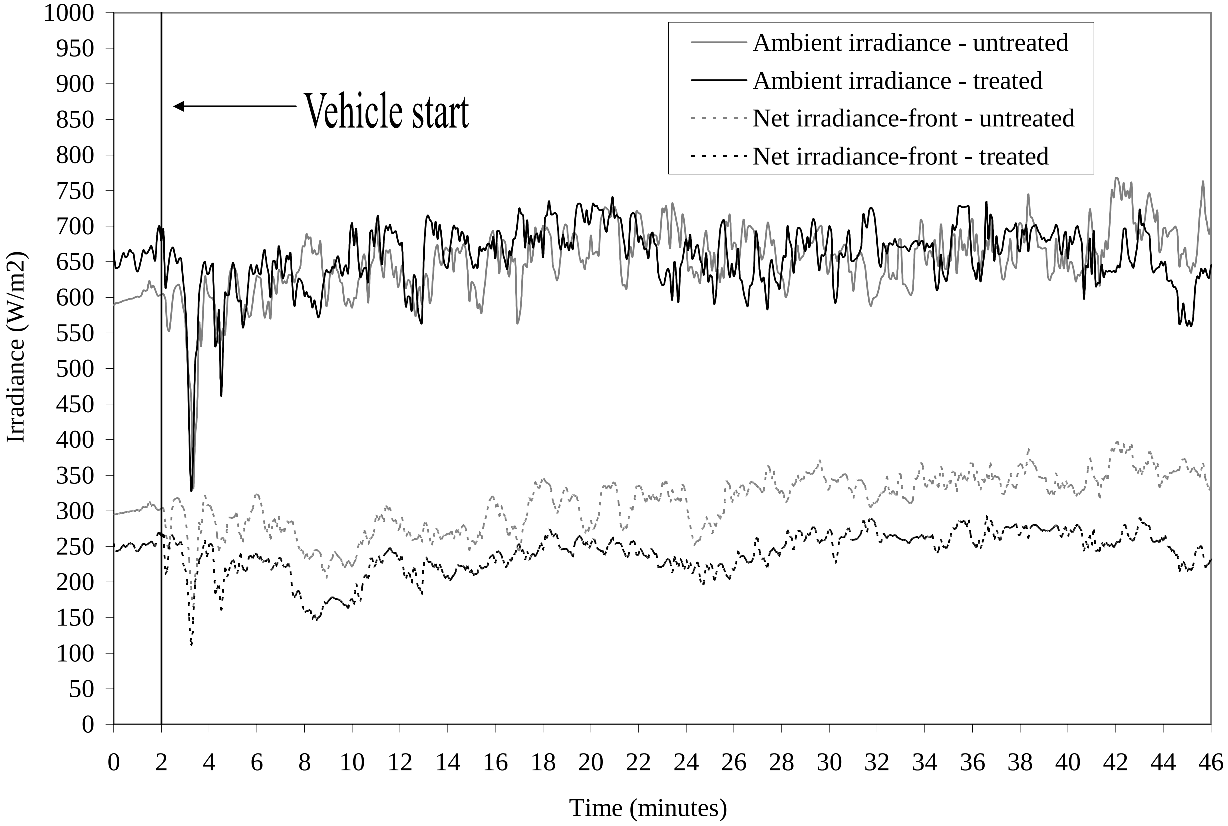

Figure 3. Treated and untreated ambient and net irradiance-front over the course of the drive.

