TA-259
LBL-26552

Effects of Glazing and Ventilation Options on Automobile Air Conditioner Size and Performance

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December 30, 1988

This work was supported by the Stratospheric Ozone Protection Program, Office of Program Development, Office of Air and Radiation of the U.S. Environmental Protection Agency under Contract No. DW89933085-01-0, through the U.S. Department of Energy under Contract No. DE-ACO3-76SF00098.

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Executive Summary

Effects of Glazing and Ventilation Options on Automobile Air Conditioner Size and Performance

The Lawrence Berkeley Laboratory has performed a preliminary analysis of the effects of glazing and ventilation on automobile cooling loads and air conditioner capacity limits. The study was accomplished as part of the Environmental Protection Agency's efforts to reduce the release of chlorofluorocarbons into the earth's atmosphere from automobile air conditioners. We investigated the characteristics of standard and sports-model sedans using numerical simulations of the heat transfer processes under static-soak conditions. In addition, an annotated bibliography was created that documents other relevant research relevant to both static-soak and highway driving conditions. These studies and our own results suggest that:

- Glazing is a major contributor to the cooling loads that dictate the size of automobile air conditioners.

- The use of new glazing technology in conjunction with other design features, e.g., ventilative cooling when parked, provides a viable means of reducing cooling system size in many parts of the country.

- Continuing work is needed to perform additional analytical and experimental investigations under highway driving conditions that will document the magnitude of the cooling unit size reduction possibilities.

There are promising new glazing technology options that provide substantial reductions in solar heat gain. Selective glazings are available today that substantially reduce cooling loads. Optical switching films now under development will provide additional solar load control capability in the future. This has important implications in the effort to reduce CFC emissions from the current generation of automotive air conditioners. Improved glazings may lead to lower CFC emissions in the following ways:

- Reduced solar heat gain and lower interior air temperature may lead fewer people to select air conditioning as an option in some climatic regions in the U.S. This will reduce the total number of CFC-charged systems and reduce emissions.

- Smaller air conditioning systems could provide equivalent levels of comfort in cars with improved glazings. Existing CFC-charged systems of smaller capacity could be used, reducing total CFC volume per vehicle in use and ultimately reducing total CFC emissions from leakage or when the cars are scrapped.

- There are few practical alternatives to air conditioning systems of current design as long as the peak cooling capacity must remain high. If the peak cooling power and system size can be reduced, alternative cooling system approaches that reduce or eliminate CFC emissions may become possible. These include:

  (a) hermetically sealed systems with internal electric drives
  (b) lower-pressure systems with reduced leakage and loss
  (c) systems based on different CFC refrigerants with lower ozone depletion
  (d) other innovative cooling systems not based on CFC refrigerants

The selection of one or more of these alternatives will depend on many technical, market, and economic factors. Each, however, depends on our ability to develop new glazing designs and ventilation strategies with substantially reduced cooling loads. This report suggests that this is a challenge that can be met by the automotive and glazing industries.

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1. Introduction

Solar load control is an increasingly important problem to the auto and glass industry because contemporary models are tending to use more highly sloped glazing and the total glass area has been steadily increasing. These trends are a direct result of customer preference as well as the industry's desire to reduce drag and improve fuel efficiency. Increasing slope and area results in much greater solar heat gain, higher interior temperatures, reduced comfort and amenity, increased degradation of interior surfaces, and the requirement of larger air conditioning units. At the same time, engines are being downsized to reduce weight and improve fuel economy and are less able to handle the power drain of the larger air conditioners that are required.

A recent concern to industry and government is the role played by automotive air conditioners as a source of chlorofluorocarbon (CFC) release into the atmosphere. Increased cooling loads will lead to even larger air conditioning units, which will exacerbate this problem. There is a need for technologies and design solutions that substantially reduce air conditioner size so that cooling system alternatives with greatly reduced CFC emissions can be utilized.

Auto and glazing manufacturers and others are actively looking for new glazing technologies to help control solar heat gain, including selective glazings that transmit visible but reject near infrared; angle-selective glazings that reject high-angle sun: switchable glazings that actively or passively change transmittance properties; solar-cell systems that provide forced ventilative cooling; and other techniques of altering glass and vehicle optical and thermal properties.

Air conditioner size is determined by the need to achieve comfort under several different environmental operating conditions. Most obvious is the static-soak situation in which the car sits in the hot summer sun for an extended period of time and the air conditioner is required to cool down the interior. Surface temperatures within a closed vehicle can reach over 93°C (200°F) and the entire thermal mass of the car interior is raised to a high temperature. Glazing can be responsible for over 70% of this peak load condition. When the vehicle is moving, the solar heat gain is still substantial but other thermal conditions change. The air flow over the car surface will reduce the heat buildup, as will the ability to flush the solar load from the space with "cooler" outside air. However, in some climates a large latent cooling load will be added in this air conditioning (AC) mode and over 50% of the load can be due to outside air. Switching to recirculating AC mode reduces the latent load but requires that the AC unit be capable of removing the entire solar load. Thus one can see that control of solar heat gain is crucial to any strategy to reduce cooling loads and air conditioner size.

Until recently there was little interest or effort to control cooling loads. One problem was that the effectiveness of many real or hypothetical solar load reduction solutions has been difficult to evaluate. Some manufacturers used simulation models, but most could not accurately model the detailed transient thermal behavior of the passenger compartment of the car with nonstandard glazings and predict surface temperatures. Field tests in cars with new glazing materials provided some useful data but this testing process was time-consuming and costly, and could not cover all models with all glazing configurations and all climatic conditions. Lack of accurate performance predictions has impeded research on new glazing technology and has also slowed progress toward good technical solutions for fuel-efficient, environmentally safe, comfortable cars. Automotive

engineers are unlikely to downsize air conditioners or switch to much smaller, novel cooling systems without the assurance that new glazing technologies will perform as expected.

This report describes results of our work for the Environmental Protection Agency to clarify the role of glazing relative to other automotive components as a contributor to sensible cooling and air conditioner sizing and to determine the impacts of new glazings and related load control strategies such as adding a ventilation option to AC controls. We first present and discuss results of new numerical simulation studies of the static-soak condition, followed by a literature review of the effects of glazing related to city and highway driving. We analyzed expected hours of operation at peak capacity in several parts of the continental U.S. and then relate automotive air conditioning requirements to population size. This latter work was performed to give insight into air conditioner sizing needs relative to automobile density. We then discuss commercially available and emerging glazing products that can provide the thermal control capabilities discussed in the analysis section.

2. Glazing and Ventilation Performance

a. Solar Spectrum Characteristics

Thermal radiation can be characterized by observing its spectrum, which shows the relationship between energy flux or blackbody emissive power in W/m^2-microns and the wavelength of radiation expressed in microns. Figure 1 shows the spectra associated with solar radiation and several blackbodies at varying temperatures. The thermal radiation spectra can be separated into three distinct regions: (1) ultraviolet (.30-.40 microns); (2) visible (.40-.77); and (3) infrared (.77-100). Near-infrared (.77-2.5 microns) and far-infrared (2.5-100) regions are sometimes treated separately depending on the phenomena being discussed. As seen in Figure 1, solar radiation effects occur almost entirely below 3 microns. In this region, glass is transparent to incident radiation. At longer wavelengths, glass becomes opaque to incident radiation. This is known as the greenhouse effect: short-wavelength solar radiation penetrates exterior glass surfaces and heats interior surfaces that thermally radiate at longer wavelengths that cannot be transmitted back through the glass.

Reference 11 states "Federal law (American Standard Safety Code 261-1938) requires that all glass in passenger automobiles must transmit 70% of the visible light weighted to illuminant 'A'. Illuminant 'A' is a blackbody radiating at 1416°C (2581°F). This is approximately the relative weighting of energy from automobile headlamps. Figure 1 shows the relative energy of the solar spectrum and the weighting of illuminant 'A'. Illuminant 'A' is weighted more heavily in the red region of the spectrum where the solar energy starts dropping off. Therefore, glass with a high transmission in the red and yellow regions of the spectrum and a low transmission in the infrared, blue, and ultraviolet regions can satisfy the legal requirements and control a large part of the solar energy. It is theoretically possible to transmit only 28% of the total solar radiation by this method." The remaining portion of the solar spectrum can be absorbed and/or reflected. Glass research being conducted by the automobile and glass manufacturing companies both in this country and abroad has concentrated on the development of new products that can provide this type of solar control.

b. Static-Soak Conditions

The start-up load on an automobile air conditioning system is determined by the solar load buildup under static-soak conditions. Because of this fact, in a parked car, glazing is the most important determinant of cooling loads. To show the effects of glazing, we performed numerical simulations that document the interior air and dash/seat surface temperatures of a prototypical standard sedan

and a sports model sedan with a highly sloped large rear window. The simulations cover the course of an entire day under soak conditions in Phoenix, Arizona. This analysis was accomplished using a finite difference heat transfer computer simulation program called ESP (Ref. 14). ESP has been used for over 10 years to analyze convective, conductive, and radiative heat flows in buildings. Its algorithms are well tested and have been experimentally verified in test cells and buildings.

Figure 2 shows the two test automobiles. The standard sedan had 2.66 m^2 (28.63 ft^2) of window area distributed in a typical configuration. Overall length, width, and height were 4.34 x 1.65 x 1.16 m (14.24 x 5.41 x 3.81 ft). The sports model sedan had 3.79 m^2 (40.80 ft^2) of glass area. Its dimensions were 4.68 x 1.83 x 1.08 m (15.35 x 6.00 x 3.54 ft). We performed a parametric variation of glazing properties including varying solar transmittance, reflectance, and absorptance. In this way we were able to bound expected performance characteristics for a wide range of glazings rather than concentrating on a few specific glazings. Thus our results are generalizable to most future glazing products.

The simulations were conducted using weather data for a June day in Phoenix, Arizona. Outside air temperature increased during the course of the day from 27°C (81°F) at 8 a.m. to a peak of 40°C (104°F) at 6 p.m. The incident solar radiation on a horizontal surface peaked at 3 p.m. at a value of 1050 W/m^2 (333 Btu/hr-ft^2). The cars were facing due north so that the maximum solar exposure occurred on the rear windows.

Figures 3 and 4 present the interior air temperature variations for the two models. Glazing results are shown for four solar transmittances: 83%, 43%, 23,% and 3% for limiting reflectance and absorptance values. The reflective glazings in our study have a very small absorptance, 5-10%, while the absorptive glazings have a comparable level of reflectance. These glazings should be considered hypothetical and do not represent actual products. A transmission of 83% is a clear glass; a 43% value is indicative of a selective reflective or absorptive glass; 23% represents a special reduced-transmission glazing; and in the case of the very low transmittance, 3%, we are referring to a "privacy glass" that could permit vision out and be either almost totally reflective or totally absorptive. Table 1 shows typical values of these parameters that are in use today in various car models. An ideal glazing with a 70% visible transmittance could have a total solar transmittance of only 28% and the reflectance and absorptance properties would vary within the range of our simulations.

Both car models show the same relative difference for the glazing property variations. The peak interior air temperature for the standard sedan is 62°C (144°F) and occurs at 3 p.m., whereas the sports model peak occurs at both 11 a.m. and 3 p.m. at a value of 69°C (156°F). These values are for the glazing transmittance level of 83%. Using reflective glazing provides a substantial reduction in air temperature as the transmittance is decreased on both cars. In fact, the peak interior temperature can be made the same as the outside air temperature by using an essentially opaque surface. The same is not true, however, for the absorptive glazings. There is a lower limit of effectiveness for such systems because a fraction of the absorbed energy is convected and reradiated into the car. The peak temperature for the 3% transmittance glass with high absorptance in the standard sedan is 51°C (124°F); for the sports model, the limit is 55°C (131°F). These represent reductions of 11°C (20°F) and 14°C (25°F) or about half what can be achieved with the reflective glazings.

Figure 5 presents a summary plot of results from figures 3 and 4 for 3 p.m., which in most instances is the peak solar load condition. Interior air temperature is plotted against solar transmittance for the two glazing extremes. Using such information, we were able to define regions of expected performance for the two car models and obtain immediate insight into what effects configuration changes will have on solar load buildup. The performance difference

between the two glazings increases as the solar transmittance decreases, since this accentuates the difference between the effect of absorbed versus reflected radiation.

Figures 6 and 7 show the dash/seat surface temperature variations for the same conditions as above. We use one curve to represent both surfaces since there was not much variation in the calculated values of each surfaces' temperature. The standard sedan reaches a peak condition at about 12 noon with a temperature of 82°C (180°F) when using the clear glass, while the sports model approaches 110°C (230°F). These surface temperatures are significantly reduced with lower solar transmittance. For the selective glazing, i.e., 43%, the standard sedan peak temperature is reduced to 64°C (147°F). The sports sedan peak is reduced to 81°C (178°F). Unlike the interior air temperature, which varies considerably depending on whether reflective or absorptive glazing is used, the surface temperature variations are approximately the same regardless of glazing type. This is expected since the absorbed component from the glazing is distributed among all surfaces within the cars and thus does not directly affect the dash/seat as is the case with the directly transmitted solar component.

Figures 8 and 9 are presented to give some indication of other auto configuration changes that influence both interior and surface temperatures. We show variations due to interior and exterior surface absorptivities, interior mass, and infiltration/ventilation quantities. The base models used an absorptivity value of 0.4 (which represents a light color for both interior and exterior surfaces), an interior mass value of 84 kg (185 lb), and an air infiltration level of 0 air changes per hour. We parametrically varied these quantities individually using the 83% transmittance glazing configurations. The absorptivities were increased to a value of 0.9; the mass was reduced to zero; and an infiltration of 20 air changes, approximately 23 l/s (48 cfm) for the standard sedan and 28 l/s (60 cfm) for the sports model, was used to simulate either open windows or forced ventilation.

Not surprisingly, infiltration/ventilation has the most pronounced effect on temperature reduction. The base peak interior air temperature condition of 62°C (144°F) for the standard sedan is reduced to 52°C (126°F) and the sports model changes from 69°C (156°F) to 56°C (133°F). These reductions are equivalent, in the case of reflective glass, to those that occur with 43% transmittance glazing, and in the case of absorptive glass, to those reductions that occur using the 3% transmittance. This is true for both car models. Dash/seat surface temperature changes are of the same order of magnitude as the air temperature effects. Even greater surface temperature reductions would be apparent if the ventilated air were blown directly across the hot interior surfaces. The simulations assume the relatively high exterior air temperature characteristic of Phoenix. Lower outside air temperatures more typical of most other parts of the country would improve the ventilation cooling effects.

Our simulations of the static-soak condition are summarized in Figure 10. We show interior air and dash/seat surface temperatures for the sports model sedan using clear glazing with 83% transmittance and no infiltration/ventilation and results using reflective glazing with 43% transmittance with an infiltration rate of 20 air changes per hour. Peak air temperature is reduced from 69°C (156°F) to 49°C (120°F) and peak surface temperature from 110°C (230°F) to 75°C (167°F). These results indicate that a combined use of glazing properties and natural or forced ventilation of exterior air will have the most pronounced effect on solar load reduction.

The benefits of ventilation are enhanced with the use of low-transmittance glazings. Without glazing controls, the solar loads are so high that ventilation alone is not very effective. With reduced glass transmittance, a given ventilation rate becomes a more effective method of lowering interior air temperature. Previous work conducted by other investigators have also indicated that such measures are desirable. For example, references 3, 5, 7, 10, and 11 detail studies where varying glass properties were analyzed, and references 2 and 6 present results on the use of a solar-powered ventilation device in a parked situation. Reference 4 considered varying windshield angles as a way of reducing solar load buildup. We now present results from these studies.

c. Previous Studies of the Static Soak Condition

Reference 3 documents experimental tests on a sports model sedan in which production glass on all surfaces was compared to rear and side glazings coated with special films. The solar transmittances of the two special glazings were 55% and 66%, respectively; however, absorptance properties were 54% and 38%. As a result there was not much interior air temperature difference during either full-day or one-hour soak periods. The largest temperature difference, 14-17°C (25-30°F) was associated with those interior surfaces exposed to direct sunlight. After a one-hour soak with the exterior air temperature at an average value of 39°C (102°F) and solar radiation at a level of 881 W/m^2 (280 Btu/hr-ft^2), the interior air temperature reached approximately 66°C (150°F).

For a full-day soak with the ambient air varying from 31°C (88°F) at 8 a.m. to a peak of 40°C (103°F) at 3 p.m. and the solar radiation peaking at noon at 867 W/m^2 (273 Btu/hr-ft^2), the interior air temperature for the three configurations peaked at 77°C (170°F). This study also presents an interesting comparison of average vehicle breath level temperatures after a one-hour soak for eight different car models: compact, standard, luxury, and sports. Breath-level air temperatures varied from a low of 61°C (142°F) to a high of 69°C (156°F). Ambient conditions were similar to those reported above.

Reference 5 is an analytical study that investigated the size and solar transmittance characteristics of sunroofs. Sunroofs are an increasingly popular option in many new cars. Although not directly related to our work because of the emphasis on sunroof performance, the results do indicate the importance of glass transmission. With an ambient exterior temperature varying from 15.5°C (60°F) at 6 a.m. to a peak of 43.3°C (110°F) and a solar radiation peak of 977 W/m^2 (310 Btu/hr-ft^2) at noon, the peak interior air temperature at 1 p.m. varied from 76°C (195°F) for the case without a sunroof to 93°C (225°F) for a sunroof with an 80% solar transmittance. These are extremely large values and, as discussed below (references 2 and 6), are cause for photovoltaic sunroofs being implemented on some models to introduce forced ventilation.

Reference 7 is an experimental study completed in Japan. Conventional glazing with 49% solar transmittance, 5% reflectance, and 46% absorptance was compared to a newly developed laminated reflective glazing with 43% transmittance, 20% reflectance, and 37% absorptance. After a two-hour soak at 35°C (95°F) ambient temperature at a solar radiation of 767 W/m^2 (243 Btu/hr-ft^2), the car equipped with conventional glazing reached 62°C (144°F). The car using the new glazing peaked at 58°C (136°F). Instrument panel and rear shelf surface temperatures were 5-11°C (9-20°F) lower for the car with the new glazing.

Reference 10 is an analytical and experimental study that was also done in Japan. It documents the performance of ordinary glass, infrared-absorptive glass, and infrared-reflective glass under both static and dynamic conditions for a compact sedan. The characteristics of these glazings are shown in Table 1 with the exception of the ordinary glass. In this study 90% visible transmittance and 84% solar transmittance were used rather than 80% and 76%, as shown in Table 1. After a 40-minute soak at an exterior air temperature of 35°C (95°F) and solar radiation quantity of 807 W/m^2 (256 Btu/hr-ft^2), the interior air temperature was 66°C (151°F) for the ordinary glass, 61°C (142°F) for the absorptive glass, and 56°C (133°F) for the reflective glazing.

In reference 11, soak conditions were experimentally compared using two similar sports-model sedans, one with standard green-tinted glass and the other using a new solar-control glazing that maintains a 70% visible transmittance but has a solar transmittance of only 34%. The glass reflects 45% of the incident solar radiation. After a 60-minute soak at an exterior air temperature of 39°C (102°F) and incident solar radiation of 1041 W/m^2 (330 Btu.hr-ft^2), the interior air temperature of the control car with standard heat-absorbing green-tinted glass was 60°C (140°F). The car with the

new glazing was 49°C (121°F). Cool-down and driving tests were also conducted and are discussed in the next section of the report.

Reference 15 is a recently completed study that examined the feasibility of cardboard and radiant barrier car shades in reducing interior temperatures under soak conditions. It was found that the air temperature was reduced by 8.3°C (15°F) and the dashboard temperature by 22.°C (40°F) when using a conventional cardboard shade. The radiant barrier system provided an additional 2.2°C (4°F) and 4.4°C (8°F) reduction in air and dashboard temperature, respectively.

Reference 2 presents an analytical study that considered a sunroof containing photovoltaic devices to provide ventilation while parked. Also considered was a selective-reflective glazing in the sunroof to further reduce the solar-load buildup. Peak interior air and surface temperatures were obtained during a day-long soak. The outside air temperature varied from 35°C (95°F) at 6 a.m. to a peak of 46.2°C (115°F) at 3 p.m.. Although the amount of solar radiation was not given, it was probably on the order of 860 W/m^2 (273 Btu/hr-ft^2). Without ventilation, a sunroof of .46 m^2 (5 ft^2) using standard glass resulted in an interior air temperature of 75°C (167°F) and an interior mass temperature of 84.4°C (184°F). Ventilation at the rate of 48.6 l/s (103 cfm) reduces these values to 53.3°C (128°F) and 72.7°C (163°F), respectively. Using selective glazing in the sunroof results in a further reduction to 50°C (122°F) and 64.4°C (148°F). Reference 3 is another analytical study that investigated the use of ventilative cooling using a solar-powered sunroof. Peak ambient conditions were 46.2°C (115°F) outside air temperature and 977 W/m^2 (310 Btu/hr-ft^2) incident solar radiation. Ventilation reduces the interior air temperature from 107°C (225°F) to 48.8°C (120°F).

Reference 4 presents a study of front and rear windshield angles and their effect on solar load control. This was an analytical study using tinted glass with a solar transmittance of 51% (absorptance or reflectance was not given). Angles were varied from horizontal to vertical for full-day soaks with ambient exterior temperature varying from 15.5°C (60°F) at 6 a.m. to a peak of 43.3°C (110°F). Solar radiation peak was 977 W/m^2 (310 Btu/hr-ft^2). Horizontal orientation yielded the greatest interior air temperature, 88°C (190°F); a value of 72°C (161°F) was obtained with vertical glazings. This study is important in that it documents the penalty of using more highly sloped glass surfaces (penalty if one does not consider the fuel savings associated with reduced aerodynamic drag), which is the current trend among automobile designers.

d. Cool-Down and Highway Driving Conditions

Automobile air conditioner performance is usually evaluated by considering several operating regimes: cool-down after a soak period, city driving at various speeds, and highway driving at high speed. Experimental and analytical investigations may be either continuous in the sense that all the regimes above are experienced during one test, or the investigations can be discrete and each regime evaluated independent of the others. In this section of the report, we document results from each of these regimes. We begin with several of our own numerical simulations and then discuss in detail results from studies published in references 9, 10, 7, 11, and 6.

These references and conversations with individuals in the auto industry indicate that peak air conditioner cooling loads can be expected during a hot and humid day with the following ambient weather conditions :

Air Temperature	43.3°C (110°F)
Relative Humidity	40 %
Wet Bulb temperature	30.4°C (86.8°F)
Solar Radiation	1000 W/m^2 (317 Btu/ft^2)

The amount of heat buildup during static soak under such conditions, particularly the component due to solar radiation, precludes having an air conditioning system that can instantaneously cool down the interior air and surface temperatures. Typically, cool-down takes on the order of ten minutes to one-half hour or more, depending on car type, air conditioner size, and climate conditions. On the open road, operating the air conditioner in the outside-air mode during these weather conditions requires the air conditioner to be running at design or peak conditions continuously. In the recirculation mode, off-peak operation occurs since the recirculated air tends towards the comfort range that is eventually prevalent inside the car

The loads on an air conditioner are separated into distinct sensible (temperature) and latent (humidity) components. A sensible load is defined as the heat extraction required to reduce air temperature, while a latent load is the dehumidification required to reduce humidity. The ratio of these two components varies significantly depending on geographic location. For example, in Phoenix, Arizona, which is usually hot and dry in the summer, a large part of the cooling load is sensible, i.e., temperature reduction. In Miami, Florida, which is usually hot and humid in the summer, the major cooling component is latent, i.e., humidity removal. The air conditioning system cools air from either outside the car (outside-air) or inside the car (recirculated-air), or a combination of both. The relative proportion of sensible to latent varies as a function of the climate and the use of outside- or recirculated-air. In a hot and humid climate, the more outside-air that is used during air conditioner operation, the larger will be the latent component. The reverse is true of recirculated-air. These concepts are important to understand because they influence the magnitude of glazing component contribution to the cooling load.

Our simulated cool-down results are representative of an ideal air conditioning system. Our analysis considers the sensible component of the total load adequate for locations such as Phoenix. We selected a worst-case scenario and compared the cool-down characteristics of different air conditioner capacities, 1.0-2.5 KW (3415-8538 Btu/hr), using the sports model sedan equipped with two different solar transmittance glazings. The air conditioning system was turned on at the soak condition prevalent at 11 a.m. when the interior air temperature was 69°C (156°F) for the model with 83% transmittance and 55°C (131°F) for the model with 43% transmittance reflective glazing. Figure 11 shows the results of our simulations.

We see that a capacity somewhat greater than 2.5 KW (8538 Btu/hr) is required to rapidly achieve comfort conditions for the model with the high-transmission 83% glazing while the car with 43% transmittance requires about 1.7 KW(5806 Btu/hr). The determining factor causing this difference is the interior air temperature at the time of cool-down start, i.e., the lower the temperature, the lower the capacity requirements. This is more fully shown in Figure 12, which shows the relationships between sensible cooling capacity limits and interior temperatures 10 minutes after AC start. The 0.0 KW curve represents the time-start temperature change due to the glazing transmittance. The slopes of the curves indicate a 15°C (27°F) reduction in temperature for each KW increase in capacity and about a 3.5°C (6.3°F) decrease in temperature for each 10% decrease in transmittance.

Figure 12 presents the dash/seat surface temperatures during cool-down for the same conditions as above. Changes are not as large as those associated with air temperature; i.e., after 10 minutes of AC operation, the surface temperature is reduced by 10°C (18°F) for the clear glazing using a 2.5KW cooling capacity; after one hour, the temperature is reduced 21°C (38°F). Much larger changes would occur with the AC blowers oriented towards the hot interior surfaces.

Overall, our results are dramatic; they suggest a significant potential reduction in air conditioning requirements. However, neither latent loads nor cruise driving conditions were considered. The ESP simulation program, although adequate for building energy analysis, would have required extensive revision to exactly model auto air conditioning system performance. Fortunately other

researchers (Refs. 9, 10, 7, 11, 6) have performed such analysis and we now present a portion of this related work. It should be noted that the air conditioner capacity values calculated by the ESP program are usually lower than others published in the literature. This is because ESP simulates ideal heat extraction. Individual AC components such as compressors, evaporators, etc., are not treated by ESP's algorithms.

Data in Reference 9 is the most comprehensive in regard to analysis of car type, ambient weather, and driving conditions. This was a Canadian study in which subcompact, compact, and standard cars were simulated for ambient conditions of 32.2°C (90°F)-50% RH, 37.7°C (100°F)-20% RH, and 43.3°C (110°F)-5% RH. Cool-down after an initial soak, city driving at 50 kmh (30 mph), and highway driving at 100 kmh (60 mph) were investigated. During cool-down operation, recirculated-air was used by the air conditioning system, whereas during city and highway driving, 100% outside-air was used. All configurations used glazings with an 85% solar transmission value.

Table 2 is reproduced from Reference 9. The data shows the air conditioner capacities required for the different configurations and operating conditions. Peak loads range from a low of 3.2 KW (10960 Btu/hr) for the subcompact at 37.7°C (100°F)-20% RH city in driving to a high of 5.5 KW (18950 Btu/hr) for city driving by the standard sedan under hot and dry conditions, 43.3°C (110°F)-5% RH. For the subcompact sedan, there is not much variation in cooling required for the different driving conditions nor for the changing ambient weather conditions. The smallest loads for all models occur for 37.7°C (100°F)-20% RH, while the largest loads occur for the hot and dry conditions, although the hot and humid capacities are almost equivalent. The largest changes in capacities occur as a function of automobile size.

Reference 9 gives a breakdown of the cooling load components for the compact sedan under city driving for the 37.7°C (100°F)-20% RH condition. The results indicate that 35% of the cooling is due to solar radiation through glass and 42% is due to the use of outside-air by the AC system. The remainder (23%) is split between conduction, passenger heat, and engine/instrument loads. The study indicates that tinted glass with a 42% transmittance (reflectance and absorptance values are not given) results in a 50% reduction in the solar component of the cooling load with total cooling reduced by 18%. In addition, the author also states that an additional 32% reduction in total cooling could be obtained by using 25% outside-air instead of 100% outside-air.

Reference 10 is an analytical and experimental study of the performance of infrared-reflective and -absorptive glazings under various auto operating conditions. In the outside-air mode running at a fixed speed with ambient conditions of 35°C (95°F), 60% relative humidity, and a peak solar radiation of 950 W/m^2 (301 Btu/hr-ft^2) and an interior temperature of 25°C (77°F) and 60% RH, the cooling load component due to solar radiation including the reradiation from interior surfaces was 25%. Ventilation accounted for about 50% of the total load. The total cooling load on the air conditioning system was 4.6 KW (15710 Btu/hr). In the recirculation mode of operation, the solar and reradiation components were 50% and ventilation was reduced to 10%. The total cooling load was about 2.4 KW (8196 Btu/hr). Using infrared-reflective glazing with properties shown in Table 1 results in a reduction of the air conditioning system capacity of .74 KW, which is about 10-20% of the capacity required for a subcompact sedan.

Reference 7 documents an experiment at 40 kmh (24 mph) for a car equipped with conventional glazing and one with a new laminated reflective glass (see previous section on static-soak for details). The authors state that the cooling load component due to auto glass can reach 72% of the total. To arrive at such a large magnitude, we must assume that the conductive load through the glass and possibly the reradiation from the interior mass was added to the solar load. The air conditioner capacity required to achieve comfort using conventional glazing was about 2.3 KW

(7854 Btu/hr); for the new glazing, 2.0 KW (6830 Btu/hr) was necessary. Percent outside- or recirculated-air was not given in the report.

Reference 11 is an experimental study that investigated the performance of a new solar control film that reflects 45% of the incident solar radiation. A control car with standard heat-absorbing green-tinted glass was compared with a similar car fitted with the new glazing. Recirculated-air accounted for 90% of the ventilation. Thirty-minute cool-down comparisons at 50 kmh (30 mph) and 83 kmh (50 mph) indicated that the new glazing resulted in a fairly constant 3°C (7°F) interior air temperature reduction. This value was less than the 11°C (19°F) difference experienced during soak. Convective cooling of the glazing surfaces caused by the forward motion of the car is the reason for the less dramatic effect. During stop-and-go city driving tests at 42 kmh (25 mph), the car with the new glazing was cooler by 1-4°C (2-7°F) during 20-minute test periods.

