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THE EFFECTS OF INFRARED-REFLECTIVE AND ANTIREFLECTIVE GLAZING ON THERMAL COMFORT AND VISUAL PERFORMANCE: A LITERATURE REVIEW

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16. Abstract

The existing literature on the effects of infrared-reflective (IRR) and antireflective (AR) automotive glazing on thermal comfort and visual performance was reviewed. First, 78 articles on the broader topic of thermal comfort in motor vehicles were analyzed in order to establish common themes. Much of that work is based on models of thermal comfort developed in other domains (primarily architectural). It is generally agreed in architectural research that thermal comfort can be predicted if the values of six parameters are known (air temperature, humidity, air velocity, radiant temperature, occupant clothing level, and occupant activity level). Because of the major differences between vehicular and architectural environments, however, the extension of existing thermal comfort models to automotive domains is not yet validated.

Eight experimental studies that examined IRR glazing were then reviewed in detail. Results showed that IRR windshields consistently reduce cabin and interior surface temperatures. This effect is increased when IRR glazing is also applied to the side and rear windows. The use of IRR glazing has also been shown to reduce air conditioner (A/C) workload, and thus has implications for reducing A/C compressor and/or engine size. Although IRR glazing has been shown to be more efficient than infrared-absorbing glazing (a widely used solar-control glazing), the research on IRR glazing and thermal comfort is limited by a lack of statistical analysis, a lack of subjective response measures, and a tendency to not measure all six parameters listed above.

There are two main conclusions: First, automotive glazing research would benefit from both comparative analyses of thermal comfort models and examinations of how objective measures of thermal comfort correlate with subjective measures. Second, more research is needed on both the visual performance outcomes associated with IRR and AR glazing, and on the effects of thermal stress and thermal discomfort on driving performance.

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EXECUTIVE SUMMARY

The existing literature on the effects of infrared-reflective (IRR) and antireflective (AR) automotive glazing on thermal comfort and visual performance was reviewed. IRR and AR glazing are two examples of advanced automotive glazing technologies. The former prevents infrared radiation from entering the vehicle cabin by reflecting it back into the environment. The latter is designed to reduce veiling glare (light diffusely reflected from the top of the instrument panel, and that is superimposed on the image of the road scene) by using an antireflective film on the windshield. Both IRR and AR glazing have the potential to affect driver comfort and visual performance. For instance, many IRR films, while reducing the air temperature of the vehicle cabin, can also add color to the glazing and reduce light transmittance. Similarly, AR glazing may reduce veiling glare, but it is not yet clear how strongly this improves visual performance.

In order to identify common themes in the literature, 78 research articles were identified that relate to thermal comfort in motor vehicles. The articles were then categorized into the following groups: those that investigated the effect of automotive glazing on thermal comfort, those that investigated the effect of automotive heating, ventilation, and air conditioning (HVAC) systems on thermal comfort, those that investigated the effects of other automotive factors on thermal comfort, and those that investigated the effects of thermal discomfort on driving performance. Themes common to all of them were analyzed, such as the use of thermal comfort models, the direct measurement of thermal comfort, and the application of current standards that guide automotive thermal comfort research. Findings showed that much of the work is based on models of thermal comfort that were developed in other domains, primarily architectural. Among these models, Fanger's (1970) thermal comfort equation has been the most widely used in automotive research. Fanger's model suggests that thermal comfort can be predicted if the values of six parameters are known (air temperature, humidity, air velocity, radiant temperature, occupant clothing level, and occupant activity level).

The predictive value of these parameters has become well accepted within architectural research, but because of major differences between the environments of vehicles and those of buildings, models such as Fanger's are not yet fully validated in automotive domains. Some of these environmental differences include more asymmetrical radiant temperatures and higher rates of climatic change as a function of time in vehicles as opposed to buildings, the smaller and more nonuniform spaces of vehicle cabins compared to typical office spaces, and more variable air

velocities in vehicles. These environmental differences have prompted researchers to develop thermal comfort models specific to transient, nonuniform environments, but there have not been comparative analyses of these models.

Of the 78 research articles, eight experimental studies that examined the effects of IRR glazing on thermal comfort were reviewed in detail. Air temperature inside the vehicle cabin was the most common dependent variable, and glazing configuration was the most common independent variable. Results showed that cabin temperatures and interior surface temperatures are consistently reduced when IRR windshields are used, that IRR glazing appears to be more efficient than infrared-absorbing glazing, and, not surprisingly, that adding IRR treatment to side and rear windows in addition to the windshield further reduces cabin temperatures. However, because none of the studies used subjective measures of thermal comfort, and only two studies used a "thermal comfort meter" (an instrument designed to measure all of the six parameters listed above), it is difficult to estimate how the measured differences in air temperature and interior surface temperatures translate into subjective comfort. The focus of the research therefore does not appear to be on IRR glazing's effect on thermal comfort, but rather on IRR glazing's potential to reduce the solar load and ultimately increase fuel economy. The eight studies were also limited by a lack of statistical analyses.

Several studies that examined factors that affect visibility through motor vehicle windshields were also reviewed. Findings indicate that reduced light transmittance can significantly affect driver visual performance. However, no research could be located that examined the effect of IRR or AR glazing on visual performance.

Based upon our findings, we reached the following conclusions: First, automotive glazing research would benefit from both comparative analyses of thermal comfort models and examinations of how objective measures of thermal comfort correlate with subjective measures (particularly as they relate to differences in radiant temperature versus air temperature). Second, more research is needed on both the visual performance outcomes associated with IRR and AR glazing, and on the effects of thermal stress and thermal discomfort on driving performance.

GLOSSARY OF TERMS

Air temperature: the dry-bulb temperature of the air surrounding the occupant (ASHRAE 55, 1992).

Automotive glazing: a motor vehicle's windshield and side and rear windows; the material of which these are made, typically glass and/or plastic.

Breath temperature: also called "front breath temperature;" the air temperature approximately 15 cm in front of where the driver's face would usually be located in a vehicle. Usually measured by thermocouples.

Climate chamber: also called "environmental chamber;" sometimes used in automotive thermal comfort research, climate chambers are indoor test facilities that simulate climatic conditions. Usually vehicles are placed in the chamber while fans, infrared bulbs, and sprinklers simulate wind, heat, and rain.

Draft: the unwanted local cooling of the body caused by air movement (ASHRAE 55).

Effective temperature: the operative temperature of an enclosure at 50% humidity that would cause the same sensible plus latent heat exchange from a person as would the actual environment (ASHRAE 55).

Automotive HVAC system: a motor vehicle's heating, ventilation, or air conditioning system.

Instrument panel (IP) temperature: also called "dash temperature;" the surface temperature of the dashboard or instrument display inside a vehicle. Usually measured by thermocouples.

Laminated windows: a widely used automotive glazing application that use layers of glass or glass/plastic to offer unique safety and design potential.

Mean radiant temperature: the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space (ASHRAE 55).

Metabolic rate: the rate of energy production of the body (ASHRAE 55).

Operative temperature: the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. Operative temperature is numerically the average of the air temperature and mean radiant temperature, weighted by their respective heat transfer coefficients (ASHRAE 55).

Radiant temperature asymmetry: the difference between the plane radiant temperatures of the two opposite sides of a small plane element (ASHRAE 55).

Relative humidity: the ratio of the mole fraction of water vapor present in the air to the mole fraction of water vapor present in saturated air at the same temperature and barometric pressure; alternatively, it equals the ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature (ASHRAE 55).

Tempered windows: glass that is rapidly cooled during production so that it is typically stronger than laminated glass. Commonly found in automotive glazing applications, tempered glass currently competes with laminated glass, polycarbonate, acrylic resins, and other automotive glazing materials.

Thermal comfort: the condition of mind that expresses satisfaction with the thermal environment; requires subjective evaluation (ASHRAE 55).

Thermal comfort meter: an array of transducers that is designed to measure each of the four environmental parameters that predict thermal comfort (occupant activity level and occupant clothing level are not measured, but values can be manually entered into the meter). A single index value is returned that corresponds to the combined effect of all parameters.

Thermal model: an index that will predict what percentage of an average population would find a given environment thermally comfortable.

Solar heat gain coefficient (SHGC): an index for measuring interior vehicle cabin temperature that combines directly transmitted solar radiation with heat that is reradiated into the cabin from absorption by glazing.

Veiling glare: reflected ambient light, often taking the form of reflected images of the dashboard, which is superimposed on the image of the road scene.

Visual performance: used to describe the outcome of common visual tasks, such as acuity and contrast sensitivity. These tasks are believed to be essential for driving.

Visible transmittance: the percentage of the visible spectrum that is allowed to pass through a glazing product.

Wet bulb globe temperature: an index reflecting the combined effects of air temperature, air velocity, and relative humidity.

Windshield rake angle: the angle between the inclined windshield and the vertical (Schumann, Flannagan, Sivak, & Traube, 1996). Greater (more horizontal) rake angles result in a higher surface area of glass that is exposed to the sun.

INTRODUCTION

Trends in Automotive Glazing

The last fifteen years have seen many developments in automotive glazing theory and technology. Current issues include such diverse concerns as weight reduction, safety, comfort, aesthetics, cost, recycling potential, standards and regulations, the characteristics of windshields versus side and rear glass, and the implementation of multiple functions into the glass (Mori & Koursova, 2000; Young & Van Esso, 1989; McCurdy, 1998; Patrick, 1996a; Patrick, 1996b; Manfre, 1991; Weigt & Albrecht, 1987). A major problem facing manufacturers is how to synthesize these concerns into a single, robust glazing application. An improvement in one category, for instance, may prove detrimental to another. A good example of this is polycarbonate, one of the technologies that has arisen out of this effort. A type of plastic that weighs less than glass, provides potential occupant ejection mitigation, and offers more design flexibility than glass, polycarbonate has been studied for over twenty years as a possible alternative glazing material. However, because of disadvantages such as low durability (e.g., lack of scratch-resistant coatings), increased material cost, and high noise transmission, polycarbonate is only making moderate gains in automotive applications, being confined mainly to glazing modules such as sunroofs (Mori & Koursova, 2000; "Plastics will make inroads," 2001; Katsamberis et al., 1997; Kobe, 2000).

Similar considerations can be seen with the development of other glazing technologies, such as antireflective (or nonreflective), acrylic, laminated, and solar-control glazing. Antireflective (AR) windshields have been introduced into the market fairly recently, and they are designed to reduce veiling glare (i.e., internal glare caused by windshield reflectance of the dashboard or other objects inside the car). But despite the possible benefits for driver visibility, AR glazing is also characterized by high costs and low durability. Moreover, little research has been conducted on the visual performance benefits of such glass.

Although the use of acrylic glazing material has declined in past decades due to high costs and safety issues, laminated glass has proven itself a viable candidate for a variety of applications. Laminated glass, which appeared as early as the late 1920s in the U.S. and the late 1960s in most other countries, has been used almost exclusively for windshields. As opposed to the monolithic tempered glass now used in most side and rear automotive windows, laminated windshields offer some unique characteristics. Laminated windshields consist of two thin panes of glass sealed together, and thus has less total mass and offers a weight reduction. Although it is weaker than tempered glass, the two panes of laminated glass offer added design freedom for windshields and do not become opaque when broken. However, it is the interlayer (between the two panes) that makes laminated glass especially unique among alternative glazing technologies. The interlayer can consist of evacuated space or can be filled with gas (Norin, 1989), and it commonly includes a polyvinyl butyral (PVB) interlayer that absorbs ultraviolet light. Aside from PVB, the interlayer also leaves room for other functions such as heaters, coatings, and rain sensors. Moreover, because the interlayer is protected, the durability of these added features is less of a concern. A final advantage to the double-layer construction of laminated glass is the provision of noise and heat insulation, factors that are known to contribute to the comfort of vehicle occupants (Mori & Koursova, 2000; Patrick, 1996a; Patrick, 1996b).

It is generally acknowledged that comfort plays an important role in automotive design. Although the main functions of automotive glazing are to provide undistorted vision and protection from injury and exterior elements, glazing designers have discovered the potential of alternative glazing materials for addressing other concerns such as comfort. While windows can attenuate noise, for instance, it is probably the case that the more salient comfort issue is heat insulation. Anyone who has entered a car that has been parked in the sun for a few hours with closed windows on a hot summer day can attest to the “greenhouse” phenomenon that develops in vehicle cabins. Automotive glazing often allows heat into the vehicle cabin and traps it there if no ventilation is supplied. In warm climates, such as Kuwait for example, the internal cabin temperature of a car parked in the sun may reach as high as 50°C (122°F) (Chakroun & Al-Fahed, 1997), and in many areas of the United States temperatures in vehicle cabins often exceed 38°C (100°F). Because as much as 70% of the total solar heat load in a vehicle arises from sunlight incident through glazing areas (Kai & Kawasaki, 1985, as cited in Roessler & Heckmann, 1992), glazing manufacturers have a vested interest in materials that can reduce solar load. (Another study found that the heat load by solar radiation accounts for more than 50% of the entire air conditioning heat load under the recirculation air mode, and thus concluded that the control of solar radiation is the most effective means to reduce the power consumption of air conditioners (Shimizu, Hara, & Asakawa, 1982)). This interest is increased by a recent tendency for both larger glazing surface areas and windshields with larger rake angles, whereby more solar radiation is allowed to enter the vehicle (Mori & Koursova, 2000). While heating, ventilation, and air conditioning (HVAC) systems have traditionally been able to compensate for these increasing solar loads during driving conditions, they also place greater demands on the vehicle engine. Considering the fact that the overall driving population is increasing in numbers–along with increases in average commute times–it is evident that more people are spending more time in their cars. The subsequent rise in HVAC use may have detrimental effects on fuel economy and the environment despite the replacement of CFC refrigerants with a safer alternative in the 1980s and 1990s.

Taking advantage of the new potential for multifunctional glazings, manufacturers have released a wide range of materials to control solar loads. These materials are designed to block certain nonvisible wavelengths of electromagnetic radiation, the kind primarily responsible for heat and chemical degradation of the vehicle's interior (viz., ultraviolet and infrared radiation). As mentioned previously, the PVB interlayer of laminated glass can block ultraviolet (UV) rays. Infrared (IR)-absorbing and reflecting glazings are relatively newer concepts. The IR-absorbing technology was most commonly used throughout the late 1970s and 1980s and works in conjunction with laminated glass: Iron oxide is usually applied on the outer layer to absorb infrared radiation and allow visible light to pass through. The heat is then dissipated outward via convection and emission (Huber, 1988). A disadvantage of this technique, however, is the fact that some of the heat absorbed by the glass is reradiated into the cabin of the vehicle. Reflective technology, on the other hand, has seen gains since the early 1990s and works by principles similar to absorbing glasses; the difference, as one might expect, is that infrared-reflective (or IRR) glazing reflects infrared wavelengths back into the atmosphere instead of absorbing them into the glass. IR reflection has become the major focus of solar-control glazing for vehicles, mainly because it has proved more efficient than the traditional absorbing technology. (A brief discussion of the distinctive qualities between solar-absorbing and reflecting technologies can be found in Farrington, Rugh, & Barber, 2000.) Although the use of metal and dielectric thin films (or coatings) represent the most common method of achieving IR reflection, a second method includes multiple layers of glass, each with a different index of refraction and a different thickness. As light enters each layer of glass, a percentage of the infrared spectrum is reflected. As with the heat-absorbing coatings, the IRR coating approach enjoys the benefits of durability protection from the laminated glass of windshields, and may also be subject to less interference effects than the IRR layering approach, and so tends to be more widely used (Farrington, Cuddy, Keyser, & Rugh, 1999).

While IRR coatings have been effective at reducing thermal loads, they unfortunately have the potential to add color to the glazing. This is due to the aforementioned metallic/dielectric nature of the coatings. Like the tinted spectral-absorbing glass used on many of today's side and rear automotive windows, the metal used in some IRR coatings can affect the transmission of visible light (Mori & Koursova, 2000; Manfre, 1991). According to Federal Motor Vehicle Safety Standard (FMVSS) 205 and American National Standards Institute (ANSI) Z26.1, current regulations for the United States require a minimum 70% luminance transmittance for windshields; in Europe, the requirement is 75% (as cited in Weigt & Schrev, 1994; Young & Van Esso, 1989; Weigt & Albrecht, 1987). While some researchers have developed nonmetal IRR coatings that are transparent or near transparent (Rugh, Farrington, & Boettcher, 2001; Piserchi, Wheatley, Boettcher, Scott, & Gilbert, 2000; Ando, Ebisawa, Suzuki, & Ono, 1991), there has not been any published research on whether these coatings affect visual performance.

The future of IRR glazing depends on many factors. Consumers are generally receptive to a product that offers potential for increasing fuel economy while decreasing engine wear, but they are presumably not as comfortable with disadvantages such as potentially reduced visibility and higher material costs. Glazing manufacturers consequently need a reliable and valid means of measuring both the heat-reducing efficacy (i.e., thermal properties) of IRR glazing and its effect on other automotive design parameters. This in turn requires an understanding of the psychological phenomena that manufacturers and designers wish to affect, namely thermal comfort and visual performance. For instance, researchers need to know not only what thermal comfort is, but also the most appropriate way to measure it and its relative importance to the drivers and occupants of vehicles. Currently, glazing research lacks a comprehensive review or synthesis of the existing literature in this area. Similarly, there has never been a review on how new glazing technologies affect the driver and occupants of vehicles from a subjective standpoint (i.e., opinions). Such reviews may help to elucidate some complexities and direct future research.

This review focuses on two advanced glazing technologies: IRR and AR. As both kinds of glazing increase in popularity, their possible implications for driver comfort and their effects on driver vision need to be examined.