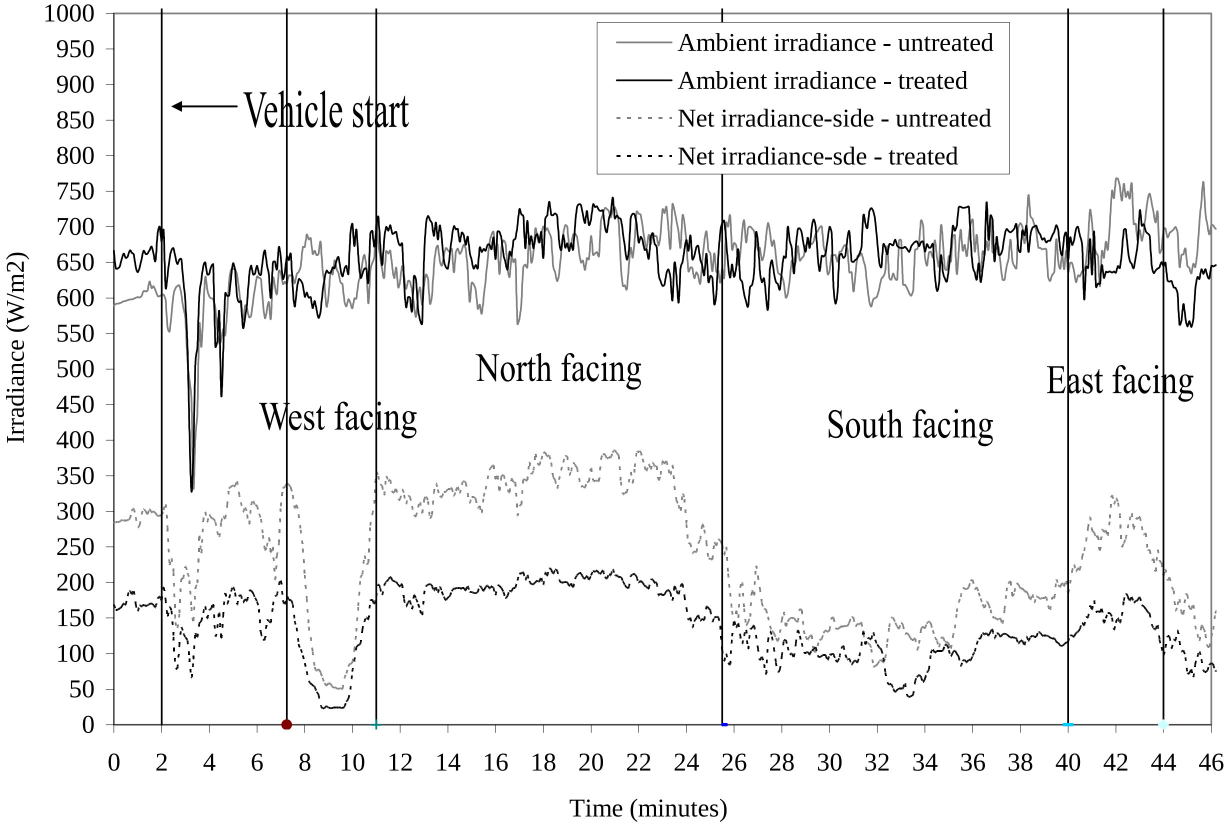

Figure 4. Treated and untreated ambient and net-side irradiance over the course of the drive.

*Air temperature*

Figure 5 compares cabin air temperature between the untreated and treated conditions as a function of time (collapsed across all participants). While the difference in initial temperature (before the vehicle's engine was started) between conditions was not significant, the difference in temperatures at vehicle start time (indicated by the vertical line next to the Y-axis in Figure 5) was significant, $t(11) = 3.3$, $p < .05$. The untreated vehicle was started at an average of 97.0° F (36.1° C) while the treated vehicle was started at an average of 92.7° F (33.7° C), a difference of 4.3° F (2.4° C). This represents the period of time in which the participant had opened the door of the vehicle, entered, shut the door, and gave initial thermal comfort ratings. The greater heat loss in the treated vehicle during this time may have been due to a lower thermal mass (i.e., a less "soaked" vehicle). As Figure 5 illustrates, the difference in air temperatures between treatment conditions persists until roughly 20 minutes into the drive, when the participants' desired air temperature begins to equalize.