Reference 6 investigated ventilative cooling with a photovoltaic sunroof as a means of reducing solar load buildup. Although AC capacity limits were not specifically addressed, interior air temperature response curves were given for cool-down from various start temperatures. After 10 minutes of air conditioner operation, for example, the auto without ventilation went from 107°C (225°F) to 42°C (108°F); while the auto with ventilation cooled from 48.8°C (120°F) to a condition near comfort at 26.6°C (80°F). Both sensible and latent cooling components were considered; however, ambient humidity and percent outside-air used by the AC system were not indicated.

In summary, our own studies and those reported in the literature indicate that decreasing the solar transmittance of automobile glazing reduces the capacity requirements of the air conditioning system. The relative differences between reflective and absorptive glazings, although large under static-soak conditions, is reduced during motion because of increased surface convection. We can conclude that in the outside-air mode of air conditioner operation, solar radiation accounts for about 25% of the total load and ventilation accounts for 50%. These figures would be reversed in the recirculation mode of operation.

e. Expected Hours at Peak Conditions

We present data in this section of the report to give some idea of the expected number of hours during a year when ambient weather conditions cause peak cooling loads to be prevalent. Reference 8 was used to tabulate the data presented in tables 3 and 4. Test Reference Year (TRY) Wet Bulb Temperatures and Dry Bulb Temperature Bins were compiled for five cities: Miami, Houston, New York, Los Angeles, and Phoenix.

Table 3 shows the number of hours that a particular base wet bulb temperature is exceeded. This number is useful for determining the significance of the humid ambient weather condition used in the Reference 9 study, i.e., 32.2°C (90°F)-50% RH, where the wet bulb temperature was about 24.4°C (76°F). We see that this condition is exceeded during a large number of hours in both Miami and Houston. New York and Los Angeles, for different reasons, do not experience many hours with extreme wet bulb temperatures; however, in Phoenix, ambient weather conditions can be hot and humid at certain times, resulting in the air conditioner operating at peak capacity.

Table 4 shows the number of hours within a particular dry bulb temperature range. This gives us an estimate of conditions comparable to the higher ambient temperatures in Table 2, since Reference 8 indicates that at such high temperatures, the mean coincident wet bulb temperatures are generally low (i.e., low relative humidity). We must also assume that the solar radiation is at a level comparable to that in Reference 8. We see that only in Phoenix is there a large number of hours when extremely hot and dry weather is encountered that requires air conditioner operation at peak capacity.

3. Relationship Between Population and Climate

We undertook a study to relate automobile cooling requirements to population density in order to better understand the geographic implications of air conditioner performance in the U.S. Reference 1 presents the results of prior LBL work to define the effect of climate on building energy performance by selection of climate regions that have the greatest relevance for the greatest number of people in the U.S. Standard Consolidated Statistical Areas (SMSA) were identified for 125 locations. Each has a population greater than 250,000.

Both heating energy and cooling energy were examined. In the case of cooling load or energy, three climate parameters were used: cooling-degree-days (temperature), latent enthalpy hours (humidity), and the ratio of available sunshine at the earth's surface to the sunshine available on a parallel plane above the earth's atmosphere (solar). Cooling-degree-days (CDD) were from a base of 18.3°C (65°F). Latent enthalpy hours (LEH) were taken from a base of 16.1°C (61°F) dew point temperature and 23.9°C (75°F) dry bulb temperature. The data were extracted from long-term SOLMET averages based on 24-25 years of measured information.

Although Reference 1 is concerned with building energy performance, the same three parameters are also relevant when analyzing automobile air conditioner cooling performance. Cooling, whether in a building or a car, is a function of three primary climate variables: air temperature, humidity, and solar radiation. Air temperature influences the sensible cooling load mainly through conduction; humidity has a direct bearing on the latent load since it characterizes the amount of moisture removal required; solar radiation affects the sensible load through the amount of transmitted, absorbed, and reflected radiation and the resultant interior and exterior surface temperature changes.

By making the assumption that the SMSA population density and distribution of the U.S. approximates automobile density and distribution, we are able to use the results from Reference 1 directly. Figures 12, 13, and 14 present the SMSA population distribution of the U.S. using CDD, LEH, and solar radiation (K_T) as distribution parameters respectively. Of primary concern for auto air conditioners are the distributions due to humidity and solar radiation (Figs. 13 and 14). The studies discussed above have shown that the cooling load component due to air temperature effects (Fig. 12) can vary from about 5% to 15% of the total load, but the major portion of the cooling load comes from humidity and solar radiation. In the outside-air mode in a humid climate, moisture removal can require more than 50% of the air conditioner's capacity. In a hot and dry climate, solar radiation effects have been shown to approach this level. These proportions should be kept in mind as one observes figures 12 through 14.

Cooling-degree-days are distributed with more than 80% of the population located in areas with less than 1200 CDD. The remaining population is located along the Gulf Coast, lower Southeast, and desert Southwest. The latent enthalpy hours distribution (Fig. 13) shows that half the population is in areas with less than 2000 LEH. Almost the whole population (on the order of 90%) is in climates with less than 10,000 LEH. The southeast and portions of Texas which have LEHs greater than 10,000 account for the remainder. The distribution using solar radiation (Fig. 14) is more uniform than either CDD or LEH. Likewise, the range of K_T values is much lower than the CDD and LEH values.

4. Technical Options for Energy Control Glazings

During the past few years the automobile and glass industries have increased their investments in research and development of new types of glazings for automobiles. Although initially driven by

consumer comfort, the industry is now also concerned with solar load reduction as a means of improving air conditioner performance.

The primary thrust of new technology for window glazings over the last decade has focussed on issues related to manufacturability and cost control (e.g., encapsulated glass parts), visibility (e.g., complex bends and higher slopes without optical distortion), safety (e.g., interior plastic surface layers), occupant convenience, (e.g., heated windshields), and amenity (e.g., low-transmittance privacy glass). Solar load control is just now emerging as a critical issue in auto glazing design. This concern is motivated by the use of more glass for styling purposes and by changing glazing geometries to accommodate aerodynamic designs to improve energy efficiency, by added concern for occupant comfort, by space limitations under the hood to fit ever-larger air conditioners and radiators, by UV degradation of polymeric materials used in auto interiors, and finally by concerns for reducing CFC emissions from auto air conditioners.

Fortunately there have been significant developments in the area of energy control coatings for glazings over the last decade, many of which have applicability to the automotive energy control problem. The area of greatest development has been energy control coatings for glass and plastic glazings for buildings. Since most of the major glass and plastic coatings companies are involved in both building construction and automotive markets there is a direct transfer of relevant interest, expertise, and in some cases, production capability.

Several important developments have occurred in coated glazings for buildings. The primary activity between 1975 and 1985 was development and commercial introduction of high-transmission, low-emissivity ("low-E") coatings, which are used to reduce heat loss. These coatings transmit sunlight but reflect the long wave infrared energy that is a principal component in heat transfer. The primary application was initially to reduce heat loss for buildings in cold climates although, as discussed below, there are other variations for hot climates. There are two major types of coatings that are produced by two different deposition methods. Multilayer metal-dielectric coatings are produced primarily by magnetron sputtering. Typical coating designs use a thin layer (100-150Å) of silver as the metal and one of several metal oxides as a sandwich around the silver to enhance transmittance, with a total coating thickness of about 500Å. These coatings are normally deposited "off-line" from the float glass production process. Because of the low temperature of the deposition process the coatings can be deposited on thin plastic ("roll coating") and rigid plastic as well as glass. A second class of low-E coatings is based on the use of doped semiconductors, such as tin-doped indium oxide. These are most commonly produced by a high-temperature pyrolytic process as the glass emerges from the float line. Typical pyrolytic coatings are single-layer coatings with a thickness of about 3000Å.

Low-E coatings were first introduced to the buildings market in 1983 and have already captured about 20% of the insulating glass market in the U.S. By the early 1990s this should increase to over 50%. A detailed discussion of the technical and market evolution of these coatings is beyond the scope of this paper but there have been significant developments in coating technology, some of which are specifically targeted for automotive applications. The first spin-off from low-E coatings for automobiles was the heated windshield. The same property that makes a low-E coating a good long wave IR reflector makes it a good low-resistance electrical conductor. By attaching busbars to the coating, electrical energy is pumped into the coating and converted into heat which can melt a thin layer of ice in less time than it takes for a engine to heat up and produce hot air for defrosting. Heated windshields for production models were first introduced by Ford in the U.S.; the coatings were spin-offs of low-E technology from Ford and Airco. (Heated windshields have been used in aircraft for years and in test cars.) Other coating developers and auto manufacturers now offer these as well. (Ref. 12)

By changing the thickness and properties of the high solar transmittance coatings, the onset of high reflectance can be shifted from the far infrared to the near infrared. These coatings will then

transmit the shorter wavelength visible light but reflect the near IR solar heat. (See section 2a.) Such coatings were offered in the architectural market to provide better sun control and reduce cooling needs in houses in the sun belt and in commercial buildings throughout the country. The value of these coatings in building applications is well established although they do not yet represent a large fraction of sales. It is these "wavelength-selective" coatings that provide the technical basis for the first generation of sun control products for auto glazings. Typical products now being offered commercially are described in references 11 and 12. Since these coatings are silver based, they must be protected within a laminated glazing design, thus limiting their current applicability to windshields. Durable, highly selective coatings for application to the interior surface of monolithic glazings are the next major requirements for automobiles.

The light levels and solar heat gain in buildings varies tremendously over the seasons and over the course of a day, so active coatings that dynamically control transmission properties have been under study for some time. These optical-switching coatings should provide even greater control of solar heat gain in cars and are now under active development by several companies. Some of the options for these optical technologies are reviewed in Reference 13. In fact, some developers believe automotive applications have replaced building applications as the preferred nearer-term application for these coatings. Optical coatings can be passive in their response to environmental stimuli, such as thermochromic (heat-sensitive), or photochromic (light-sensitive) coatings, or can be actively controlled by electrical impulse. The latter class is preferred in auto applications.

Two types of electrically controlled coatings have received the most attention; electrochromic coatings and liquid crystals. Both were originally developed for display purposes. Large-area liquid crystal coatings have been fabricated as a multilayer plastic laminate for use in test vehicles. In their low-transmittance state they are diffusing and thus obscure vision. This diffusion property is advantageous in spreading the transmitted solar gain through the car and reducing hot spots from direct sunlight. Current coatings have a limited range of light control between the switched and unswitched state of about 2:1. The switching effect is instantaneous but since they require continuous electrical power (40-80v) for the clear state, they have been used primarily for rooflights and back sidelights which are non-critical vision glazings.

Electrochromic coatings show the greatest longer-term potential. They require low voltage (usually 1-3 volts) and low power only when they are being switched, and then remain in the same optical state for hours with no power consumption until the next switching control is applied. The switching effect can occur in a time range of seconds to minutes over a wide dynamic range. The coatings are multilayer designs (typically five layers) and may be all solid-state or include solid or gel-like polymeric layers. Many material system designs are now under development and some large-area prototypes have been demonstrated for sun roofs. Both absorptive and reflective types are being investigated, with reflective the preferred type for most auto applications. The first commercial application for an absorptive coating is for rear-view mirrors, where the coating is placed in front of a silvered mirror and provides day/night control. Electrochromic coatings can be made by several commercially available deposition processes. These coatings with a highly reflective state would be particularly useful in a parked vehicle to greatly reduce the static-soak temperature buildup, as shown by our modeling in earlier sections of this report.

A final glazing option is an angle selective material with high transmittance and good optical clarity in some directions while having a high attenuation (absorption or reflection) in others. These coatings would provide the functional equivalent of the metal or plastic louvers often used with the rear windsields of sports cars. Such properties could be produced using several different coating technologies, e.g. holography.

This survey of available and emerging optical technology for auto glazings suggests that large reductions in cooling loads due to glazings can be achieved. First-generation static selective coatings are reducing total solar heat gain through the windshield while maintaining high visible

transmittance. Currently available coatings must be protected in laminated glazings, which limits their use but it is likely that more durable coatings for monolithic glazings can be developed also. The next generation of coatings will provide dynamic control to help reduce the most severe temperature extremes experienced under static-soak conditions. Smart electronics in the vehicle can sense solar position and intensity, and dynamically adjust transmittance accordingly. These coatings will modestly increase the cost of cars, but they will also provide important benefits beyond reductions in air conditioner size and resultant CFC use, such as improved comfort, reduced interior temperatures and longer lifetimes for the plastic interiors, better privacy and security, and greater overall amenity and responsiveness to the needs of occupants. If the technical development for these advanced coatings can be successfully completed it appears likely that the coatings can be cost justified in many automotive applications.

5. Conclusions: Opportunities for Downsizing Automobile Air Conditioners

The Lawrence Berkeley Laboratory has performed a preliminary analysis of the effects of glazing and ventilation on automobile cooling loads and air conditioner capacity limits. We conclude that it is possible to substantially reduce automotive air conditioner size in many parts of the country. However, further analysis is required to study the effects of glazing performance under city and highway driving conditions in hot and humid geographic locations. Nevertheless, our results have important implications in the effort to reduce CFC emissions from the current generation of automotive air conditioners. There are few practical alternatives to air conditioning systems of current design as long as the peak cooling capacity must remain high. If the peak cooling power and system size can be reduced, alternative cooling system approaches that reduce or eliminate CFC emissions may become possible. The following conclusions have resulted from our analysis:

a. The performance of reflective and absorptive glazings under soak conditions becomes very different as the transmittance property is reduced. This is because a portion of the heat absorbed by a glazing is eventually conducted and reradiated into the car's interior. With a transmittance value close to zero, the interior air temperature for a totally reflective glazing will approach the exterior air temperature during static soak. For the car models simulated in our study at peak environmental conditions, totally absorptive glazings resulted in interior temperatures that were approximately 12-17°C (22-31°F) higher than the reflective glazings with the same transmittance. Dash/seat surface temperatures under static-soak conditions with absorptive glazings are only slightly higher than the temperatures associated with reflective glazings. This is because the absorbed heat that is conducted into the car tends to be distributed to all the interior surfaces.

b. Natural or forced ventilation of exterior air into the car while parked substantially reduces the interior air temperature buildup. In a sports model sedan with a large amount of glazing we showed a 20°C (36°F) decrease in interior air temperature and a 35°C (63°F) decrease in dash/seat temperature with a 43% reflective glazing and a ventilation rate of 20 air changes per hour. ventilation is most effective when used in conjunction with selective glazings.

c. Our simulations of sensible component cool-down for the sports model sedan using an ideal air conditioner indicate that approximately a 33% cooling capacity reduction is feasible by reducing the glazing transmittance from 83% to 43% using reflective glass. There is a 15°C (27°F) reduction in interior air temperature for each KW increase in air conditioning capacity and about a 3.5°C (6.3°F) decrease in temperature for each 10% decrease in transmittance. These values are prevalent 10 minutes after air conditioning start.

d. Other studies indicate that in a hot and humid location, 50% of the load on the air conditioning system is due to ventilation when operating in the outside-air mode. About 25% is due to solar radiation through the glass surfaces. This includes the reradiation from internal

surfaces. In the recirculated mode of AC operation, the solar component can reach 50% of the total.

e. The differences between clear, reflective, and absorptive glazings is mitigated during city and highway driving because of the increased convection at the outer glass surfaces. One recent study showed that an interior air temperature difference of 11°C (19°F) between heat-absorbing and reflective glazings experienced during soak was reduced to 3°C (7°F) during city driving at 42 kmh (25 mph).

f. We recommend that additional analytical and experimental investigations be conducted to document the effects of glazing during cool-down and during city and highway driving, particularly in those locations that are characterized by high humidity. Our studies were limited to analyzing the static soak and the sensible component during cool-down. The effect of glazing on air conditioner size would vary as a function of climate and driving condition.

6. References

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7. Acknowledgements

This work was supported by the Stratospheric Ozone Protection Program, Office of Program Development, Office of Air and Radiation of the U.S. Environmental Protection Agency under Contract No. DW89933085-01-0, through the U.S. Department of Energy under Contract No. DE-ACO3-76SF00098. The authors would like to express their thanks to Bruce Birdsall and Werner Osterhaus of LBL for their contributions to the completion of this report.

Table 1

Typical Glazing Characteristics

Glass Type	Visible Trans	Solar Trans	Solar Refl	Solar Abs
Conventional	80	76	8	16
Reflective	70	34	45	21
IR Reflective	73	52	37	11
IR Absorptive	76	53	6	41

Table 2

Predicted Automotive Cooling Requirements (Ref. 9)

Car Type and Test Condition	City Driving (Cool-Down) No Outside-Air KW(Btu/hr)	City Driving 50 kmh (30mph) 100% Outside-Air KW(Btu/hr)	Highway Driving 100kmh (60mph) 100% Outside-Air KW(Btu/hr)
Sub-Compact			
90F(32.2C)DBT 50%RH	3.59(12250)	3.49(11910)	3.76(12850)
100F(37.7C)DBT 20%RH	3.46(11830)	3.20(10930)	3.41(11640)
110F(43.3C)DBT 5%RH	3.86(13170)	3.79(12950)	4.08(13940)
Compact			
90F(32.2C)DBT 50%RH	4.14(14140)	4.16(14220)	4.13(14120)
100F(37.7C)DBT 20%RH	4.01(13680)	3.76(12840)	3.73(12730)
110F(43.3C)DBT 5%RH	4.42(15100)	4.50(153800	4.47(15280)
Standard			
90F(32.2C)DBT 50%RH	5.06(17270)	5.16(17620)	5.13(17520)
100F(37.7C)DBT 20%RH	4.91(16770)	4.64(15830)	4.61(15730)
110F(43.3C)DBT 5%RH	5.36(18320)	5.55(18950)	5.52(18850)

Table 3

Annual Hours Wet Bulb Temperature Above a Base Temperature (Ref. 8)

Wet Bulb Temperature Base, °C (°F)	Miami	Houston	New York	Los Angeles	Phoenix
26.6 (80)	21	46	0	0	4
25.0 (77)	1264	801	3	0	47
23.3 (74)	3367	2054	160	0	507
21.6 (71)	5045	3181	533	3	1064

Table 4

Annual Hours Within Dry Bulb Temperature Range (Ref. 8)

Dry Bulb Temperature Range, °C (°F)	Miami	Houston	New York	Los Angeles	Phoenix
43.3-45.5 (110-114)	0	0	0	0	16
40.5-42.7 (105-109)	0	0	0	0	140
37.7-40.0 (100-104)	0	0	0	8	357
35.0-37.2 (95-99)	0	50	3	8	495
32.2-34.4 (90-94)	70	284	20	9	511

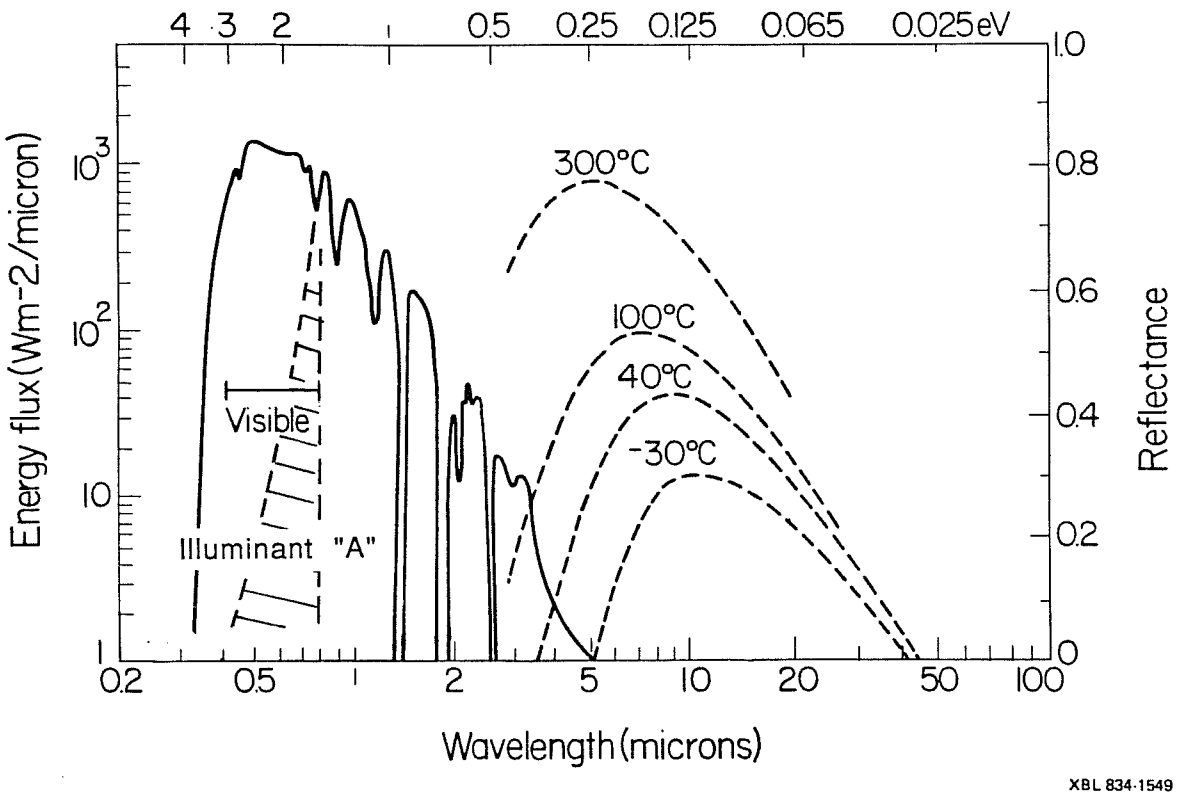
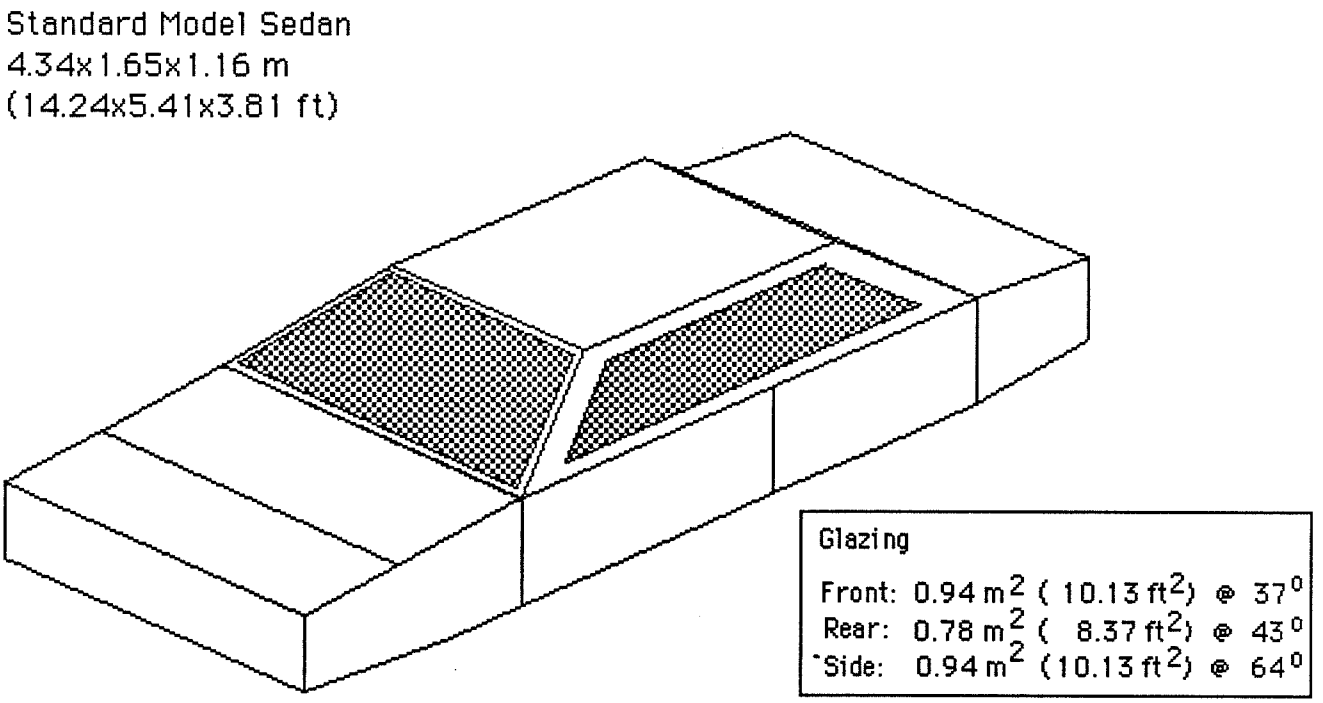


Figure 1. Spectrum of solar radiation shown with four blackbody spectral distributions. Superimposed is the idealized selective reflectance of a spectrally sensitive surface.



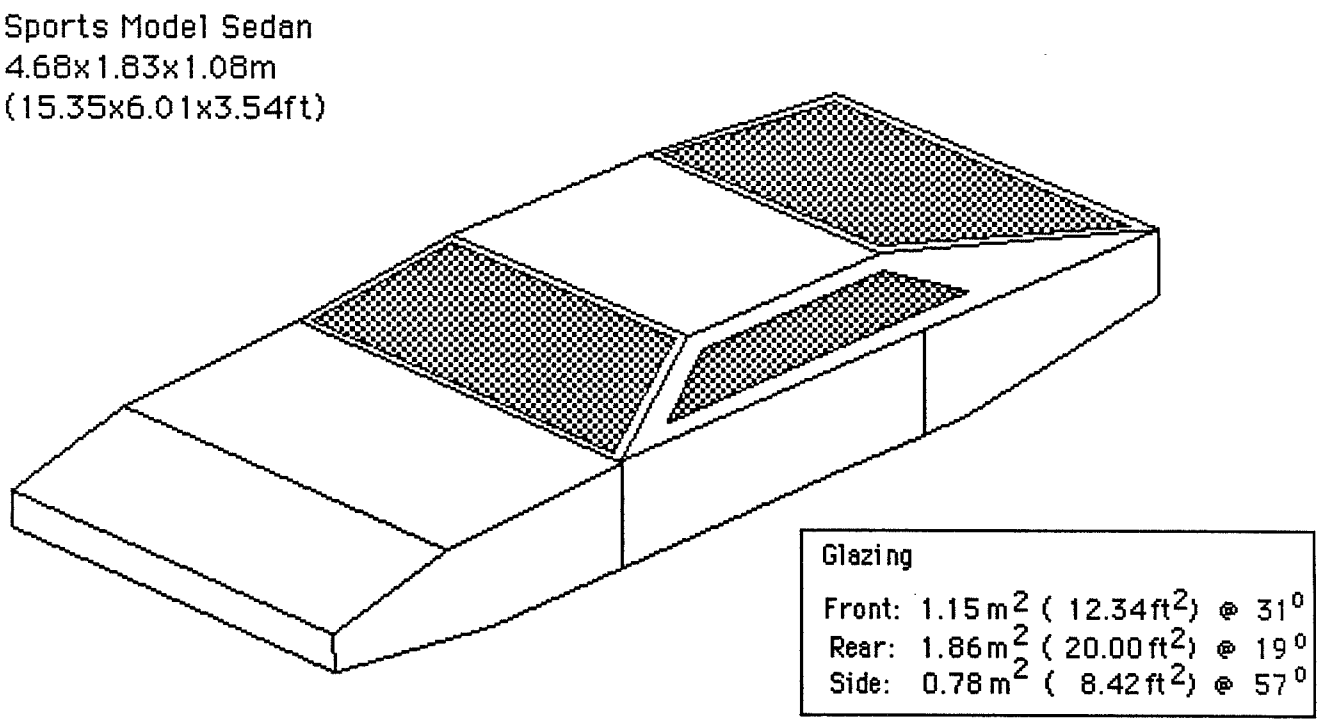
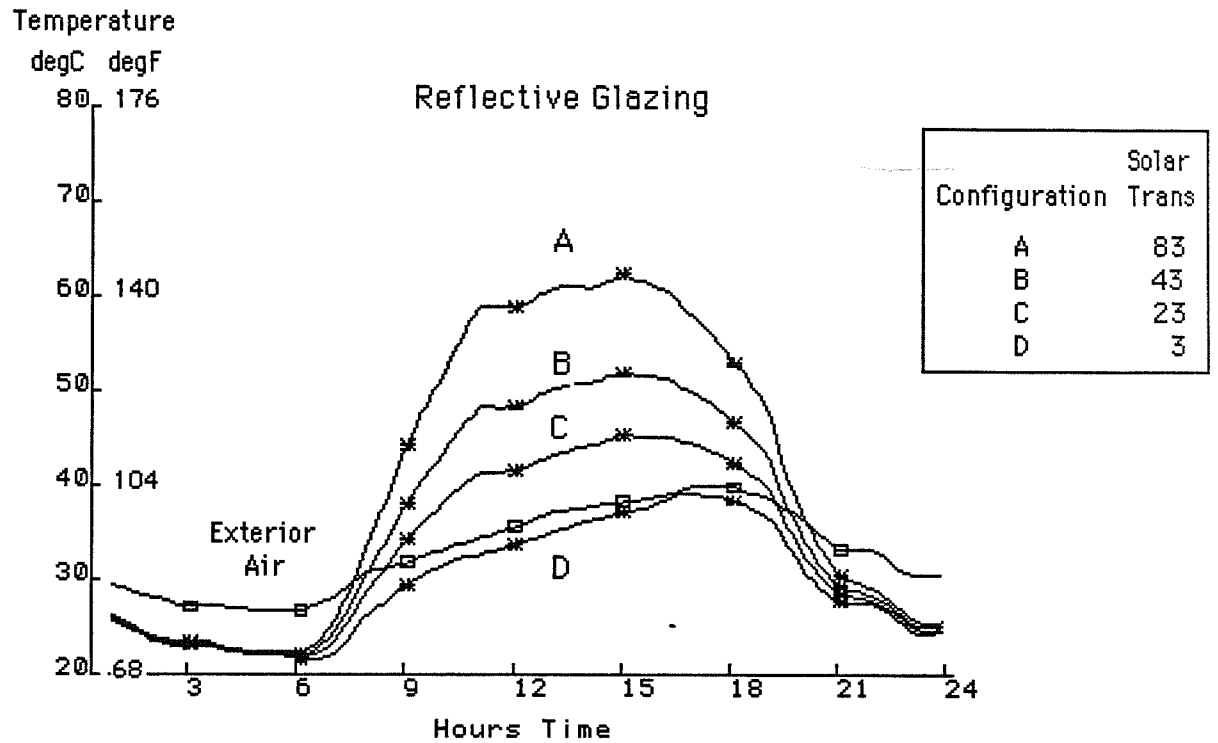


Figure 2. Perspective views of the standard and sports-model sedans used in the LBL heat transfer simulations.