Background

Although thermal comfort is only one factor that affects the driving experience, it is neither simple nor trivial. Indeed, keeping cool during hot days was even a major concern in 1884, when William Whiteley suggested placing blocks of ice on trays underneath horse drawn carriages, with a fan attached to the axel to circulate the air (as cited in Parsons, 1993). The 1920s saw the first heating systems in cars, as the production of closed-body automobiles gradually exceeded open-body models (Bhatti, 1999a). Soon after, the prototype of a self-contained automotive air conditioning system was first introduced in a 1939 Cadillac (Bhatti, 1999b).

In studies that will be examined later in this review, thermal comfort has also been linked to driving performance. Moderate thermal stress has been shown to decrease driving vigilance and increase driving errors classed as “moving violations,” (Wyon, Wyon, & Norin, 1996; Makie, O’Hanlon, & McCauley, 1974). Although thermal discomfort has been largely mitigated by HVAC systems, the idea of modifying the properties of glazing represents a more proactive approach; it is a relatively recent trend for automotive research, and it has helped to clarify some of the basic themes that underlie thermal comfort as a phenomenon.

No standards (national or international) currently guide research on thermal comfort specific to motor vehicles. Consequently, the research has been inconsistent in methodology; there are often crucial differences in the theoretical underpinnings of studies, differences in the specific products tested, and key differences in the way researchers approach the measurement of thermal comfort. Researchers who have studied thermal comfort in vehicles have adopted many concepts and methodological procedures from the only previously existing thermal comfort literature, that of architectural design (e.g., office buildings, homes, factories, etc.). This literature is broad and extensive, with a history dating into the late nineteenth century. For architecture, national and international standards do exist and include, among others, ISO 7730 (a standard that generally defines thermal comfort and how to measure it in moderate indoor climates), ISO 1550 (a standard that guides the creation and administration of subjective scales of thermal comfort), and ASHRAE 55 (an American standard similar to ISO 7730, created by the American Society of Heating, Refrigerating, and Air conditioning Engineers). However, it is a current source of contention whether these standards are indeed applicable to vehicular environments. The main problem with adopting these standards for use in vehicular environments is the many ways in which traditional architectural and vehicular environments differ. Typical differences include larger ratios of glazing to total exterior surface area in vehicles as compared to buildings, smaller spaces in vehicles, more variable air velocities and local "draughts" in vehicles that usually do not occur in buildings, and transient energy conditions (e.g., quickly changing temperatures or other thermal conditions) of vehicles versus the usual steady-state energy balances in buildings (Temming, 1980; Madsen, Olesen, & Reid, 1986; Olesen & Rosendahl, 1990; Brooks & Parsons, 1999).

Furthermore, just as vehicular thermal comfort research has relied on architectural literature, research specific to the thermal comfort effects of glazing has also relied heavily on automotive HVAC research. This is important because HVAC research has developed its own unique methodology with specific aims, namely to measure the performance parameters of HVAC systems. As will be seen in this review, research on HVAC performance usually includes a static "soak" test, in which the vehicle is left in the sun anywhere between one and eight hours while environmental measurements are made. This is usually followed by a dynamic "cool-down" period, in which the air conditioners in the test and control vehicle are simultaneously turned to full power. What researchers tend to measure is either the time it takes for the vehicle's thermal environment to become "comfortable" once the air conditioning is started or, alternatively, the actual level of output from the HVAC system. There has been a noticeable lack of discussion in the existing literature as to whether this method is appropriate for measuring the thermal comfort effects of automotive glazing.

Another issue facing vehicular thermal comfort research is modeling. The twentieth century saw a general push toward modeling thermal comfort. While modeling is an integral part of scientific work, there are two potential problems with this approach as it relates to thermal comfort. Firstly, the models are used in part to diminish the variability common to subjective human judgments and perception (Hymore, Tweadey, & Wozniak, 1991; Wyon, Tennstedt, Lundgren, & Larsson, 1985), yet it is ultimately the subjective human judgments that are meant to be modeled. This may set up a contradiction if researchers rely too heavily on environmental and other physical measures at the expense of subjective responses. Secondly, the rise of competing models has resulted in many experiments that are based on different underlying theories (as to what constitutes thermal comfort and what elements to measure). This is especially true in the architectural thermal comfort literature. As more models are used, there is less ability to generalize across studies and consequently less ability to assess the level of knowledge we have about thermal comfort. The majority of automotive research that employs modeling has primarily used one model, Fanger's thermal comfort equation (1970). The reliance on one model helps researchers generalize across studies, but the question remains whether this particular model is the most appropriate to use (or if it is necessary at all). Granted, this admission betrays a general skepticism toward trying to model psychological phenomena, but the concern is no less legitimate. This is because models, by their very nature, have at their core the motivation to eliminate the human subject from the experimental process. Researchers who take a design/engineering perspective understandably find this approach desirable because models allow for low-cost, proactive research that can be carried out early in the design process. In this way, engineers can use a "thermal index" (a single number that represents what percentage of the population would find a given environment comfortable) to guide and inform their designs. It is not the aim here to rebuke such approaches, but rather to emphasize the fact that thermal comfort is principally a psychological phenomenon. Even if a model is found that overwhelmingly correlates with human subjective response, it is important that the model does not eliminate the human subject altogether. It is clear that a balance needs to be attained between scientific rigor on one hand, and timesaving and cost-effective development schedules on the other (Kataoka & Nakamura, 2001; Brown & Jones, 1997; Matsunaga, Sudou, & Tanabe, 1997; Parsons, 1993).

Thus, the current state of affairs leaves many unanswered questions. Are the currently existing standards for measuring thermal comfort in architectural domains applicable to vehicular environments? If not, is there a need for an international standard for measuring thermal comfort in vehicles? To what extent should models be used in such research? What are the most appropriate models? As mentioned above, Fanger (1970) is often used in automotive applications; but this model (when applied to vehicular environments) has been critiqued or slightly modified by several researchers (Huizenga, Hui, & Arens, 2001; Brooks & Parsons, 1999; Brown & Jones, 1997; Furuse & Komoriya, 1997; Gach, Lang, & Riat, 1997; Wang, 1994; Hagino & Hara, 1992; Laviana & Rohles, 1987; Temming, 1980), mainly because Fanger's equation was originally intended for steady-state environments (such as architectural settings). Other researchers have used Fanger's equation as part of a larger computation of automobile passenger thermal comfort, but the computation also includes the geometry of glass properties and the structural design of the car itself (Ingersoll, Kalman, Maxwell, & Niemiec, 1992a; 1992b). Questions also remain about glazing research in particular. How should independent and dependent variables be defined? What role should HVAC systems play when testing the effects of different glazing technologies? Finally, is it possible to design a test method that simultaneously measures the effects of automotive glazing on both thermal comfort and visual performance of the driver?

This literature review on the effects of IRR and AR glazing on thermal comfort and visual performance was designed to highlight some of the above questions, or at least to introduce them in a cogent manner, and to help define the next step for a human factors study of IRR glazing's effect on thermal comfort. This is primarily because a literature review has not previously been conducted on either automotive glazing's effect on thermal comfort or on the general assessment of thermal comfort in automobiles. In the sections that follow, the reviewed articles are classified into groups based on subject matter, and themes common to all of the articles are identified (e.g., the development of models, testing methodologies, and the current standards). The definition of thermal comfort is then presented, and issues of thermal comfort as they relate to the drivers and passengers of motor vehicles are examined. From there, the reviewed literature is briefly analyzed with respect to the models that are used, the standards that guide the research, and common methodological design. This is followed by a deeper analysis of the existing research on IRR glazing, and a final section discusses the factors that influence visibility through motor vehicle windshields. Because we could find no research regarding driver visual performance and IRR or AR glazing, we instead outline some key issues.

Reviewed Literature

We located a total of 78 published reports that are relevant to thermal comfort in motor vehicles. Because the literature is broad in scope and the main focus of this review is on IRR and AR glazing and thermal comfort, this review is limited to these 78 articles and does not represent all of the existing research on thermal comfort. The 78 articles are categorized in Table 1 according to topic, and whether they are experimental or theoretical works. Notice that research on glazing and HVAC systems dominate the reviewed literature. The third topic in Table 1, nonspecific or multiple factors, refers to studies that dealt with some of the other factors mentioned in the previous section (e.g., heated seats, upholstery, the combined effect of noise, vibration, and heat on passenger comfort, etc.). Finally, two studies that examined the effects of thermal discomfort on driving performance are listed under the fourth topic in Table 1. Please note that the research on thermal comfort related to components other than glazing was not comprehensively covered in this review. That is, articles not directly related to glazing were collected and analyzed only to identify basic methods and to detect common themes. The data from nonglazing studies are not reviewed here, nor are the methods critiqued in any significant way.

Table 1
Classification of papers.

Topic	N	Approach	
		Experimental	Theoretical
Effects of glazing on thermal comfort	29	18	11
Effects of heating, ventilation, and air conditioning on thermal comfort	23	13	10
Nonspecific or multiple factors affecting thermal comfort	24	16	8
Effects of moderate thermal stress on driving performance	2	2	0

The distinction between experimental studies and theoretical papers was defined as follows. An experimental study carried out a direct experimental manipulation, and the change in the dependent variable(s) was quantified in some manner. A theoretical paper, on the other hand, either described current automotive technology and relevant knowledge, or proposed a new model or theory for automotive thermal comfort research. A paper, for instance, that reviewed the history of HVAC development and outlined future challenges for manufacturers was classified as a theoretical HVAC paper. This distinction is especially important for the automotive glazing research that we have reviewed. For instance, the 11 papers that we have classified as "glazing/theoretical" do not typically describe any theory as such. Instead, the majority describes either new glazing technology or provides a commentary on the current state of the industry, including consumer needs and research possibilities.

Upon review of the existing literature, it quickly became apparent that the research topics are interrelated. Because HVAC systems play an integral role in the thermal environment, it is difficult to examine glazing research in isolation. Consequently, though the focus of this review is primarily the glazing research, the 78 papers will be examined and discussed to the extent that they help to define issues that face automotive thermal comfort research. Although there will be a section towards the end of this review dedicated solely to glazing research, an initially broader focus will help highlight important issues and add perspective. To supplement this focus, three themes will be examined: models, standards, and methods. We have already said a little about models and standards and their relevance to the current topic. What follows will be a more detailed analysis of the different models that have been proposed, the standards that are in existence, and the methods that have been used in experimental studies.

When considering the research process, the relationships among these three themes must be properly understood. Figure 1 shows one way to envision these relationships.

Models -----------------→Standards ------------→ Measurement (Method)

Figure 1. Themes that are common to thermal comfort research articles.

On one hand, it is the model of thermal comfort that guides both the creation of standards for research and the methods that follow in future research. On the other hand, the models themselves are usually based on (and refined through) data obtained by experimental study. So in that sense, it is the methods themselves that guide the creation of models. A standard is often grounded in theory, and since, in this case, the theory usually takes the form of a model, Figure 1 shows the standards being guided by the modeling process. Figure 1 is a simplistic picture, though the reality is a complex, interrelated process that mirrors the research topics themselves.

WHAT IS THERMAL COMFORT?

The agreed-upon definition of thermal comfort is "that condition of mind which expresses satisfaction with the environment" (ASHRAE 55, 1992; ISO 7730, 1994). As Parsons (1993) points out in a chapter on the subject, this definition emphasizes the fact that thermal comfort is first and foremost a psychological phenomenon. As such, it is a classical example of the mind/body problem (i.e., how do the environmental and physiological correlates of thermal comfort translate into a cognitive evaluation?). Though this question is interesting in and of itself, most of the scientific enquiry on thermal comfort has been in applied areas, with emphasis on finding practical solutions to common problems. The objective of research has been twofold: to find an operational definition of thermal comfort that is based on quantitative measures (i.e., the environmental parameters and physiological conditions that correlate with psychological comfort), and to build models of thermal comfort that are based on that operational definition. Instead of "Why do people feel comfortable or uncomfortable?", the question has become "What environments will produce thermal comfort?" More specifically, because of variance among individuals, what environments will produce thermal comfort for the highest possible percentage of a given group of people?

For obvious reasons, a complete historical coverage of the one hundred or so years of research on thermal comfort will not be presented here. Such reviews have been written, though the most recent summary of the research is Parsons (1993). Parsons suggested that the industrial revolution instigated a need to scientifically study what has presumably always been a human concern: how to maintain thermal comfort. Heavy industry in factories exposed many workers to volatile and potentially dangerous environments. Similarly, with the rise of the information age, office buildings became an extremely common working environment. Soon, achieving a thermally comfortable working environment became an issue of prime importance. Figure 2 shows the historical trends of thermal comfort research. The study of thermal comfort in motor vehicles developed from both basic thermal comfort research and applied work relating to factories and buildings. The first research on motor vehicles dealt mainly with agricultural vehicles (i.e., tractors) and public transport systems such as subways, trains, and buses.

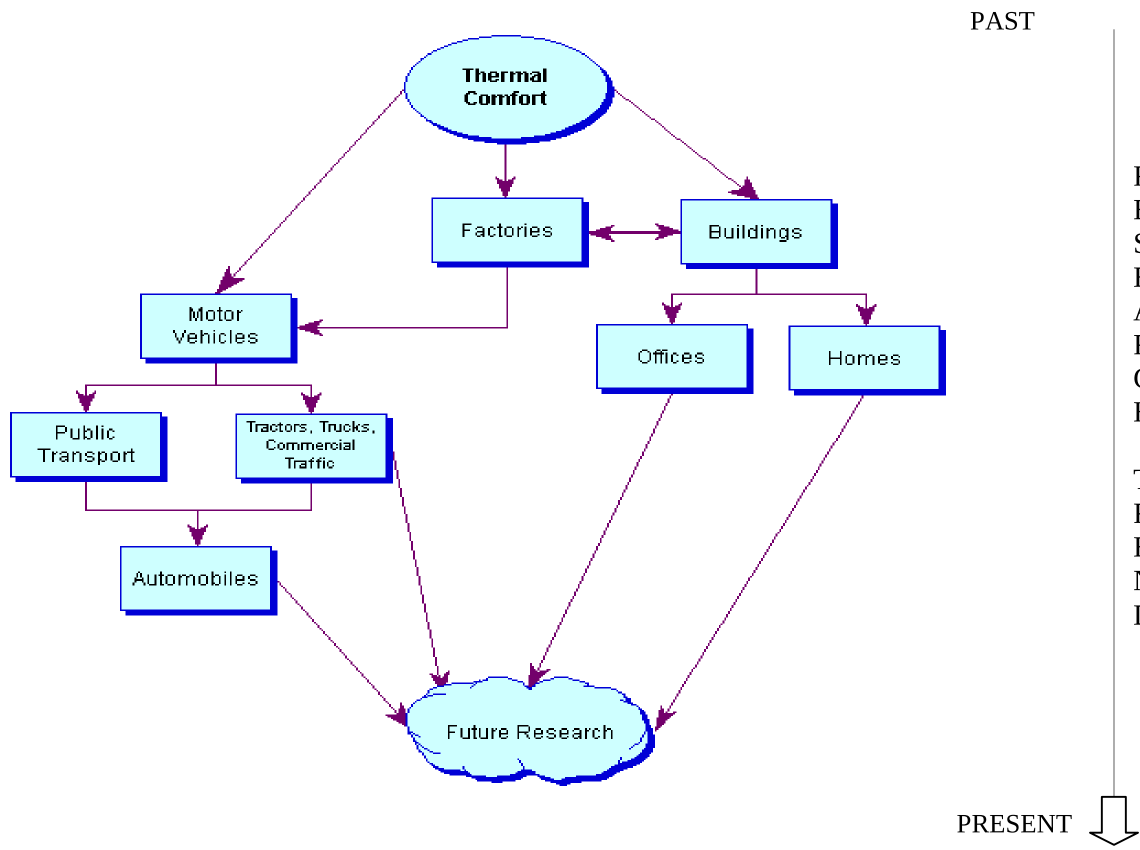

Figure 2. The historical trend in thermal comfort research.

Intuitively, one might assume that air temperature alone is the deciding comfort factor, and that simply raising or lowering the temperature of the air would easily manipulate levels of comfort. However, this assumption was challenged as early as the beginning of the nineteenth century. Since then scientists have focused on a more holistic climatic interpretation, one that includes such environmental parameters as humidity (absolute or relative), air velocity, air temperature, and radiant temperature. In addition, laws of human heat exchange were incorporated into the equation, taking into account such variables as human activity level, clothing level, and heat loss through skin diffusion, sweat secretion, latent and dry respiration, radiation, and convection. The most notable figure to use such a human heat balance equation in the application of thermal comfort analysis was P.O. Fanger. His seminal work, *Thermal Comfort*, published in 1970, outlines the required conditions for thermal comfort and presents an equation to predict what proportion of an average population would find a given environment decidedly uncomfortable. His *predicted mean vote* (PMV) and *predicted percentage dissatisfied*

(PPD) became the basis for several standards on thermal comfort, the most significant ones being ISO 7730 (1994) and ASHRAE 55 (1992). The PMV is based on the following ASHRAE subjective scale:

Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

Though one could theoretically give this scale to groups of subjects, the ultimate aim of Fanger's model is to use the thermal comfort equation to calculate the PMV for any particular environment. This can be done if one knows the values of the six environmental parameters (air temperature, humidity, radiant temperature, air velocity, activity level, and clothing level). When the PMV equals zero (or the environment is rated as "neutral"), the PPD should equal five. This means that for any comfortable environment, approximately five percent of an average population will still rate it as uncomfortable. When the PMV equals –2 or +2, the PPD will equal 80, meaning that 80% of the population will be dissatisfied, and so on. The relationship between PMV and PPD is thus a U-shaped curve, as illustrated in Figure 3.