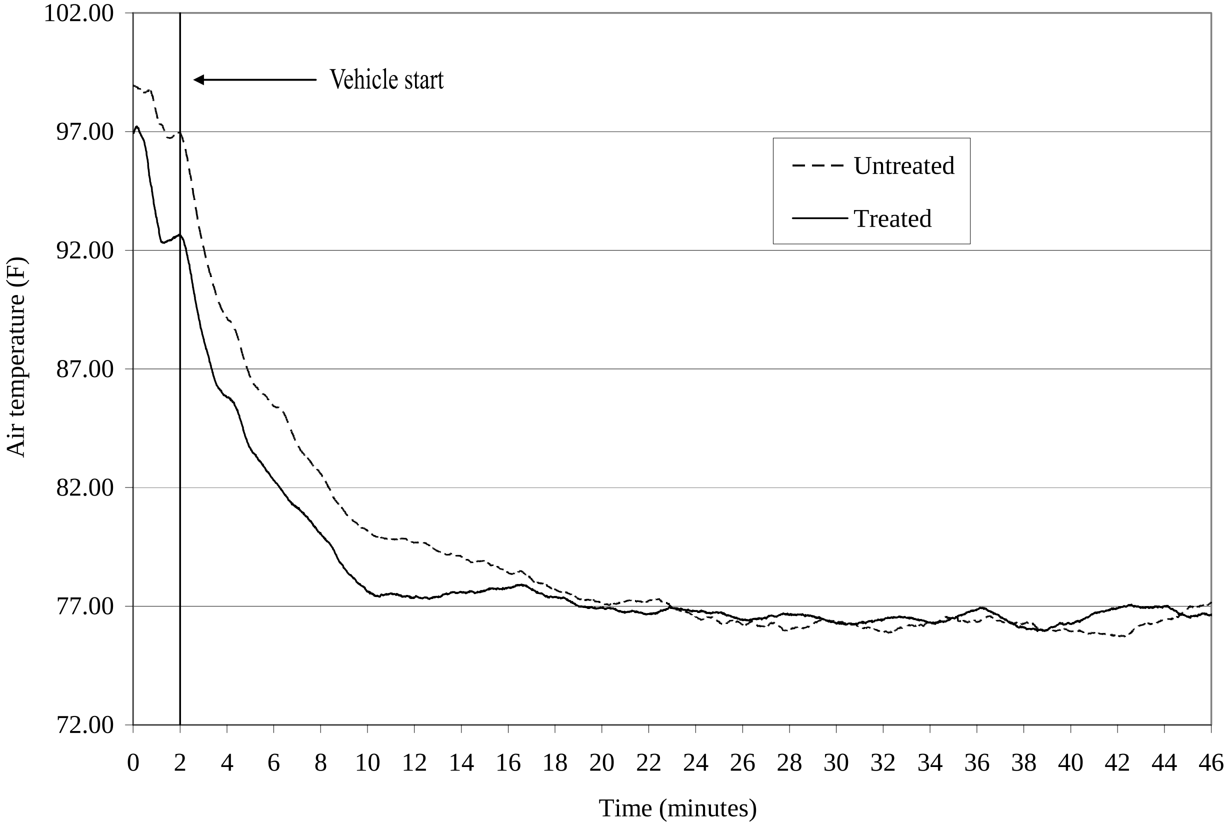

Figure 5. Average cabin air temperature over time.

From Figure 5, it can be observed that the drives had two main phases: a cool-down from the initial air temperature (during which participants continually indicated that they were too hot), and a relatively steady-state period (during which the participants presumably found a comfortable air temperature and maintained that temperature by oscillating between indications of being too hot or too cold). Figure 5 would also seem to suggest that there was no clear difference in the steady-state comfortable air temperatures between the IRR-treated drives and the untreated drives. To examine this question more closely, a logistic regression was performed to determine the air temperature at which each participant was 50% likely to say that he/she was too hot or too cold. This was inferred to be the "comfortable" air temperature for each participant for that particular drive. When each participant's comfort point was established, a repeated-measures analysis of variance (ANOVA) was performed that included the within-subjects factor of treatment and the between-subjects factors of age group and gender. There was no significant main effect of treatment on participants' comfortable air temperature, although the data followed the expected trend. Participants were comfortable at an average air temperature of 76.0° F (24.4° C) in the untreated condition and 76.6° F (24.8° C) in the treated condition.