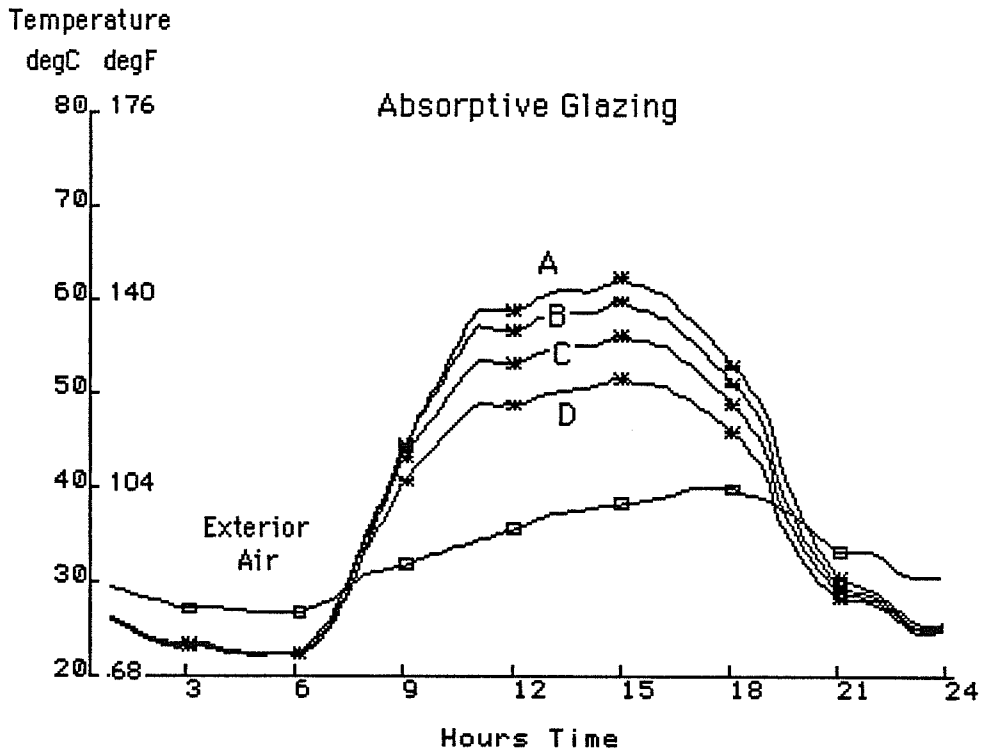
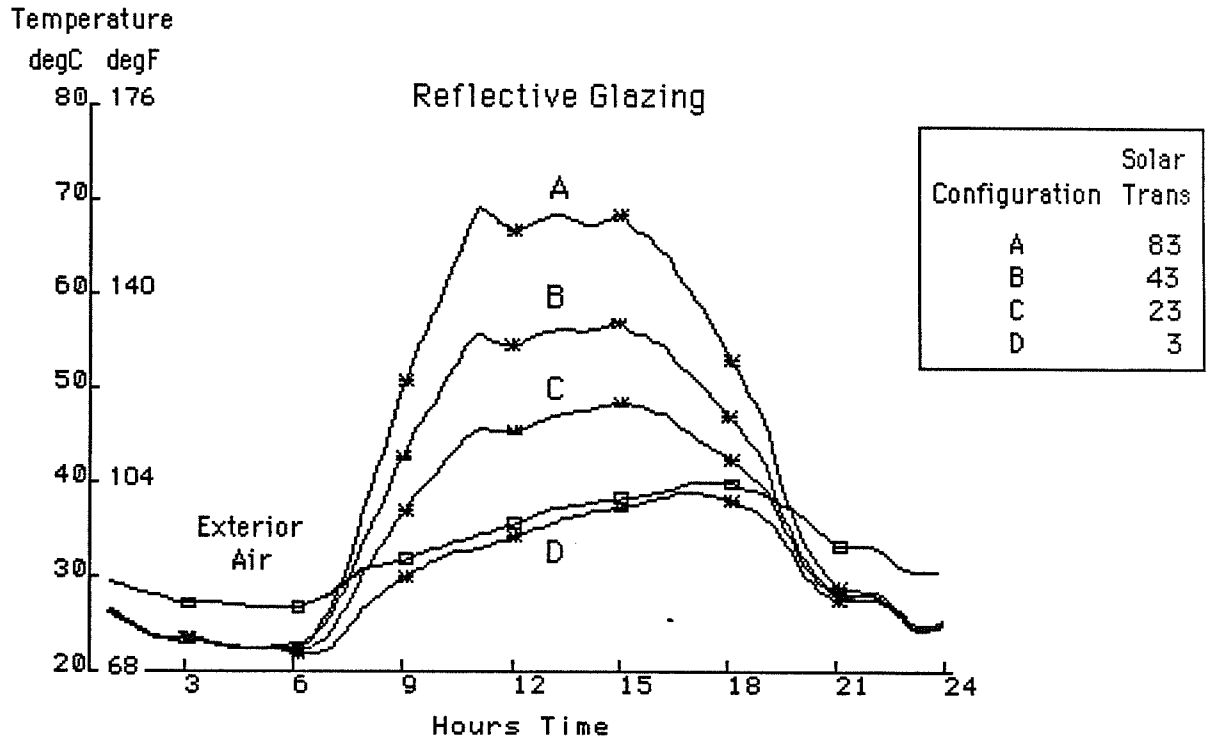


Figure 3. Interior air temperature for the standard sedan during a full-day soak in Phoenix, Arizona. Values are given as a function of transmittance for both reflective and absorptive glass.



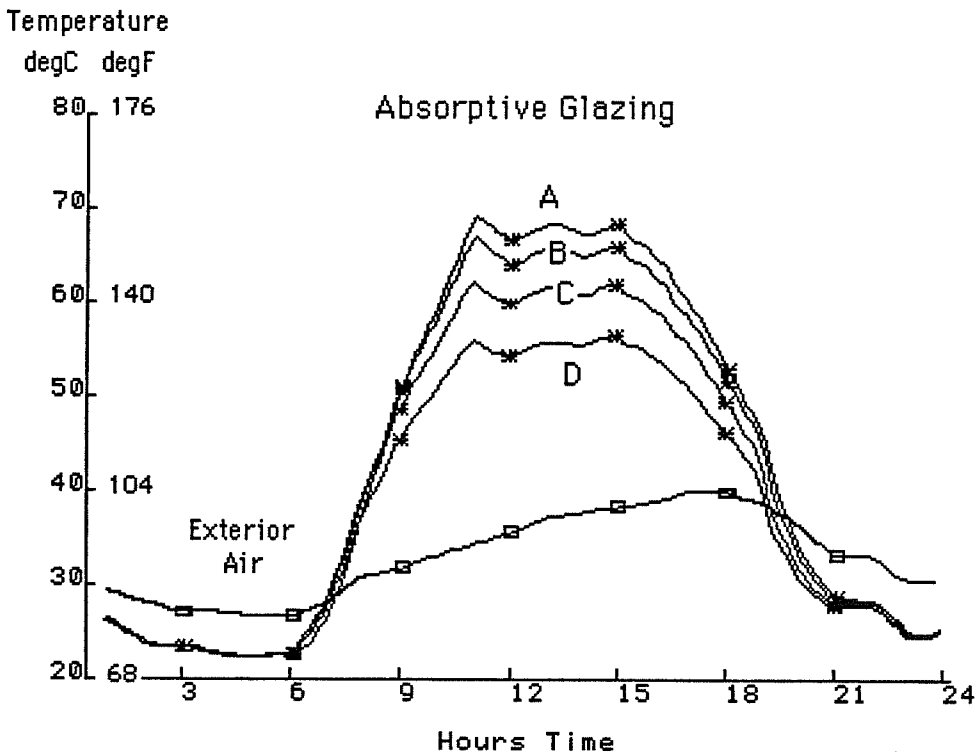


Figure 4. Interior air temperature for the sports sedan during a full-day soak in Phoenix, Arizona. Values are given as a function of transmittance for reflective and absorptive glazings.

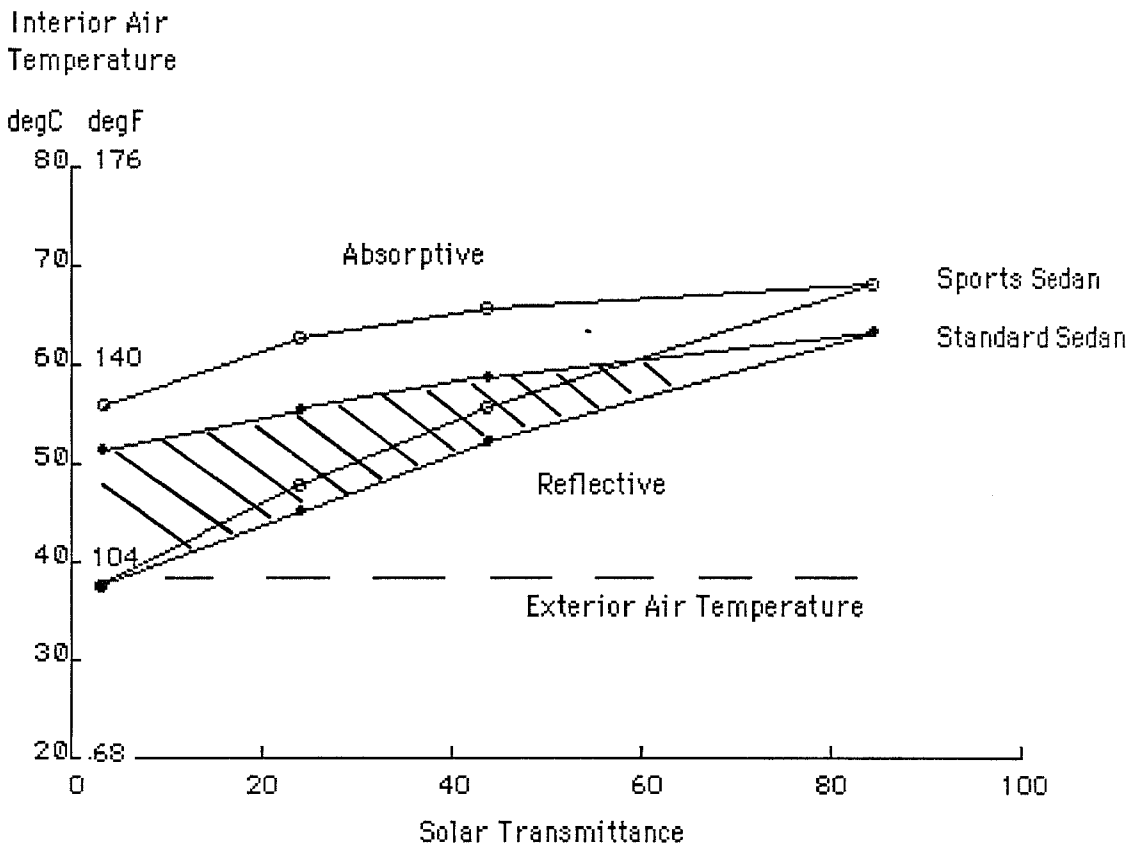
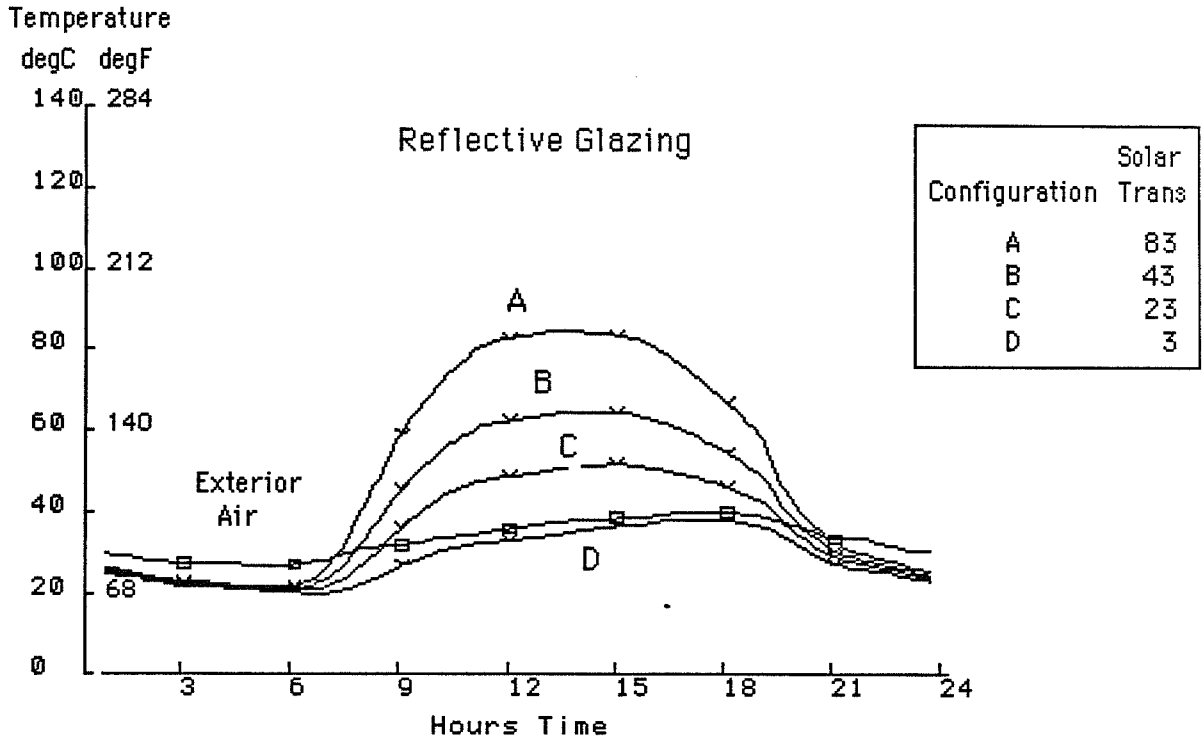


Figure 5. Peak interior air temperatures for the standard and sport sedans as a function of solar transmittance. Values occur at 3 p.m. and are shown for reflective and absorptive glazings.



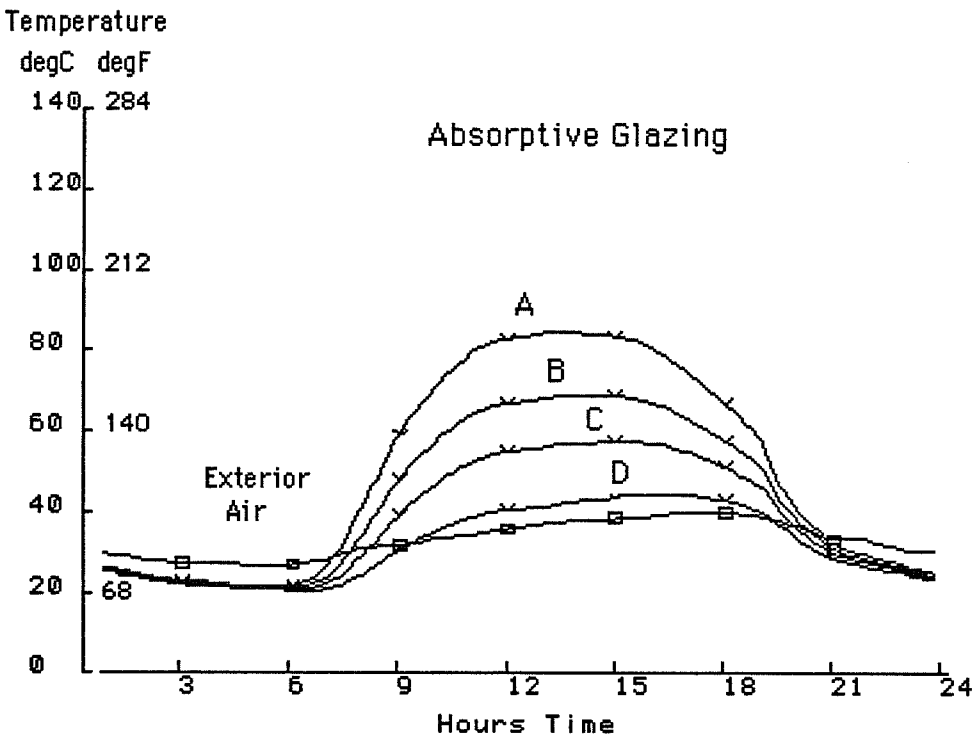
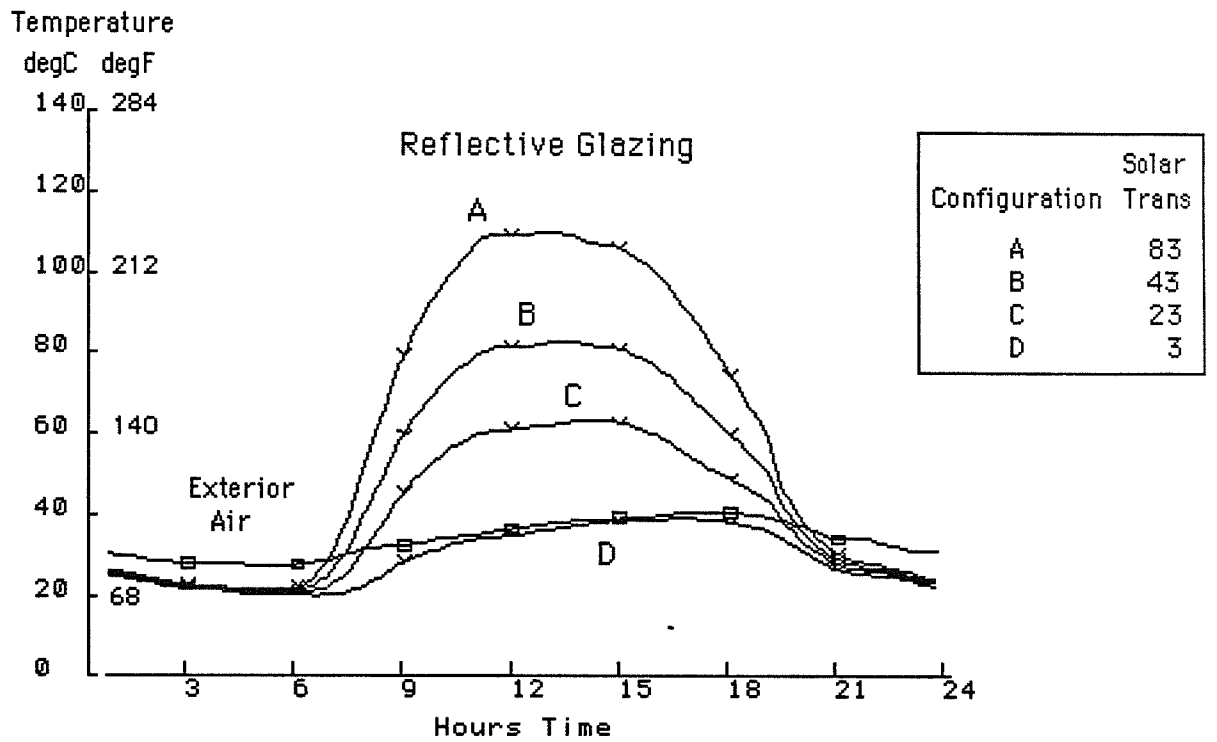


Figure 6. Dash/seat surface temperature for the standard sedan during a full-day soak in Phoenix, Arizona. Values are given as a function of transmittance for reflective and absorptive glazings.



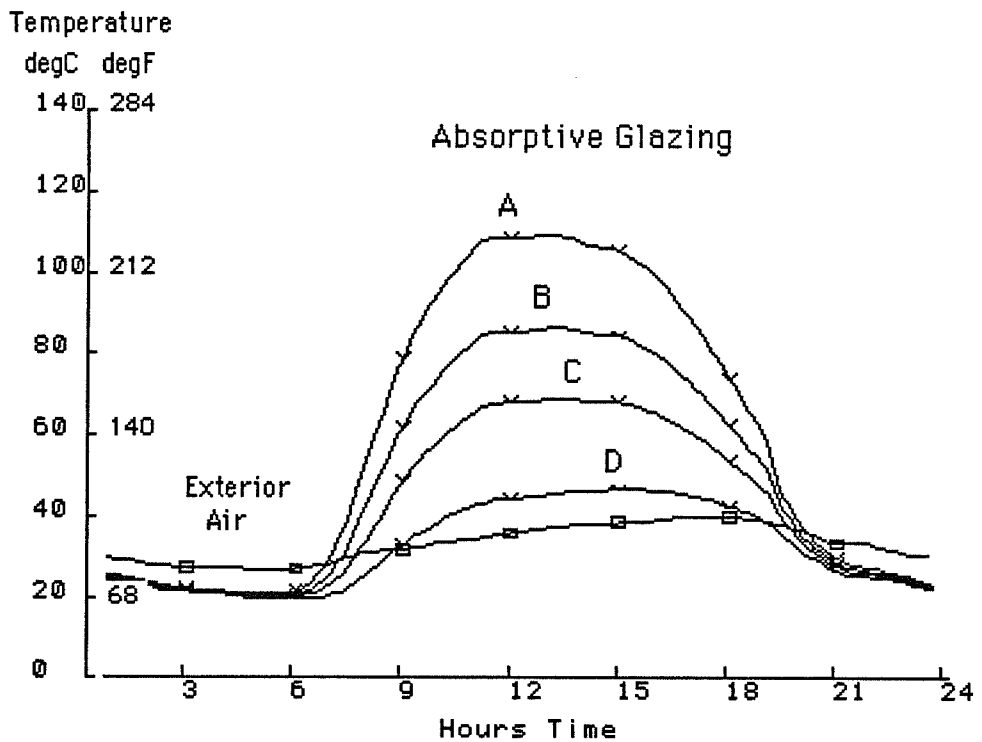
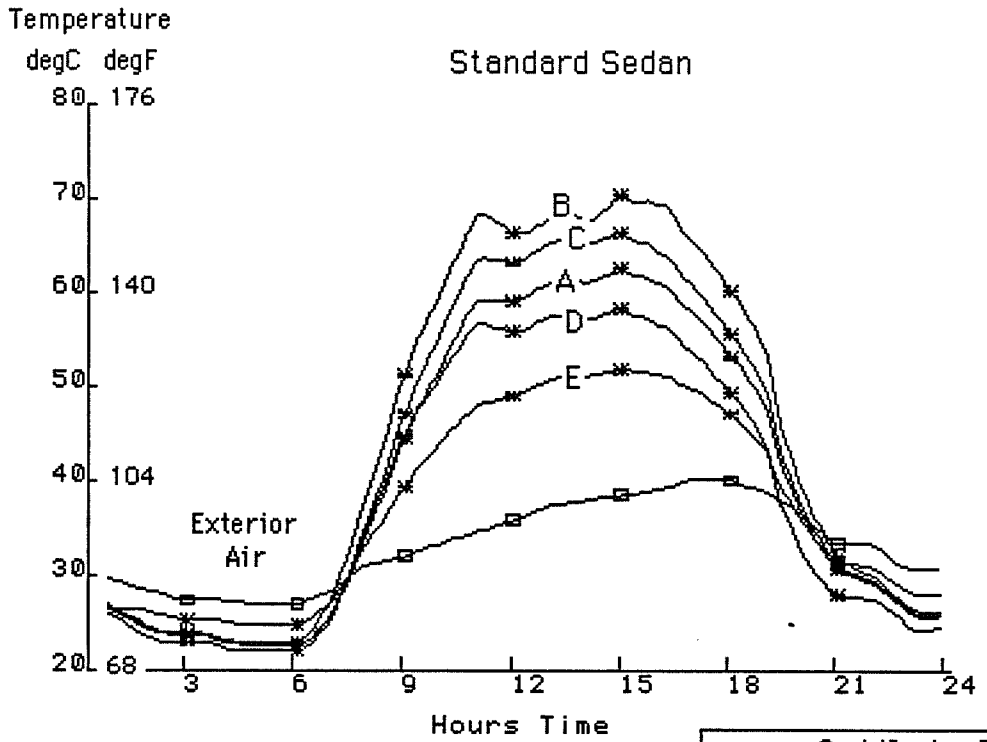
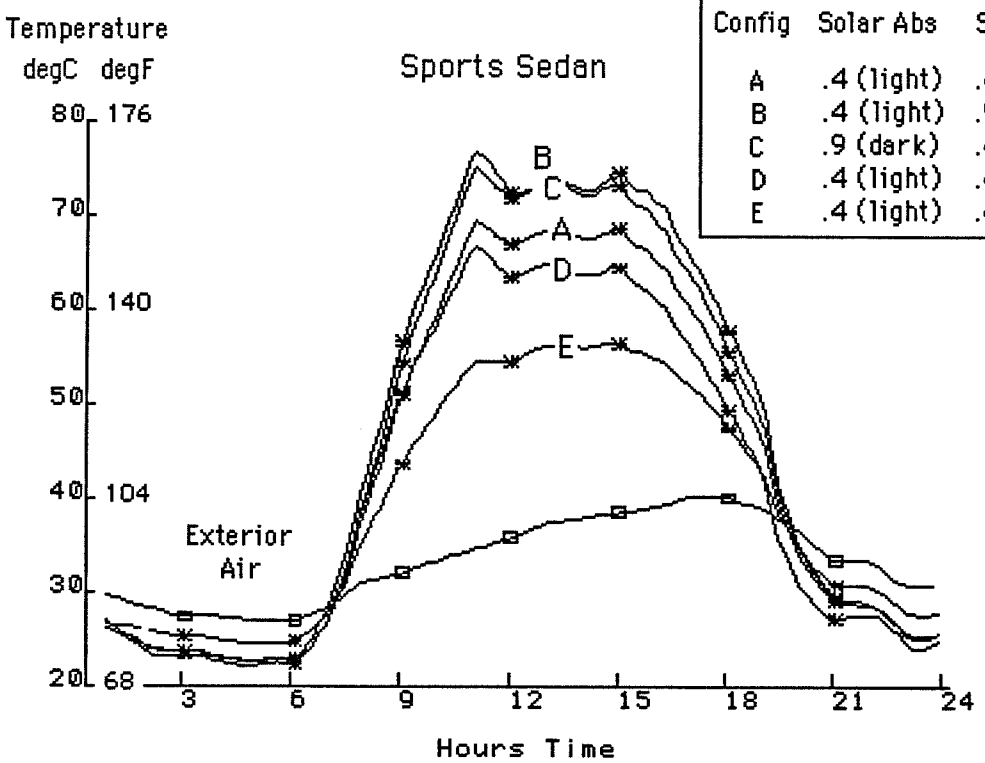


Figure 7. Dash/seat surface temperature for the sport sedan during a full-day soak in Phoenix, Arizona. Values are given as a function of transmittance for reflective and absorptive glazings.

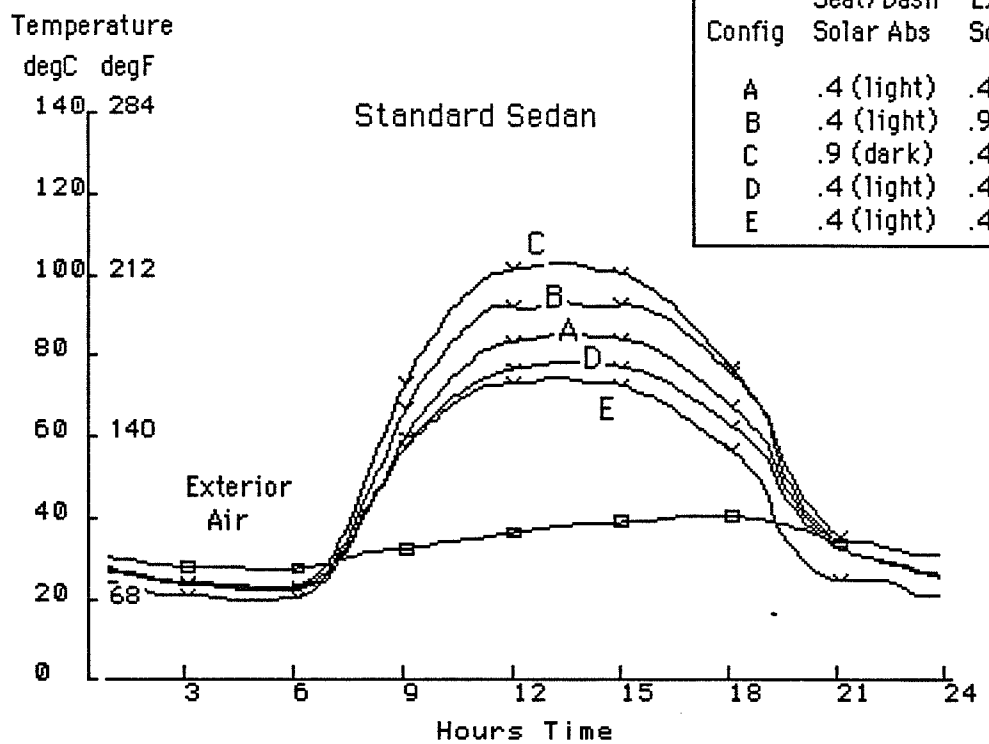




Config	Seat/Dash Solar Abs	Exterior Solar Abs	Infil	Thermal Mass
A	.4 (light)	.4 (light)	0	84 kg
B	.4 (light)	.9 (dark)	0	84
C	.9 (dark)	.4 (light)	0	84
D	.4 (light)	.4 (light)	0	0
E	.4 (light)	.4 (light)	20	84

Figure 8. Interior air temperature for the standard and sports sedans during a full-day soak in Phoenix, Arizona. Values are given as a function of varying configuration properties for the models with 83% solar transmittance glazings.