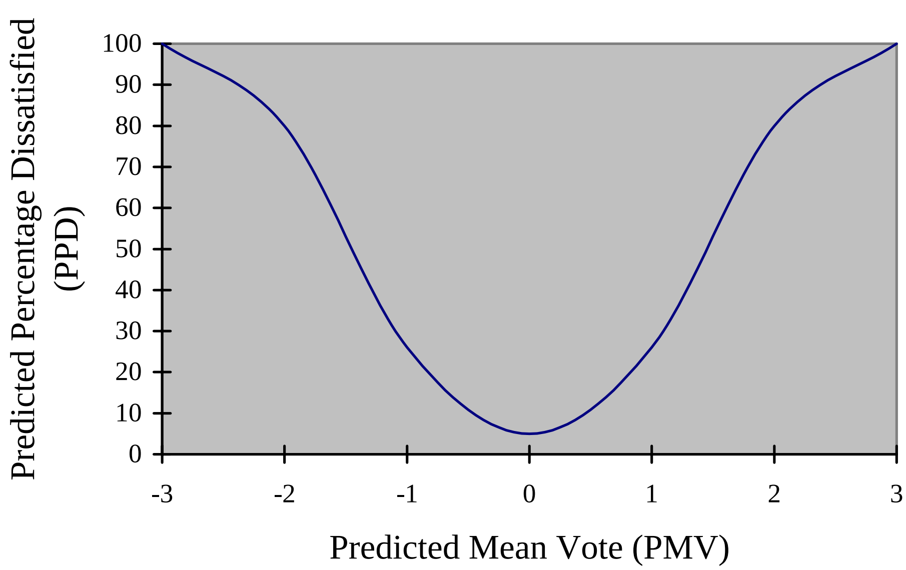

Figure 3. PPD as a function of PMV.

The equations that led Fanger to develop the concept of PMV and PPD are based on the physiological processes that underlie human heat balance. The final "thermal comfort equation" is too complex to be solved without the use of a computer, and for this reason, it is not presented here. However, several chapters of Fanger's 1970 publication are devoted to an explanation of this equation.

A vehicle represents a "moderate" thermal environment; as such, Fanger's equation has been the most widely used for automotive research (as Fanger's equation has been validated numerous times for moderate environments). Similarly, ISO 7730 is entitled "Moderate thermal environments–Determination of the PMV and PPD indices and specification of the conditions for thermal comfort." ISO 7730 will be discussed in detail later, but it is important to note some of the environmental phenomena that are introduced by Fanger and the standard. There is first the distinction between local thermal comfort and whole-body thermal comfort. Whole-body thermal comfort precludes local discomfort; that is, for an individual to be "comfortable," there can be no single part of the body that feels uncomfortable. Local thermal discomfort can be caused by high radiant temperature asymmetry, temperature differences across the body (usually vertical), or contact with hot or cold surfaces, but it is usually considered in terms of *draught*, or local discomfort caused by air movement (ISO 7730). Unfortunately, all of these phenomena are common to a vehicle cabin. For instance, radiant heat from the windows can affect the upper part of the body while air currents toward the floor can cause local discomfort for the feet. While Fanger addresses some of these concerns, his equation is based on experiments carried out in uniform environments where single parameters were tested. The automobile environment is nonuniform and dynamic, and it is likely that most occupants will experience discomfort from more than one source simultaneously (Brooks & Parsons, 1999). The next section provides more details about the environmental differences between buildings and vehicles.

Other models that have influenced thermal comfort research to a lesser degree include (as cited by Parsons, 1993): Houghton & Yagloglou (1923, 1924); Yagloglou & Miller (1925); Dufton (1929, 1936); Gagge et al. (1971, 1972); and Madsen, Olesen, & Christensen (1984). All of them combine the various environmental variables into single measures. *Effective temperature*, r*esultant temperature*, *equivalent temperature*, and o*perative temperature* are just some of the concepts to come out of these models, and most of them represent some combination of air temperature, radiation, humidity, and so forth, that can be then plugged into an equation.

To date, the models by Gagge and Fanger are the most widely used. The former is based upon a transient energy balance and was originally developed to examine human response to hot and cold stress, while the latter, as mentioned above, is based upon a steady-state energy balance (Brown & Jones, 1997). It is interesting that Fanger's model dominates automotive literature, considering that the energy balance in a vehicle contains many transient conditions, specifically during warm-up and cool-down periods.

THERMAL COMFORT IN MOTOR VEHICLES

Differences Between Buildings and Vehicles

The first study to systematically analyze the different environmental parameters of motor vehicles versus those of buildings was Temming (1980). The author does not examine the physical differences in environments per se, but rather explores the different thermal comfort requirements that result from those physical differences. He does this by comparing the known literature of the time and then making proposals based on the available data. For instance, he points to the past research on recommended interior air temperatures, noting that few researchers have agreed on what constitutes the most appropriate comfortable air temperature. As an explanation for this phenomenon, Temming suggests that air temperature zones within the occupant space of vehicles are neither homogenous nor desired to be homogenous. Whereas the air temperature in heated rooms generally increases with height away from the floor, this temperature gradient is not acceptable for motor vehicles. In the latter environment, the foot space is expected to have a higher temperature than the head zone. Moreover, the appropriate mean air temperature depends both upon the operating state and upon the "class" of the vehicle. The former refers to the steady-state versus transient energy balance we mentioned earlier. The latter refers to the size and quality of different kinds of vehicles. A larger car with leather upholstery during warm-up conditions may have an entirely different optimum air temperature than, say, a small economy-class car during steady-state driving conditions.

Regarding air velocity, Temming observes that low air-flow velocities within the occupant space are required at low exterior temperatures, and a slow to moderate air-flow is required at high exterior temperatures. Whereas heated air should be directed toward the bottom half of the occupant's body, cool air should be directed toward the upper half. Because of limited flow volume capacity in vehicles (as opposed to buildings), the air-flow can only be directed to smaller sections. No data were available for air velocity fluctuations or pulsating streams. Nor were quantifiable data available concerning radiant temperature, but Temming did note the potential for extreme radiation effects (due to glazing) for thermal comfort in vehicles. Humidity was thought to play a minor role.

The two most significant differences in environmental parameters between buildings and vehicles appear to be the nonuniformity and transient energy of the latter. These are followed by the larger area of glazing (on average over 24% of the total surface area (Rolle, Romitelli, & Savasta, 1992)), higher air velocities found in vehicles (e.g., proximity of the air vents to vehicle occupants, open windows, etc.), relative immobility of occupants (Norin, 1989), and the intensity and direction of solar radiation, not necessarily in order of importance. The main difficulty lies, however, with the fact that the environment in a vehicle is dynamic; that is, the climatic conditions in a vehicle have the potential to dramatically change. Even so, to say a vehicular environment is "transient" is misleading–transient conditions only really exist for the first few minutes that a vehicle is operated under hot or cold ambient climates. As Olesen & Rosendahl (1990) observe, a truck, for instance, during warm-up or cool-down conditions is "somewhere between a transient condition and the slow transient condition." In other words, the environmental changes are not as rapid as the term "transient" implies, and the conditions actually lie between transience and steady-state. However, even with this relatively small amount of transience, measurement problems still arise. For instance, it has been observed that a person exposed to a low ambient temperature, which then increases rapidly, will indicate a feeling of thermal neutrality before the ambient temperature has reached the steady-state comfort level. The reverse occurs when a person exposed to a high ambient temperature experiences a rapid decrease; he or she will report thermal neutrality before the temperature has reached the steady-state comfort level. If the temperature change is stopped when the person reports neutrality, he or she will become uncomfortable again when acclimated to the change (Olesen & Rosendahl, 1990). Will these effects be seen during the warm-up and cool-down of vehicles? The important point is the dynamic quality of both the stimulus and the response. In an environment with potentially unpredictable climatic change, it may be much more difficult to predict and/or control the required thermal comfort levels.

Nonuniformity is an equally challenging problem for two reasons. Firstly, there are many variations of local thermal discomfort that can result from nonuniform environments (e.g., draughts, asymmetric thermal radiation, vertical air temperature differences, and local discomfort caused by surface contact). Secondly, there has been little research on how to ameliorate these local discomfort problems. The two types of local discomfort of most concern for glazing manufacturers are asymmetric thermal radiation and vertical temperature differences. Radiation that heats the upper parts of the body may cause discomfort even when cabin temperatures are within acceptable ranges. Similarly, if the air temperature in sunlit areas–usually corresponding to areas above the legs–is increased due to solar load, the feet may become locally uncomfortable (i.e., too cold). Local comfort has become known as the fourth necessary condition for thermal comfort. The other three necessary conditions (proposed by Fanger, 1970) are as follows: that the body is in heat balance, that perspiration rate is within subjective comfort limits, and that mean skin temperature is within comfort limits.

Contributing Factors

Before any meaningful research on thermal comfort in vehicles could be conducted, researchers had to identify what vehicular factors contribute to the cabin's thermal environment. There is evidence to suggest that many factors can potentially affect the climate of vehicle cabins (Hymore, Tweadey, & Wozniak, 1991). Some factors include interior upholstery, the interior and exterior colors and overall size of the vehicle, the clothing of the passengers, thermal insulation, and the passenger capacity of the vehicle cabin (Schacher & Adolphe, 1997; Shuster, 1998; Madsen, Olesen, & Reid, 1986). The last factor points to a rather unique characteristic of vehicle cabins: Their relatively small size means that each individual person in the cabin can affect the thermal environment. This is because every individual radiates a certain amount of heat; if a car is filled to capacity with occupants, the cabin temperature is likely to be higher than if a single person occupied the vehicle. By and large, however, there are two factors that dramatically affect the vehicular environment: HVAC systems and glazing materials. HVAC systems were designed specifically for this purpose, but the effect of glazing materials may not be as obvious. To understand why glazing is an important factor, it is useful to understand the relationship between solar radiation and glazing materials.

Solar Radiation and Glazing: Transmittance, Reflectance, and Absorptance

Solar radiation may be one of the most substantial factors to affect the climate inside a motor vehicle. One may think of radiation in terms of reflectance and absorptance. For instance, every exterior surface of an automobile, including the roof and doors, reflects and absorbs certain portions of solar energy. A portion of the absorbed energy acts, in turn, to increase the air temperature within the vehicle cabin. In this regard, glazing is no different from any other material. Glazing has the potential to directly transmit solar energy (as is most apparent in standard clear glass), absorb energy in between layers of glass, or reflect solar energy back into the atmosphere. For this reason, glazing is often defined by its levels of transmittance, reflectance, and absorptance. It must also be remembered that the solar energy that is transmitted into the cabin also will be absorbed and reflected by whatever is inside, including upholstery, dashboard materials, and occupants. In every case, the temperature of whatever is absorbing solar energy will increase. Indeed, most experimental studies that have tested solar control glazing have focused on the measurement of temperature, either of the air in the cabin or of the interior surfaces of the automobile. This is in contrast to many other kinds of automotive thermal comfort research that have focused on broader measures of thermal comfort (i.e., ones that include all six environmental parameters). This difference in methodology occurs most likely because many researchers believe that solar control glazing for motor vehicles ultimately affects a single environmental parameter: temperature.

A further distinction is made concerning the wavelength of solar radiation that is allowed to transmit through automotive glazing. Figure 4 illustrates the standard wavelength distribution of the solar spectrum. The solar spectrum in Figure 4 was produced by the SOLAR2000 model (Tobiska et al, 2000) that is available for scientific and engineering research applications at http://Spacewx.com. Notice that ultraviolet (UV) rays, visible (V) light, and infrared (IR) rays have the highest irradiance levels. That is, these three wavelength regions represent the vast majority of solar radiation.

One may note that IR rays represent about half of the wavelength distribution of solar energy. IR radiation is felt by humans as heat, and it is for this reason that glazing manufacturers have focused on the rejection of IR wavelengths. Products that absorb or reflect a certain portion of solar radiation are known as “spectrally selective” glazing. The challenge, as mentioned before, is to allow the required amount of visible light to be transmitted by the glazing while at the same time rejecting as much IR radiation as possible. Doing so would significantly affect three of the causes of local thermal discomfort, (viz., asymmetric thermal radiation, vertical air temperature differences, and discomfort caused by contact with hot surface temperatures).

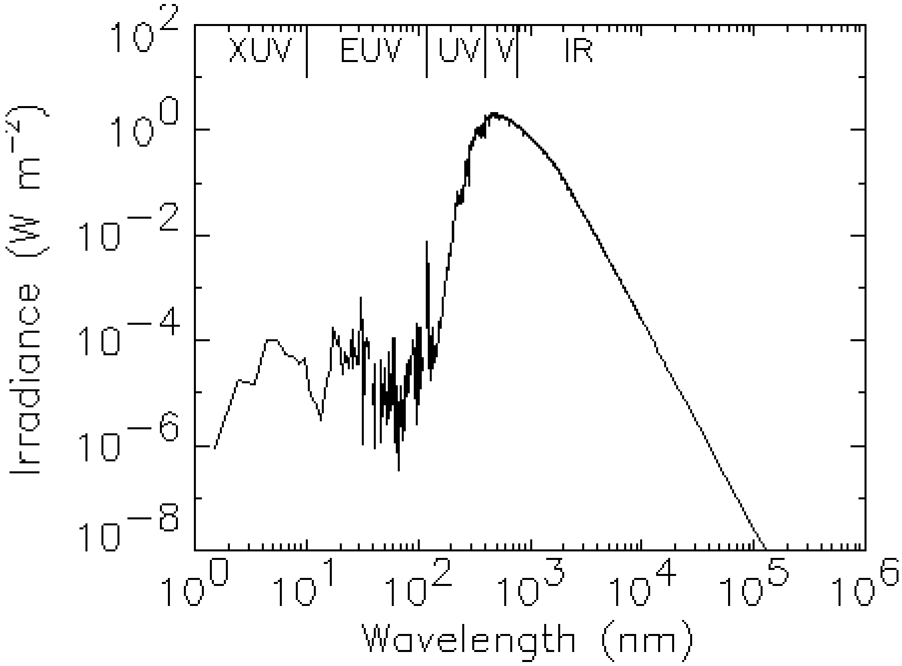

Figure 4. The solar spectrum from 1 to 1,000,000 nm (Tobiska et al., 2000).

To measure the thermal effect of spectrally selective glazing, it is useful to use a "solar heat gain coefficient" (SHGC), an index that takes into account the directly transmitted solar radiation and the added heat resulting from reradiation into the cabin (following absorption) by the glazing. Measured against the glazing's visible light transmittance (Tv), the ideal automotive solar control glazing would have a low SHGC and a high Tv. (A Tv value of .7 corresponds to a transmittance of 70%, the minimum allowed by federal regulation for automotive windshields). Figure 5, taken from a Federal Technology Alert from the U.S. Department of Energy's Federal Energy Management Program (Lee, 1998), shows the SHGC and Tv of commercially available, spectrally selective, dual-pane products for the nonresidential window market. While these glazing products are not designed for automotive windshields per se, the graph displays the general relationship between SHGC and Tv. For instance, it is possible for two pieces of glass to have the same SHGC and yet appear very different because they transmit different levels of visible light. The diagonal line in Figure 5 represents a value of 1 for the "light-to-solar-gain ratio" (LSG), or the ratio between SHGC and Tv (LSG=Tv/SHGC). As indicated by the darkened oval in Figure 5, most commercially available, spectrally selective products for nonresidential windows have an LSG between 1.25 and 2. The area toward the bottom of Figure 5, labeled "forbidden zone," represents a physically impossible product (due to the fact that any amount of visible transmittance will necessarily cause at least some heat gain).

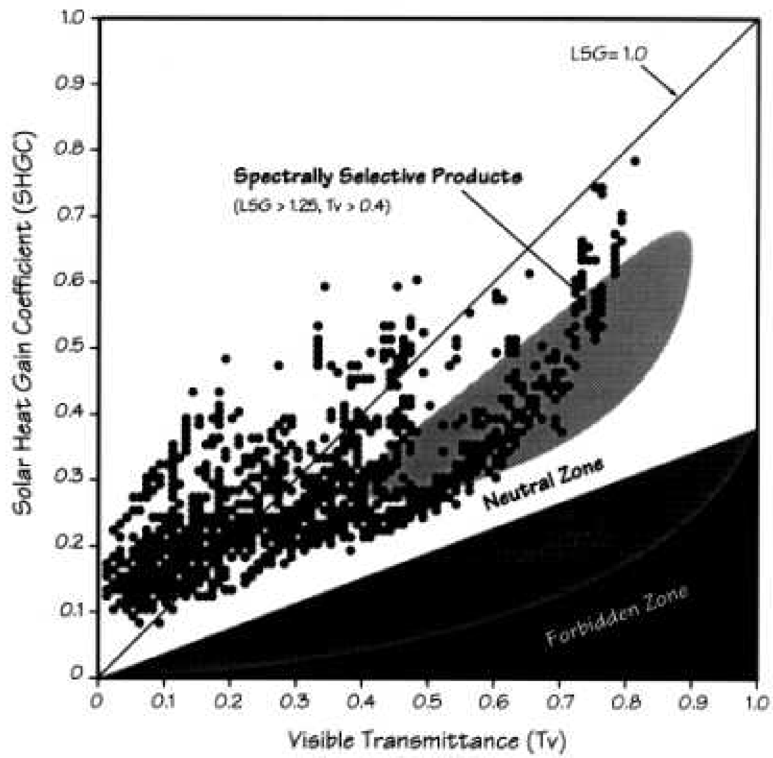

Figure 5. Center-of-glass properties of commercially available, dual-pane, spectrally selective glazing, coatings, and films for commercial applications (Lee, 1998).

METHODOLOGICAL ISSUES FOR MEASUREMENT OF THERMAL COMFORT

There are three major quantifiable aspects of thermal comfort: environmental conditions, physiological conditions, and psychological conditions. The first is comprised of the six environmental parameters of air temperature, humidity, air velocity, radiant temperature, occupant clothing level, and occupant activity level. One may think of the combined effect of these parameters as the *stimulus*. In contrast, the *response* makes up the other two categories of measurement, and includes both physiological responses and psychological responses. We have already discussed how many models attempt to use the stimulus conditions to predict the response. However, this approach assumes that one has already measured the environmental parameters, a task that in and of itself requires an understanding of the unique environmental characteristics of a vehicle.