*A/C compressor state*

For each drive, the compressor was measured from the time the engine started until the vehicle was turned off. Because of the initial air temperature difference between treated and untreated drives (treated drives began at a lower air temperature), one might expect to see an A/C compressor bias during the cool-down phase of the drives (i.e., more cooling of the untreated vehicle cabin was required during cool-down). For this reason, A/C compressor state was analyzed separately for cool-down and steady-state periods. Steady-state was defined as the first point in time at which the average "comfortable" air temperature was equal between the two treatment conditions (approximately 20 minutes into the drive).

Table 2 shows the average number of minutes that the A/C compressor was on for each drive. Both treatment conditions and phases of the drive (cool-down vs. steady-state) are compared. For both phases of the drive, there was a decrease in A/C compressor use during drives with IRR treatment. Paired-samples t-tests showed these decreases to be significant, $t(11) = 3.3$, $p < .05$ (cool-down) and $t(11) = 2.4$, $p < .05$ (steady-state). As Table 2 indicates, during the entire drive the compressor was on for an average of almost six minutes less in the treated condition, a reduction of almost 17%.

Table 2
Average minutes of A/C compressor use per drive.

| Condition | Cool-down | Steady-state |
|---|---|---|
| Untreated | 15.2 | 18.5 |
| Treated | 12.5 | 15.5 |
| Difference | 2.7 | 3.0 |

*Fuel consumption*

The method of measurement for fuel consumption was somewhat crude: To gain a general sense of how much fuel was consumed after each day—there were usually a total of three sessions per day—the vehicle was refilled using the same pump from the same gas station. Using the slowest automatic setting, the tank was allowed to fill to its natural cut-off point. Receipts noting the number of gallons purchased were saved and tabulated. This means of measuring the consumption of fuel, while not ideal, may provide a general idea of whether less fuel was used during the drives with IRR treatment. Drives from 11 of the 12 participants were averaged (there was missing data from one participant's drive). The average fuel consumption for untreated drives was 1.48 gallons while the average consumption for treated drives was 1.39 gallons. A paired-samples t-test showed this difference to be marginally nonsignificant, $t(10) = 1.9$, $p = .09$.

### Subjective measures

*Ratings at each body location*

Because participants had indirect control over the air temperature in the vehicle cabin, one would not necessarily expect to see significant differences in thermal sensation ratings at each body location between treatment conditions. Each participant's ratings were averaged from his/her first reversal of hot/cold opinion to the end of the drive (representing each participant's steady-state period). While ratings in the treated condition were consistently lower (cooler), paired-samples t-tests showed no significant differences.

### *Hot/Cold response*

On average, participants in the treated condition took less time to make their first reversal from “too hot” to “too cold” (ten minutes in the treated condition vs. 12 minutes, 50 seconds in the untreated condition). This is not surprising considering the lower initial air temperature in the treated condition; a lower initial air temperature would predictably lead to a decrease in the time required to reach thermal comfort.

# DISCUSSION AND CONCLUSIONS

The IRR treatment was associated with a decrease in A/C compressor use, a decrease in the average amount of fuel consumed during each drive, and a decrease in the time required to reach thermal comfort. These findings are consistent with previous research on the physical effects of adding IRR treatment to a vehicle's glazing (see, for example, Devonshire and Sayer, 2002, for a review of experimental work in this area), and suggests clear benefits from the application of IRR treatment. Of particular interest is the fact that A/C compressor use was reduced even during steady-state driving, which suggests that the A/C had to "work harder" to achieve the same level of cabin air temperature for moderate levels of solar irradiance. Thus, not only did the A/C not have to achieve as much initial cooling in the IRR-treated vehicle, but there was continually less strain placed on the A/C throughout the drive.