Config	Seat/Dash Solar Abs	Exterior Solar Abs	Infil	Thermal Mass
A	.4 (light)	.4 (light)	0	84 kg
B	.4 (light)	.9 (dark)	0	84
C	.9 (dark)	.4 (light)	0	84
D	.4 (light)	.4 (light)	0	0
E	.4 (light)	.4 (light)	20	84



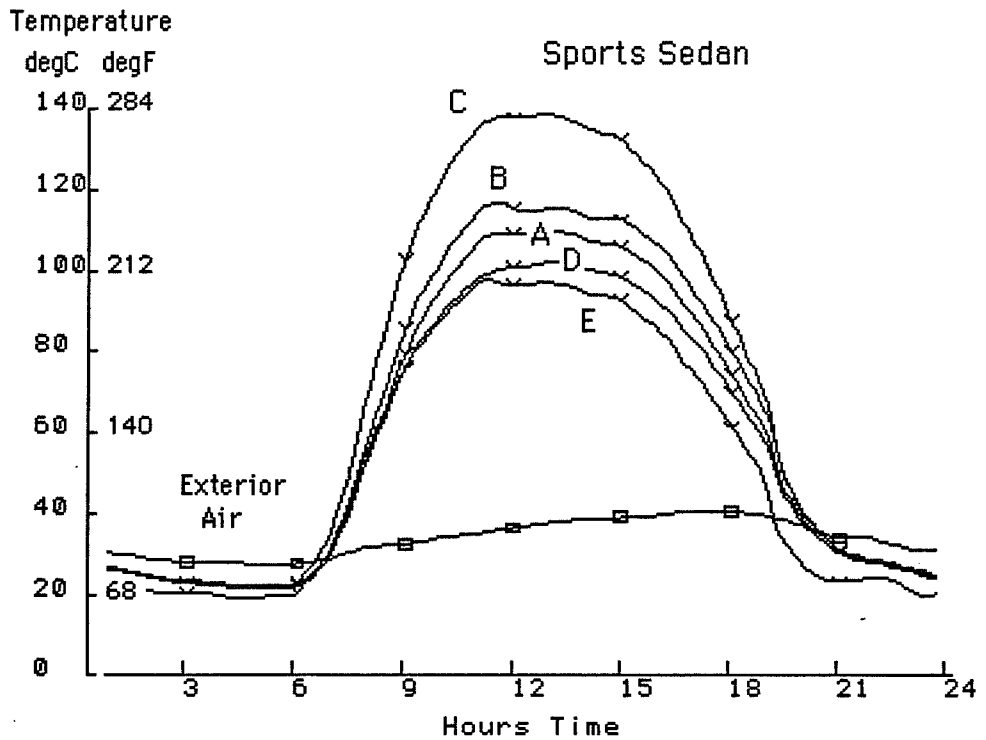
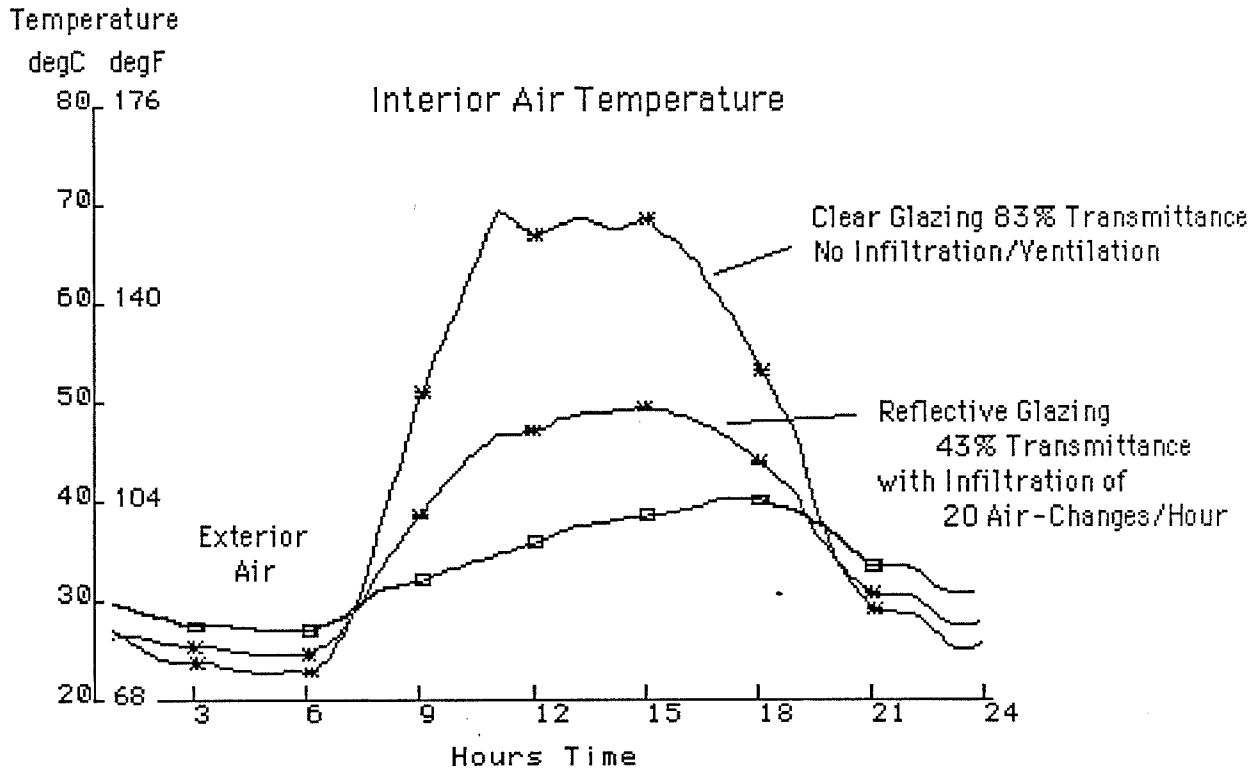


Figure 9. Dash/seat surface temperature for the standard and sports sedans during a full-day soak in Phoenix, Arizona. Values are given as a function of varying configuration properties for the models with 83% solar transmittance glazings.



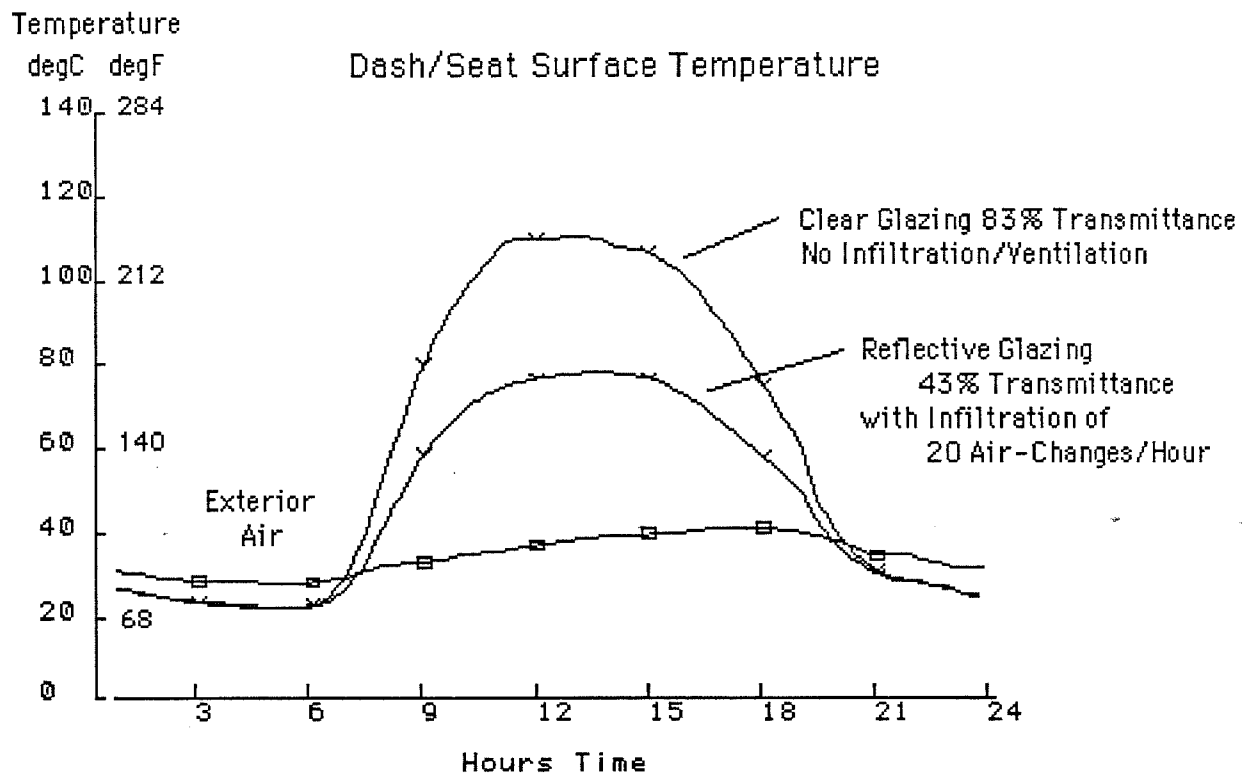
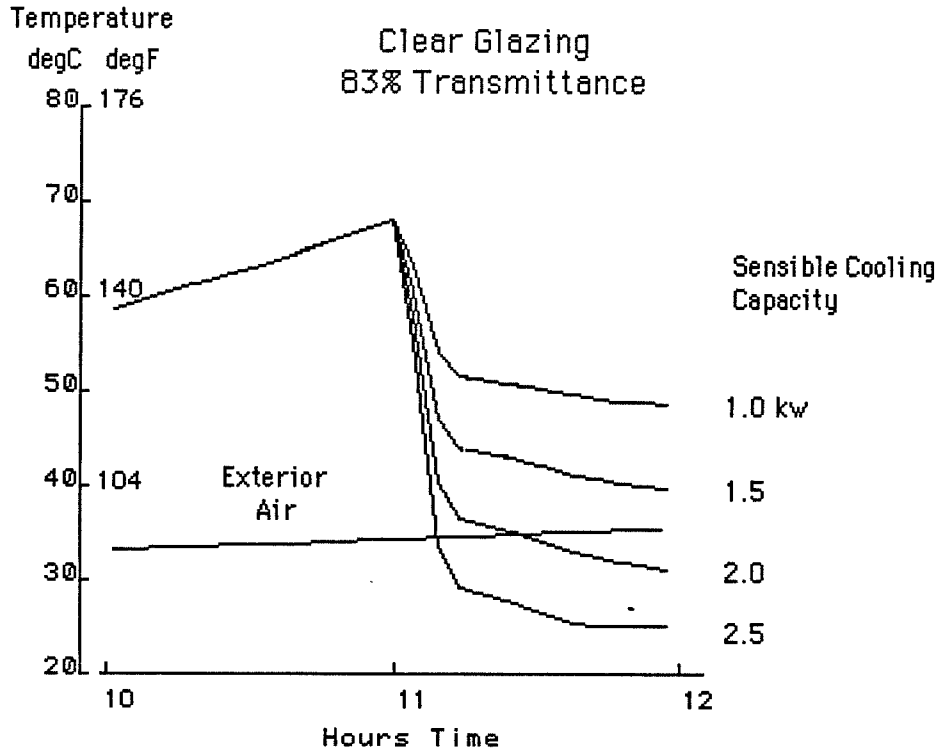


Figure 10. Interior air and dash/seat surface temperatures for the sports sedan during a full-day soak in Phoenix, Arizona. Values are given for an 83% transmittance glazing with no infiltration/ventilation and for a reflective glazing with 43% transmittance with an infiltration of 20 air changes per hour.



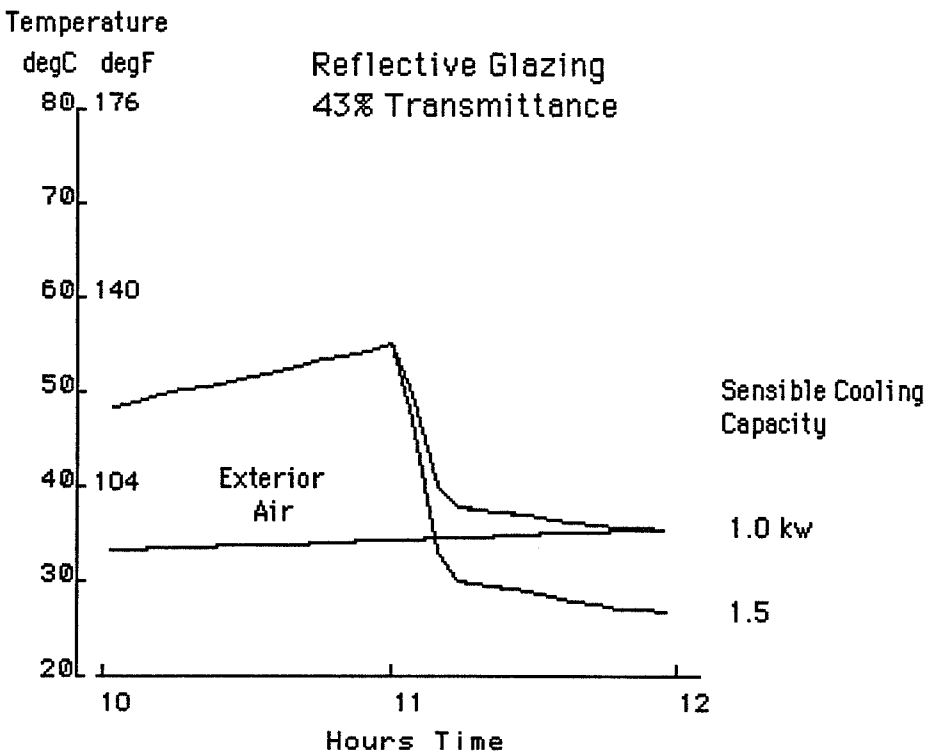
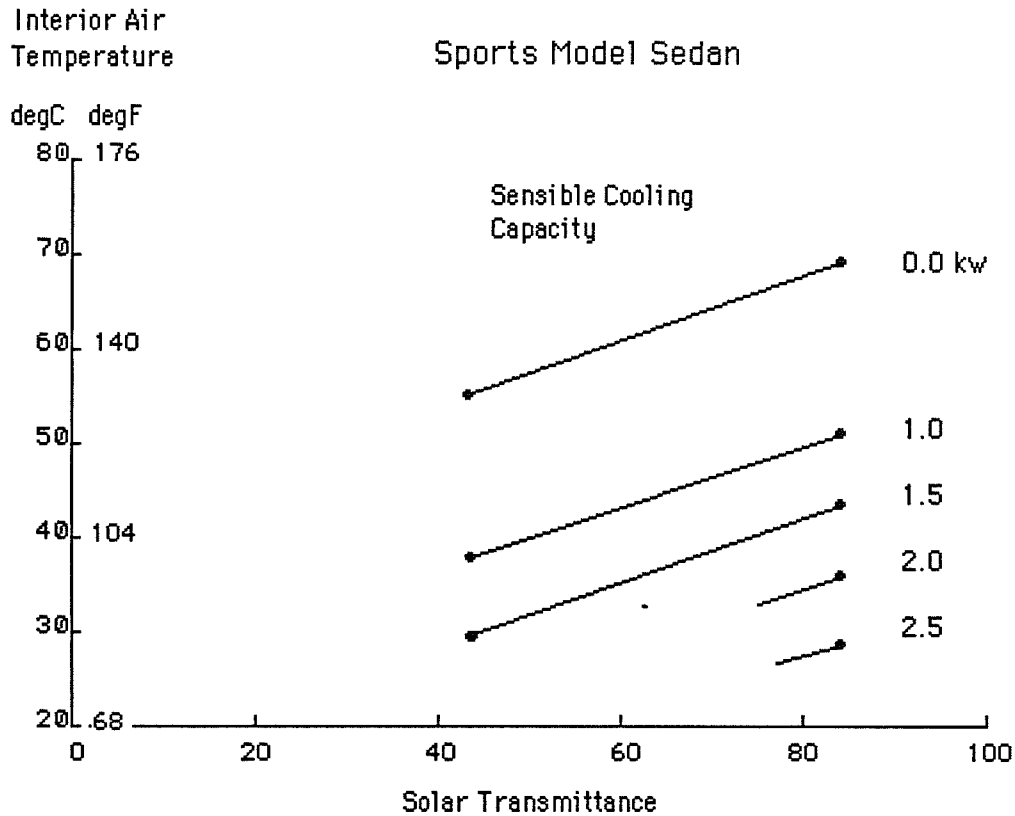


Figure 11. Interior air temperature during cool-down for the sports sedan after an initial soak. Cool-down begins at 11a.m. Results are shown for an 83% transmittance glazing and reflective glazing with 43% transmittance for varying sensible cooling capacities.



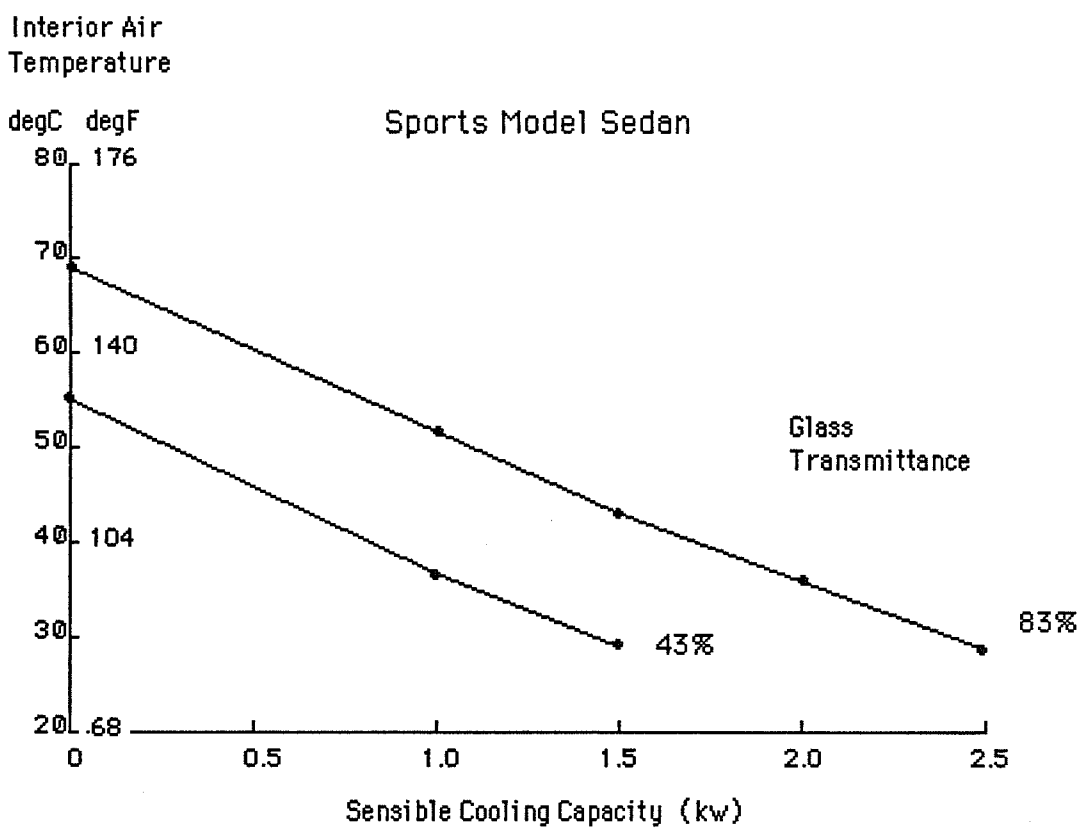
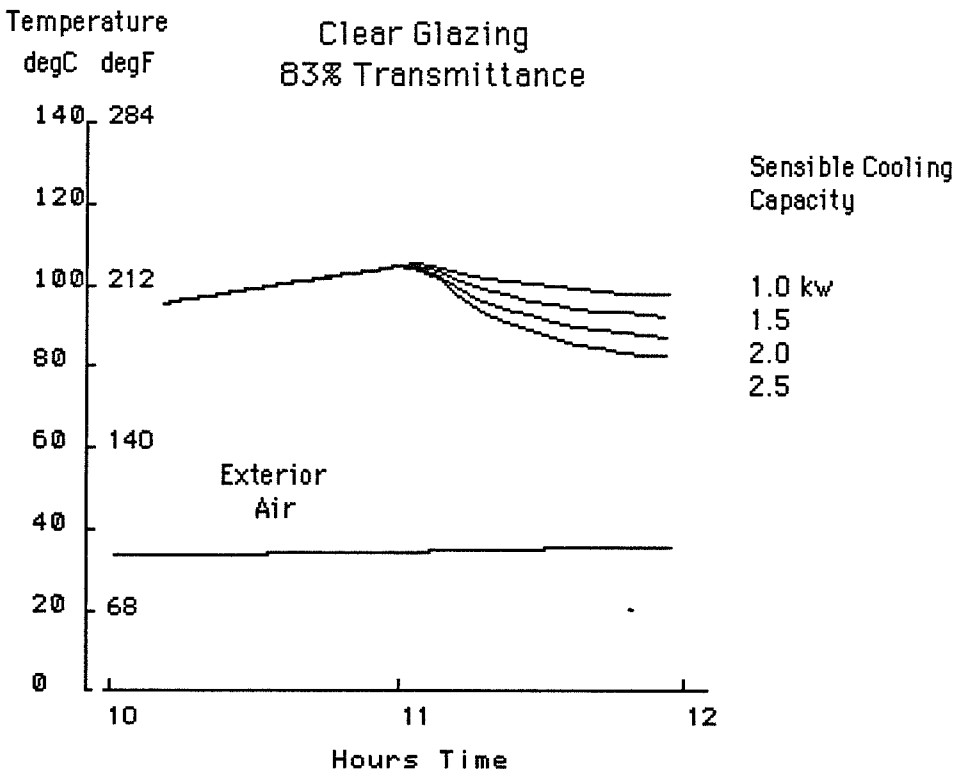


Figure 12. Interior air temperature 10 minutes after the start of cool-down for the sports model sedan. Results are shown as a function of glazing transmittance and sensible cooling capacity.



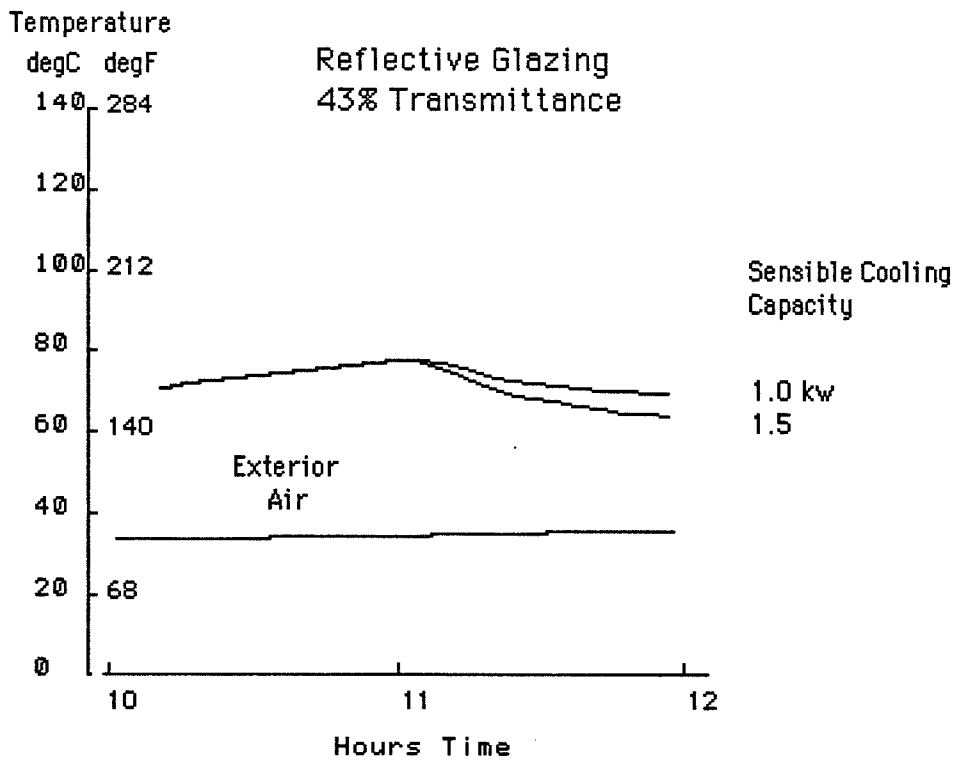


Figure 13. Dash/seat surface temperatures during cool-down for the sports sedan after an initial soak. Cool-down begins at 11a.m. Results are shown for an 83% transmittance glazing and reflective glazing with 43% transmittance for varying sensible cooling capacities.

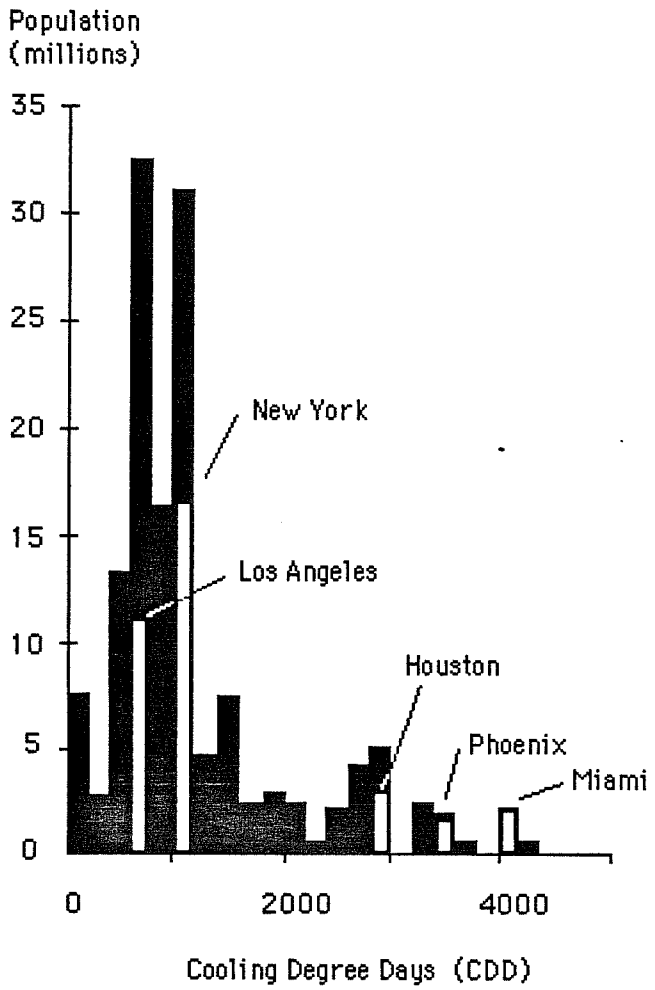


Figure 14. Population distribution of the continental United States using cooling degree days as a distribution parameter. Cooling degree days are measured from a base of 18.3°C (65°F). (Source: Ref. 1)

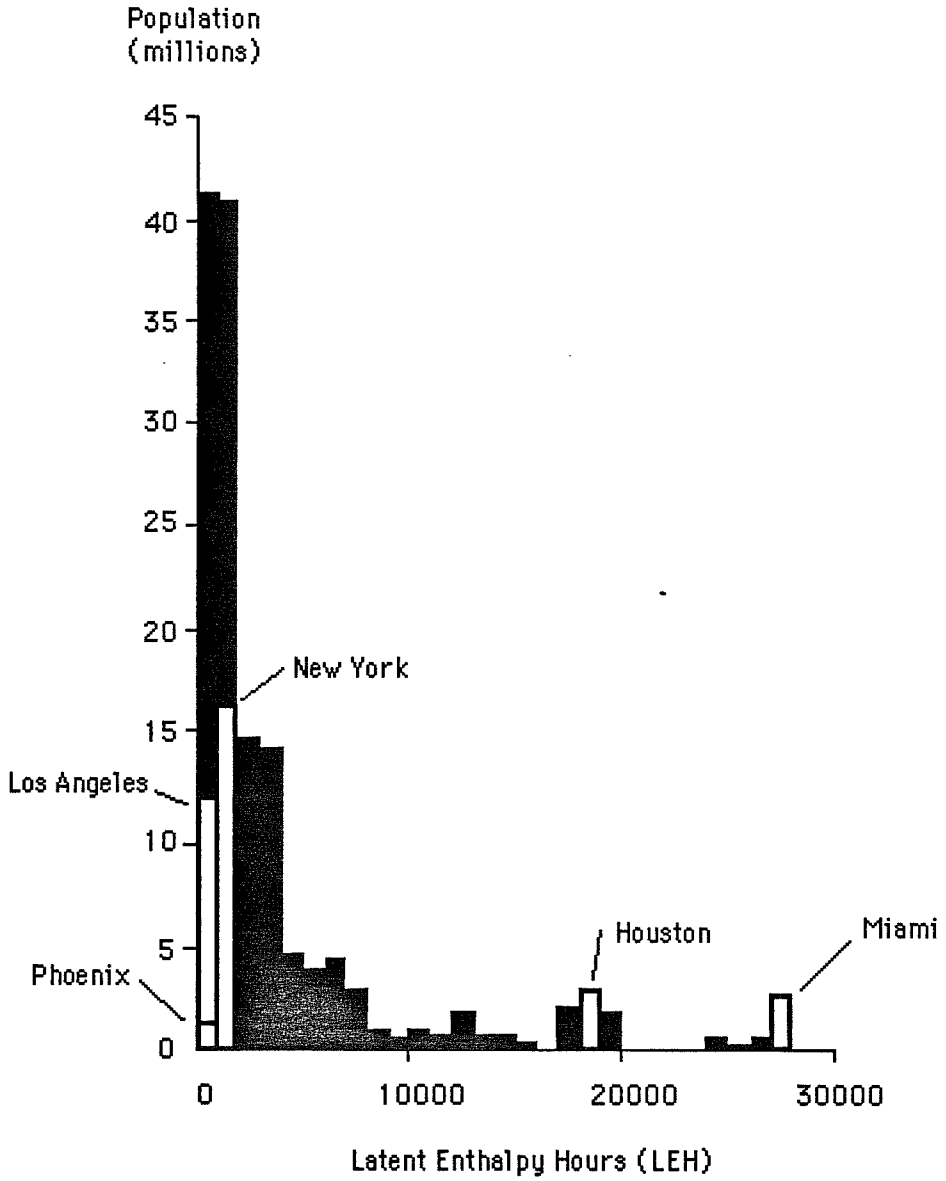


Figure 15. Population distribution of the continental United States using latent enthalpy hours as a distribution parameter. Latent enthalpy hours are measured from a base of 16.1oC (61oF) dew point temperature and 23.9°C (75°F) dry bulb temperature. (Source: Ref. 1)

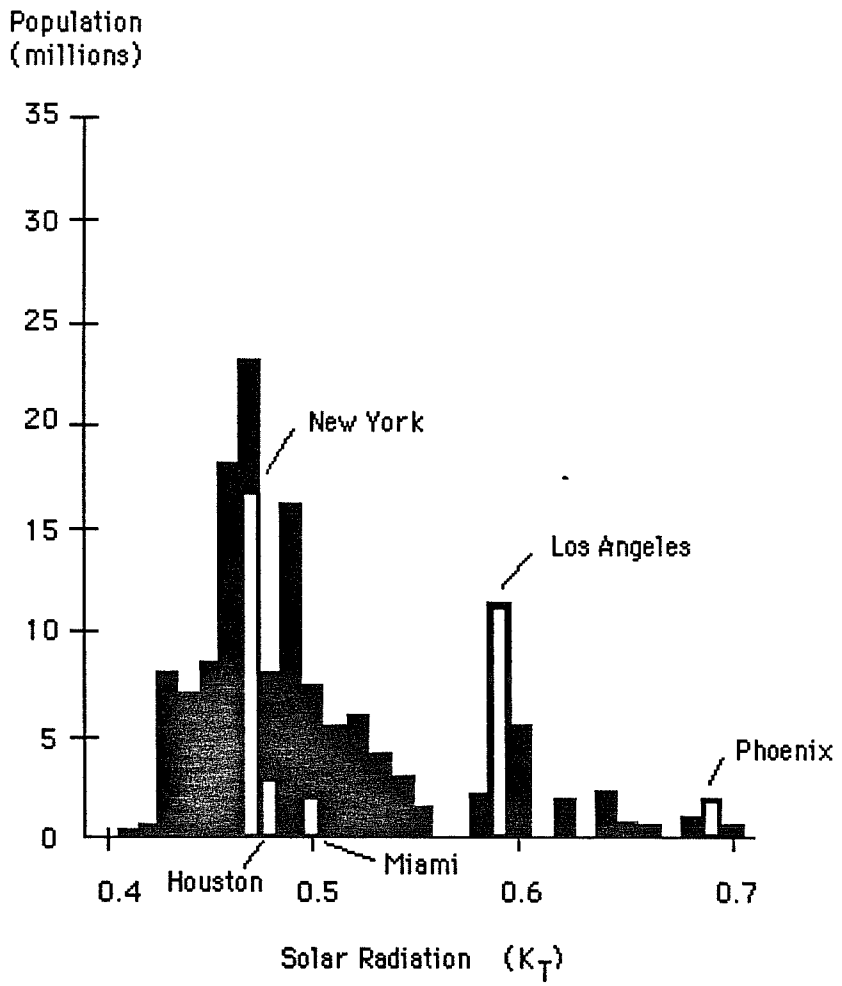


Figure 16. Population distribution of the continental United States using solar radiation as a distribution parameter. KT is the ratio of the average global horizontal radiation to the average extraterrestrial horizontal radiation. (Source: Ref. 1)

Appendix A

Interior Surface Temperature Mapping Using Infrared Imaging Technology

We documented the temperatures of the dashboard, steering wheel, and front seat surfaces during a static soak with an infrared imaging system. This experiment was conducted at the Lawrence Berkeley Laboratory using a 1984 Chevrolet Citation which is shown in Figure A.1. The ambient air temperature varied from 18°C (64°F) in the early morning to 28°C (82°F) at 2 p.m.. Solar radiation peaked at about 1 p.m. at a value of 810 W/m^2 (257 $Btu/hr\text{-}ft^2$). We oriented the car facing north with the IR camera (Figure A.2) positioned either in the rear of the car or outside the left front window. An AGA Thermovision 780 infrared imaging system was used for the purpose of gaining insight into surface temperature distributions under the above conditions. The tests were not planned to be comprehensive, but were made to determine the feasibility of performing more extensive experiments in the future. Also, although we measured actual dash and seat surface temperatures, these were not correlated to the infrared images. The presented photographs are included in this report so that readers can better understand the nature and capabilities of infrared imaging technology as applied to the overall objectives of this study.