Measuring the Six Environmental Parameters (Stimuli) in a Motor Vehicle

Very few articles have explicitly defined the environmental differences between motor vehicles and other human occupancies. However, much can be learned about the unique environmental parameters of a vehicle if one examines the ways researchers have attempted to measure them. ISO 7726 describes some methods for measuring physical qualities related to thermal comfort; only specifications are standardized, not specific instruments. Similarly, chapter four of Parsons' 1993 book, *Human Thermal Environments*, outlines physical measurement techniques for all six environmental parameters. Whereas it has been the tendency to use individual instruments (e.g., thermocouples, globe thermometers, net radiometers, hot-wire anemometers, hygrometers, etc.) to measure single parameters in buildings, automotive research has adopted a different approach, most likely because of the small available working space and the dynamic driving tests that are required when making thermal measurements. Installing large amounts of equipment in vehicle cabins is time-consuming and cumbersome, and presents difficulties when one wishes to measure all parameters in the same position. Two unique solutions have developed from these constraints: the thermal comfort meter and the thermal manikin.

The thermal comfort meter was first introduced by Olesen in 1982. First known as the B&K Thermal Comfort Meter, it consisted of a single heated transducer that measured the *equivalent temperature* (i.e., the combined measurement of air temperature, mean radiant temperature, and air velocity). Not only did this meter reduce the required amount of total instrumentation, but it also addressed the fact that radiant temperatures and air velocities are markedly different in vehicles as opposed to buildings. The B&K Thermal Comfort Meter also permitted the setting of different clothing values, activity levels, and vapor pressures. Thus, the holistic model of Fanger's thermal comfort equation could be addressed with one instrument; indeed, this was a major step that made the prediction of thermal comfort without human subjects more efficient. The one parameter that the B&K Comfort Meter failed to include was relative humidity, but subsequent thermal comfort meters have been designed in which one can tailor the system to specific needs. For instance, the Innova® UA1276 Comfort Module has transducer connections for humidity, air velocity, and temperature, and other modules can be custom built by selecting different transducers. Some researchers have found that by using three of these meters where a human occupant would sit (i.e., one at head level, one at the seat cushion, and one at foot level), rather precise measurements can be made of the thermal environment (Madsen, Olesen, & Reid, 1986; Olesen & Rosendahl, 1990).

The other solution is the thermal manikin. First introduced in 1985 by Wyon, Tennstedt, Lundgren, and Larsson, Volvo's "Voltman" was a life-sized manikin with 17 thermal sections. Each section maintained a skin-temperature distribution supposedly identical with that of a human occupant in thermal comfort. The manikin measured dry heat loss on a sectional basis, as well as other parameters such as temperature, engine and road speed, sun direction and intensity, air conditioner unit states, and so forth. It was hoped that, much like the thermal comfort meter, the manikin would serve as a means of gathering the environmental data (i.e., measuring the stimulus) to enable thermal comfort prediction. Voltman was not the first thermal manikin, but it was the first specifically designed for vehicle studies. Parallel studies with human subjects were conducted during the design process of Voltman, and it was believed that the manikin fairly represented a human heat-balance process.

It is interesting to note Wyon et al.'s arguments in favor of using a thermal manikin because they foreshadow some of the psychological measurement issues covered below. For example, they state that "human subjects cannot be expected to remember in detail how they felt in another vehicle on a previous occasion, so as to be able to make relative judgments, nor to be able to make any reproducible absolute assessment. 'Management Evaluation' is notoriously idiosyncratic." They further describe the use of a manikin as a viable alternative to the "expensive, time-consuming hit or miss of subjective assessment by large groups of users." Hence, we already see relatively early in the vehicular thermal comfort literature (i.e., the early 1980s) some concerns regarding the variability of human perception.

Variations of the thermal comfort meter and thermal manikin have been used in much of the research up to the present time. This is not to say that individual measuring instruments are no longer used, but increasing numbers of studies employ comfort modules, manikins, or both. To give a general idea of the prevalence of their use, of the 78 reviewed papers that dealt with some aspect of thermal comfort in vehicles, 14 directly used either or both of the technologies. In addition, all 14 studies were conducted between 1986 and 1999. Six studies have used manikins (Conceicao, Silva, & Viegas, 1997; Matsunaga, Sudou, & Tanabe, 1997; Madsen, 1994; Rolle, Romitelli, & Savasta, 1992; Madsen, Olesen, & Reid, 1986; Wyon et al., 1985). Ten studies used a thermal comfort meter or module (Alcobia & Silva, 1999; Matsunaga et al., 1997; Chakroun & Al-Fahed, 1997; Moyer, 1995; Hymore, Tweadey, & Wozniak, 1991; Manfre, 1991; Olesen & Rosendahl, 1990; Young & Van Esso, 1989; Weigh & Albrecht, 1987; Madsen et al., 1986). Finally, a few studies that used an array of single instruments to measure individual parameters include: Brooks and Parsons (1999), Brown and Jones (1997), and Stancato and Onusic (1997). The vast majority of the remainder of experimental papers directly measured at least one physical parameter of the environment.

Measuring the Response: Physiological Measures

When measures of response to a thermal environment are taken, they may involve both physiological and psychological measures. However, studies that involve human subjects can be both time-consuming and challenging. Recall the comments cited above from Wyon et al. (1985); subjective judgments of comfort can prove to be extremely variable. Moreover, many researchers have been concerned about the sensitivity of subjective detection. That is, alternative glazing technologies may indeed make a difference in the climates of motor vehicles, but the magnitudes may be relatively small (as compared to the large differences caused by HVAC systems). In fact, the differences may be so small as to be virtually undetectable using subjective assessment. None the less, just under one third of the experimental papers on thermal comfort used human subjects in their designs; this represents 16 papers (or 21% of the 78 thermal comfort papers reviewed). Measuring the response to the thermal environment is arguably the closest researchers can get to measuring thermal comfort; if nothing else, response measures can validate or invalidate the existing models of thermal comfort by supplying data to support or refute them.

Because even moderate thermal stress has rather obvious physiological effects, physiological measurements can act as an objective "yardstick" to compare with subjective response. Heat, for instance, typically causes increases in heart rate, perspiration, skin temperature, and internal body temperature. Almost any measurable change in human physiology caused by environmental change can be used as a dependent variable. Because skin temperature is a relatively easy parameter to monitor (via thermocouples, thermistors, infrared sensors, etc.), it is the one most commonly used. Internal body temperature and heart rate require close physical contact between the subject and the instrument, which may cause both discomfort and experimental interference. Furthermore, changes in heart rate can also occur due to other factors, such as excitement, nervousness, activity, and so forth, making it a difficult parameter to correlate with thermal variations. Finally, measures of body-mass loss (e.g., such as sweat secretion) can be taken, but usually require either weighing the subject before and after the study, or collecting the sweat into a receptacle, both of which are typically impractical.

Indeed, the general impracticality of physiological measurements is reflected by their relative lack of use; of the 78 papers on thermal comfort reviewed, only 12 actually used physiological measurements of human subjects. This represents just less than one quarter of the experimental thermal comfort studies. Of the 12 papers, nine used direct measurements and include: Brooks and Parsons (1999); Brown and Jones (1997); Furuse and Komoriya (1997); Wei and Dage (1995); Taniguchi, Aoki, Fujikake, Tanaka, and Kitada (1992); Roessler and Heckmann (1992); Stayner, O'Neill, and Whyte (1985); Kaufman, Turnquist, and Swanson (1976); and Mackie, O'Hanlon, and McCauley (1974). The remaining three papers used indirect physiological measurements (e.g., calculations of skin temperatures using neural networks, or calculations of the alpha-tau product for human skin using an index of human skin spectral reflectance data), and include: Ueda, Taniguchi, and Aoki (1997); Ueda, Taniguchi, Asano, Mochizuki, Ikegami, and Kawai (1997); and Goodman (1991). Skin temperature was the most commonly measured parameter. Interestingly, most of the papers came from automotive research areas other than glazing (e.g., HVAC research).

Measuring the Response: Psychological Measures

In chapter three of Parsons' 1993 book on human thermal environments, he discusses psychological responses. He points out that psychological responses to thermal environments can fall into two categories: thermal sensation (in which the "output" is cognitive or affective judgments of a stimulus), and actual behavior (in which the "output" is some observable behavior, such as looks of displeasure, chattering of teeth, or measures of driving performance). While it is clear that the link between people's thermal environment and their response to that environment is far from completely understood, there are many ways of quantifying the psychological response. They include psychophysical methods such as magnitude estimation, and methods of behavioral analysis such as recording driving errors. One common psychophysics method involves the administration of a questionnaire that asks the subject to rate his or her degree of discomfort. Because this last approach is the most straightforward and easiest to implement, it has traditionally been the most popular.

Before specific studies are examined, a few things should be mentioned about psychological measures. The first relates to their appropriate place in thermal comfort research. ISO 10551 contains some interesting comments regarding this subject. The introduction includes the following statement: "The data provided by this [psychological] assessment will most probably be used to supplement physical and physiological methods of assessing thermal loads… and thus may complete data provided by predictive approaches described elsewhere in this series." Similarly, ASHRAE 55 says that thermal comfort "…requires subjective evaluation." Finally, ISO 10551 goes on to say:

> The subjective nature of the data obtained using judgment scales leads some experts to doubt their benefit and prefer "objective", physical or physiological data. The question of the validity of subjective data as regards thermal environments can be viewed in two distinct ways:
>
> a) The first approach corresponds to the following question: To what extent is the information provided by these data the same as that provided by "objective" data?
>
> The relation which may or may not exist between objective and subjective data will be examined with the aim of substituting collection of the former by that of the latter, which are more easily obtained. This International Standard is not concerned with this approach, however interesting it may be once the relation has been established.

> b) The second approach corresponds to the following question: What is the intrinsic value of the data supplied by these scales?
>
> The opinions held by persons about the thermal environments in which they work have a value in themselves. It is up to the ergonomist whether or not to take them into account. The reputation of these data for lack of reliability does not justify dismissing them out of hand. The aim of this International Standard is precisely to improve their reliability by specifying the appropriate tools to use in collecting them and the requirement for using them.

The intrinsic value of subjective assessment is not addressed in this review. It is important to note, however, that subjective assessment is considered by many to be an integral component of thermal comfort analysis. Still, of the 16 reviewed experimental papers that used human subjects, only a handful actually used or emphasized psychological response measures. Four papers used a subjective scale similar to (or based on) the ASHRAE scale cited above, and they include: Hamilton and Stewart (1986), Atkinson (1986), Brown and Jones (1997), and Alcobia and Silva (1999). One paper used a forced-choice simultaneous-comparison design in which subjects had to choose which arm felt warmer when both arms were subjected to different climatic conditions (Roessler & Heckman, 1992). These five papers represent 10% of the reviewed experimental thermal comfort research. Two more papers used behavioral measures–they examined the effects of moderate thermal stress on driving performance. (The two studies are reviewed in the next section.) Of the eight experimental papers reviewed that tested the effects of IRR glazing on thermal comfort, none used psychological measures in their designs. The surprisingly small number of papers to use psychological measures suggests a general under-representation of psychological assessment in automotive thermal comfort research. Although this has to do with the aforementioned concerns about variability and the existence of confounding psychological variables (e.g., such as mood, expectation of comfort, attitudes, etc.), it might also be indicative of a general absence of understanding of psychophysiological techniques and processes.

Thermal Comfort and Driving Performance

Driving performance has been a topic of intense study over the last fifty years. While a major focus of such research is drug and alcohol intoxication, a handful of studies have examined the effects of thermal discomfort on driving performance. There also exists a vast literature on the negative effects of thermal discomfort on a wide range of nonvehicular performance measures (see Parsons, 1993, for a brief review).

Two specifically relevant experiments were conducted by Mackie, O'Hanlon, and McCauley for the U.S. Department of Transportation between 1972 and 1974. The first experiment was designed to determine the effects of heat stress on nonprofessional male and female car drivers. The main independent variable was *wet bulb globe temperature* (WBGT), a measure that was developed soon after *effective temperature.* The WBGT is a measurement that combines air temperature, air velocity, and relative humidity. Two experimental conditions existed: a "hot" car in which the WBGT was held at 32°C (90°F), and a "comfortable" car, in which the drivers were allowed to adjust the WBGT at will (they all selected values within the range of 16-20°C (60-68°F)). Vibration and noise levels were controlled. The dependent variables were grouped in three major categories. Under the performance variables, steering wheel motion, vehicle speed, accelerator motion, brake activation, and driver errors were recorded. Under physiological variables, electro encephalography (EEG), electrocardiogram (ECG), blood pressure, urine volume, sweat rate, and rate of excretion of adrenaline, noradrenaline, and the 17-Oh corticosteroids were recorded. Finally, under subjective reports, ratings of alertness and fatigue were recorded. A secondary task was also used as a dependent performance variable; the task involved having to press a foot switch in response to a rearview mirror-mounted light signal. Ten female and ten male volunteers between the ages of 25 and 35 drove under each experimental condition. The experiment produced approximately 240 hours of recorded data taken over 22,526 km (14,000 mi.) of driving. The drivers in the "hot" condition made a significantly greater number of large corrective steering adjustments, made a significantly greater number of lane drifts, and during the second half of the trip performed significantly worse on the secondary task than the drivers in the "comfortable" condition. Variations in speed control and driver technical errors were also increased among the "hot" drivers, but not significantly so. The results for subjective ratings agreed with the physiological data in that the participants in the "hot" car showed a dramatic increase in rated fatigue, particularly in the second half of the run. Although both the drivers in the "comfortable" car and the "hot" car experienced a lack of rated alertness during the run, the drivers in the "hot" car experienced a much sharper decline in rated alertness in the second half of the run than did the drivers in the "comfortable" car.

The purpose of Mackie et al.'s second experiment was to see if these findings extended to truck drivers engaged in regular line-haul operations (i.e., moving freight in high mileage operations). Both passenger cars and trucks were used, and the experimental design is shown in Table 2.

Table 2
Experimental Design (Mackie, O'Hanlon, & McCauley, 1974).

Temperature	Vehicle properties: Condition One	Vehicle properties: Condition Two
Comfortable 20°C (68°F) WBGT N = 10	Passenger car Noise low/Vibration low	16-Series Freightliner Noise moderate/Vibration mod.
Hot 27°C (80°F) WBGT N = 10	Passenger Car Noise low/Vibration low	16-Series Freightliner Noise moderate/Vibration mod.

Hours of observation: 344 Kilometers on the road: 14,270 (22, 960 mi.)

The dependent variables were the same as in the first experiment, but the subjects were all professional drivers. This experiment showed fewer significant performance differences between the "hot" and "comfortable" drivers, although "hot" drivers generally rated themselves as less alert and more fatigued than "comfortable" drivers. In addition, all physiological measures showed increased thermal stress for "hot" drivers. The authors therefore concluded that hot conditions negatively affect both nonprofessional and professional drivers, with performance being a greater concern among nonprofessionals.

A more recent study conducted by Wyon, Wyon, and Norin (1996) examined 83 drivers (51 males, 32 females) ages 25-65. The authors used a dynamic driving test (one hour over at least four laps of a predetermined route in Sweden). The independent variable was the cabin temperature in the car (either 21°C (70°F) or 27°C (81°F)), and the major dependent variable was driving vigilance, or "the assignment of attention to essential sources of information of varying degrees of priority within the driving task." Subjects were required to press a foot pedal and make verbal reports regarding various signals that arose unexpectedly while driving. The signals were controlled by the experimenter and included such things as engine and generator warning lamps, windshield wipers turning on unexpectedly, the car horn sounding, and so forth. The negative effect of the moderate heat stress on vigilance was statistically significant. At the higher temperature, the proportion of missed signals was 50% higher, and response times were 22% longer than they were at the lower temperature. Moreover, overt driving errors were observed significantly more often at 27°C (81°F) than at 21°C (70°F), but for women only.

MODELING AND THE THERMAL INDEX

When thermal comfort was defined earlier in this report, Fanger's PMV model (1970) was introduced to represent a prototypical model of thermal comfort. It was mentioned that the ultimate aim of such a model is to predict how comfortable an average population would find a given environment. Indeed, this aim is at the heart of all thermal comfort models, and it takes the form of the *thermal index*. The thermal index is a tool that is used for designing and assessing thermal environments and, when used to assess comfort, provides a means of analyzing an environment in terms of the individual parameters that correspond to comfort. A thermal index consists of a single number, the result of a particular calculation. Parson aptly divides thermal indices into two categories: rational indices and direct indices. Rational indices are primarily mathematical and use heat transfer equations to predict human response. Because the physiological state of heat balance is only one factor of thermal comfort, these equations should be used with empirical equations that relate skin temperature, rate of perspiration, and skin wetness to comfort. Direct indices, on the other hand, are more common in automotive thermal comfort research; they consist of direct physical measurements of the parameters that correspond to the human perception of thermal comfort (e.g., air temperature, relative humidity, etc.). An index makes it possible to see how two different environments, with different parametric values, can produce the same net thermal comfort for occupants. Moreover, one can see how changes in a single parametric value affect the index. The thermal index can be an effective way to predict subjective thermal comfort from physical parameters. Considered from the design perspective, an index can save substantial time and resources through quantitative prediction of thermal comfort.

Of the 78 papers on thermal comfort reviewed, 36 made use of thermal models or indices. Of these 36 papers, eight introduced new models specifically for thermal comfort in motor vehicles. They include: Farrington, Rugh, and Barber (2000); Benasser, Dauphin-Tanguy, and Riat (1999); Stancato and Onusic (1997); Brown and Jones (1997); Ingersoll, Kalman, Maxwell, and Niemiec (1992a); Ingersoll et al. (1992b); Stayner, O'Neill, and Whyte (1985); and Lassow, Lustenader, and Schoch (1972). Also, a number of other papers not reviewed in this report (because they do not specifically address motor vehicles) are relevant because they introduce new thermal comfort models or indices that are applicable to vehicular concerns. For example, some researchers in architecture have realized that current models both fall short in areas such as subjective assessment, and fail to account for transient environmental conditions. The titles of some of the papers may help illustrate the point: “A model of human physiology and comfort for assessing complex thermal environments,” (Huizenga, Hui, & Arens, 2001); “Thermal comfort and sensation under transient conditions,” (Wang, 1994); and “Thermal comfort: a new approach for subjective evaluation,” (Laviana & Rohles, 1987). Similarly, in their 1997 paper entitled, “A new transient passenger thermal comfort model,” Brown and Jones attempt to adapt architectural models to the unique environments of automobiles. The paper is covered in greater detail later in this review.