While these physical effects of adding IRR treatment are important, the present study was designed to test a hypothesis regarding the relationship between a physical effect (namely, a reduction in radiant heat) and the air temperature at which comfort is reached and maintained. Although it had been hypothesized, a statistically significant effect of treatment was not seen. Most of the discussion that follows will be focused on possible reasons why this was the case.

In Devonshire and Sayer (2003b), a stationary experiment with direct radiant heat coming from only one side of the vehicle, participants were comfortable at an average air temperature of 2.5° F (1.4° C) higher in conditions with IRR treatment. Of the many differences between that study and the present one, it is interesting to compare irradiance levels between studies. The average ambient irradiance that participants in Devonshire and Sayer (2003b) experienced was 795.9 W/m$^2$ (*SD* = 179.8), compared to 661.1 W/m$^2$ (*SD* = 170.7) in the present study. It is also interesting to compare the untreated net irradiance values from that study to the untreated net irradiance-side values from the present study, as they represent the exact same measure (the same vehicle and sensor were used, although the sensor was on the front driver-side window ledge for Devonshire and Sayer, 2003b, and on the front passenger-side window ledge for the present study). Participants experienced an average of 404.7 W/m$^2$ in Devonshire and Sayer (2003b) compared to 238.7 W/m$^2$ in the present study. That is, participants' *untreated* net irradiance in the present study was, on average, less than the average *treated* net irradiance (for one layer of IRR film) in Devonshire and Sayer (2003b). One reason an effect of IRR treatment on comfortable air temperature was not seen in the present study may have been the lower levels of radiant exposure largely associated with unseasonably cloudy conditions during testing.

Variability in ambient irradiance during the drives may have also played a role in the absence of a statistically significant effect of IRR treatment on comfortable air temperature. In many instances, participants experienced a much higher level of cloudiness during one drive than the other. Figure 6, for instance, shows one example of this. The figure shows ambient irradiance data from one participant, and illustrates the much larger variability in ambient irradiance during the untreated drive compared to the treated drive.