The AGA system uses a "thermal range" and a "thermal level" to indicate the relative temperature differences between the color contours. The "thermal range" represents the range in degrees centigrade of the color spectrum that is presented along the left side of the display as seen on the attached photographs. The specific range is shown at the top of the display. The "thermal level" is the temperature value of the isotherm zero point. For our tests, the thermal level was about 32°C. Surface temperatures can be estimated by adding the thermal level to the thermal range value associated with a particular color.

Figure A.3 shows a photograph of the dashboard that corresponds to the infrared images shown in figures A.4 and A.5. These figures represent the same image using two different thermal ranges, as shown by the numbers "50" and "20" at the top of the figures. Notice that as the thermal range gets smaller, a greater variety of colors appear on the image, indicating a greater sensitivity to the actual temperature values. The hot spots are those exposed to direct sunlight: steering wheel, gear shift lever, and the top of the dashboard. Other hot spots are seen in figures A.6 through A.8, which show the steering wheel and seat cushions as viewed from the left front window.

The Thermovision 780 system had neither a real-time video capability nor a computer interface for data reduction. The system is about eight years old. Today IR technology has advanced so that the newer systems have both these items, a fact that enables more rigorous analysis. We believe that with proper calibration and further development studies, infrared imaging systems could be a very powerful tool for validation of simulation models and also help provide a more detailed quantitative and qualitative understanding of solar heat gain and cooling loads in automobiles. We plan to refine and use these techniques in future studies.

Figure A.1

Figure A.2

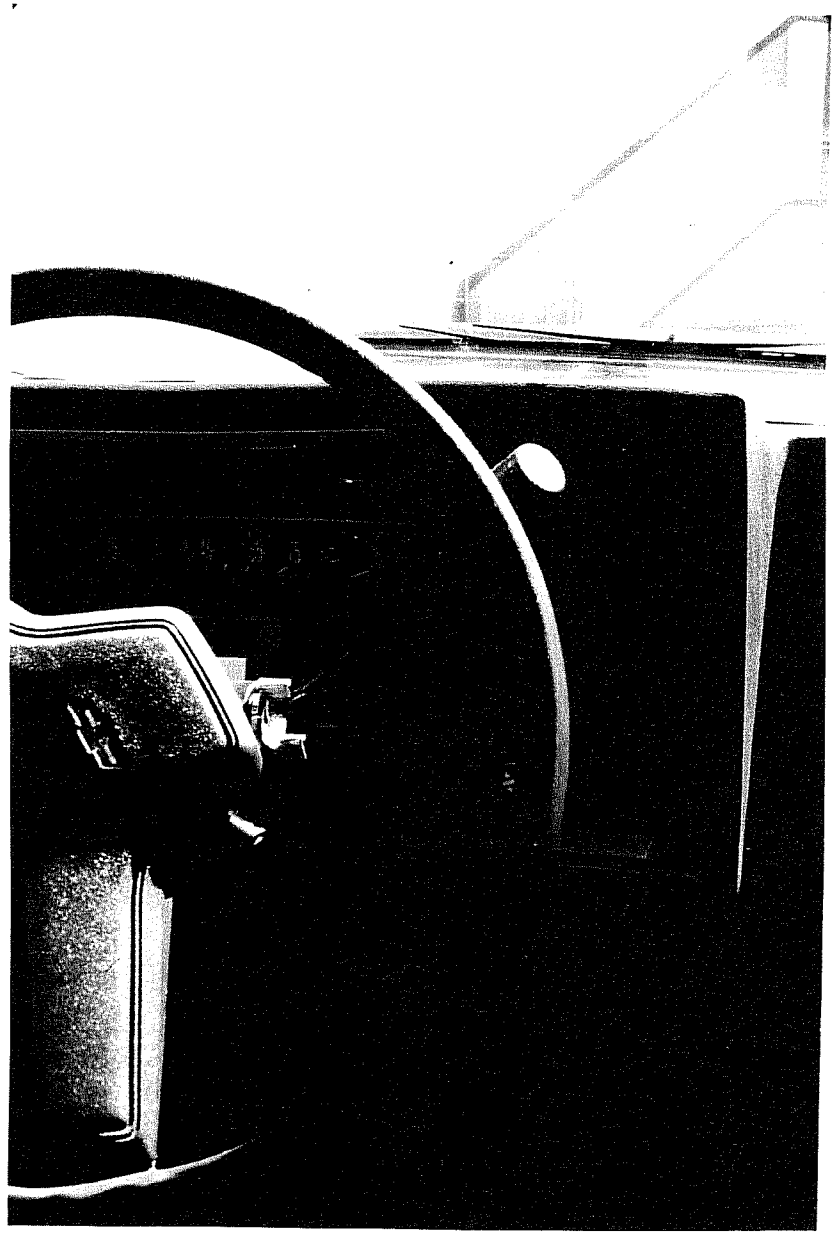


Figure A.3

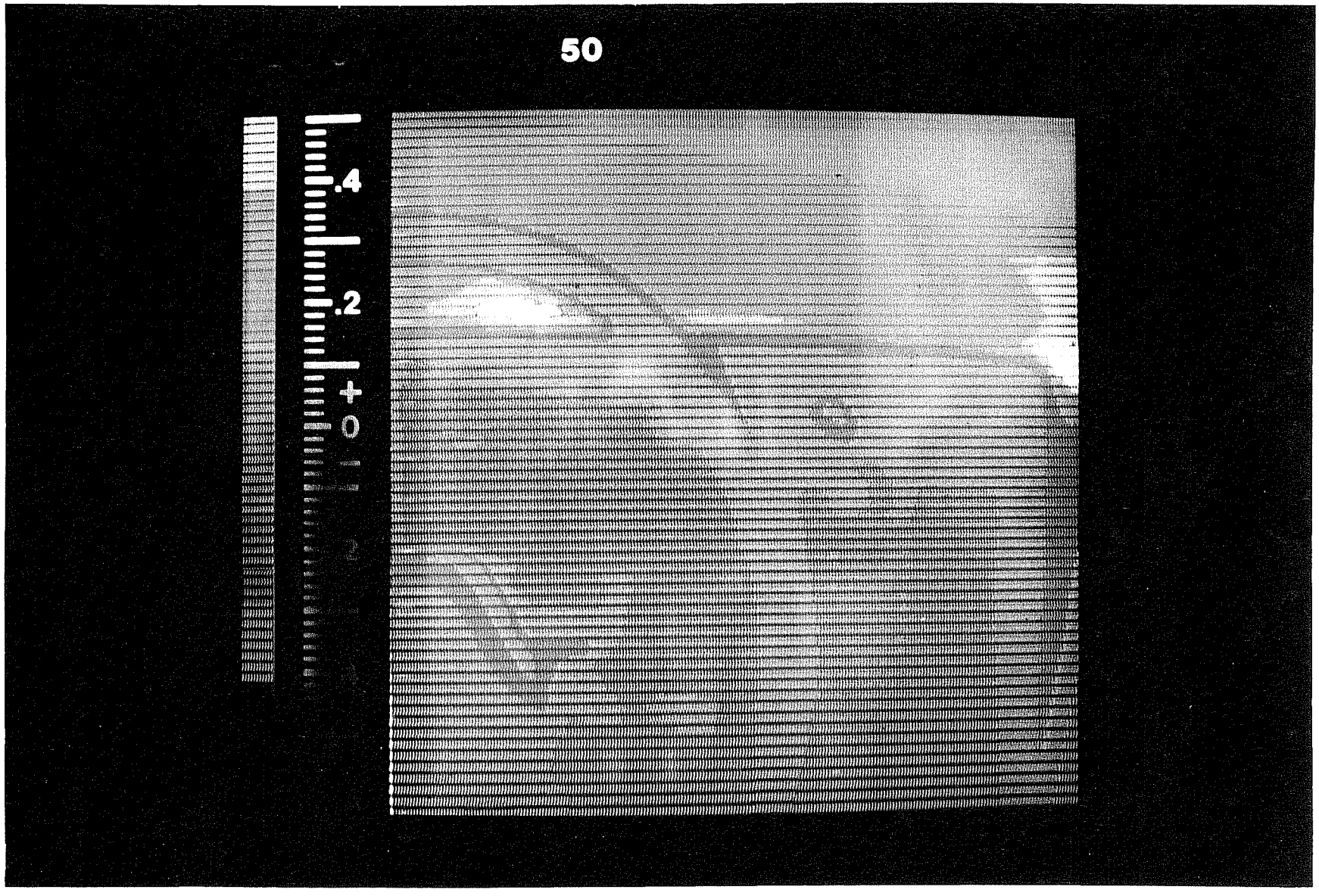


Figure A.4

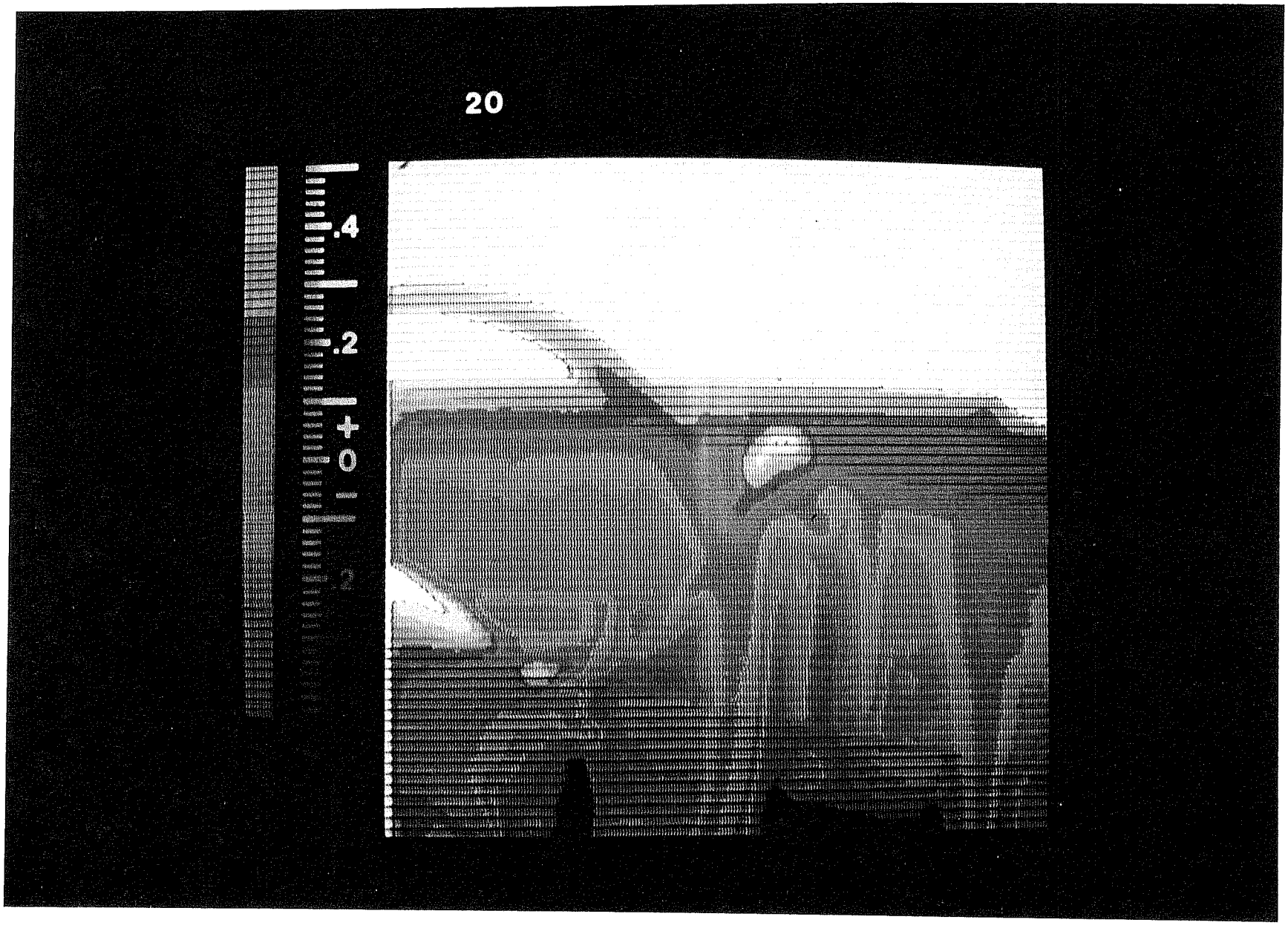


Figure A.5

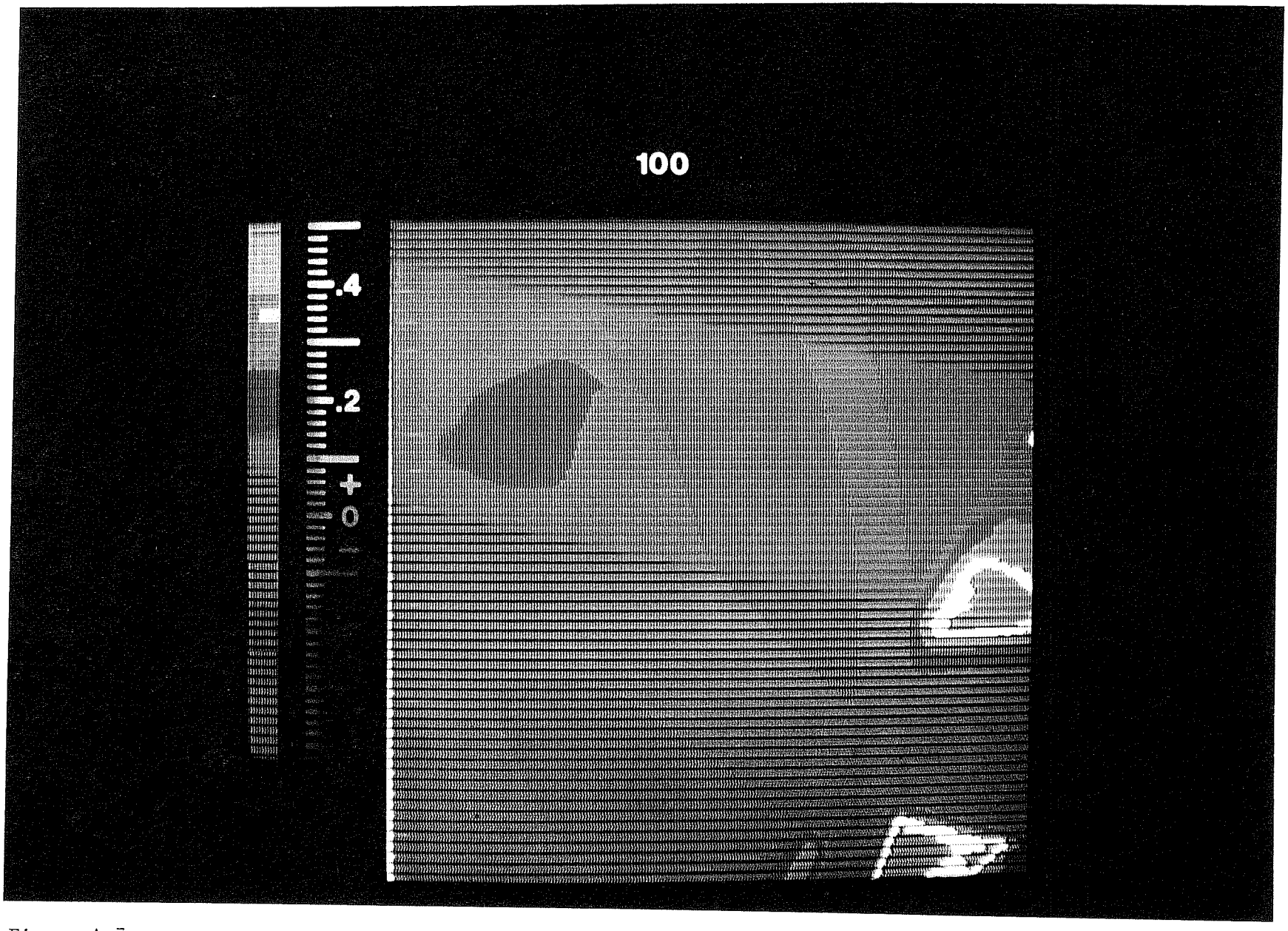


Figure A.7

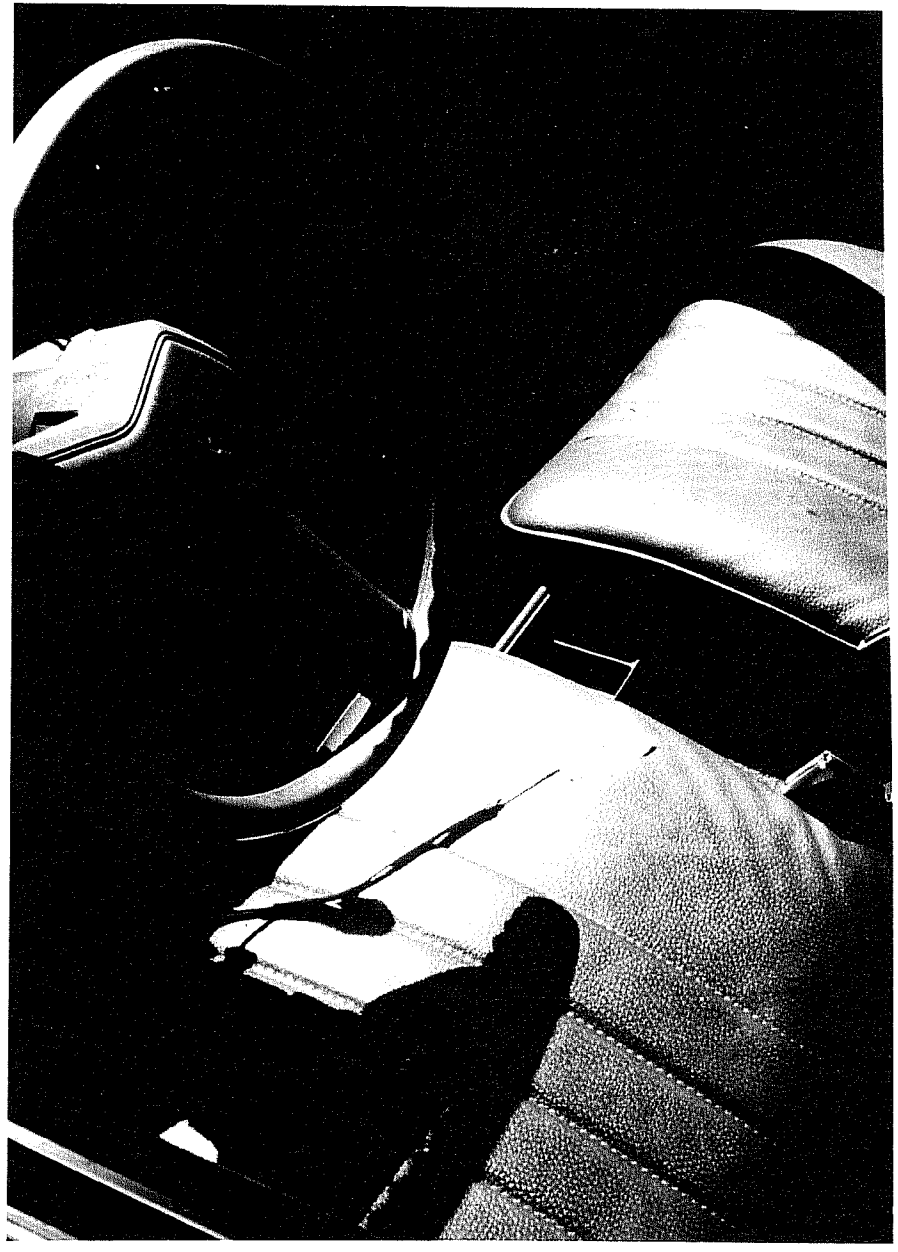


Figure A.6

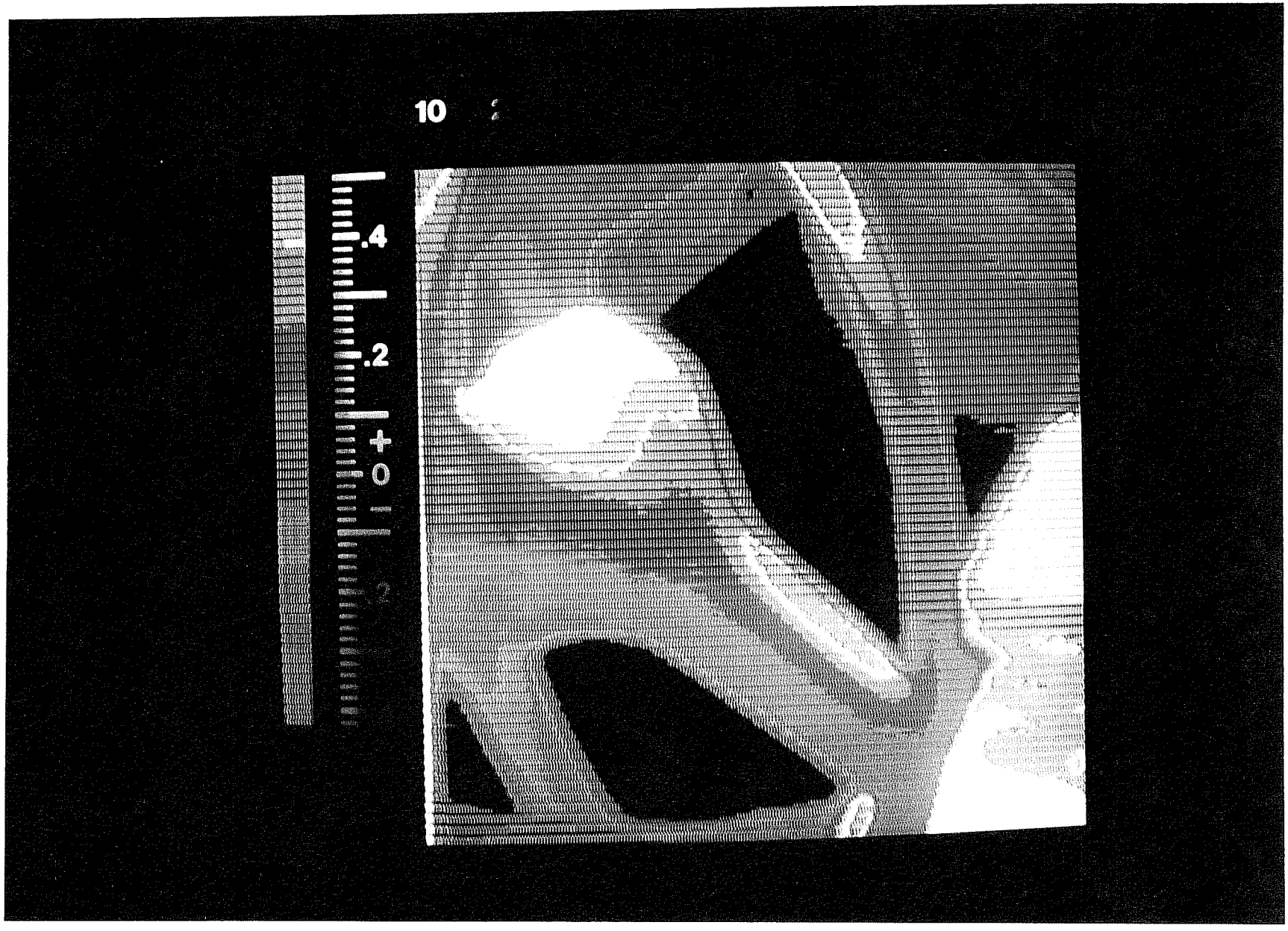


Figure A.8

Appendix B

Annotated Bibliography

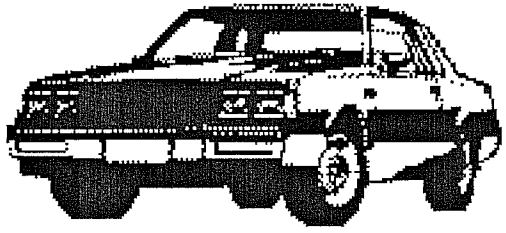
We constructed an annotated bibliography during the course of this study using the Apple® Macintosh® operating system in conjunction with Apple's HyperCard™ software product. The bibliography was distributed via floppy disk to individuals in industry and government who expressed interest in the subject matter of this investigation. We are including a paper version of the bibliography as an appendix so that readers of this report will have convenient access to this data base.

Annotated Bibliography and Data Base

Automobile Glazing and Air Conditioner Performance

Prepared by
Windows and Daylighting Group
Lawrence Berkeley Laboratory
Berkeley, California 94720
October 1, 1988

Funded by
Office of Air and Radiation
U.S. Environmental Protection Agency



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DRAFT - For Review Purposes Only

This HyperCard™ application is an annotated bibliography for a study on automobile glazing and air conditioner performance. It was created by the Windows and Daylighting Group of the Applied Science Division, Lawrence Berkeley Laboratory. The work is being supported by the U.S. Environmental Protection Agency as part of its concern for the depletion of the earth's ozone layer caused in part by CFC emissions. Automobile air conditioning is a major source of CFC emisssions. LBL's task is to define the relationships between automobile glazing, ventilation, and air conditioner performance to help identify practical strategies for reducing CFC emissions.

The bibliography contains abstract information on 19 references arranged in chronological order. Detailed information is provided for 11 references that have data specifically relevant to the LBL study. Reviewers are asked to contact Robert Sullivan, Staff Scientist at LBL, at (415) 486-6843 with comments and/or recommendations for additional references.

This work was supported by the Stratospheric Ozone Protection Program, Office of Program Development, Office of Air and Radiation of the U.S. Environmental Protection Agency under Contract No. DW89933085-01-0, Stephen Andersen, EPA Project Officer.

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No	Year	Title/Author/Affiliation	Source/Topic
1 *	1988	Auto Solar Control P. Young, R. Bernardi; Airco Solar Products	SAE 880050 Glazing
2 *	1988		SAE 880048 Glazing
3 *	1988		Unpublished Glazing
4	1987		SAE 872000 Glazing
5 *	1987		SAE 870031 Sunroof
6 *	1987		SAE 870036 Glazing
7	1986	T. Kase, M. Kawai, M. Ura; Nissan	SAE 861362 Glazing

Master Index

Use scroll bar at right for display.

Click reference to view abstract.

(*) References have detailed information.