Nevertheless, Fanger’s Predicted Mean Vote (PMV) remains a solid and fairly reliable thermal comfort index. In the field of basic thermal comfort research, the PMV model has been validated numerous times. However, while it is still commonly used in many applied areas, there has been relatively little experimental validation of the PMV model for automotive applications. Of the 36 reviewed papers that used or referred to a thermal comfort model, 16 used the PMV (or a close derivative). This is not surprising since, as mentioned earlier, Fanger’s PMV index has become the basis for the only existing standards in this area of research. Many other models exist, however, and new ones are frequently emerging. There have been very few attempts to analyze or compare the competing models, and this lack of synthesis can be detected in the research. For instance, the literature includes at least 13 distinct models or indices within general thermal comfort research. (This number is probably conservative; there are numerous computer models that have recently been developed as well, although we have not attempted to count how many currently exist, nor have we evaluated any of them. Presumably, more will be developed, and it is difficult to characterize how much they differ from each other.) It is also unclear how the results of scientific experiments are affected by the models that motivate them; if the models themselves differ significantly, it may become impossible to generalize across studies. Articles that discuss some of the methodological and modeling issues that face thermal comfort research include: Olesen (2000), Powitz and Balsamo (1999), Parsons (1993), and Gagge, Fobelets, and Berglund (1986).

STANDARDS

The current standards that apply to thermal comfort research for moderate thermal environments include ISO 7730, ISO 10551, ISO 9886, ISO 7726, ISO 9920, ISO 11399, and ASHRAE 55. Other standards do exist, but they are strongly influenced by the aforementioned ones and are not frequently cited (e.g., standards by the European Committee for Standardization, and the National Institute for Occupational Safety and Health). The relatively large number of existing standards demonstrates the fact that thermal comfort has been a major concern around the world. Each ISO standard considers a specific topic relevant to the study of the thermal environment and its effects on human comfort. For instance, whereas ISO 7730 defines the calculation of the PMV based on the six environmental parameters, ISO 10551 examines subjective scales of measurement. ISO 7726 gives the required specifications for the instruments that measure physical parameters. ISO 9866 reviews the evaluation of thermal strain by physiological measurements. ISO 9920 estimates the thermal characteristics of different clothing ensembles. Finally, ISO 11399 reviews and defines each relevant standard, providing examples of how and where they might best be applied. This last standard is useful because it was designed not only to describe the underlying principles of the ergonomics of the thermal environment, but also to help researchers select which standards to use for their specific applications (Parsons, 1993).

By far the most widely cited standards are ISO 7730 and ASHRAE 55. They were first adopted in 1984 and 1981, respectively. Though the two standards are very similar, they have minor differences that make them distinct. For instance, the former is an international standard, while the latter originated in the U.S. (with the American Society of Heating, Refrigerating, and Air conditioning Engineers). As one might infer from the name of the society, ASHRAE 55 has been frequently used in automotive HVAC research. For the most part, however, the two standards are practically the same, and researchers commonly cite both of them as aiding in their research designs.

Recent editions of ISO 7730 and ASHRAE 55 have added material concerning local discomfort (i.e., draughts), radiant temperature asymmetry, metabolic rates for different activity levels, garment insulation values, and even a computer program that calculates the PMV and PPD. Given these additions, it would appear that the standards may now work well for nonuniform, transient environments, but this remains an open issue. For instance, though they define the different kinds of local discomfort and give the acceptable comfort ranges for them, they provide only a small amount of detail, and do not discuss nonuniform environments per se.

THE RESEARCH: AUTOMOTIVE GLAZING AND THERMAL COMFORT

The previous categorization of the papers (HVAC, glazing, miscellaneous factors, and driving performance) was a heuristic meant not only to highlight the different foci of research, but also to illustrate themes that are common to all of them. For instance, the 23 papers that considered the effect of HVAC systems on thermal comfort ranged from the development of newer or enhanced systems to the historical development of HVAC systems as a whole, and some examined the effects of HVAC size, performance parameters, and style on levels of thermal comfort. When these papers are compared to the glazing research, similar themes can be found, leading to the conclusion that a recognizable relationship exists between an automobile's glazing components and its HVAC system. That is, the compressor size and level of output of HVAC systems can be minimized through more efficient solar control glazing. This relationship is becoming critical as automotive designers increase glazing surface area and seek to decrease engine size in order to improve fuel economy. The remainder of this section further categorizes the research on the effects of automotive glazing on thermal comfort. The results of those articles that specifically examine IRR glazing are then reviewed and critiqued.

A Closer Look at Automotive Glazing Research

There has been relatively little research on the effects of automotive glazing on thermal comfort. Of the 18 experimental papers that tested glazing, seven specifically examined solar-absorbing glass, two exclusively examined solar-reflecting glass, six compared solar-absorbing and solar-reflecting glass, one examined laminated glass, one examined the effects of window covers, and one examined polycarbonate. Table 3 lists these studies according to this classification.

Table 3
Experimental glazing research by category.

Solar-Absorbing	Solar-Reflecting	Comparison: Absorb/Reflect	Laminated Glass	Window Covers	Polycarbonate
Roessler & Heckmann (1992) Hymore et al. (1991) Ando, Ebisawa, Suzuki, & Ono (1991) Goodman (1989) Huber (1988) Weigt & Albrecht (1987) Atkinson (1986)	Rugh, Farrington, & Boettcher (2001) Young & Van Esso (1989)	Farrington, Rugh, & Barber (2000)* Moyer (1995) Goodman (1991) Manfre (1991) Sullivan & Selkowitz (1990) Shimizu, Hara, & Asakawa (1982)	Fritsch (1991)	Chakroun & Al-Fahed (1997)	Katsamberis, King, & Skabardonis (1997)

* See also: Farrington, Cuddy, Keyser, & Rugh (1999).

Eight of the 18 experimental glazing studies listed above conducted at least part of their experiments on testing grounds in Phoenix, Arizona. All eight of these studies tested solar-absorbing or solar-reflecting glass. Stated another way, over half of the studies that tested solar control glazing (i.e., solar-absorbing or reflecting) were conducted in Phoenix. This is probably because researchers generally desire to test automotive glazing during peak solar load conditions. Indeed, as one author commented, “Such environments [Arizona and California] are typically used by auto manufacturers to test air conditioning systems because they must have enough capacity to provide sufficient cooling even at idling speeds and on the hottest days” (Moyer, 1995). This appears to be an example of how HVAC research has affected the milieu in which automotive glazing research takes place. However, after review of the solar-control glazing research, it does not appear that testing in such environments is necessary; it is perhaps only a matter of convenience, because of the low precipitation and extreme solar conditions found there.

IRR Glazing and Thermal Comfort

Table 4 summarizes the literature on the effects of IRR glazing on thermal comfort in automobiles. Testing methods, independent and dependent variables, any analytical methods used, and the results are listed. The Analytical Methods column refers to any models that were either used or developed in a given study. However, unless a model was directly used to calculate or interpret the data that was presented in the paper, for the sake of brevity, we will avoid presenting the details of those models here. Usually, these models are presented toward the end of an experimental paper, showing how the researchers plan to use the collected data to simulate further hypothetical results. Finally, the heading of Table 4 includes page numbers that indicate where in the review more detailed descriptions of the studies can be found. Descriptions of the studies listed in Table 4 end on page 54 of this report.

The reviewed articles have some limitations in common. For example, no statistical analyses were reported in any of the studies. Results were usually reported in terms of actual temperature differences, and many times only a fraction of the collected data was actually reported. For the results that were reported, many articles relied on graphs alone to convey information–no actual values were given.

A preliminary look at the research revealed the fact that, of the studies that specified the nature of the glass being tested, every one used an IRR film or coating. This represents five of the eight papers. None of the studies specifically tested an IRR glazing product that used the layered glass method (in which multiple layers of glass with different indexes of refraction are used to reflect infrared wavelengths).

Rugh, Farrington, and Boettcher (2001). Rugh et al. tested the thermal properties of a solar reflecting film (SRF) that was non-metallic and colorless. Two vehicle test programs were initiated – a pair of minivans and a pair of SUVs were tested between 1999 and 2000. For each test, one vehicle was left with the standard manufacturer's glass while the other had the SRF applied to some or all of its windows. Before experimental testing began, both vehicles underwent a baseline test in which each vehicle's production glazing was used. This was done in order to characterize any difference between the vehicles.

Table 4
Effects of IRR glazing on thermal comfort in automobiles. (Located on pages 39-46).

Study	Testing Methods	Independent Variables	Dependent Variables	Analytical Methods	Main Results
Rugh et al. (2001)	Outdoors – 2 minivans and 2 SUVs were tested: 2 experimental & 2 test vehicles Day 1 – Soak Test, followed by a cool-down test Day 2 – Coheat test	Glazing configuration (solar-reflective film (SRF) applied to some or all vehicle windows, or SRF applied to only the windshield).	Average temperatures, time required for vehicles to cool down, and the difference in heater power between baseline & test vehicle.	Model used to determine air conditioning compressor size with and without SRF.	SRF on all windows decreased temps. and cool-down times, and increased required heater power, as compared to standard glass and SRF on only the windshield. Statistical significance not reported.
Farrington et al. (2000, 1999)	Outdoors – one car was used. Two different tests: a soak test using combinations of SRF and ventilation options, and a coheat test using different glazing products.	SRF on or off, windows open or closed, IRR windshield vs. standard glass.	Cabin temperature and heater power (watts).	Computational fluid dynamics model to predict air velocities and temperatures.	Open windows, SRF on, and IRR windshield decreased cabin temperatures and increased required heater power. Statistical significance not reported.
Moyer (1995)	Outdoors – 2 sets of minivans w/ varying glazing dimensions. One or two hour soak test, followed by four drives of 15 minutes each traveling in different directions & speeds.	Type of glass: Solex®, Solargreen® (IR-absorbing), or Sungate® (IRR). Also compared two privacy glasses.	18 air temps., glass temp., interior materials temps., solar sensor, air flow & heat flux transducers, and comfort meter readings.	A minivan thermal simulation model was used w/ a computer program that simulates glass properties.	Sungate glass had the worst visible light transmittance, but consistently decreased the thermal conditions in the vehicle cabin. Statistical significance not reported.
Goodman (1991)	Test method not specified.	Type of glass: 1. Base glass 2. Tinted privacy 3. Solar-absorbing 4. Solar-reflecting	Direct & indirect solar gain, solar absorption by car interior & human skin, UV transmission.	Absorption by car interior & human skin was calculated through thermal indices.	Solar-reflecting glass reduced heat gain more than solar-absorbing glass. Statistical significance not reported.

Table 4
Effects of IRR glazing on thermal comfort in automobiles (cont.). (Located on pages 48-53).

Study	Testing Methods	Independent Variables	Dependent Variables	Analytical Methods	Main Results
Manfre (1991)	Outdoors, 2 cars were used. Soak test, followed by driving conditions at average speed of 80 kph. with air conditioning on.	Type of glass: 1. Clear base glass 2. Green tinted glass 3. Solar-absorbing 4. Solar-reflecting 5. Solar-reflecting w/ polyester sheet	Internal air temperature, interior surface temperatures, and comfort meter readings.	None	10°C diff. in interior surface temp. found with absorbing glass; 15° with reflecting glass. Air temp. differences were only found for reflecting glass--soak test with no ventilation. Statistical significance not reported.
Sullivan & Selkowitz (1990)	Numerical computer simulation of vehicle soak test.	4 levels of solar transmittance (83%, 43%, 23%, & 3%), and varying levels of solar reflectance and absorption.	Interior air temperatures and dash/seat surface temperatures.	None	At every level of solar transmittance, IRR glass reduced air and surface temperatures over IR absorbing glasses. Statistical significance not reported.
Young & Van Esso (1989)	Outdoors, 2 cars were used. 4 series of following tests: -Static 8-hour soak test -Dynamic test with 1-hour soak, highway cool-down, and city driving -Repeat of the dynamic test	Presence or absence of Aircool™ IRR coating on windshield or on all vehicle windows.	Air temperature, interior surface temperature, and time required to reach "comfort."	None	Aircool™ reduced time required to reach comfort, and reduced surface and air temperatures over the stock tinted glass, especially when applied to all windows. Statistical significance not reported.
Shimizu et al. (1982)	Numerical computer simulation, and laboratory tests of heat load using an actual vehicle. IRR and IR-absorbing glazing were tested under both static soak and cool-down conditions.	Type of glass: 1. Ordinary glass 2. IR-absorbing 3. IR-reflecting	Heat load through glass (calculated from direct measurement of the air temperature in the passenger compartment).	Development of air conditioner heat load model.	IRR glass lowered cabin temperatures more effectively than IR-absorbing glass and ordinary glass for both soak and cool-down conditions. Statistical significance not reported.

Each pair of minivans and SUVs was identical in make, model, and color. A two-day test sequence was used; on Day 1, a soak test was conducted in which the peak temperatures were recorded for both the baseline (vehicle "A") and test vehicle (vehicle "B"). When the peak temperatures were attained, a stationary cool-down test was performed in which the vehicles were operated at idling speed with the air conditioners at maximum fan speed and 100% recirculation. On Day 2, a "coheat" test was performed (i.e., the power of a ceramic heater required to maintain the cabin interior air temperature at a constant level was measured). As the solar transmittance through the glass increased, the heater power decreased, and the difference in heater power between the baseline and test vehicle represented the solar power reflected by the SRF. The independent variable for this study was therefore the glazing configuration. For the minivans, vehicle B had two configurations that were tested: all glazing with the SRF, and SRF applied to the windshield only. For the SUVs, vehicle B had four configurations that were tested: all glazing with the SRF, SRF applied to windshield and four sidelites, SRF applied to windshield and two sidelites, and SRF applied to the windshield only. Three of the dependent variables consisted of average temperature readings: breath temperature, instrument panel (IP) temperature, and windshield temperature. Additional dependent variables included the time required to reach 25°C (77°F) for cool-down tests, and the difference in heater power between the baseline and test vehicles for the coheat tests. Accordingly, thermocouples were located near the passenger breath, rear left breath, and driver foot positions. Surface thermocouples were also placed on the IP, the windshield interior, driver sidelite, and left rear privacy sidelite.

For the minivans, the SRF applied to all glazing reduced the average breath temperature by 4.6°C (8.3°F) while the SRF windshield-only condition reduced the average breath temperature by 2.5°C (4.5°F). IP and windshield temperatures were similarly reduced, with the greatest effect seen on the vehicle with SRF on all glazing. Most dramatically, the windshield temperature was reduced by 9.5°C (17.1°F) with SRF on all glazing and by 8.7°C (15.7°F) for SRF on the windshield only. For the vehicle with SRF installed on all glazing, the time to 25°C (77°F) was reduced by 3.75 minutes (this equates to a reduction of approximately 19% in air conditioning compressor power). The windshield-only SRF vehicle had similar results, though the numbers are not reported. Finally, the coheat test determined that the SRF on all glazing reflected an average of 486 W of solar power between the hours of 10:00 a.m. and 2:00 p.m., whereas SRF on the windshield alone reflected 348 W.

For the SUVs, similar results were found, but of a lesser magnitude. The SRF applied to all glazing resulted in a reduction in average maximum breath temperature of 1.8°C (3.2°F) and a reduction in IP temperature of 3.4°C (6.1°F). Average breath temperatures were also reduced in an expected direction for the other glazing configurations. For instance, SRF on the windshield and four sidelites decreased breath temperature by 1.3°C (2.4°F), SRF on the windshield and two sidelites decreased breath temperature by 0.9°C (1.6°F), and SRF on the windshield only decreased breath temperature by 0.4°C (0.7°F). According to the authors, the smaller effect of SRF for the SUVs as compared to the minivans may have been caused by differences in window area and windshield angles, and by differences in the time of year that the testing was performed.

The authors conducted two additional tests, which employed foil covering over either the roof of the vehicles, or over all of the windows. Standard glass was left in both vehicles, and the purpose of the tests was to determine whether temperatures might also be reduced through non-glazing applications or special high performance heat-rejecting glazing. Temperatures were indeed reduced, especially for the test condition of foil on all windows. Foil on the roof of the car yielded similar results as having SRF on all glazing. The authors conclude their study by developing a model to predict the corresponding fuel economy and tailpipe emissions over the SCO3 drive cycle for the different glazing configurations.

<u>Farrington, Rugh, and Barber (2000, 1999)</u>[1]. Farrington et al. used the same general method as the above study. Only one car was used, a 1997 Plymouth Breeze, and the authors tested nine different glazing configurations. Only the windshield was manipulated; all of the other windows were production-stock glass. The first test consisted of a coheat test with five experimental conditions: an SRF applied to the windshield with all of the windows closed, an SRF applied to the windshield with all of the windows slightly open, no SRF applied with all of the windows closed, no SRF applied with all the windows slightly open, and an opaque windshield with all of the other windows insulated with 2.5 cm (1 in.) of foam material. As expected, the opaque windshield required the most heating power, followed by the SRF

[1] Farrington et al.'s 1999 and 2000 publications report the same experimental data. They are thus treated as one study in this review.

on/windows open condition. The SRF on/windows closed condition followed closely after, and heater power was greatly reduced for the SRF off/windows open and closed conditions. The SRF on/windows closed condition had 64% more thermal gain than the SRF on/windows open condition. This led the researchers to conclude that a combination of SRF and ventilation can make dramatic differences in cabin temperatures. A static soak test was also conducted with two of those five conditions (SRF on/windows closed and SRF off/windows closed) in which cabin temperature was the dependent variable. The SRF kept the cabin about 9°C (16°F) cooler than the cabin temperatures without the SRF.