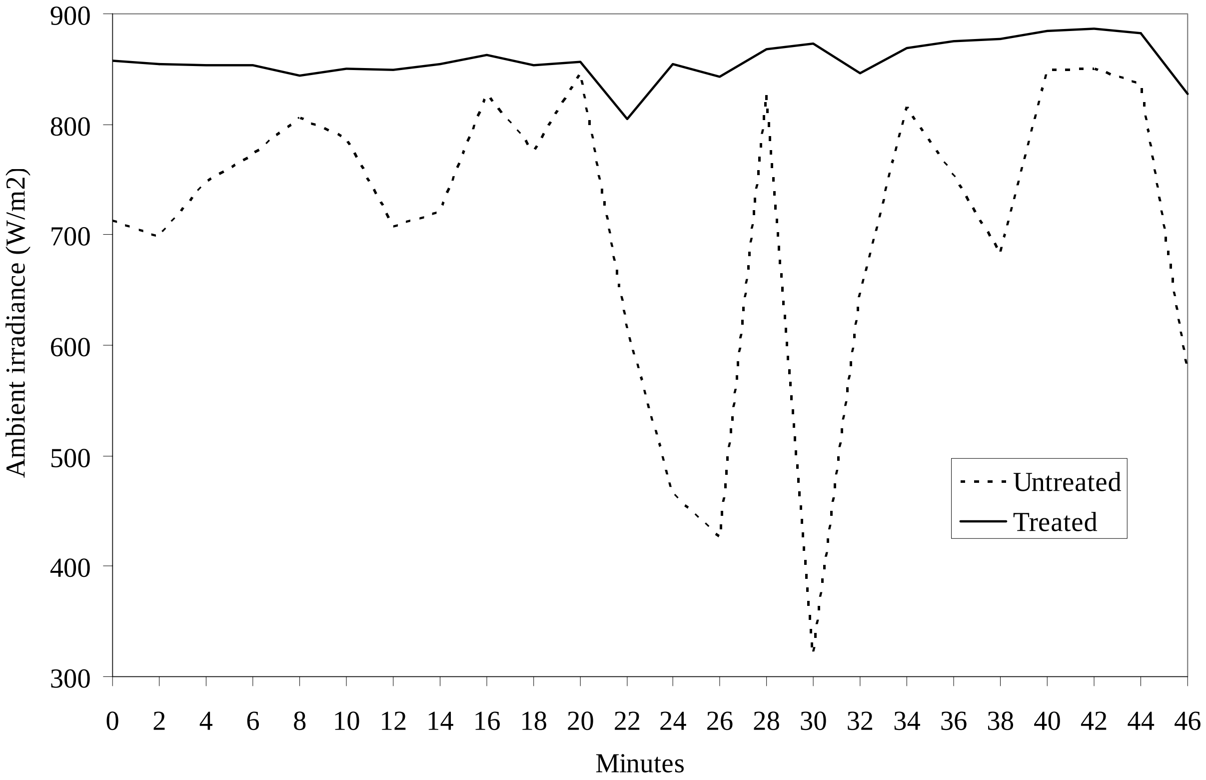

Figure 6. Ambient irradiance during the treated and untreated drives for one participant.

In addition, recall from Figure 4 that the first half of the drive was associated with a larger effect of IRR treatment on the net irradiance-side measure because that side of the vehicle was facing the sun. One unfortunate circumstance of this study was the fact that that period of the drive also at least partially corresponded to the cool-down phase, when most participants were still too hot. By the time most participants reached a comfortable air temperature, irradiance hitting the passenger-side window was lower and there was not as large of an effect of IRR treatment.

While the results of the present study confirmed previous research on the physical effects of adding IRR treatment to a vehicle’s glazing, our central hypothesis was not supported. The lack of a statistically significant effect of IRR treatment on comfortable air temperature seems to conflict with results from Devonshire and Sayer (2003b) and is therefore inconclusive. Differences in method between the two studies may account for the lack of an effect: For instance, the present study employed a dynamic driving scenario in which there were more confounding variables. Future research is needed to further isolate and explore the relationship between radiant heating of the skin and comfortable air temperature in a vehicle.

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# APPENDIX

## Map of Route

**Subject Instructions**

Thank you again for your participation in this study.  Today's procedure will work in the following way:

At the beginning of today's drive, the experimenter will lead you outside to the car in the parking lot.  Only when the experimenter prompts you to enter the car (not before), please open the front passenger door and enter the car **as quickly as possible**.  Once you are seated comfortably, you will be asked to put on the seatbelt.  Other than putting on the seatbelt,  you should not make any adjustments to the car's interior.

Before the experimenter starts the car and begins to drive, you will be asked to place your hands on a horizontal wooden bar that is attached to the dashboard in front of you.  Pieces of blue tape will indicate exactly where your hands should be placed.  You will be asked to keep your hands in these locations throughout the entire drive.

You will then be asked to give several ratings of your thermal comfort.  Using this scale (a copy of which will be placed in the car for you to refer to), we will ask you to rate how hot or cold your right forearm, your left forearm, and both of your legs feel.  The experimenter will then start the car and begin to drive.

Every two minutes, the experimenter will ask you to give more ratings of your forearms and legs, and will also ask you to indicate whether, overall, you are too hot or too cold.  Your response cannot be "comfortable" or "just right."  Every time the experimenter asks, you must either say that you are too hot or too cold, even if you are only slightly so.  If you do feel perfectly comfortable, try your best to determine whether you would ideally like it a bit warmer or cooler, and indicate either "too cold" or "too hot" to the experimenter when you are prompted.

You will be asked to rate your comfort and to indicate whether you are too hot or too cold every two minutes for the duration of the drive (approximately 45 minutes).  Do not worry about keeping track of time; the experimenter will prompt you for your ratings.

We urge you again to notify the experimenter immediately if at any time you feel dizzy, light-headed, or otherwise too uncomfortable to continue.  Water will also be available to you before, during, and after your drive.

Before we get started, do you have any questions?