Click to continue

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No	Year	Title/Author/Affiliation	Source/Topic
1 *	1988	Auto Solar Control P. Young, R. Bernardi; Airco Solar Products	SAE 880050 Glazing
2 *	1988	Effect of Glass Angles on the Cooling Loads of Automobile Air Conditioners; J.P. Chiou; University of Detroit	SAE 880048 Glazing
3 *	1988	Potential for Down-Sizing Auto Air Conditioners Using Innovative Glazing Technology; R. Sullivan, S. Selkowitz; LBL	Unpublished Glazing
4	1987	Improved Solar Control Car Glazing in the Rearward Field of View P. Weight, H. Albrecht; Volkswagen	SAE 872000 Glazing
5 *	1987	Sunroofs and the Cooling Loads of Automobile Air Conditioners J.P. Chiou; University of Detroit	SAE 870031 Sunroof
6 *	1987	Photovoltaic Glazing for Automotive Applications P. Aschenbrenner, J. Anderson; Arco Solar	SAE 870036 Glazing
7	1986	A New Electrochromic Device for Automotive Glass T. Kase, M. Kawai, M. Ura; Nissan	SAE 861362 Glazing

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No	Year	Title/Author/Affiliation	Source/Topic
8 *	1986	Occupant Comfort Requirements for Automotive Air Conditioning W.J. Atkinson; Sun Test	SAE 860591 Glazing
9	1986	Comfort Evaluation of Heating and Air Conditioning Systems H. Kawamoto, Y. Hosokawa, M. Suto, K. Nakajima; Nihon Radiator	SAE 860590 Comfort
10 *	1986	Application of Solar-Powered Ventilator in Automobiles J.P. Chiou; University of Detroit	SAE 860585 Ventilation
11	1986	New Methods for Evaluation of the Thermal Environment in Auto-motive Vehicles; T.L. Madsen, B. Olesen, K. Reid; General Motors	ASHRAE Trans Comfort
12 *	1985	Development of a Laminated Heat-Reflecting Glass Y. Kai, E. Kawasaki; Nissan	JSAE Review Glazing
13	1985	A New Method for the Detailed Assessment of Human Heat Balance in Vehicles; D. Wyon, C. Tennstedt, I. Lundgren, S. Larsson; Volvo	SAE 850042 Comfort
14 *	1982	Analysis on Air-Conditioning Heat Load of Passenger Vehicle S. Shimizu, H. Hara, F. Asakawa; Toyota	JSAE Review Glazing

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No	Year	Title/Author/Affiliation	Source/Topic
15	1979	The Heat Transfer Coefficient of a Passenger Car Body J. Nitz, W.H. Hucho; Volkswagen	SAE 793148 Car Body
16	1979	Passenger-Car Ventilation for Thermal Comfort J.Temming, W.H. Hucho; Volkswagen	SAE 790398 Comfort
17 *	1979	Comfort Criteria for Air Conditioned Automotive Vehicles F.H. Rohles, S.B. Wallis; Kansas State University, Ford	SAE 790122 Comfort
18 *	1975	Simulation Modeling of Automobile Comfort Cooling Requirements D.W. Ruth; University of Manitoba	ASHRAE Journal Air Conditioning
19	1974	Cooling Effect of Car Ventilators M. Asakai, Y. Sakai	JSME Bulletin Ventilation

Help Find

Title

Auto Solar Control

Author

P. Young, R. Bernardi

Affiliation

Airco Solar Products

Source

SAE Paper 880050, February 1988

Type of Study

Experimental, Glazing, Solar Load Control

Abstract

The trend in automotive design today is towards a more aerodynamic look with increased outward visibility. This results in larger glass areas. On current sports cars, 70% of the load on the air conditioner is due to solar heating through the glass.

At Airco Solar Products, a solar control coating has been produced that is only 36% transmissive to solar radiation, yet transmits 70% of the visible spectrum weighted to illuminant "A".

Computer models predict that this coating can reduce the heat loads on automobile air conditioners up to 22%. Actual tests under high solar load conditions indicate a 9.4 C difference in interior temperature after a one hour soak as compared to standard glass.

1988 P. Young et al. SAE 880050

Model

1988 Pontiac Firebird

Ambient Weather

Phoenix, Arizona, June
38.9 C, 60% RH, 1041 W/sqm

Driving Conditions

Static Soak
Cool-Down, Test Track Driving, 48 km/h
Cool-Down, Test Track Driving, 80 km/h
Cool-Down, City Driving, 40 km/h

Primary Interests

Glazing, Cooling Load Reduction

Conclusions

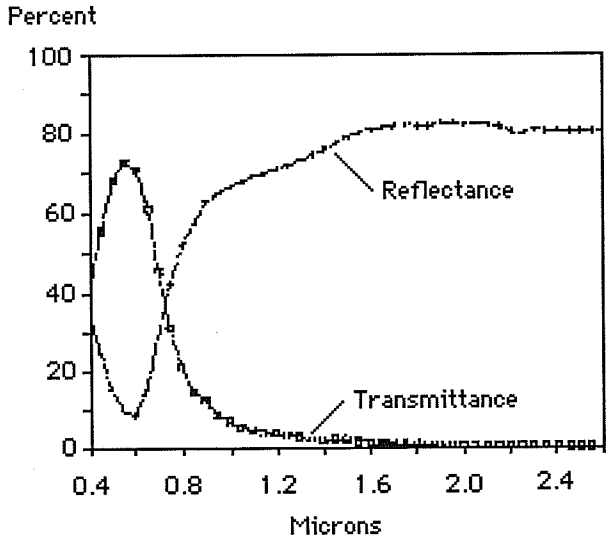
High solar transmission of automotive glass results in the need for special materials and very large air conditioners.

A film has been developed which can be sputtered onto glass and will greatly reduce the solar energy transmission of the glass while still maintaining the legal 70% visible transmission. Results showed the film significantly reduced the interior air temperature.

The passenger compartment temperature was 9.4 C (17 F) lower with the coated glass and only 12.2 C (22 F) above ambient air temperature as compared to standard absorbing glass.

The film can be produced in mass quantities for the U.S. automotive market.

Glass Transmittance and Reflectance as a Function of Wavelength



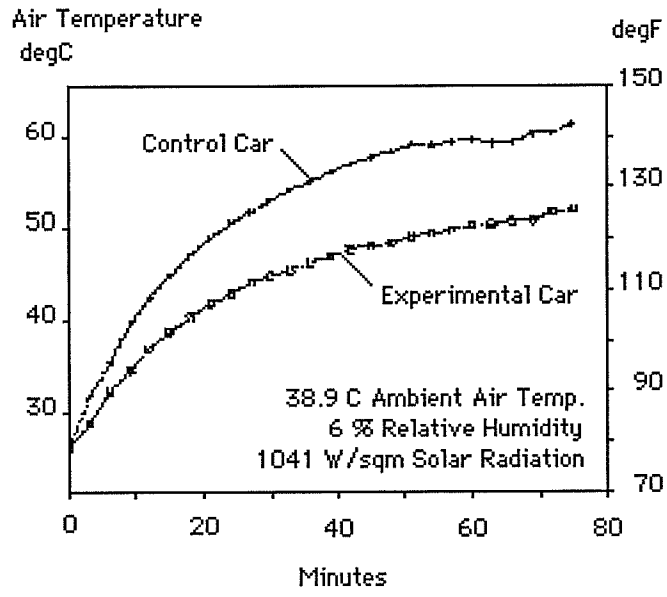
The developed film is a simple stack of thin metal and dielectric layers. The metal is highly reflective in the infrared spectrum to reflect the invisible heat from the sun. Dielectric layers "anti-reflect" the metal in the visible wavelengths.

The coated glass reflects over 45% of the incident solar radiation and transmits only 34%. It will also transmit 70% of the visible light weighted to illuminant "A".

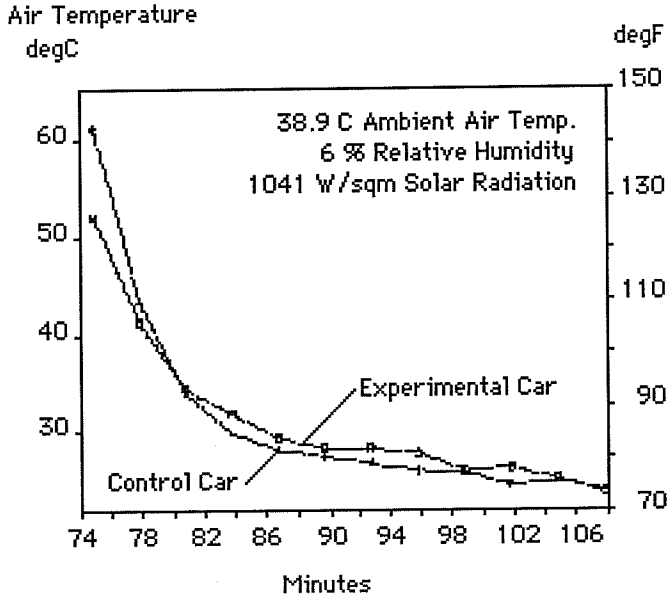
One-Hour Soak
Interior Temperatures

A one-hour stationary soak test was conducted with the windshield exposed to direct sunlight from the South. All windows were rolled up.

The standard absorbing glass in the control car transmits and re-radiates absorbed energy into the car. Heat is then trapped by the greenhouse effect. The solar control glass in the experimental car reflected enough solar energy to keep the car 9.4 C (17 F) cooler than the control car and only 12.2 C (22 F) above ambient air temperatures. The control car reached temperatures around 60 C (140 F), the experimental car reached temperatures around 50 C (122 F).



Interior Temperatures after Highway Driving at 48 km/h and 80 km/h



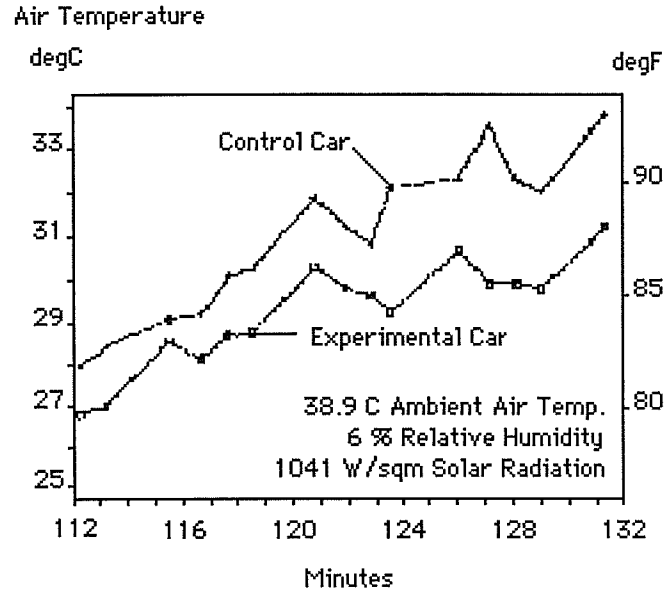
After the soak test the engines were started and the air conditioning set to maximum. Both cars were driven over a test track at 48 km/h (30 mph) for 5 miles. Then the speed was increased to 80 km/h (50 mph) for another 5 miles.

The test data shows that the experimental car was as cool as the control car, not significantly hotter. When the cars are moving at higher speed, heat absorbed by the standard glass is convected to the outside air, thus reducing the difference between absorbing and reflecting glass.

Interior Temperatures under City Driving Conditions

City driving was simulated as follows: accelarate to 40 km/h (25 mph), then stop for 30 seconds. Repeat 16 times with every fourth stop 2 minutes long.

The experimental car stayed much cooler (by 1 to 4 C or 2 to 7 F). This difference increased as the test continued. The film coating had a significant effect on the temperature inside the car.



Title

Effect of Glass Angles on the Cooling Loads of Automobile Air Conditioners

Author

J.P. Chiou

Affiliation

Mechanical Engineering Department
University of Detroit, Detroit, Michigan

Source

SAE Paper 880048, February 1988

Type of Study

Analytical, Glazing, Air Conditioning

Abstract

This paper presents the characteristics of the directional total transmissivity of solar insolation through the glass panels of windshield, backlight and side windows of automobiles. The effect of the glass angles on the interior air temperatures of the automobiles and the cooling loads of their air conditioners are discussed.

As the modern trend of automobile design tends towards large glass areas and larger glass angles their effect on the required capacity for the air conditioner gradually becomes more important.

Help Index Data

Click "Data" for more information

Find

1988 J.P. Chiou SAE 880048

Model

Typical Passenger Car without Sunroof

Ambient Weather

June 21th at 32 degN Latitude
43.3 C, 20% RH, 946 W/sqm

Driving Conditions

Static Soak
Cool-Down

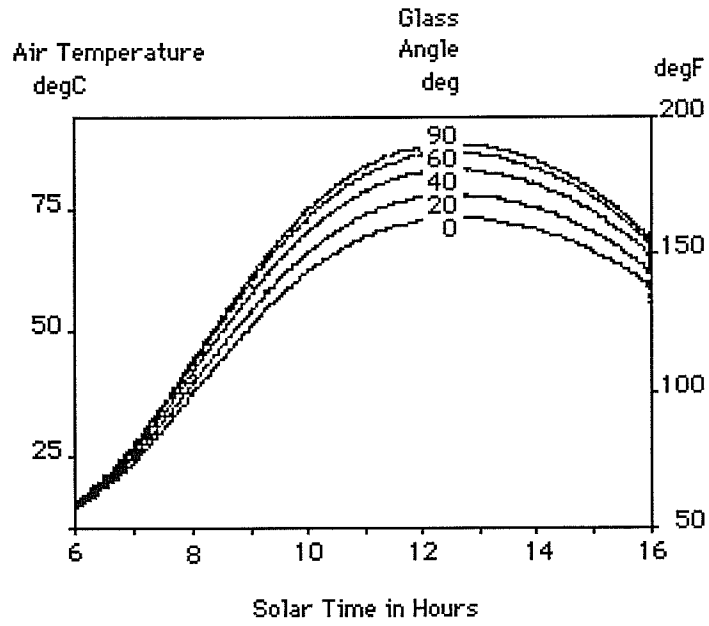
Primary Interests

Glazing Angle, Cooling Load Reduction

Conclusions

When the glass angle increases from the vertical to the horizontal (glass panel in vertical position: glass angle = 0), the angle of incidence of the solar insolation on the glass panel generally decreases. Then the directional total transmissivity of the solar insolation through the glass panel increases, as does the solar radiant energy transmitted to the glass. The interior air temperature of the vehicle increases accordingly. More air conditioner capacity is required.

Under peak solar conditions, there is an approximate difference of 17 C (30 F) in interior air temperature when the glass angle is changed from 0 degrees (vertical glass panel) to 90 degrees (horizontal glass panel) and a 25% increase in the air conditioner capacity required to achieve comfort.



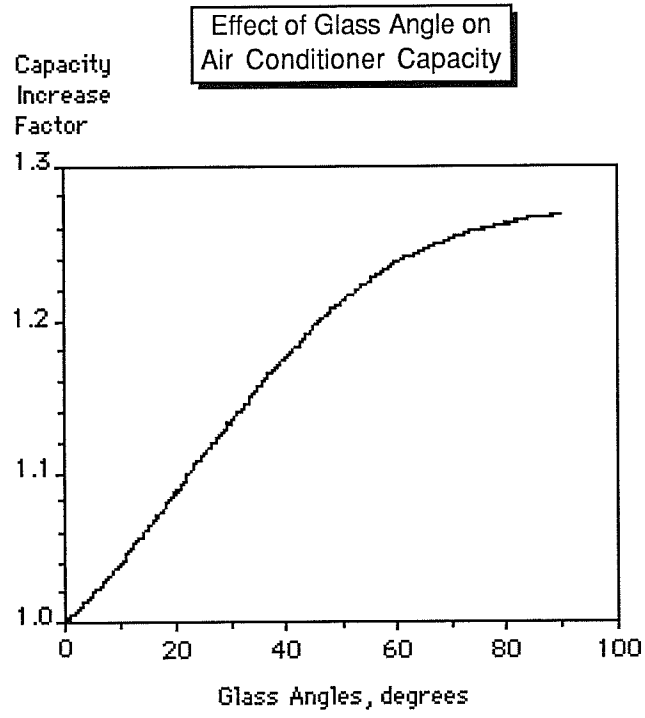
Effect of Glass Angle on Interior Temperature

The computer simulation shows that the larger the angles of the glass panels, the higher the interior temperature under soaking conditions. The smaller the glass angles the lower the solar heat load on the air conditioner.

The glass angles used here are defined as the acute angle between the glass panel and the normal to the horizontal plane. They vary only for the windshield and the backlight. The glass angles of the side windows are fixed at 15 degrees.

This figure presents the relationship between the angle of the glass panels and the capacity increase factors of the air conditioner of the automobile. The larger the glass angles of the windshield and backlight, the higher the capacity increase factor of the air conditioner.
In other words, the required capacity of the air conditioner increases with increasing glass angles.

The capacity increase factor is the ratio of the capacity of the air conditioner of any vehicle to that of the baseline vehicle (glass angle = 0).



Title

Potential for Down-Sizing Automobile Air Conditioners Using Innovative Glazing Technology

Author

R. Sullivan, S. Selkowitz

Affiliation

Lawrence Berkeley Laboratory, Berkeley, California

Source

Unpublished notes, January 1988

Type of Study

Analytical, Parametric, Glazing, Air Conditioning

Abstract

A preliminary draft report was prepared that documented the variation of interior air and surface temperatures of a sports model sedan over the course of an entire day under static soak conditions. We studied the effects of solar load reduction by systematically changing the glazing solar transmittance for each window. Temperature, humidity, wind, and solar conditions for a June 30th day in Phoenix, Arizona were used in the analysis. Also investigated were varying interior and exterior surface absorptivities, infiltration levels, and interior mass. An ideal air conditioner was simulated to study the cool-down response characteristics.

Help Index Data

Click "Data" for more information

Find

1988 R. Sullivan et al. Unpublished

Model

Sports Model Sedan

Ambient Weather

Phoenix, Arizona; June 30th,
40 C , 5% RH, 861 W/sqm

Driving Conditions

Static Soak
Cool-Down (sensible component only)

Primary Interests

Glazing, surface absorptivity, infiltration, interior mass, air conditioner sizing

Conclusions:

Solar radiation through automobile windows is the dominant source of heat buildup during static soak conditions.

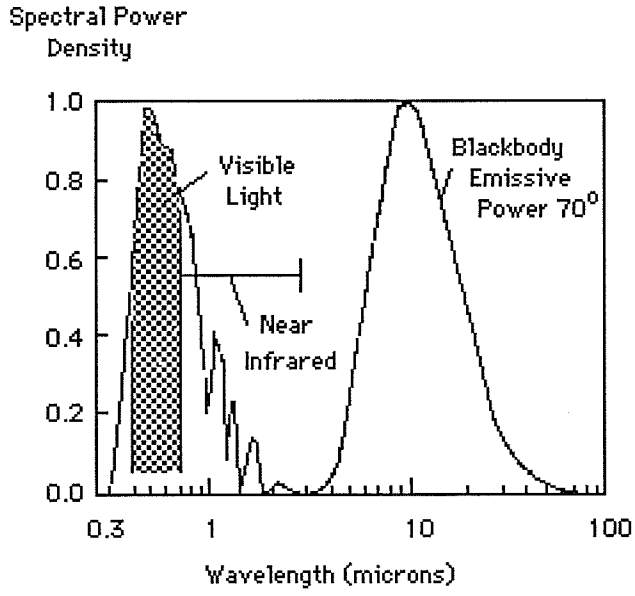
A significant reduction in solar load can be achieved by reducing the solar transmittance of the windows.

Heat buildup can also be reduced significantly through ventilation and/or infiltration of outside air. This prevents the interior surfaces from overheating and re-radiating to the air.

Through combined improved glazing and ventilation, the required air conditioner capacity to achieve comfort during cool-down can be reduced.

1988 R. Sullivan et al. Unpublished

Solar Spectrum Characteristics



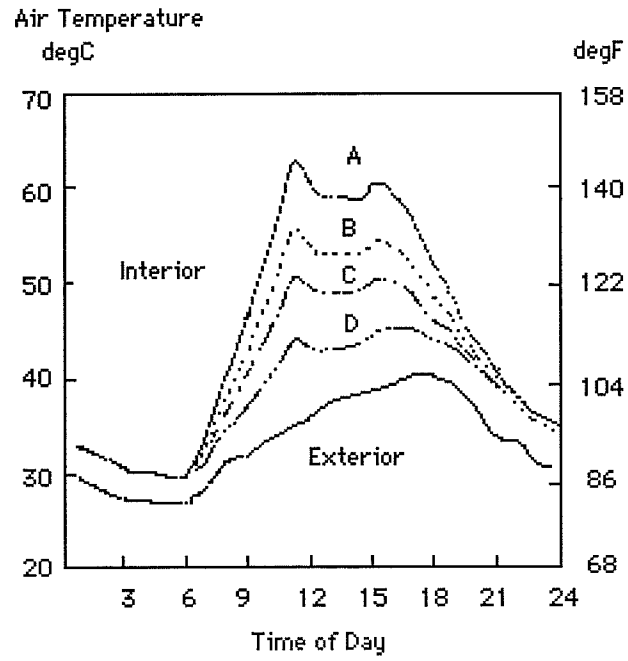
This figure shows the solar spectrum and the area of concern in developing new glazing products for automobiles. Current U.S. government regulations require that about 70% of the visible portion of the spectrum be maintained. Thus solar control can best be obtained by eliminating as much infrared radiation as possible. One could also, under static soak conditions, decrease the amount of radiation in the visible part of the spectrum.

1988 R. Sullivan et al. Unpublished

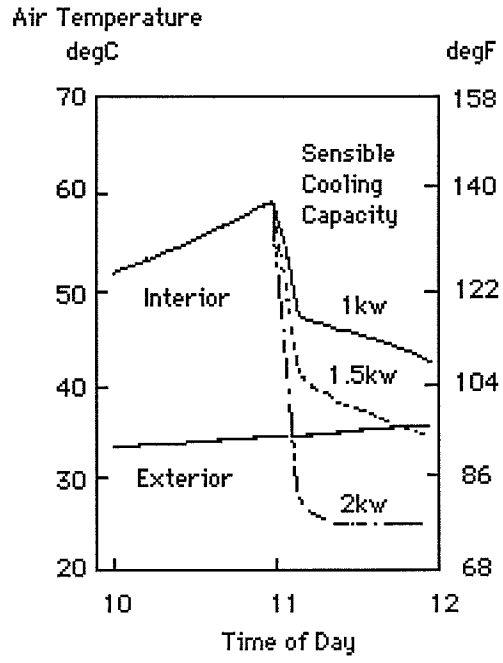
Interior Air Temperature for Varying Glazing Solar Transmittance

The interior air temperature build-up under full-day soak conditions in Phoenix, Arizona on a June 30th is shown on this figure for a sports model sedan. Outside air temperature varies from about 29 C (85 F) in the morning to 40 C (104 F)in the late afternoon. Incident solar radiation peaks at 861 W/sqm (80 W/sqft) at midday. The interior air temperature is seen to gradually approach the outside temperature as each window is progressively made more opaque to solar radiation.

Transmittance at Normal Incidence			
	Front	Rear	Side
A	0.83	0.83	0.83
B	0.43	0.43	0.43
C	0.43	0.23	0.23
D	0.43	0.03	0.03



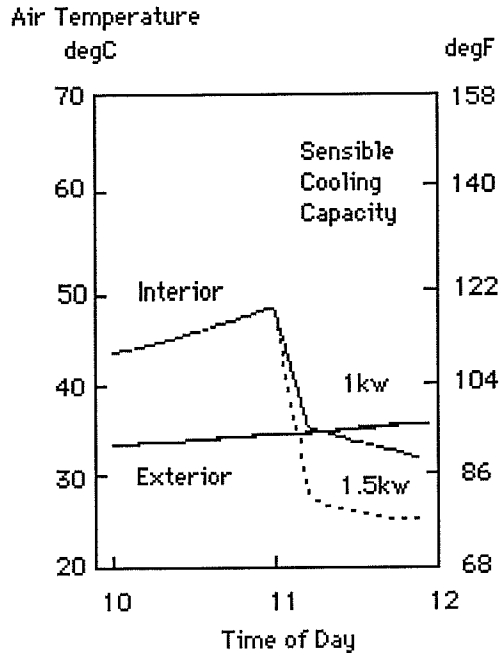
1988 R. Sullivan et al. Unpublished



Air Conditioner Capacity Effects on Cool-Down Characteristics

We show on this figure the sensible load cool-down characteristics for the sports model sedan with clear glazing on all windows (83% transmittance). Three air conditioner capacities are presented and the results indicate that at least a 2 kW unit is required to achieve comfort. Outside temperature and solar radiation quantities are the same as on the previous figure.

1988 R. Sullivan et al. Unpublished



Air Conditioner Capacity Effects on Cool-Down Characteristics

Comfort is achieved using a 1.5 kW capacity airconditioner by reducing the glazing transmittance of the front windshield to 43% and of the side and rear windows to 23%. The interior air temperature build-up at 11am is reduced approximately 10 C (18 F) when using the lower transmittance glazing.

Title

Improved Solar Control Car Glazing in the Rearward Field of View - An Approach to Update Regulations

Author

P. Weight, H. Albrecht

Affiliation

Volkswagen

Source

SAE Paper 872000, February 1987

Type of Study

Experimental, Glazing, Comfort

Abstract

An investigation was carried out by means of a driving simulator to determine how drivers react when looking through windshields with varying degrees of luminous transmittance in the range of 90% to 40%. A windshield with scattered light produced by surface damages was also investigated.

Results obtained show that a small amount of scattered light impairs the driver's vision much more than windows with a normal depth of tint. Dark windows can be tolerated in locations in the car where the images normally observed are of high contrast levels.

Title

Sunroofs and the Cooling Loads of Automobile Air Conditioners

Author

J.P. Chiou

Affiliation

Mechanical Engineering Department, University of Detroit, Detroit, Michigan

Source

SAE Paper 870031, February 1987

Type of Study

Analytical, Sunroof, Glazing, Air Conditioner

Abstract

The net solar heat load of the vehicle with a sunroof without a sunshade will increase and the interior air temperature of the vehicle will be relatively higher than that in a similar vehicle not equipped with a sunroof. The cooling load of the air conditioning system will thus increase accordingly.

This paper presents a discussion of the thermal characteristics of an automobile equipped with a sunroof. The sunroof's impact on the transient temperature responses of the vehicle when exposed to solar radiation and the effect of the sunroof on the cooling load demands of the automobile are presented.

Help Index Data

Click "Data" for more information

Find

1987 J.P. Chiou SAE 870031

Model

Generic 4-Door Sedan

Ambient Weather

June 21st at 32 degN Latitude
43 C, 15% RH, 969 W/sqm

Driving Conditions

Static Soak
Cool-Down (from various initial starting temperatures)

Primary Interests

Sunroof Solar Load Performance

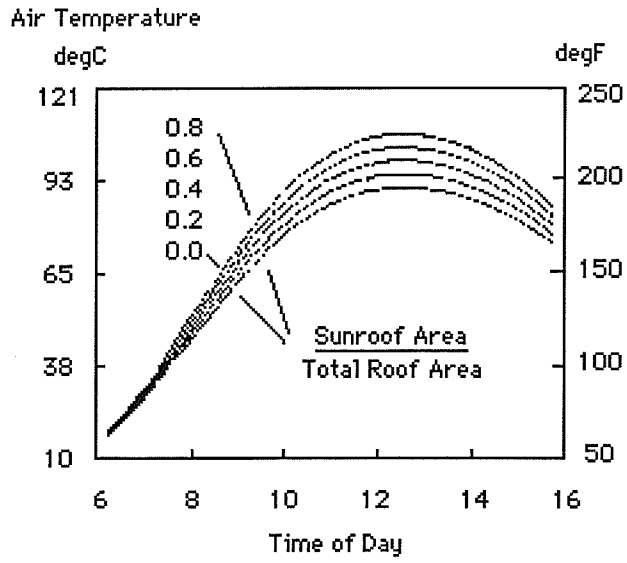
Conclusions:

Sunroof size has a larger impact on reducing the interior air temperature and cooling load demand than does changing the glass transmittance.

For a vehicle equipped with a sunroof whose area is 80% of the roof area and solar transmittance of 60%, the interior air temperature reaches a value of 108 C (227 F) under peak solar load conditions. A vehicle without a sunroof approaches 91 C (195 F).

For a vehicle equipped with a sunroof whose area is 80% of the roof area and solar transmittance of 60%, it takes about 25 minutes to reach comfort conditions. A vehicle without a sunroof takes about 10 minutes.

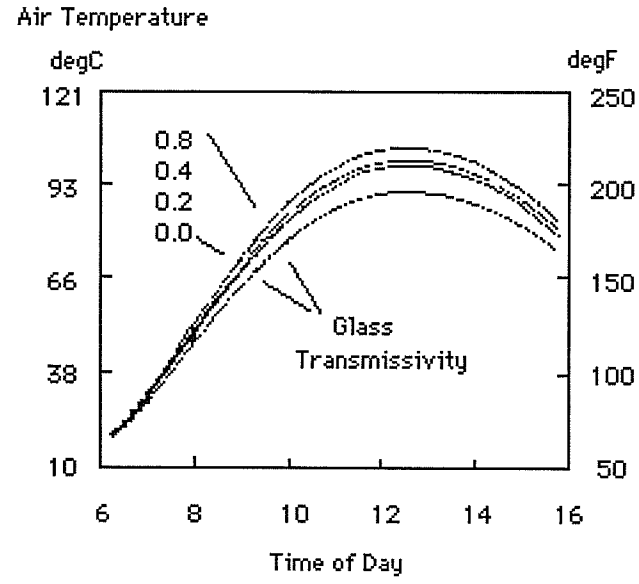
Effect of Sunroof Area on Interior Air Temperature Under Static Soak



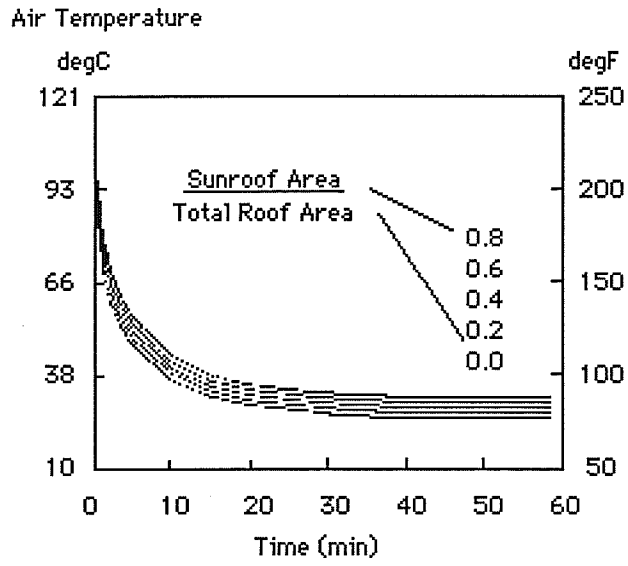
Under peak solar load conditions, the interior air temperature varies between 91 C (195 F) for a vehicle with no sunroof to 108 C (227 F) for a vehicle with an 80% area sunroof. The rate of change of air temperature with area is relatively constant at peak conditions at about 0.2 C (0.4 F) per unit area. Sunroof solar transmittance was fixed at 80%.