The authors then tested three different windshields supplied by PPG Industries: Solex®, a standard windshield; Solargreen®, an IR-absorbing windshield; and Sungate®, an advanced ultraviolet and IRR windshield. Because the "opaque" condition was also used for this test, a total of four experimental conditions existed. Another coheat test was performed under outdoor solar conditions. While the data for heater power (in watts) is presented in the paper, it is easier to analyze the results for windshield thermal gains (which were calculated by the authors from the coheat test). Solex® had the highest level of heat gain (1.94), followed closely by Solargreen® (1.82). Sungate® followed with a heat gain of 1.66, while the opaque condition had the lowest thermal gain (1.00). From these data, it was concluded that advanced solar control glazing (especially IRR glazing) can significantly affect the cabin temperatures in vehicles, and therefore may reduce vehicle emissions caused by excessive HVAC use.

A critique of this study is that the researchers only used one vehicle. Using only one vehicle does eliminate any possible differences between the baseline vehicle and test vehicle, but it also means that only one condition can be measured at a time. Thus, Farrington et al.'s results are difficult to interpret because environmental conditions (e.g., ambient temperature, humidity, etc.), which were not measured, could have changed for each test condition. Furthermore, there is no description of the experimental procedure (e.g., how the car was equipped or how measurements were taken). This also makes it difficult to interpret the findings.

<u>Moyer (1995)</u>. Moyer tested the same products as in the above study (viz., Solex®, Sungate®, and Solargreen® windshields). However, Moyer tested them on minivans and included a comparison of GL-20™, an improved tinted privacy glass, with Solarcool® coated Solargray® glass (also from PPG Industries). Environmental measurements were more

comprehensive in this study, and included the following: 18 air temperatures (six measurements each were taken at breath level, floor level, and seat arm levels), glass temperature measurements (inside and outside), material temperatures (including the instrument panel, steering wheel, and seats), three solar sensors, air flow and heat flux transducers, air temperature measurements in the cooling stream (including positions at the air conditioning outlets and the return air duct), a tachometer, and two comfort meters per minivan. This represents one of only three studies reviewed here that used a comfort meter to obtain data. All of the vehicles tested had white exteriors and matching interiors, and the tests were run in Phoenix, Arizona.

The test method consisted of a one or two hour soak followed by drives of 15 minutes at 48 kph (30 mph) traveling east, then 15 minutes at 48 kph (30 mph) traveling west, 15 minutes at 81 kph (50 mph) going north, and 15 minutes at 81 kph (50 mph) going south. This was meant to both simulate city and highway driving, and to ensure that each vehicle received an equal amount of solar exposure. Following each test, a computer program calculated and compared the air conditioner compressor work rates for each vehicle. Two sets of minivans were used. The first set consisted of an identical pair of minivans with a windshield of 2 m^2. The second set consisted of a pair of identical minivans, except with a smaller windshield of 1.4 m^2.

For all data, results were only presented graphically (showing dashboard average temperature, average breath temperature, solar sensor irradiance levels, and work done on the refrigerant and percent of work reduction, all plotted over 120 minutes), so exact numbers cannot be reported here. First, Solex and Sungate glazing were compared to each other in the vans with 2 m^2 windshields. Both of these vans were glazed with Solarcool coated Solargray privacy glass. Sungate outperformed Solex in all reported categories. Next, the same vans were compared using Solargreen vs. Sungate (i.e., IR-absorbing vs. IR-reflecting) glazing. While Sungate outperformed Solargreen during the soak test, the magnitudes were generally small and Solargreen actually caused lower breath temperatures during driving conditions. Finally, Solargreen was compared to Solex in the second set of minivans (those with the 1.4 m^2 windshields). In this test, the Solex-equipped van had GL-20 privacy glass in “non-vision areas,” (not defined by the authors, but assumed to be all glazing to the rear of the B-Pillar) and the Solargreen-equipped van had Solarcool-coated Solargray privacy glass in “non-vision areas.” For all listed measures, Solargreen and Solarcool-coated Solargray privacy glass outperformed Solex and GL-20 privacy glass. The results of these tests led the author to conclude that solar control glass (Sungate in particular), in combination with the improved privacy glass, reduced cabin temperatures and increased comfort. Further tests also showed that these solar control glasses have a statistically significant positive effect on the colorfastness of automotive interior materials.[2] That is, thermal degradation of materials may also be reduced by using glazing that blocks UV and infrared wavelengths of light. The data presented in the paper showed that a Sungate laminate (i.e., IRR coating) resulted in the least amount of average brightness change and average color change for five different kinds of interior automotive materials. The Solargreen laminate (i.e., IR-absorbing coating) performed slightly worse than Sungate, but better than Solex.

Goodman (1991). Goodman compared the relative merits of solar reflective glass and solar absorbing glass as opposed to base glass in four basic areas: direct vs. indirect solar gain, direct solar absorption by the car interior, direct solar absorption by human skin, and UV transmission. While experimental data are presented, there is no mention of test method or statistical significance. For the first category, direct vs. indirect gain, the solar absorption and transmittance properties are listed for four glass products: tinted base glass, solar absorbing glass, privacy glass, and a solar reflective glass windshield. The presented data show that, as expected, the privacy glass has the highest solar absorption (71%) and the lowest solar transmittance (14%). In contrast, the tinted base glass has the highest solar transmittance (59%) and the lowest solar absorption. Although the solar absorbing glass absorbs more solar radiation than the solar reflecting glass (50% compared to only 30%), the solar absorbing glass also transmits more solar radiation than the solar reflecting windshield (44% compared to 40%). This demonstrates that solar absorbing glass presents a trade-off, an increase in indirect gain with a decrease in direct gain. The solar reflecting windshield decreases both direct and indirect gain, but still falls within the 70% transmittance requirement. Although this relationship holds for a vehicle in motion, the researchers point out that as the speed of a car increases, more absorbed energy is lost to the ambient air and the solar gain becomes more a function of the differences in solar transmittances. For instance, the data for a car at idle are compared with those of a car traveling at 89 kph (55 mph). While the direct solar gain remains the same for both the idle car

[2] This is one of the only instances of noted statistical significance in the reviewed papers. While the hard data was presented in tabular format, no specific levels of significance were reported, nor was it specified what statistical analyses were conducted.

and high-speed car, the indirect gain is substantially lower for the high-speed car. In other words, solar absorption into the car interior is reduced at higher speeds. The total solar gain is thus more dependent on the solar transmittance of the glazing material.

The direct gain by the car interior is calculated by defining an absorption-transmittance product for a given automotive interior surface. Reflection curves for two typical automotive fabrics were generated by a spectrophotometer, and the absorption was found by subtracting the reflectance from unity. The absorption of the fabric and the transmittance of the glass were integrated over discrete intervals and multiplied by the appropriate weighting factor of the sun for that interval for wavelengths .3 to 2.3 microns. The absorption-transmittance product for the two materials followed the same pattern as the direct vs. indirect gain. That is, the base glass caused the most solar gain and the privacy glass caused the least solar gain. The solar reflecting glass caused less gain than the solar absorbing glass, but this difference was relatively small.

The same calculation was then used to find the alpha-tau product for human skin (using the spectral response of human skin, found in the ASHRAE Handbook of Fundamentals). Absorption by human skin followed the same pattern as above (determined for two skin colors): base glass caused the most absorption (33% for white, 46.5% for black), followed by solar absorbing glass (26% for white, 36% for black), solar reflecting glass (23% for white, 34% for black), and privacy glass (8% for white, 11% for black).

Goodman's last category of analysis, UV transmission vs. visible light transmission, is also of interest. Solar reflecting glass showed a higher visible light transmission than the solar absorbing glass, but both showed less than the base glass. The solar reflecting glass also showed a dramatically lower UV transmission over solar absorbing glass, but this was most likely due to the fact that the author used a windshield configuration for the solar reflecting glass and not for the solar absorbing glass. Consequently, the solar reflecting glass contained the PVB interlayer that blocks UV light, but the solar absorbing glass did not contain this layer.

The report does not include much detail. Virtually no mention is made of experimental procedure, and the methods of data analysis are at best briefly described. The author also acknowledges that the construct of "comfort" was not addressed through his study. He adds that "A complete model of human comfort would have to include the air temperature, humidity, air velocity, clothing, metabolic activity, indirect radiation, and the direct radiation just described." Furthermore, the author's comparison of an IRR windshield to other kinds of glass that were not in windshield configuration is questionable, as windshields have specific characteristics that may affect the thermal properties of the glass (e.g., curvature, the presence of the PVB layer, etc.).

Manfre (1991). Manfre tested five kinds of solar control glazing in a series of tests run in Arizona and Italy. Clear glass was compared to a green tinted glass, an absorbing tinted solar control glass, a clear glass with the internal surface of the exterior layer coated with a multilayer silver based film (i.e., IRR coating), and a clear glass with PVB sandwiching a polyester (PET) sheet coated with a multilayer silver based film (IRR) on the external side. Thus, the latter two glasses were classified as IRR glazing. The tests consisted of a soak test (between 10:00 a.m. and 2:00 p.m.), followed by driving conditions at an average speed of 80 kph (50 mph) with the air conditioning on. The direction of driving—sun in front or back—was changed every half hour. Thermocouples were installed in the vehicles to measure air temperature and interior surface temperature of the dashboard and steering column. Also, a thermal comfort meter was used to measure the PMV index for each car during soak and driving conditions.

Results were only reported for a few test conditions. However, a summary of the results included the following observations: The surfaces of the interior trim that were directly exposed to the sun during soak conditions showed a maximum of 10°C (18°F) of difference in temperature between glazing with normal green glasses and the IR-absorbing tinted glass. The maximum temperature difference became 15°C (27°F) when the IR-reflecting glass was used for the windshield and back windows, and IR-absorbing glass used on the side windows. The overall difference between the clear glass and the solar control glasses never exceeded 17°C (31°F), but temperatures were consistently lower for the solar control glasses. For air temperature differences, there was no significant variation between the green tinted glass and the IR-absorbing glass. Variations with a maximum of 5°C (9°F) between the green tinted glass and IR-reflecting glasses existed, but only in the case of soak conditions without any ventilation. That is, when the A/C was on, IR-reflecting glass had little effect on the temperature. Comfort meter readings were not reported, and no reason is given for this. However, some comments in Manfre's introduction may shed light on this omission:

> Just to mention our opinion, through our tests, the comfort relationship does not give any useful indication for glasses in soak conditions (discomfort level); in driving conditions, with or without A/C, human comfort depends too much on such other factors as air flow, both direction and magnitude, and its humidity from the outside climate (except in desert like Arizona) [sic]. These are difficult to control by the comfort sensor, especially in the cool-down test to test different solar control glasses for comfort. Better reliability should be given by the thermal manikin equipped with several transducers and by a more pragmatic approach.

Though Manfre never specifies what a more pragmatic approach might be, the point made is a significant one, as Manfre's study represents one of only three of the 18 experimental glazing studies to use any measurement of thermal comfort. More is said about this later.

Sullivan and Selkowitz (1990). Sullivan and Selkowitz provided a review of the literature up to that point and investigated the characteristics of standard and sports-model sedans using numerical simulations of the heat transfer processes under static soak conditions. The simulations document the interior air and dash/seat surface temperatures of a prototypical standard sedan and a sports model that has a highly sloped large rear window. The simulations cover the course of an entire day under summer environmental conditions in Phoenix, Arizona (using actual weather data as input). The computer simulation model allowed the researchers to choose four levels of solar transmittance for glazing: 83% (a typical clear glass), 43% (a typical selective reflective or absorptive glass), 23% (a special "reduced-transmission" glazing), and 3% (a typical privacy glass). Within each category of solar transmittance, the researchers were also able to vary the levels of solar reflectance or absorption, thus allowing any possible configuration of glazing technology. Table 5, taken directly from the paper, is a useful presentation of typical glazing characteristics, and it was the basis of the researchers' analysis. Although it is never specified what the "reflective" category refers to (as opposed to IR reflective), the numbers indicate that this kind of glazing would just meet the 70% visible light transmission regulations while reflecting a significant amount of solar radiation. Notice also that only two types of glazings in Table 5 would meet the European visible light transmission regulations of 75% (viz., clear glass and IR-absorptive glass).

Table 5
Typical glazing characteristics (Sullivan & Selkowitz, 1990).

Glass Type	Visible Transmission	Solar Transmission	Solar Reflection	Solar Absorption
Conventional	80	76	8	16
Reflective	70	34	45	21
IR Reflective	73	52	37	11
IR Absorptive	76	53	6	41

Results of the simulation are presented for reflective and absorptive glazing for each of the four solar transmittances, a 2 x 4 design. The researchers do not specify whether their "reflective" glazing is spectrally selective (i.e., whether it is specific to infrared wavelengths), but they do add that the reflective glazings in their study have a very small absorptance, 5-10%, while the absorptive glazings have a comparable level of reflectance. Results for both reflective and absorptive glazing indicated that interior air temperature was reduced as a function of decreasing solar transmission. That is, the 83% transmission resulted in the highest temperatures; the 3% transmission resulted in the lowest temperatures. This relationship held true for both the standard and sports model sedan. These results are consistent with the literature the authors reviewed. Moreover, the reflective glazing outperformed the absorptive glazing. For instance, if reflectance is theoretically maximized (as in an opaque glazing), the peak interior air temperature can be made the same as the outside air temperature. This is not true, however, for the absorptive glazing. There is a "lower limit of effectiveness" for the latter glazing because a fraction of the absorbed solar radiation is reradiated into the cabin of the vehicle. The results of the simulation indicated that the peak temperature for the 3% transmittance glass with high absorptance in the standard sedan was 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 of what can be achieved with the reflective glazing. Stated another way, the performance difference of reflective vs. absorptive glazing increased as the solar transmittances decreased. Further results also suggested added benefits from ventilation options. A clear glazing with 83% transmittance and no ventilation is compared with a reflective glazing with 43% transmittance and infiltration of 20 air-changes/hour. The reflective glazing with ventilation reduced peak air temperature from 69°C (156°F) to 49°C (120°F) and peak dash/seat surface temperature from 110°C (230°F) to 75°C (167°F).

Computer simulations have the obvious disadvantage of reduced external validity, and that must be kept in mind when interpreting Sullivan and Selkowitz's results. However, the benefits of such procedures include the possibility of analyzing any configuration of glazing specifications, even those that are not yet in production. If the thermal properties of the glass are known, it is relatively easy to predict changes in temperature associated with the use of different glazing configurations.

Young and Van Esso (1989). Young and Van Esso tested Aircool™ automobile solar control coated glass under desert driving conditions to determine its effect on the interior comfort and temperature of the vehicle. Aircool is a sputter deposited stack of thin dielectric and metal layers that reflects IR wavelengths. As in many other experiments, two cars were used, one as an experimental car and one as a baseline control. Thermocouples were used to measure surface and air temperatures inside the vehicle cabin, and a thermal comfort meter was used to calculate the PMV.

1988 production model Dodge Daytonas with white exteriors and red interior trim were used for the testing. Baseline tests were run to determine any differences between the vehicle specifications. Seventeen thermocouples were mounted in each car, and comfort meter transducers were mounted on the front passenger's seat back and neck rest. The test method (taken directly from the paper) was as follows:

1. The first series was a baseline test. The stock tinted glass was used in both vehicles.
2. For the second series, an Aircool windshield was installed in the experimental vehicle, and the stock side, rear, and quarterlites were left in place.
3. In the third series, side, back, and quarterlites coated with Aircool were installed in the experimental car that already had the coated windshield in it.
4. The fourth series was a repeat of the baseline with tinted glass reinstalled in all positions of the experimental car.

Each series consisted of the following three tests:

A) A static eight hour soak (8 a.m. to 4 p.m.).
B) A dynamic test consisting of a one hour soak, a highway cool-down segment, followed by a city driving simulation.
C) Repeat of the dynamic test. (In the third series there were two repeats).

Throughout all four series of tests, the control car had tinted stock glass in all six positions and never underwent a glass change.

For the static soak test, thermocouple readings were taken every hour on the hour, with extra readings at 11:30 a.m., 12:30 p.m., and 1:30 p.m. The cars were aligned parallel and faced south; this was meant to produce the largest solar load. For the dynamic tests, both cars had all doors (and rear hatch) opened to air out the interiors. Then, both cars were closed and left to soak for one hour. Initial thermocouple readings were taken at the end of the hour, and then the engines were started simultaneously with the A/C at 100% recirculation. The cars then proceeded south at 48 kph (30 mph) and readings were taken at discrete timed intervals for five miles. The cars then turned around and proceeded north at 81 kph (50 mph). The city driving simulation consisted of four segments of three 30-second stops at each corner of a city block followed by a two-minute stop. During the two-minute stop, a full set of readings was taken.

The authors claim that the Aircool coating had a "significant" effect on air temperature reduction, although levels of statistical significance were not reported. For the static soak test, average air temperature reduction in the front of the car due to an Aircool windshield was 12°C (21°F), and the reduction with all Aircool glass was 16°C (29°F). The average air temperatures in the rear of the car were reduced 4°C (8°F) and 9°C (16°F) respectively. For interior surface temperature reduction, the average instrument panel temperatures were most affected, with reductions of 14°C (26°F) with an Aircool windshield and 17.8°C (32°F) with all Aircool glass. The soak test temperatures rose above the operating range of the comfort meter (60°C, 140°F), so no data could be obtained.

The dynamic test showed similar performance benefits of the Aircool coating. For instance, the car with the Aircool coating reached "comfort" (defined at a PMV value of zero) in approximately 7.5 minutes, whereas the control car attained comfort in approximately 12 minutes. This represents a reduction of 38%. This effect was more pronounced when Aircool was applied to all windows. The experimental car took an average of 14.5 minutes to reach comfort (the ambient air temperature was higher than during the Aircool-windshield test), while the projected time to reach comfort for the control car was 22 minutes (the car never actually reached a comfort level during testing).

Young and Van Esso's study represents one of the most developed procedures for measuring the effect of glazing on thermal comfort. As will be seen later, the components of this study can serve as a useful model for future research. Two vehicles (first subjected to baseline tests) were tested outdoors for all phases of the vehicle's possible running conditions. Different glazing configurations were tested (e.g., windshield only, windshield plus all windows, etc.). Finally, comfort meter readings were taken and reported for publication. However, there were subjective and/or physiological measurements from human subjects. Later in this review, we will examine some experimental procedures that used Young and Van Esso's method, but also included these other measures of thermal comfort.

Shimizu, Hara, and Asakawa (1982). Shimizu et al. is the earliest reviewed study that experimentally tested an IRR windshield. As part of a larger study that was designed to analyze the air conditioning heat load of common four-door sedans, the experimental test was conducted after the researchers determined that more than 50% of the entire air conditioning heat load (under the recirculation air mode) can be attributed to solar radiation. This determination was the result of an experimentally validated model and equation of the heat balance of a typical passenger compartment. The authors concluded that the control of solar radiation was the most effective means to reduce the power consumption of air conditioners. Consequently, three different windshields were tested in an indoor laboratory (with infrared bulbs to simulate solar heat and a fan to simulate wind). A test vehicle with the following specifications (taken directly from the paper) was used:

Table 6
Specifications of test vehicle (Shimizu et al., 1982).

<table>
<tr><th colspan="2">Position</th><th>Area</th><th>Type of glass (thickness)</th><th>Inclination</th></tr>
<tr><td colspan="2">Front window</td><td>0.789 m^2</td><td>Infrared absorption (5 mm)</td><td>36.5°</td></tr>
<tr><td colspan="2">Side window</td><td>0.986 m^2</td><td>Infrared absorption (4 mm)</td><td>68.0°</td></tr>
<tr><td colspan="2">Rear window</td><td>0.730 m^2</td><td>Infrared absorption (4 mm)</td><td>42.0°</td></tr>
<tr><td colspan="2">Roof (Color: Dark blue)</td><td>1.740 m^2</td><td colspan="2"></td></tr>
<tr><td rowspan="2">Passenger compartment</td><td>Color</td><td colspan="3">Black</td></tr>
<tr><td>Mass of parts</td><td colspan="3">48.1 kg (Instrument panel, seat and console box, etc.)</td></tr>
</table>

The total heat load from solar radiation was tested using the following types of glass:

Table 7
Characteristics of test glasses (Shimizu et al., 1982).

	Visible rays	Entire wavelength		
Type of glass	Transmissivity	Transmissivity	Absorptivity	Reflectance
Ordinary glass	0.90	0.84	0.08	0.08
IR-absorbing glass	0.76	0.53	0.41	0.06
IR-reflecting glass	0.73	0.52	0.11	0.37

The test method is never specified in the authors' report. Tables 6 and 7 represent the only detailed information that was given in regards to the testing apparatus or procedure. For instance, the authors report the results for a dynamic driving test, but only describe the method by saying "a vehicle was driven at a fixed speed after having been exposed to the blazing sun for a long period." The heat load was calculated from the direct measurement of the air temperature in the passenger compartment (though the exact equation used is not specified).

The results were consistent with the above studies: IRR glass resulted in the lowest temperatures for a static soak test, a cool-down test with the engine at idling speed, and a dynamic driving test. IR-absorbing glass followed with lower temperatures than ordinary glass, but higher temperatures than IR-reflecting glass. The static soak and cool-down was performed indoors, but no mention was made of experimental procedure for the outdoor dynamic driving test. Reported results showed, however, that air temperature in the passenger compartment was decreased by about 10°C (18°F) at the start of running compared to ordinary glass (for the dynamic test) and about 8°C (14°F) ten minutes after starting when IRR glass was used for all windows.

Applicable Methodology Outside of IRR Glazing Research

To find a practical direction for a human factors study of IRR glazing's effect on thermal comfort, we have selected four of the 78 thermal comfort papers that represent a more holistic approach to the problem. Three of them test solar control glazing products, and all four studies include an array of subjective and objective measurements. By reviewing the method of each study, it is hoped that a feasible human factors test procedure will emerge. Each paper was selected based on its unique angle and approach to the study of automotive thermal comfort.

Atkinson (1986). Atkinson performed two experiments on occupant comfort. The first involved no glazing manipulation but is useful to discuss because of its methodological design. The purpose of Atkinson's first experiment was to determine subjective ratings of comfort for seven different makes and models of passenger vehicles (nothing was changed about the vehicles; Subjects were simply required to rate the vehicles relative to each other). The vehicles were driven by groupings of approximately four occupants each over a pre-determined test schedule. A total of 24 subjects participated, and for each vehicle, subjective and objective measures were taken. The test began with a one-hour soak with all windows closed. Five minutes before the end of this soak period, all personnel were pre-soaked in the area where the vehicles were located (i.e., each person was given a chance to acclimate to the ambient air temperature by standing or sitting (not specified) near the automobile's location). Test-team personnel then entered the vehicle one at a time with only one door open at a time. The vehicle was then started and driven away, using the following schedule:

1. Low speed operation, 48 kph (30 mph), approximately 15 min., 9 km (5.7 mi.)
2. Mid speed operation, 72 kph (45 mph), approximately 15 min., 15 km (9.6 mi.)
3. City traffic, four cycles, approximately 22 min., 4 km (2.7 mi.)

   City traffic drive cycle max. speed: 40 kph (25 mph)

Drive	.3 km (.2 mi.)
Idle	30 sec.
Drive	.3 km (.2 mi.)
Idle	30 sec.
Drive	.3 km (.2 mi.)
Idle	120 sec.

The vehicle directions for each 120-second idle were south, east, north, and west, to control for the wind-effect of any one direction. The test time was between 12:00 p.m. and 4:00 p.m. in Phoenix, Arizona. Although engineering data were obtained during the drive cycles (e.g., system air flow, air, and breath temperatures), the main focus of the study was a subjective thermal comfort evaluation that was taken for each occupant nine times over the test period. The evaluation consisted of a comfort appraisal form, a one-page questionnaire that asked each subject to rate the comfort of each part of the body. No mention is made of exactly when or in what manner the comfort appraisal forms were filled out. Each subject was allowed to move the cooling vents at will and monitored their comfort for the duration of the test.

Atkinson's second experiment involved a solar-absorbing window film. No human subjects were used; however, the method follows the same soak-test procedure as many of the studies cited above. No cool-down test was conducted. Rather, two soak tests were run, one for one hour, and one that ran from 8:00 a.m. to 5:00 p.m. For this particular test, only thermocouples were used. They were placed at ten separate locations, including the center of the rear floor under the hatch, the rear hatch gas shock surface, the front and rear breath of vehicle (at the center only–not at driver and passenger positions), the front and rear inside seat foam near "H" point, the top center of the instrument panel, the front and rear floor 2.5 cm (1 in.) above the surface, and the top of the steering wheel surface.

Atkinson's two experiments contain many common elements of automotive thermal comfort research, including outdoor testing, soak-tests and cool-down tests, and subjective evaluation. If the seven experimental cars in experiment 1 were replaced with different glazing configurations, it would be possible to obtain subjective evaluations for glazing applications.

<u>Hymore, Tweadey, and Wozniak (1991)</u>. Hymore et al. provided perhaps the most detailed description of a possible solar control glazing test procedure. The authors point out in their introduction that "if not understood and controlled, normal system variations may offset or hide potential system improvements" that may result from improved solar control glazings. Furthermore, they argue, indoor testing facilities (i.e., "wind tunnels") usually have light that is biased toward the infrared, creating the potential for erroneous results. The best test for a solar control glazing, therefore, is an outdoor test using two identical vehicles. Finally, they argue that, while thermal comfort is an important construct to consider, its measurement is best carried out by sensitive instrumentation such as the thermal comfort meter. The authors' field test procedure therefore aims to eliminate and/or standardize as many environmental and equipment variables as possible and to accurately measure the thermal environment.

The first step, according to the authors, is to standardize the baseline and test vehicles. This is done by carrying out a series of tests on two vehicles that are the same make, model, color, and trim (i.e., A/C systems, instrument panels, etc.). The authors recommend the following tests: airflow and body leakage tests, comparative wind tunnel tests (to evaluate A/C system performance by measuring baseline cool-down times), and a collected output test (to determine individual register airflows for the A/C systems). The authors then list a series of procedures that can be used to make equalizing adjustments to the A/C systems between cars (not listed here for the sake of brevity).

The second step is to outfit each car with the appropriate measuring equipment. They recommend an automated data logging system, a means to input subjective comfort ratings into the data logger, a minimum of three comfort meters per vehicle (mounted in an array to simulate the head, trunk, and legs of a front seat passenger), a roof-mounted pyranometer to continuously measure solar radiation, and a series of thermocouples mounted at specific points. The authors suggest two “front breath” temperature readings, one across the vehicle headliner, 15.2 cm in front of the driver’s face, and one 15.2 cm down from the headliner. They also suggest thermocouples mounted to surfaces where temperature build-up most affects A/C performance, such as the top of the instrument panel, mounted in the A/C recirculation door opening, and mounted in each A/C register opening to assist in baseline standardization. Finally, the authors suggest a portable weather station or source of daily weather data.

The physical alignment of equipment is also crucial. The front seats must be positioned equally; so too must the comfort meter array that is located in the passenger seat. Each sensor of the comfort meter array should be compared against its counterpart in the other car. The A/C registers must also be in a standardized position. The authors recommend that the left two registers (driver vents) be positioned directly forward. The right two registers (passenger vents) should be “directed at the comfort meter array to cause ‘comfort’ to be achieved approximately the same time as an average passenger would.”

Daily standardization must take place before each day of testing begins. In a garage or other controlled environment, the authors suggest the following tests: check A/C systems for leaks, and a garage cool-down comparative test in which the vehicles are controlled for different glazings (by covering them) and in which data is recorded every 30 seconds to insure standardization. Before testing actually begins, the authors suggest “drying out” the A/C systems by operating them in high fan/vent mode until register air temperatures equal ambient air temperatures. Also, they suggest the continuous monitoring of weather information such as wind speed, wind direction, ambient air temperature, relative humidity, and average solar radiation.

The soak testing should begin at the same time and location every day and all vehicles should face the same direction. All doors should be left open for a minimum of ten minutes prior to the start of the soak, to further insure that vehicle interiors reach ambient temperatures equally. Air conditioning controls should be set to allow the maximum operation to begin when the engine is started. Before closing the doors for the soak, computer data loggers should be started at exactly the same time, followed by closing the doors at the exact same time. Data loggers should record information at least every two minutes. Any personnel who will be driving for the cool-down test should become acclimated to the heat and then enter the respective cars simultaneously when the cabin temperatures reach at least 60°C (140°F).

The cool-down testing should begin at the same time and location every day. Vehicles should be driven around a circular track to allow radiation to enter all sides. There should be an alternation of direction and vehicle positions on each subsequent cool-down test. Further, the authors suggest, if only drivers will be participating in the evaluation, they should alternate vehicles on subsequent drives; if additional evaluators are involved, a random seating order should be used. Evaluators should record a subjective comfort rating at least every two minutes. When the cool-down test is completed, the A/C system should be "dried out" again to eliminate condensation. When all of the series of tests are completed for the day, the two vehicles should be placed in storage.

Using this test method, the authors were able to corroborate objective and subjective measures of thermal comfort for different glazing configurations during both soak and cool-down driving conditions. The degree of confidence was therefore increased regarding the relatively small temperature differences that were found between glazings. Though this method was used to assess solar-absorbing glasses, there is no reason why it cannot be used to test IRR glazing.

Brown and Jones (1997). Brown and Jones performed a study that was designed to test a new transient passenger thermal comfort model. While it did not incorporate the evaluation of glazing, it is useful to discuss this study not only because of its design, but also because it serves as a good example of a comparative assessment of automotive thermal comfort models. This comparative assessment is needed because of the of the rising number of highly complex competing models. This study examined subjective as well as physiological and environmental measures of comfort. It is therefore the only study that employed a truly holistic approach to the measurement of thermal comfort.

Instead of using a thermal comfort meter or a manikin, the authors used a collection of individual instruments to measure the environmental parameters.[3] This method can be significantly less expensive than other options. Type T thermocouples were used to measure the air temperature in ten locations: head, left and right shoulders, torso, left and right sides of the waist, left and right thighs, and left and right feet. The mean radiant temperature was measured using globe thermometers and radiometers. Relative humidity transducers were placed in three locations: torso, thigh, and foot. Finally, omni-directional transducers were used to make air velocity measurements at the head, torso, shoulder, waist, thighs, shins, and feet locations. Output from all instrumentation was recorded every 15 seconds with a data logger.

Because this study did not test glazing, there are some differences in the overall methodology. For instance, the testing was not conducted outdoors. Rather, the front section of a full-size vehicle was placed in a climate control chamber. Temperature and humidity-controlled air was directed into the vehicle's climate control system. A total of 18 test conditions were simulated, and a total of 216 subjects (108 women and 108 men) participated in the study. There were two phases. The first phase was used to develop a transient thermal comfort model, and the second phase was used to validate that model. For both phases, the authors had two primary environmental conditions: winter and summer.

Phase 1: Model development. For the winter tests, the ambient temperature was –18°C (-4°F), there was no solar load, and the supplied temperature (i.e., climate control system) varied from 38°C (100°F) to 60°C (140°F). For the summer tests, the ambient temperature was 43°C (109°F), the solar load was 1 kW/m^2, and the supplied temperature varied from 18°C (64°F) to 29°C (84°F). The subjects spent 60 minutes in a pre-conditioning chamber, during which time they were read instructions, instrumented with six skin temperature thermistors, and had their core body temperatures measured. All subjects wore standard-issue clothing (e.g., sweat pants, sweat shirt, ski jacket, T-shirt, etc.) that did not change throughout the experiment. At the end of the pre-conditioning period, the subjects entered the climate chamber and were seated in the vehicle. Each subject spent a total of 45 minutes in the vehicle, during which time their skin temperatures were recorded every minute and subjective comfort ratings were taken every two minutes, using the following subjective scale (Table 8):

[3] Although a manikin was not used, much of the instrumentation was applied to a wooden "stick-person" that was placed in the driver's seat of the vehicle.

Table 8
Subjective rating scale (Brown & Jones, 1997).

Numerical Rating	Subjective Rating
1	Cold
2	Cold/Cool
3	Cool
4	Cool/Comfort
5	Comfort
6	Warm/Comfort
7	Warm
8	Hot/Warm
9	Hot

Phase 2: Model validation. For the validation experiments, a mid-size vehicle was used for the winter tests and a full-size vehicle was used for the summer tests. A total of 48 test subjects participated in this phase of the research. The environmental conditions remained approximately the same, except that the range was extended to include slightly more severe ambients (i.e., slightly hotter in the summer and slightly colder in the winter). This was done in order to test the robustness of the model. Two subjects (a driver and passenger) were run at a time. Subjects were allowed to acclimate to a "room temperature" laboratory room for half an hour before testing began. Then, the subjects entered the environmental chamber and stood for five minutes before entering the vehicle. The total time spent in the chamber was 40 minutes. During the first 10 minutes, the subjects gave subjective ratings every minute (every two minutes for the final 30 minutes of the test). In addition, for each test condition, the stick-person was used to record environmental data in both seating locations. (This was done separately from the human subject tests.)

When all tests were complete, the authors used the clothing (a constant value), initial physiological state of each subject, and the entire range of environmental measurements as inputs to the new thermal comfort model that they had developed. They then compared the actual subjective responses and physiological data to the predicted responses from three different thermal comfort models: Fanger's PMV index, Gagge's thermal comfort model, and the authors' new model. Graphs can be found in the report that show how the actual responses compared to what the models predicted.

Brooks and Parsons (1999). The final automotive thermal comfort study examined is one that tested the effects of heated seats on occupant comfort. Brooks and Parsons conducted an environmental chamber study using eight subjects in a repeated-measures design over a five-week period. Four different environmental conditions were simulated, as indicated in Table 9:

Table 9
Environmental conditions (Brooks & Parsons, 1999).

Trial	Dry bulb temperature (°C)	Mean radiant temperature (°C)	Air speed, V (m/s)	Relative humidity, ϕ (%)
1	5	5	< 0.2	40
2	10	10	< 0.2	40
3	15	15	< 0.2	40
4	20	5	< 0.2	30

The fourth trial was meant to simulate driving in an automobile with generally comfortable air temperature (provided by the HVAC system) but with a radiant temperature asymmetry condition of 15°C (59°F) (i.e., cold door and window). Although the authors never specify whether the participants were actually seated in a vehicle, it is clear that the participants were seated in some fashion, as evaluations were made for the heated seat and the control seat.

Relevant to our topic are the kind of measurements that the authors took during the study. Subjective, physiological, and environmental measures were all taken to assess the thermal comfort effects of the heated seat. Subjective measures included a questionnaire at the start of each session and every 15 minutes thereafter (seven in total per trial). The questionnaire consisted of three separate parts: thermal sensation, thermal comfort, and alertness. Both sensation and comfort questionnaires were based on ISO 7730 and ASHRAE 55 and required a response for seven points on the body: head, torso front and back, hands, thighs front and back, and feet. The 10-point Karolinska Sleepiness Scale (KSS) was used as a measure of alertness/sleepiness. Physiological measures included six participant skin temperatures recorded at one-minute intervals using thermistors at the following locations: mid-thigh (ventral and dorsal), chest and back, back of hand, and top of foot. Finally, environmental measures included two dry bulb air temperatures, one black globe temperature, one ceiling temperature, and one relative humidity measurement that were all recorded at one-minute intervals throughout the experiment. Although the environmental chamber is not thoroughly described, the authors mention that for the trials at 5, 10, and 15°C (41, 50, and 59°F), the participants sat side-by-side facing the wall with a blind between them to prevent them from viewing each other's questionnaires. For the 20°C condition, the participants were seated back-to-back for what the authors refer to as a "cold wall" condition. In this condition, the north wall of the environmental chamber was kept at 5°C while the south wall was kept at 20°C. This was meant to simulate a radiant temperature asymmetry of 15°C when the participants were facing east or west (i.e., similar to a cold door and window inside an automobile). The authors do not describe how the temperatures of the walls were manipulated.