Effect of Sunroof Transmittance on Air Temperature Under Static Soak

Under peak solar load conditions, the interior air temperature varies between 91 C (195 F) for a vehicle with no sunroof to 104 C (220 F) for a vehicle with a sunroof of 80% transmittance. The rate of change of air temperature with transmittance varies significantly with a rather large, abrupt increase in temperature at low transmittance values, followed by a more gradual temperature increase with increasing transmittances. Sunroof area was fixed at 60% of the roof area.



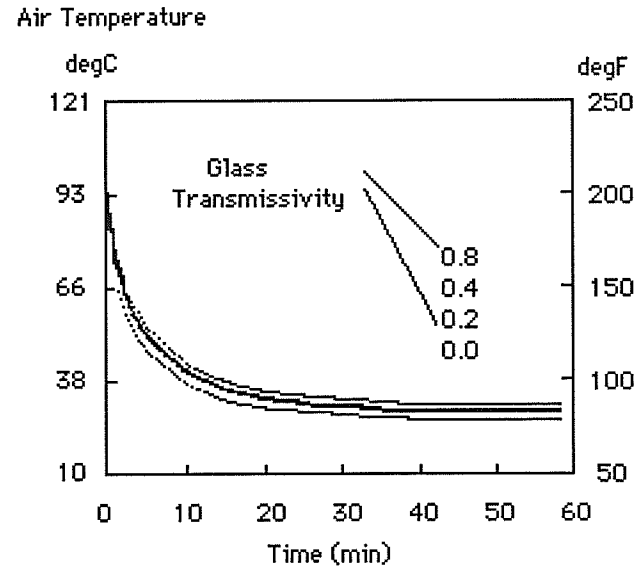
Effect of Sunroof Area on Cool Down Characteristics



This figure shows the effects of sunroof area on cool down characteristics. Starting conditions correspond to the peak temperatures shown on page 2 of this series. As an example of the response time, it is seen that a temperature of 32 C (90 F) is reached within 10 minutes for the vehicle without a sunroof. For a vehicle equipped with a sunroof whose area is 80% of the roof area, it takes about 25 minutes to reach the same condition.

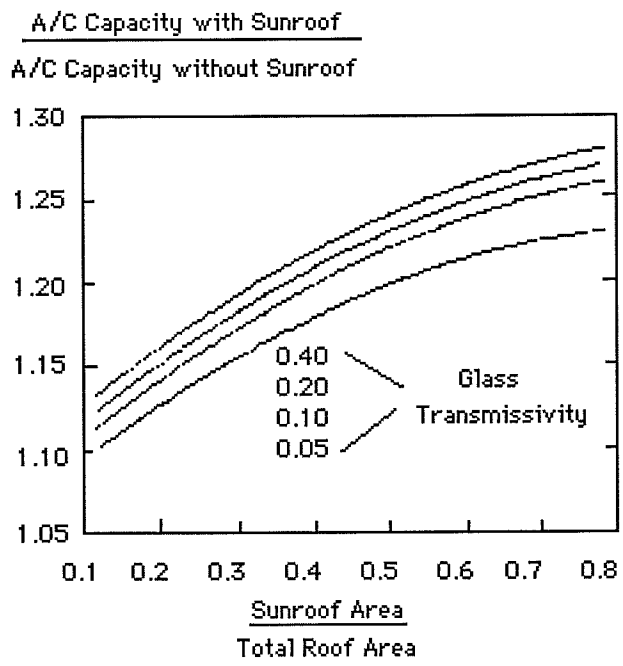
Effect of Sunroof Transmittance on Cool Down Characterictics

This figure shows the effects of sunroof glass transmittance on cool-down characteristics. Starting conditions correspond to the peak temperatures shown on page 3 of this series. As an example of the response time, it is seen that a temperature of 32 C (90 F) is reached within 10 minutes for the vehicle without a sunroof. For a vehicle equipped with a sunroof whose solar transmittance is 80%, it takes about 20 minutes to reach the same condition.



1987 J.P. Chiou SAE 870031

Effect of Sunroof Area and Transmittance on A/C Capacity



This figure presents the relative capacities of air conditioning systems required for vehicles equipped with several different sunroofs. The relative capacity is defined as the ratio of the capacity of the air conditioning system required for a vehicle with a sunroof to that required without a sunroof. The capacity of the vehicle with the sunroof is defined as that needed to reduce the air temperature at the end of 10 minutes to within 0.3 C (0.5 F) of the A/C unit of the vehicle without a sunroof. Results indicate that surface area has a much greater effect on A/C sizing than does sunroof glass transmittance.

Title

Photovoltaic Glazing for Automotive Applications

Author

R. Aschenbrenner, J. Anderson

Affiliation

ARCO Solar Incorporated

Source

SAE Paper 870036, February 1987

Type of Study

Analytical, Parametric, Ventilation, Glazing

Abstract

A computer simulation of an automobile has been prepared which enables the spectral characteristics of the glass windows, semi-transparent photovoltaic sunroofs, and special solar control coatings and films to be incorporated into the thermal analysis. This paper presents the resultant interior temperatures for three vehicle configurations when subjected to various ventilation flow rates, convection conditions, and solar control coatings.

Help Index Data Click "Data" for more information Find

1987 R. Aschenbrenner et al. SAE 870036

Model

Generic Sedan with Sunroof

Ambient Weather

August 15th at 32 degN latitude,
46 C, (Solar radiation not given, probably about 861 W/sqm)

Driving Conditions

Static Soak

Primary Interests

Ventilation, Photovoltaic Sunroof, Glazing, Solar Load

Conclusions

Solar-powered ventilation systems in conjunction with highly selective metal/metal oxide films on the sunroof glazing surface significantly lower the automobile interior air temperatures for parked automobiles.

With a 0.46 sqm (5 sqft) sunroof and selective glass, the air temperature is reduced from 75 C (116 F) to 50 C (112 F) and the interior mass temperature from 84 C (184 F) to 64 C (149 F).

For an 1.67 sqm (18 sqft) "Glassroof" case, the air temperature is reduced from 78 C (173 F) to 47 C (116 F) and the mass temperature from 96 C (204 F) to 67 C (153 F).

This table shows the reduction in interior air and mass temperature associated with using a photovoltaic sunroof (.46 sqm, 5 sqft) that supplies ventilation at a rate of 49 l/s (103 cfm) and a glassroof (1.67 sqm,18 sqft) that supplies ventilation at a rate of 109 l/s (230 cfm).

The PV glass itself is responsible for a small reduction in temperature because of its spectral transmission characteristics; however, the major reduction is due to the use of outside air ventilation.

Effect of PV Roof and Ventilation on Interior Air and Mass Temperatures

Configuration	Air Temp degC	Mass Temp degC
Steel Roof	72	80
Sunroof, Clear Glass	75	84
Sunroof, PV Glass	73	81
Sunroof, PV Glass w/Ventilation	53	72
Glassroof, Clear Glass	78	96
Glassroof, PV Glass	72	83
Glassroof, PV Glass w/Ventilation	47	75

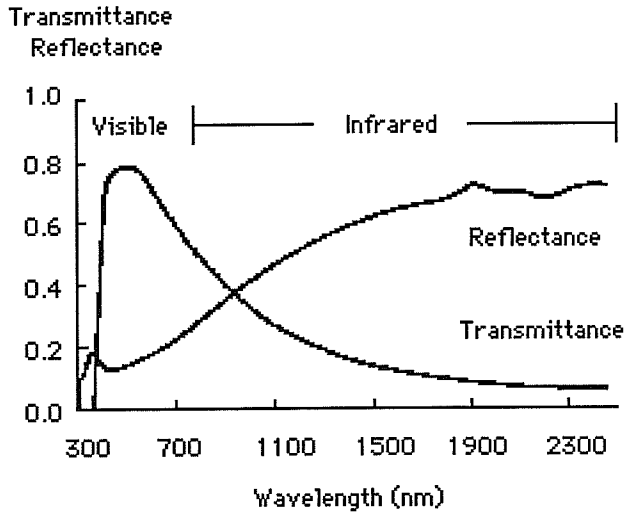
Effect of Ventilation Flow Rate Sunroof Case		
Flow Rate l/s	Air temp degC	Mass Temp degC
0	74	81
11.8	64	77
23.6	58	76
47.2	54	74
70.8	51	73
94.4	49	72

Since the goal is to reduce both the air and interior mass temperature, the optimum is probably near 47.2 l/s (100 cfm) for the "Sunroof" case and 200 cfm (94 .4 l/s) for the "Glassroof" case.

The variation in interior air and mass temperature for the sunroof and glassroof configurations as a function of ventilation flow rate is shown in these tables. There is a diminishing return with each incremental increase in air flow.

Effect of Ventilation Flow Rate Glassroof Case		
Flow Rate l/s	Air Temp degC	Mass Temp degC
0	73	84
11.8	58	79
23.6	53	77
42.7	49	76
70.8	47	76
94.4	46	75

Spectral Characteristics of Metal/ Metal Oxide Coated Glass



Coating systems have been developed which have metal or metal oxide compound films sandwiched between oxide films. These coatings are quite selective and allow 70-75% visible transmittance, but greatly reduce infrared transmittance. Typical transmission and reflection characteristics are shown on this figure for a metal oxide coated glazing.

The thermal performance of highly selective metal/metal oxide glazing is compared with clear glass for three automobile configurations in this table. In this analysis the visible light transmission is approximately 70%, and the total energy input to the automobile is about 53% of the clear glass input due to the transmission reduction in the near-infrared region.

The table shows that the highly selective glass coating is very beneficial, and by itself, significantly reduces the interior temperatures. However, the results are even better when used in combination with solar-powered ventilation.

Effect of Highly Selective Metal/Metal Oxide Glazing on Interior Air and mass Temperatures

Configuration	Air Temp degC	Mass temp degC
No PV Roof/Ventilation		
SteelRoof, Plain Glass	73	81
SteelRoof, Selective Glass	64	68
Sunroof, Clear Glass	75	84
Sunroof, Selective Glass	64	69
Glassroof, Clear Glass	78	96
Glassroof, Selective Glass	64	73
With PV Roof/Ventilation		
Sunroof, Plain Glass	53	73
Sunroof, Selective Glass	50	64
Glassroof, Plain Glass	48	76
Glassroof, Selective Glass	47	67

Title

A New Electrochromic Device for Automotive Glass - The Development of Adjustable Transparency Glass

Author

T. Kase, M. Kawai, M.Ura

Affiliation

Nissan Motor Company, Japan

Source

SAE Paper 861362, September 1986

Type of Study

Glazing

Abstract

A new transparent type electrochromic device (ECD) has been developed. It consists of two electrochromic thin films facing each other, one of "prussian blue" (PB) and the other of tungsten trioxide (WO3). PB exhibits a high intensity of coloration and is blue in the oxidized state and transparent in the reduced state. By electrode position, the PB layer can be formed on large substrates at low cost.

This ECD was applied to large, curved automotive glass. It reversibly turns from dark blue to transparent at low operating voltage and maintains the same intensity of coloration without the aid of an external power supply. Compared with photochromic glass, it achieves a greater color change in a shorter time and its light absorption can be changed at will. It shields passengers from the discomfort of glare and heat flow through glass.

Title

Occupant Comfort Requirements for Automotive Air Conditioning Systems

Author

W.J. Atkinson

Affiliation

Sun Test Engineering

Source

SAE Paper 860591, February 1986

Type of Study

Experimental, Parametric, Comfort, Glazing

Abstract

This paper describes the occupant comfort levels of seven production vehicles when evaluated under "real world" owner test conditions and the effects of film on glazing surfaces and interior vehicle temperature.

Today, the automotive industry is a world market and the products must meet the demand of the owner. Sun Test Engineering has run an air conditioner evaluation program to determine levels of performance of various a/c products in Phoenix, Arizona the last several years. In the summer of 1985, 17 vehicles were evaluated for customer satisfaction and the results of 7 vehicles are presented in this paper. Additional test programs were conducted on the effect of film applied to the glazing surface.

1986 W.J. Atkinson SAE 860591

Model

Seven Standard Sedans, One Sports Model

Ambient Weather

Phoenix, Arizona;
36 -41 C , 17% RH, 871 W/sqm

Driving Conditions

City driving, various speeds
Static Soak (1 hour)
Static Soak (full day)

Primary Interests

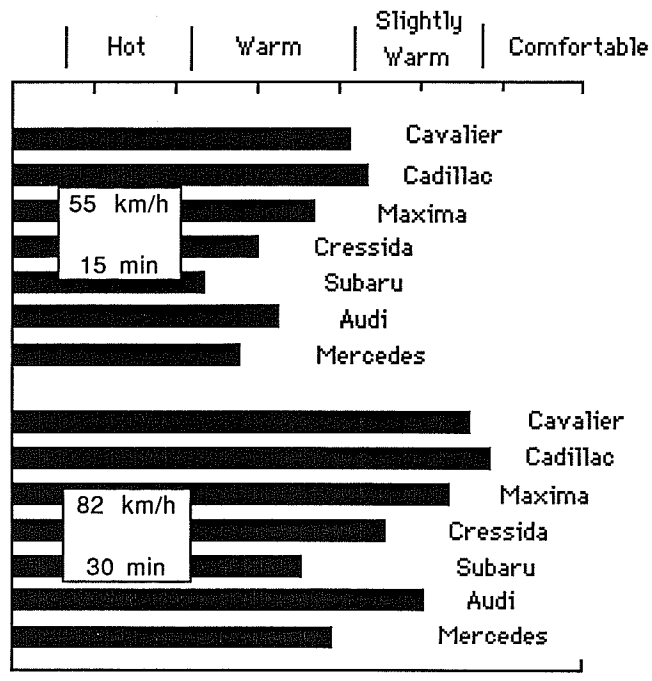
Comfort evaluation, interior air temperature buildup, glazing

Conclusions

In recent years, vehicles have become more fuel efficient, however, the a/c systems require the same, if not more, power to satisfy the owner's needs.

With smaller vehicles and increased glazing surfaces, the load demands are greater on a/c systems.

Better consideration for vehicles' styling to reduce solar heat input, improved systems air flow and efficient outlet location and design will be required to provide the needs of the future customer.



Average Four Seat Passenger Comfort After 15 and 30 Minutes

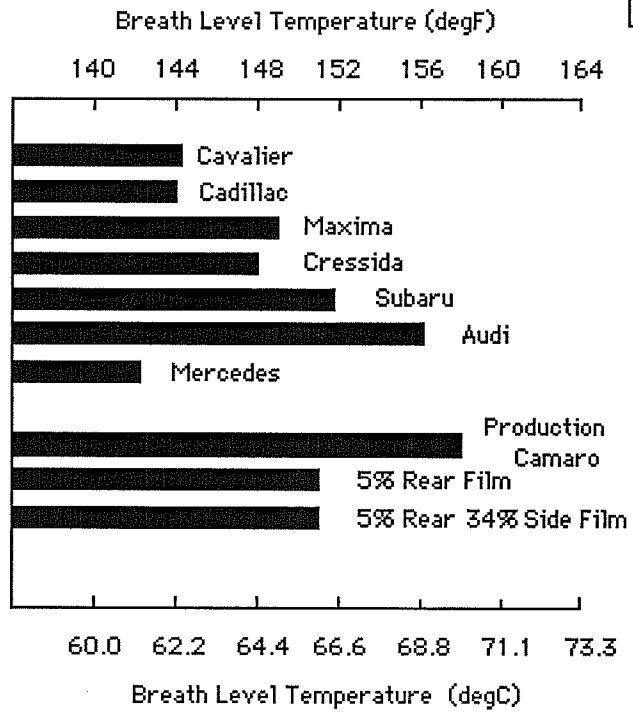
This chart shows the relative comfort achieved for seven vehicles under two driving conditions. Test procedures included an initial one-hour soak, followed by low-speed operation at 55 km/h (30 mph) for 15 min, then mid-speed operation at 82 km/h (45 mph) for 30 minutes, and a fourth cycle of city traffic driving for approximately 22 minutes.

The best performing vehicles had these common items:

(1) highest system air flow
(2) good a/c outlet location
(3) percentage of outside air bleed

1986 W.J. Atkinson SAE 860591

Breath Level Temperature Buildup for Different Car Models

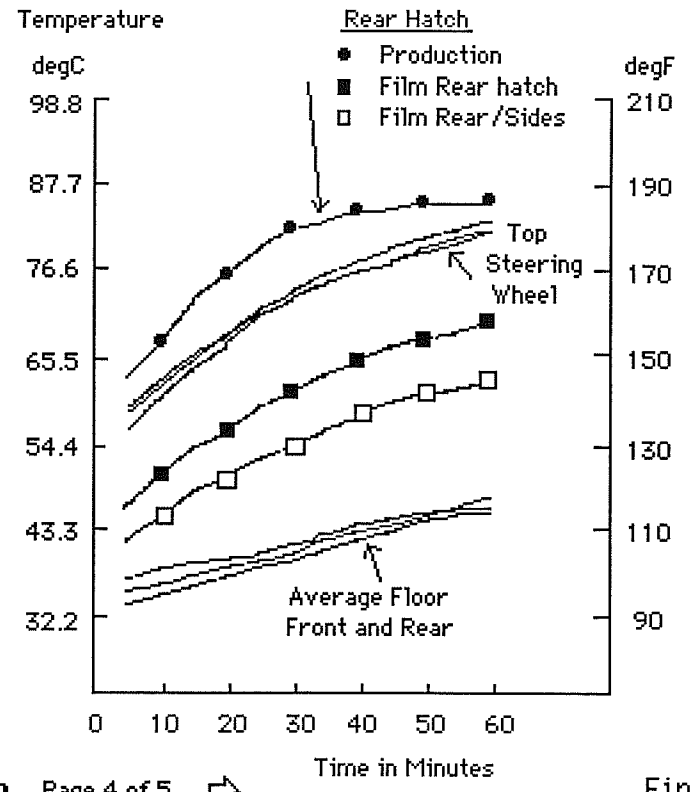


Breath level soak temperatures for a one-hour soak are shown on this chart for the seven test vehicles in addition to a production Camaro that was used to study the effect of film on glazing surfaces. Vehicles with more vertical side glass result in reduced heating of the seats and floor material. Reduced instrument panel and rear package shelf surface temperatures result with controlled window glazing elements.

The Camaro yields the highest temperature; however, with the addition of a solar reduction film (55% solar transmittance) to the rear window, a significant drop in temperature is obtained.

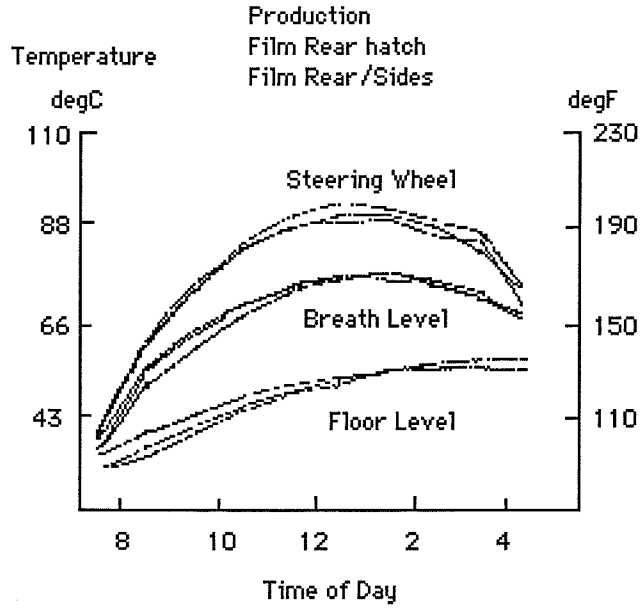
One-Hour Soak Interior Temperatures

Various temperature buildups during a one-hour soak for the production Camaro with and without solar reduction films are shown on this plot. The most dramatic effect due to the film occurs for the rear hatch shelf surface temperature. There is essentially no change in surface temperatures for the steering wheel and floor due to the film.



1986 W.J. Atkinson SAE 860591

Full-Day Soak Interior Temperatures



Full-day soak tends to obscure the relative differences in surface temperatures due to using a solar reduction film on the rear and side windows. In this situation, the solar input from the windshield and instrument panel becomes a major source of heat input.

Use of ventilation during soak would help reduce this heat buildup by lowering interior surface temperatures and thus the re-radiation.

Title

Comfort Evaluation of Heating and Air Conditioning Systems

Author

H. Kawamoto, Y. Hosokawa, M. Suto, K. Nakajima

Affiliation

Nihon Radiator Company, Japan

Source

SAE Paper 860590, February 1986

Type of Study

Experimental, Comfort

Abstract

Wind tunnel tests were conducted using a total of 65 subjects to determine a broad spectrum of individual comfort concerns. The heating and air conditioning system was modified in a test vehicle to allow independently controlled air outlet temperatures, quanties, velocities, and other considerations for comfort. Tests were conducted in a wind tunnel with various ambient temperatures, with and without sun load. The results of these tests provide us with the data of many elements that are required for each part of a passenger's body to achieve overall comfort.

Help Index Find

Title

Application of Solar-Powered Ventilator in Automobiles

Author

J.P. Chiou

Affiliation

Mechanical Engineering Department, University of Detroit, Detroit, Michigan

Source

SAE Paper 860585, February 1986

Type of Study

Analytical, Ventilation, Air Conditioner

Abstract

The feasibility of application of a solar-powered ventilator in an automobile is discussed. The ventilator can effectively prevent the interior of the automobile from rising excessively when the vehicle is soaked in an environment of high solar radiant flux and high ambient temperature. The operating cost of the solar-powered ventilator is almost nil. A numerical method developed for determination of the effect of this ventilator on the interior temperature of the automobile is presented and discussed.

Help Index Data

Click "Data" for more information

Find

1986 J.P. Chiou SAE 860585

Model

Generic 4-Door Sedan

Ambient Weather

June 21st at 32 degN Latitude
43 C, 15% RH, 969 W/sqm
32 C, 15% RH, 969 W/sqm

Driving Conditions

Static Soak (with and without ventilation)
Cool-Down (from various initial starting temperatures)

Primary Interests

Solar load control, ventilation

Conclusions:

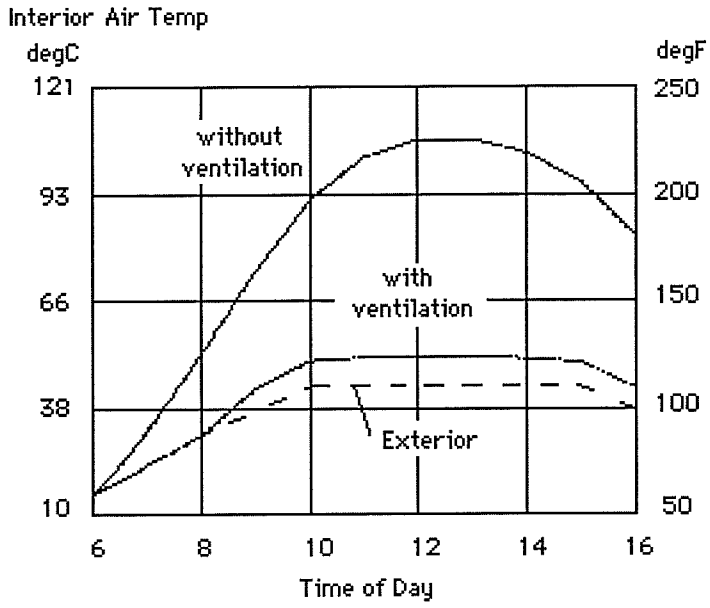
The interior air temperature of the automobile can rise rapidly to 93 C (200 F) or higher when the automobile is soaked under the conditions of strong solar radiant flux and the ambient temperature is 32 C (90 F) or higher.

The use of a ventilator can effectively prevent the interior temperature of the automobile from rising excessively.

A solar-powered ventilator was found to be economically feasible for the luxury car market.

If the cost of the photovoltaic device decreases significantly and/or its energy conversion efficiency is increased, then the market penetra tion would be excellant for all automobiles.

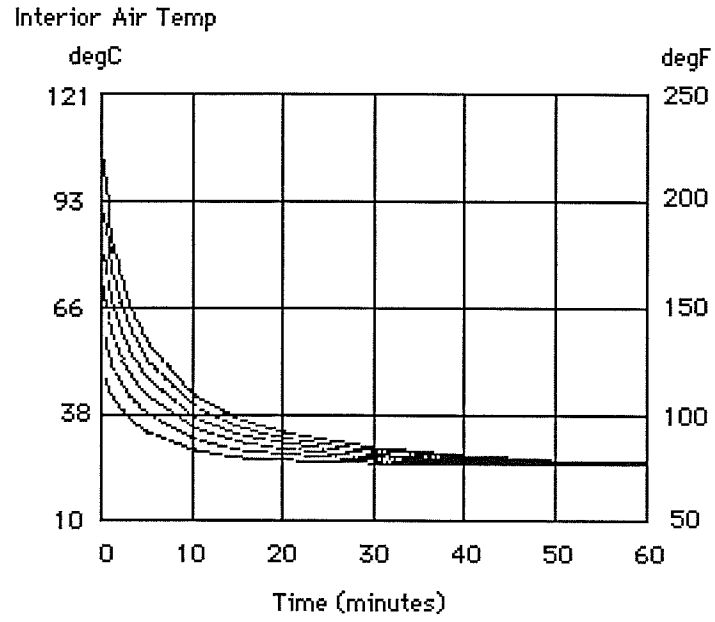
Ventilation Effect on Interior Air Temperature Buildup



This figure presents the average interior air temperature of the automobile over the course of a day with and without a solar-powered ventilator. The exterior ambient temperature reaches 43 C (110 F) at 10 a.m. The interior air temperature approaches 107 C (225 F) at 12 a.m. without ventilation; with ventilation, the value is about 49 C (120 F). A similar situation is apparent for lower exterior ambient air temperatures.

Cool-Down Characteristics for Various Starting Temperatures

The higher the interior air temperature build-up, the longer the cool-down time required. This figure shows the cool-down response characteristics using a typical air conditioning unit with various initial temperature levels. The exterior air temperature profile is shown on the previous figure and the solar radiation peaks at 969 W/sqm (90 W/sqft) at 12 a.m.



Title

New Methods for Evaluation of the Thermal Environment in Automobile Vehicles

Author

T.L. Madsen, B. Olesen, K. Reid

Affiliation

Technical University of Denmark, General Motors Corporation

Source

ASHRAE Transactions V92 P1 1986.

Type of Study

Experimental, Comfort

Abstract

A new method for the evaluation of the thermal environment in automobiles has been tested in steady-state conditions and non-steady-state conditions like warm-up periods (as in winter-time) and cool-down periods (as in summer-time). The investigation was conducted in a wind tunnel where airspeeds of up to130 km/h (70 mph) were achievable at temperatures between -18 C and +40 C (0 F and 104 F) . A realistic sun load on the car was also simulated during the test.

Title

Development of a Laminated Heat-Reflecting Glass

Author

Y. Kai, E. Kawasaki

Affiliation

Nissan Motor Company, Japan

Source

JSAE Review, August 1985

Type of Study

Experimental, Glazing, Air Conditioning

Abstract

This paper describes the development of a heat-reflecting laminated glass that substantially reduces the amount of heat transmitted. Also discussed are the results of an analysis done on various problems encountered in manufacturing the glass as well as the results of the performance evaluation and safety confirmation tests that were conducted.

Calculations of the heat influx from various parts of the vehicle indicated that the heat influx from the front, rear, and side window glass accounted for 71.8% of the total. These results suggest that the most important factor in reducing the heat influx of a vehicle is lowering the heat transmittance of the window glass.

Help Index Data

Click "Data" for more information

Find

1985 Y. Kai et al. JSAE Review

Model

Compact Sedan

Ambient Weather

34 C, 70% RH, 764 W/sqm

Driving Conditions

Static Soak
City Driving, 39 km/h
Highway Driving, 97 km/h

Primary Interests

Glazing, Cooling Load Component Breakdown, Cooling Load Reduction

Conclusions:

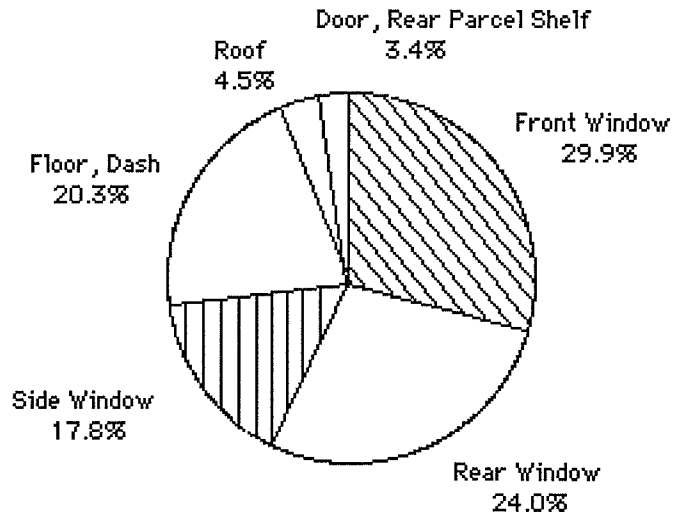
A heat-reflecting laminated glass has been developed that provides high transparency and reflects over 20% of the near-infrared rays.

In evaluation tests using actual vehicles, the newly-developed glass significantly reduced the temperature rise in comparison with conventional glass.