It is quite possible that the use of an environmental chamber may allow for more sophisticated measurement techniques, such as those used in the studies by Brooks and Parsons and Brown and Jones. For instance, the lack of a driving task probably makes it easier for participants to give subjective ratings of comfort. In addition, physiological measurements are probably somewhat easier to take when the subjects are not driving a vehicle. However, the studies by Hymore et al. and Atkinson suggest that a using a more complete test method under real driving conditions is not only possible, but also highly desirable.

Thus, the possible approaches for the future of automotive IRR glazing ultimately depend upon the question being asked. If the question is, "What effect does IRR glazing have on HVAC system performance and interior cabin temperatures?" then the most practical approach would be to simply measure these parameters experimentally. If the question is instead, "What effect does IRR glazing have on the thermal comfort of vehicle occupants?" then the test methodology needs to include accepted and standardized measures of thermal comfort, including comfort meters (or the equivalent) and/or thermal manikins, physiological data, and subjective assessments of comfort.

A human factors approach to understanding the effects of IRR glazing would most likely involve the second of these two questions. Accordingly, test methodology would contain common elements from both the four papers we examined above and the eight experimental IRR glazing papers reviewed earlier. These include using at least two vehicles in an outdoor test;

conducting a series of tests that include soak-test, cool-down, city-driving, and highway-driving components; using different glazing configurations that include a “solar-control windshield only” condition and a “solar-control all glazings” condition; and taking as many measurements of thermal comfort as possible. Out of all of the papers reviewed, Hymore et al. (1991) supplied the most thorough example of how such a test might be carried out.

THE RESEARCH: AUTOMOTIVE GLAZING AND VISUAL PERFORMANCE

Visible transmission is a crucial consideration for advanced glazing technology because of its potential to affect how much light reaches the driver and how that light is perceived (e.g., color, glare, etc.). The addition of solar control glazing, for example, almost always reduces the transmission of light in the visible range, even if only marginally. There is a growing body of evidence that suggests reduced transmission can cause problems concerning target detection, especially when there is low contrast between the target and the background. There is also evidence to suggest that veiling glare (i.e., reflected ambient light, often taking the form of reflected images of the dashboard, that is superimposed on the image of the road scene) can also cause visibility problems (Schumann, Flannagan, Sivak, & Traube, 1996). Concerning driver visual performance, both IRR and antireflective (AR) glazing may have an effect, the former because of possible reduced transmission, and the latter because of the possibility of reduced glare. This is clearly an area in which experimental research is needed.

Although the last five to ten years have seen a growing interest in AR glazing's potential to reduce veiling glare, a review of the literature uncovered no research on the effects of AR glazing on visual performance. Much like the automotive thermal comfort research, the existing studies on AR glazing have concentrated on engineering data as opposed to direct human factors research (see, for example, Boulos et al., 1997). In fact, there has been relatively little research done on veiling glare at all. There was only one study we could locate that directly examined the effects of veiling glare on visual performance (Schumann et al., 1996). This study found that both large windshield rake angles (i.e., windshields that are more horizontal) and high dashboard reflectance decrease visual performance, especially for older subjects. Because rake angle and dashboard reflectance are the leading influences on veiling glare, the conclusion that veiling glare decreases visual performance was supported. The next step for the research seems clear: to test AR glazing's affect on the same measures of visual performance through a human subjects experimental design. To this end, the method employed by Schumann et al. may be very useful; the design allows for individual variables to be controlled and thus provides a means to isolate the affect of AR glazing.

Welsh, Rasmussen, and Vaughan (1978). Research on the effects of IRR glazing on visual performance was equally difficult to find. Only one study that experimentally tested solar-reflective glazings could be located, and that was conducted by Welsh, Rasmussen, and Vaughan. This particular study did not specify whether the glazings were spectrally selective, but it examined three kinds of “sunscreen films,” distributed under the names of Solar Master PSL-80 bronze, PSL-80 gold, and M-80 silver. The “gold” and “silver” glasses were found to have similar light transmission characteristics and each one performed equally in preliminary tests, so results were only presented for two sunscreen panels (“bronze” and “silver”) and for the clear non-coated plate glass. Light transmission values for the “clear,” “silver,” and “bronze” panels were respectively 92, 18, and 8%.

The subjects consisted of 10 male and two female volunteers, ages 24-64. The authors report that all subjects had 20/20 distant visual acuity (nine had corrected vision) and were all color-normal. The authors evaluated visual performance in a laboratory that was divided into two sections, a display area and an observation booth. The subjects viewed the test displays from a distance of 6m (20 ft.) while seated in the booth. Luminance levels were controlled for each area independently–three 100 W daylight-blue bulbs, which were adjusted by a variable power source to provide 1.0, 5.0, and 50.0 fL (3.4, 17.2, and 171.5 cd/m^2, respectively) on the display, illuminated the display area. Brightness levels in the booth were obtained with one daylight-blue bulb and were adjusted to provide 1.0 (3.43 cd/m^2) and 5.0 fL (17.2 cd/m^2). The data were obtained with brightness level combinations on the display and in the booth respectively of 1:1, 5:1, 50:1, 5:5, and 50:5 fL.

Dependent variables consisted of visual acuity (as measured by a series of Landolt C figures), percentage of correct answers in a contrast discrimination test (contour identification of different shapes on display cards), and percentage of correct answers in a target identification task (identification of a red, green, or white light that was presented for three seconds at three different intensities and three different aperture sizes). The first two visual tasks were evaluated for all glazing samples at all five of the brightness combinations. Target identification was only evaluated at the brightness combination of 5:1.

The results indicated that there was little or no impairment of visual acuity at any of the luminance combinations when viewing through the clear (control) panel. Both sunscreen panels were shown to be detrimental to visual acuity except at the 50-fL (171.5 cd/m^2) target luminance level. For example, under a moderate brightness level (5.0 fL, 17.2 cd/m^2), visual acuity through the “clear,” “silver,” and “bronze” panels was 20/20, 20/24, and 20/29, respectively.

Comparable acuities scored under dim lighting (1.0 fL, 3.4 cd/m^2) were 20/22, 20/35, and 20/42. No statistical analyses of these differences were reported. For the contour identification task, performance was near 100% for all three panels. However, contrast discrimination decreased for the sunscreen panels when the target luminance levels were lowered. This was especially true for those targets having a relatively low figure-to-ground contrast ratio. Finally, results for the target identification task indicated that both sunscreen panels yielded overall lower recognition values than did the clear panel, with the greatest differences between the panels tending to occur at the lower and intermediate brightness levels. For these calculations, data for all three aperture sizes were combined to yield an overall recognition value for each light at three intensity levels. This was done despite the fact that there was a general improvement in recognition as the aperture size increased for all light sources. There were no statistical analyses reported for either the contour identification task or the light-source detection task. Nevertheless, the results were consistent with the other reviewed studies, particularly those concerning the relationship between light transmittance and visual performance.

Sayer and Traube (1994). Although only one study was located in which solar-reflective glazing was tested, there exists a greater amount of research relating to tinted (i.e., solar-absorbing) glazing. Tinted glazing has been available since the early 1950s and sporadic research has been conducted since that time. Most of this research was included in a comprehensive review by Sayer and Traube. In their review, the authors summarized and critiqued 33 studies on the effects of motor vehicle window transmittance, reflectance, veiling glare, wear, dirt, and spectral properties on driver visual performance and privacy. Nineteen of these studies specifically examined the issue of tinted windshields or windows, and how they affect driver vision. The results of their review are briefly summarized here.

The results of the 33 reviewed studies were far from consistent. Basic methodological design and theory often differed significantly among studies. However, the authors could make some general conclusions. For instance, the most influential factor affecting the visual performance of the driver appeared to be transmittance. Fifteen of the 33 studies specifically varied windshield or window transmittance, and 10 of those reported that reduced levels of transmittance had a negative effect on target detection and identification. This is especially true when luminance levels are low (as in dusk or nighttime conditions). What is less clear, the authors point out, is the degree of effect that specific transmittance levels have on these visual tasks. This is due to differences in method that preclude direct comparisons between studies. However, Sayer and Traube made the generalization that a reduction in transmittance from 100% to 50% will usually produce a reduction in driver visual performance on the order of 10-20%, depending somewhat on the nature of the visual task and how performance is quantified.

While transmittance seemed to be the most influential factor affecting visibility, the authors also found several studies that examined factors such as dirt, glare from oncoming vehicles through tinted windshields, and windshield wear. In general, light-scattering from both dirt and windshield wear was found to have a negative effect on driver visual performance, and tinted windshields were found not to significantly decrease glare from oncoming vehicles. They could find no studies that examined veiling glare or selective spectral transmittance glazing.

Two studies not reviewed by Sayer and Traube include Miles (1954) and LaMotte, Ridder, Yeung, and De Land (2000). Both of these studies examined the effects of tinted windshields and windows on driver vision. For the sake of brevity (and because the results from these two studies are consistent with the rest of the literature review), only the abstracts will be presented in this review. They can be found in the appendix.

DISCUSSION

IRR Glazing and Thermal Comfort

In summary, all of the eight individual studies that experimentally tested the thermal effects of IRR glazing found that IRR reduced average temperatures and generally outperformed IR-absorbing glass. Moreover, applying IRR film to all windows (as opposed to just the windshield) and adding ventilation to an IRR-equipped vehicle during soak conditions were both found to further reduce cabin temperatures within the vehicle (not surprisingly). It was also generally concluded that there is a limit to the effectiveness of absorbing glazing for reducing cabin temperatures because a portion of the absorbed solar energy is reradiated into the vehicle cabin. This problem is avoided with IRR glazing because the glass immediately rejects most of the infrared wavelengths.

As already noted, a minority of the studies used comprehensive measures of thermal comfort. Comfort meters were used in only three studies; subjective human responses (or physiological measures) were not taken for any of the studies. (That is, with the possible exception of Goodman (1991), in which physiological measures were inferred from environmental data.) In fact, there are only four instances of the phrase "thermal comfort" in all eight of the papers. A look at Table 4 will reveal that dependent variables instead consisted of various environmental parameters (e.g., interior air temperature, heater power, surface temperature, etc.). Out of the three studies that used comfort meters, PMV values were only reported in one of them (Young & Van Esso, 1989). Stated another way, there was only one study that reported results in terms of the combined six environmental parameters that influence thermal comfort. Although this fact does not detract from the value of the findings, it does illustrate that researchers have not placed emphasis on IRR glazing's effect on the thermal comfort of vehicle occupants per se, but rather have concentrated on its effects on the thermal environment of vehicle cabins. One possible reason for this is IRR glazing's role in the reduction of air conditioner size and output.

It is possible to make the claim that glazing actually has no direct effect on occupant thermal comfort, but rather may have a substantial positive effect on the reduction of HVAC compressor size and frequency of use. If this perspective were indeed the dominant one, we might expect to find the phrase "thermal comfort" more frequently in HVAC research than in glazing research. Moreover, we might expect to find frequent references in glazing research papers regarding the reduction of HVAC compressor size. When we examine the literature, this is exactly what we find. A comparison of the titles of the 23 papers we have classified as "HVAC" thermal comfort research and the 30 papers we have classified as "glazing" thermal comfort research, revealed that the phrase "thermal comfort" or "comfort" appears in the titles of 15 HVAC papers (65%); they only appear in the titles of eight glazing papers (27%). Furthermore, out of the papers we have reviewed, 13 individual references within the text of the articles (representing almost one quarter of the HVAC and glazing papers) could be found regarding the potential of solar control glazing to reduce air compressor or engine size. Recognition of this potential is also reflected in the method of the studies: As indicated in Table 4, many experimental studies of IRR glazing have used a "cool-down" test in which the glazing's thermal performance is measured as a function of how quickly the air conditioning system can cool the vehicle cabin after a prolonged soak period. Indeed, the soak test followed by the cool-down has become the most widely used test method for automotive thermal comfort research, most likely because it includes the full range of thermal conditions. Use of the cool-down test in glazing research implies that many researchers are interested in advanced glazing's potential to affect thermal comfort indirectly.

The ongoing thermal comfort project at the National Renewable Energy Laboratory (NREL) is a good example of thermal comfort analysis directed toward HVAC systems. Researchers from NREL have not only developed new vehicular thermal comfort models and thermal manikins (McGuffin, 2001), but have also specifically looked at IRR glazing's potential for reducing HVAC compressor size (Farrington et al., 1999, 2000). In this approach, HVAC systems are believed to be primarily responsible for the comfort of vehicle occupants. The challenge, then, is not to find ways to increase the thermal comfort of occupants per se, but rather to keep the occupants comfortable with a minimum of power consumption by the vehicle.

Because there have been so few studies that have used subjective measures of thermal comfort when assessing solar control glazing, it is difficult to characterize the subjective benefits of using such glazing. For instance, because radiant temperature appears to vary to a greater extent in motor vehicles than in buildings, solar control glazing's primary value may be its ability to reduce asymmetric radiant temperature. In other words, IRR glazing may reduce the sensation of hot skin on the upper parts of the body, and that may be viewed by the subject as a significantly more “comfortable” condition. This is in contrast to the smaller affect that IRR glazing seems to have on the air temperature alone.

Automotive Glazing and Visual Performance

The only existing research on the effects of solar control glazing on visual performance has found that, to the extent that such glazing reduces visible transmittance, it can also reduce the visual performance of the driver. This conclusion has not escaped solar control glazing manufacturers; indeed, out of the 29 papers that we reviewed on the effects of glazing on thermal comfort, many of them contained references to U.S. and European regulations on visible light transmittance. As one researcher commented, “A theoretically perfect solar control film transmits the minimum visible energy needed to satisfy legal requirements and reflect[s] <u>all</u> of the solar energy in the ultraviolet and infrared” (Young & Van Esso, 1989). Many questions are still unanswered. For instance, what are the differences in visual properties between IRR glazing and IR-absorbing glazing? As we mentioned earlier, manufacturers are beginning to develop metal-free IRR coatings that are near transparent. If tinting can be avoided, reduced transmittance will not be an issue. Even if IRR coatings do reduce transmittance, however, it may still be beneficial to apply IRR films to the side and rear windows of motor vehicles, areas where driver vision is not as critical. Because IRR glazing’s effect on visual performance is not yet known, it is clear that more research needs to be conducted.

GENERAL CONCLUSIONS

Based upon our findings, the following conclusions can be made. First, motor vehicles are unique thermal environments. Not only do vehicles in general differ in important ways from the interior spaces of buildings, but vehicles also differ significantly from each other. In light of the rising number of competing models and standards that influence thermal comfort research, the automotive literature would benefit from comparative analyses to see which models and standards are most applicable to vehicular environments. Second, automotive glazing research has not typically used a full array of measurement techniques for assessing the thermal comfort of vehicle occupants. In order to both validate the existing thermal comfort models, and to ensure that the psychological phenomenon of thermal comfort is being properly addressed, glazing research would benefit from including subjective and/or physiological measurements and environmental measurements that combine all six known relevant parameters in their experimental designs (air temperature, humidity, air velocity, radiant temperature, occupant clothing level, and occupant activity level). Third, IRR glazing appears to be effective at reducing cabin and interior surface temperatures within vehicles, more so than IR-absorbing glazing. This conclusion, however, is limited by the fact that researchers have not reported statistical analyses of their results. Fourth, because of the environmental differences that IRR glazing can cause in vehicle cabins, IRR glazing materials have the potential to improve automotive fuel economy and reduce HVAC compressor and/or engine size. Fifth, both light transmittance of automotive glazing, and veiling glare, may have effects on driver visual performance. Thus, more research is needed on the visual performance outcomes associated with IRR and AR glazing. Sixth, more research is also needed on the effects of thermal stress and thermal discomfort on driving performance.

APPENDIX:

Abstracts of Two Studies Regarding Windshield and Window Tinting on Visual Performance

Title: Visual effects of pink glasses, green windshields, and glare under night-driving conditions (Miles, 1954).

Abstract:

A green windshield at night reduces acuity from 20/32 to 20/46, and combined with pink glasses to 20/60. Resolution thresholds decreased from 10 to 42 seconds of arc, so that a pair of objects that could be seen through a clear windshield at 100 feet decreased to 25 feet through the green. Other visual functions found "defective in night-driving conditions with tinted glass" were stereo acuity, instant counting span, discrimination of angular velocity, simultaneous contrast, intensity change, and direction of a line target." Headlights should be designed larger in area "since glare is inversely proportional to the area of the source."

Title: Effect of aftermarket automobile window tinting films on driver vision (LaMotte et al., 2000).

Abstract:

This study was conducted to determine the level of automobile window tint that causes a significant reduction of vision for automobile drivers. Contrast sensitivity was measured on 20 participants, of whom 10 were age 20 to 29 years and 10 were age 60 to 69 years, through a stock automobile window (control) and two windows darkened with plastic film. For the younger drivers, a car window with 37% transmittance did not significantly reduce contrast sensitivity, but a darker tint of 18% transmittance reduced contrast sensitivity at higher spatial frequencies. For the older drivers, a tint of 37% transmittance significantly reduced mid- to- high spatial frequency contrast sensitivity. The typical state standard (no tint with less than 35% transmittance) would thus seem to be appropriate for younger drivers; however, further examination of the standard may be necessary in regard to older drivers. Actual or potential applications of this research include guidelines and regulations regarding tinting of automobile windows.

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