The passenger compartment air temperature was 1.5-4.1 C (2.7-7.4 F) lower when the new glass was used and the surface temperatures of the instrument panel and rear panel shelf were 4.8-11.0 C (8.6-20 F) lower.

The air conditioner cooling load was reduced by about 270 W.

Component Heat Influx During City Driving at Low Speed

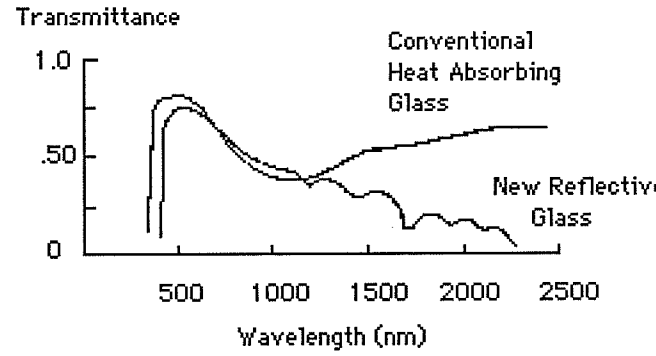


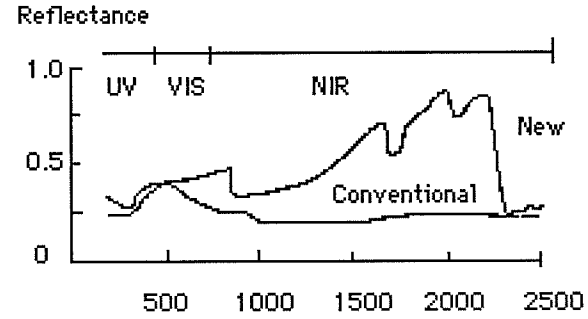
The heat influx component breakdown for the various surfaces is shown on this figure using conventional clear glazing. The windows represent 72% of the total. The exterior air temperature is 35 C (95 F) with a 70% RH and an incident solar radiation amount of 764 W/sqm (71 W/sqft). The car speed is 40 km/h (24 mph). Interior air temperature is 20 C (68 F).

(Since the ventilation air component to the total cooling load is not presented in the figure, it is difficult to determine what portion of the airconditioner load is due to the glazing.)

Transmittance and Reflectance Characteristics of Glazings

The visible and near-infrared solar spectrum characteristics of conventional heat-absorbing glazing and a new reflecting glass are shown on these figures. The newly developed glass provides visible light transmittance above the 70% level required for automotive safety glass. However, a distinctive feature of this new glass is that the near-infrared transmittance is suppressed by the increased reflectance in this region.





Solar Optical and Heat Transmittance Comparison of Glazings

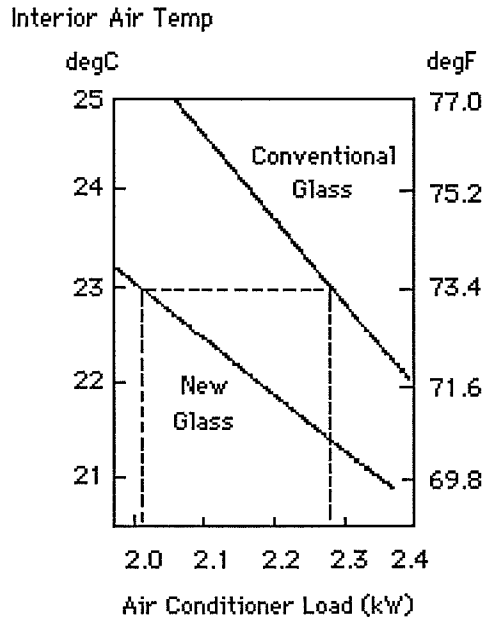
Characteristic	New Glass	Conventional
Visible Trans	74.6 %	76.9 %
NIR Transmittance	43.2 %	49.0 %
NIR Reflectance	20.1 %	4.7 %

This table shows the optical properties of the newly-developed glass as compared with those of conventional heat-absorbing glass for a thickness of 4 mm (.15 in). Transmittance figures are given at normal incidence; the reflectance was measured using a 10 degree angle of incidence.

The amount of heat transmitted into the vehicle interior is shown in this table. It is seen that the newly-developed reflective glass transmits 16% less heat than conventional heat-absorbing glass.

W/sqm	New Glass	Conventional
Incident Radiation	736	
Heat Transmitted	198	317
Heat Transm. (%)	26.9	43.1

Air Conditioner Load Comparison for Different Glazings



Air conditioner loads under city driving conditions in relation to passenger compartment air temperature are presented on this figure for conventional glazing and the new reflective glass. The cooling capacity needed to maintain the interior air temperature at 23 C (73 F) is 2.01 kW for the vehicle equipped with the newly-developed glass, but is 2.28 kW for the vehicle equipped with conventional glass. This means a savings of about 270 W .

Title

A New Method for the Detailed Assessment of Human Heat Balance in Vehicles - Volvo's Thermal Manikin, VOLTMAN

Author

D.P. Wyon, C. Tennstedt, I. Lundgren, S. Larsson

Affiliation

National Swedish Institute for Building Research, Volvo Car Company, Sweden

Source

SAE Paper 850042, Februray 1985

Type of Study

Experimental, Comfort

Abstract

By simulating in detail the dry heat loss of the human body, using a clothed, full-size thermal manikin whose 17 sections maintain a "skin temperature distribution" identical with that of a human occupant in thermal comfort, the effect of the vehicle microclimate on sectional heat loss can be rapidly and accurately measured.

The voltmann system is based on a digital process-control computer capable of monitoring all relevant physical quantities in the vehicle as well as controlling the manikin. It can be rapidly installed in a standard vehicle, using the existing 12-Volt power supply. Extensive field trials in the Artic areas of Sweden and in Death Valley, California have already demonstrated its utility and reliability under extremes of cold and heat.

Title

Analysis on Air Conditioning Heat Load of Passenger Vehicle

Authors

S. Shimizu, H. Hara, F. Asakawa

Affiliation

Toyota Motor Corporation, Japan

Source

JSAE Review, November, 1982

Type of Study

Analytical, Experimental, Glazing

Abstract

In order to examine ways to reduce the power consumption of air conditioning systems, we have established a simulation program on the heat load of an air conditioner of a passenger vehicle through theoretical and experimental studies. By using this simulation program it was found that the heat load by solar radiation accounted for more than 50% of the entire air conditioning heat load under the recirculation air mode. We came to the conclusion that the control of solar radiation was the most effective means to reduce the power consumption of air conditioners.

In the case of a 4-door sedan with an 1.8 liter engine, 20 to 30% of the air conditioning heat load can be reduced by adoption of an infrared reflection glass for all windows.

1982 S. Shimizu et al. JSAE Review

Model

Compact 4-door sedan

Ambient Weather

34 C, 60% RH, 807 W/sqm

Driving Conditions

Static Soak
City (Cool-Down) Recirculation Mode
City (Cool-Down) Fresh Air Mode

Primary Interests

Solar Load Component Breakdown, Solar Load Reduction Methods

Conclusions:

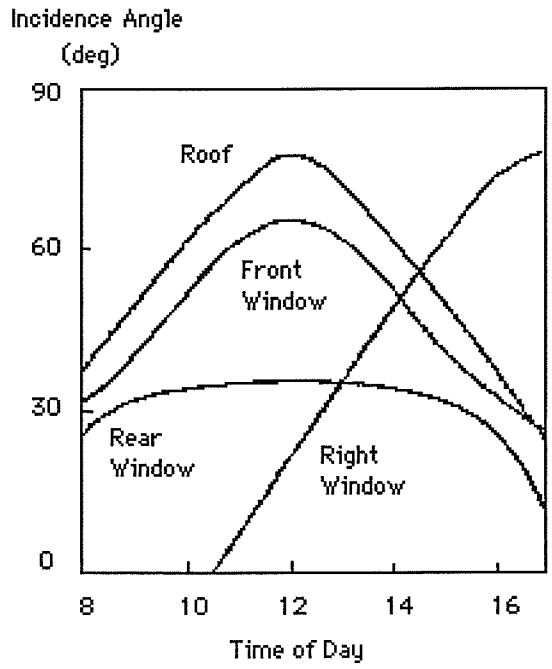
Solar radiation accounted for 50% of the cooling load during recirculation mode operation.

Solar radiation accounted for 26% of the cooling load during fresh air mode operation.

Ventilation accounted for 50% of the cooling load during fresh air mode operation.

Infrared reflective glass reduces interior air temperature under soak conditions by 10 C (18 F) when compared to ordinary clear glass.

Solar Radiation Incidence Angle for Time of Day



The dynamics of solar radiation and vehicle surfaces can be understood from this figure and the next. Here, incidence angles of the sun's rays to vehicular surfaces are shown as a function of the time of day for a car traveling in a southerly direction at 35 degrees north latitude in June. The left window curve would be the mirror image of the right window about midday.

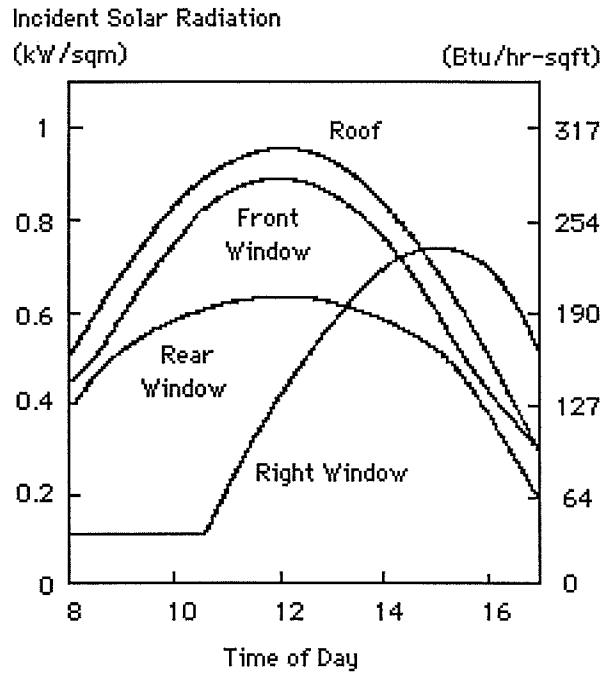
The window surface inclinations in degrees from the horizontal are as follows:

Front	36.5
Side	68.0
Rear	42.0

Amount of Solar Radiation for Time of Day

The amount of solar radiation incident on each surface varies during the course of the day. This figure shows the variation for a vehicle traveling south at 35 degrees north latitude in June. Surface inclinations are as indicated on the previous figure.

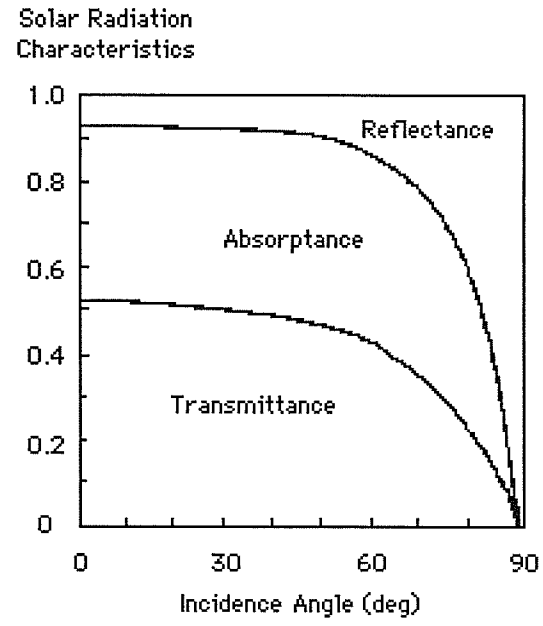
The roof is the most horizontal surface and therefore the highest amount of solar radiation is striking this surface.

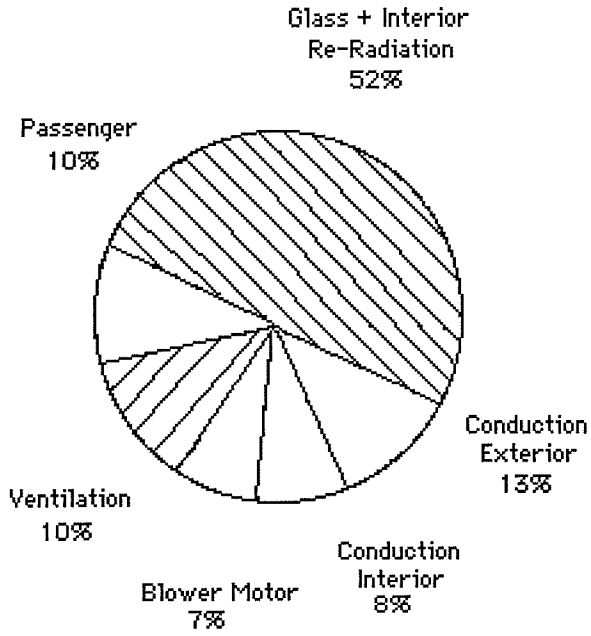


Glass Characteristics for Varying Angle of Incidence

These curves show the transmittance, absorptance, and reflectance variation with angle of incidence of a 5 mm (0.2 in) thick infrared absorption type glazing.

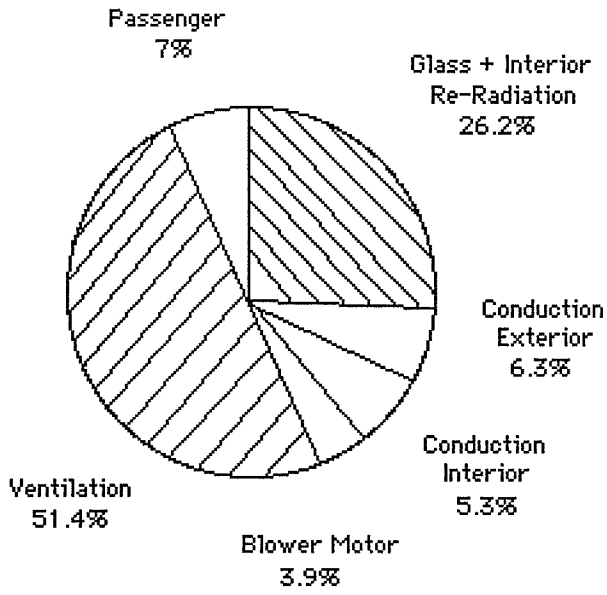
Reducing the thickness to 3 mm (0.12 in) increases the transmission to about 0.65 at zero incidence. The reflectance increases very slightly and the absorptance decreases so that the sum remains 1.0.





Air Conditioning Load Breakdown in Recirculation Mode

In the recirculation air mode running at a fixed speed, the solar radiation through the glazing accounts for more than 50% of the total cooling. The glass in this case is the infrared absorptive glazing with the characteristics shown on the previous page. Outside air temperature is 35 C (95 F) with 60% relative humidity. Interior air temperature is 25 C (77 F) and 60% RH. Incident solar radiation is as shown on page 3 at noon.



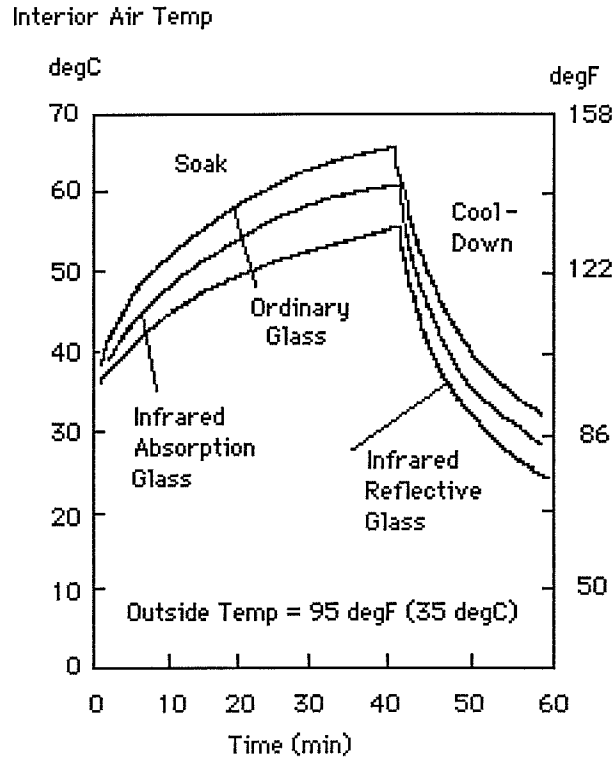
Air Conditioning Load Breakdown in the Fresh Air Mode

In the fresh air mode running at a fixed speed, ventilation accounts for more than 50% of the total cooling load. The load component due to solar radiation through the glass is about 26%. Test conditions are as discussed on the previous page. In both the recirculation and fresh air modes, the cooling load can be reduced by using an infrared reflective glazing as shown on the next page.

Glazing Comparison During Soak and Cool Down

Both the car interior air temperature buildup under soak conditions and the cool-down during air conditioner operation are shown in this figure for the three types of glazings shown below. At the transition between soak and cool-down there is a 10 C (18 F) difference between clear and infrared reflective glazing.

Glazing Type	Visible Trans	Trans	Solar Abs	Ref
Clear	0.90	0.84	0.08	0.08
IR Absorptive	0.76	0.53	0.41	0.06
IR Reflective	0.73	0.52	0.11	0.37



Title

The Heat Transfer Coefficient of a Passenger Car's Body

Author

J. Nitz, W.H. Hucho

Affiliation

Volkswagenwerk, West Germany

Source

SAE Paper 793148, February 1979

Type of Study

Analytical, Experimental, Car Body

Abstract

The heat transfer coefficient of the car's body is one of the parameters controlling the heat balance inside the passenger compartment under steady-state and transient conditions. Applying the analogy to the heat exchanger, the heat transfer coefficient of a car can be measured with no regard to the inhomogeneity of the heat transferring surface. A formula connecting the heat transfer coefficient with driving speed and ventilation air flow is derived from experiments, and holds for the three classes of cars considered.

Help Index Find

Title

Passenger-Car Ventilation for Thermal Comfort

Author

J. Temming, W.H. Hucho

Affiliation

Volkswagenwerk, West Germany

Source

SAE Paper 790398, February 1979

Type of Study

Experimental, Ventilation, Comfort

Abstract

For cost reasons, passenger cars sold in moderate climatic zones frequently come without factory-installed air conditioning. Therefore, the temperatures in the vehicle occupant compartment may rise above the thermal comfort range during hot summer months. In order to provide for a maximum of thermal comfort under those circumstances, occupant compartment ventilation should satisfy certain clearly defined requirements. The paper submits the physiological rationale and a concrete description of these requirements. Also presented is a computing process that permits prognoses of the airflow velocities downstream from the fresh air outlets.

Title

Comfort Criteria for Air Conditioned Automotive Vehicles

Author

F.H. Rohles, S.B. Wallis

Affiliation

Kansas State University, Ford Motor Company

Source

SAE Paper 790122, February 1979

Type of Study

Experimental, Ventilation, Comfort

Abstract

From 1973 to 1977 a series of laboratory tests involving almost 3000 people were conducted to determine the factors that contribute to the thermal comfort of automobile passengers while using air conditioning under summer heat loads. Four studies are reviewed in this paper. The first study evaluates the effect of register size, air flow rates, and discharge temperature. The second study was designed to define the criteria for comfort during various cool-down modes of operation. The third study was similar to the second but used different ambient conditions. Study four investigated seasonal acclimation during both winter and summer.

1979 F.H. Rohles et al. SAE 790122

Model

1973 Ford LTD 4-Door Hardtop

Ambient Weather

43 C, 40% RH, 990 W/sqm
32 C, 70% RH, 990 W/sqm

Driving Conditions

City Transient Cool Down
City Stabilized Period

Primary Interests

Comfort Conditions, Ventilation Register Location, Ventilation Flow Rate and Temperature

Conclusions

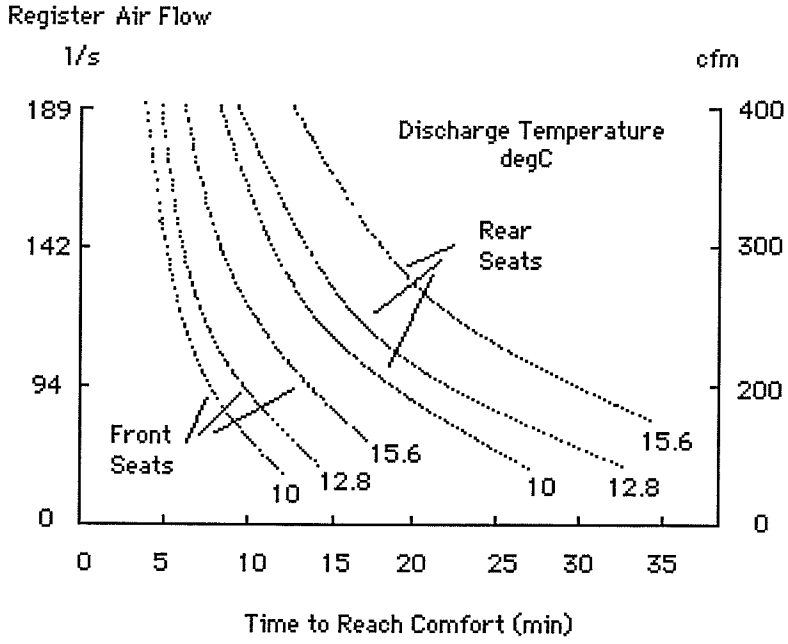
Comfort of the occupant is mainly determined by two air masses: the ambient air surrounding about 80% of the body and the moving air plume blowing on the upper, front, 20% of the torso.

Register size had little effect on the time to reach a comfortable condition. In contrast, the time to reach comfort was largely dependent on the air flow rate, the discharge air temperature, and the seating location.

Cooling with fresh air was no different so far as the length of time to reach comfort was concerned than cooling with recirculation air.

1979 F.H. Rohles et al. SAE 790122

Time to Reach Comfort for Varying Register Air Flow and Temperature

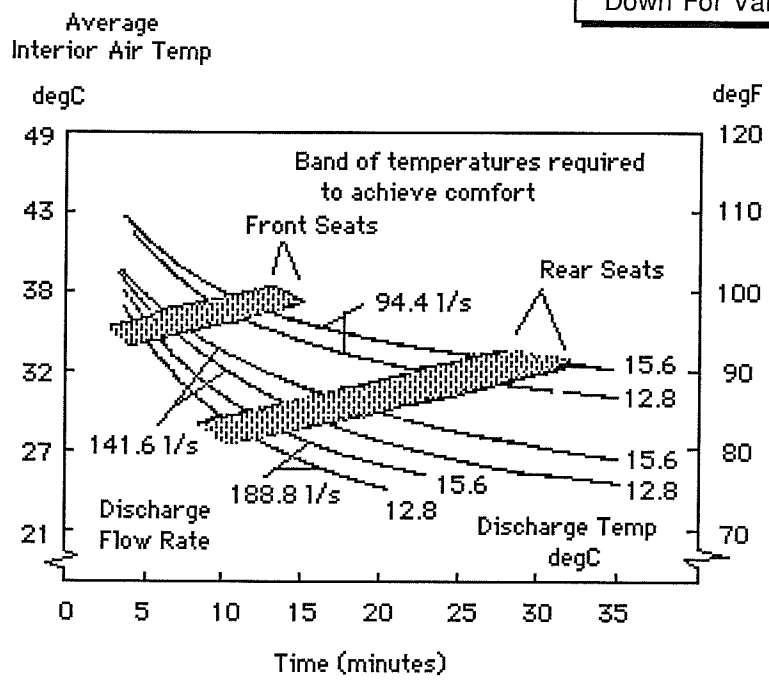


The time to reach comfort was largely dependent on air flow rate, the discharge air temperature, and the seating location. This figure summarizes the relationships among the various parameters.

When 2200 subjects were exposed for 45 minutes to an environment of 43 C (110 F)/40% RH, the time to reach comfort in the front seat varied from 4 minutes with an air flow of 189 l/s (400 cfm) to 18 minutes with 71 l/s (150 cfm). In the rear seat, the times were 8.5 and 39 minutes respectively.

1979 F.H. Rohles et al. SAE 790122

Interior Temperatures During Cool Down For Various Air Flow Rates



At the time comfort is reached, there is a relationship between the ambient temperature in the vehicle and the register discharge air temperature. This figure shows these relationships for various discharge flow rates. Superimposed on the cool down curves are bands of average interior ambient temperatures at the time comfort was reached. The temperatures range from 34.4 C (94 F) to 37.7 C(100 F) for the front seats and 27.8 C (82 F) to 33.3 C (92 F) for the rear seats.

Title

Simulation Modeling of Automobile Comfort Cooling Requirements

Author

Douglas W. Ruth

Affiliation

University of Manitoba, Winnipeg, Manatoba, Canada

Source

ASHRAE Journal, May 1975

Type of Study

Analytical, Parametric, Airconditioning

Abstract

A mathematical simulation model is developed to study the comfort cooling requirements of automobiles. The model is used to predict cooling requirements of sub-compact, compact, and standard cars. It is extended to study the effect of sealing the car, reducing fresh air intake, and tinting the window glass. The effect of altering the slope of the window is also investigated. It is shown that by proper design the cooling loads may be reduced by 50%.

Help Index Data

Click "Data" for more information

Find

1975 D.W. Ruth ASHRAE Journal

Model

Sub-Compact, Compact, Standard

Ambient Weather

A: 32.2 C, 50% RH, 828 W/sqm
B: 37.7 C, 20% RH, 828 W/sqm
C: 43.3 C, 5% RH, 828 W/sqm

Driving Conditions

City (Cool-Down) Recirculation
City (48 km/h) Fresh Air
Hwy (97 km/h) Fresh Air

Primary Interests

Air Conditioner Sizing, Cooling Load Component Breakdown, Cooling Load Reduction Methods.

Conclusions:

The average required cooling for automobiles ranges from 3.5 kW (1 ton) for sub-compacts to 5.3 kW (1.5 tons) for standard cars.

The largest contributors to the cooling load are fresh air intake and solar radiation.

Adding body insulation to cars cannot result in substantial cooling load reduction.

Reducing the fresh air intake and sealing the car body can result in a 30% saving in cooling requirement.

Tinting the glass can result in an 18% saving in cooling requirements.

Appreciable load reduction can be realized by altering the slope of the front and rear windows.

Predicted Automobile Cooling Requirements (kW)			
Test Condition Temp./RH	City Cool-Down	City Driving	Highway Driving
	Sub-Compact		
32.2 C/50%	3.59	3.49	3.76
37.7 C/20%	3.46	3.20	3.41
43.3 C/ 5%	3.86	3.79	4.08
	Compact		
32.2 C/50%	4.14	4.16	4.13
37.7 C/20%	4.01	3.76	3.73
43.3 C/ 5%	4.42	4.50	4.47
	Standard		
32.2 C/50%	5.06	5.16	5.13
37.7 C/20%	4.91	4.64	4.61
43.3 C/ 5%	5.36	5.55	5.52

This table shows the cooling requirements for various models and test conditions. A 3.5 kW (1 ton) system (12,000 Btu/hr) is adequate for sub-compacts. Compacts require 4.4 kW (1.25 tons) and standard cars require 5.3 kW (1.5 tons). These values agree quite well with the ratings of the currently available air conditioning units.

Breakdown of Cooling Load		
Load	Value (kW)	% Total
Solar	1.31	34.8
Conductive	0.52	13.8
Fresh Air	1.58	42.0
Passenger	0.29	7.8
Instrument	0.06	1.6
TOTAL	3.76	100

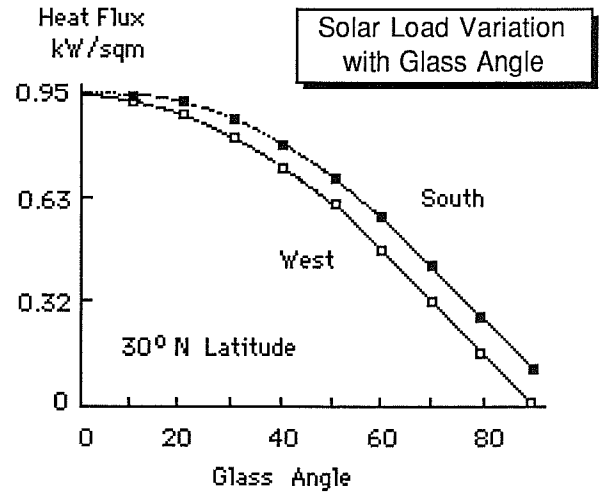
This table shows the cooling load breakdown for the compact sedan under city driving conditions at a temperature of 37.7 C (100 F) and relative humidity of 20%. The two biggest contributors are fresh air and solar radiation.

Breakdown of Conductive Load		
Load	Value (kW)	%Total
Windows	0.26	6.9
Body	0.03	0.7
Firewall	0.23	6.2
TOTAL	0.52	13.8

The conductive load breakdown is shown on this table. Adding insulation to the body or firewall or reducing the glass conductance is seen to provide little reduction to the cooling load.

Cooling loads can be reduced by sealing the body and reducing the amount of fresh air through the blower system. A reduction of 32% can be achieved in this manner. Tinted glass reduces the transmitted solar radiation from 85% to 42%. This lowers the cooling load by 18%.

Reduction of Cooling Loads		
Action	Total Load (kW)	%Total
None	3.76	100.0
Reduce Fresh Air	2.58	68.5
Tinted Glass	3.10	82.3
Both of above	1.91	50.8



Typical front and rear windshields are at angles of 45 degrees or less from the horizontal. Increasing these angles reduces the solar load. For the condition shown, the total load can be reduced by about 6%.

Title

Cooling Effect of Car Ventilators

Author

M. Asakai, Y. Sakai

Affiliation

Nissan Motor Company, Japan

Source

JSAE Bulletin No. 6, 1974

Type of Study

Experimental, Ventilation

Abstract

In order to evaluate the cooling sensation produced by a car ventilator, we devised a method, based on the average value of a wide variety of vehicle models, to measure the velocity of the air flow which creates a cooling effect on the human body. When continuously exposed to a current of air flowing at a certain velocity for a certain period of time, the human body adapts itself to it and the cooling sensation decreases. We have found, however, that when exposed to a pulsating wind, the human body will maintain the cooling sensation at the same level as at the beginning regardless how much time has passed. Further, we have found that with the air flow characteristic of a simple circular nozzle, we can apply a particular characteristic equation to such a small volume object as a motor vehicle.

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