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Delphi Thermal Systems

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ABSTRACT

Heating and cooling automotive seats are a relatively new technology that delivers conditioned air to the occupant's seat providing an overall improvement in occupant comfort. This paper combines experimental and computational data to describe the effect of seat cooling on occupant comfort. Included are (1) a review of current seat cooling technologies, (2) the introduction of an innovative seat cooling technology using the vehicle's HVAC system, (3) the inclusion of thermal comfort seat strategy for improving overall comfort, and (4) validation of the thermal comfort seat strategy with experimental data. The paper focuses on the occupant's overall comfort in cooling mode under different ambient conditions.

INTRODUCTION

The thermal comfort of occupants in a vehicle is conventionally provided by the central heating, ventilation, and air conditioning (HVAC) module of the vehicle. Occupants are heated or cooled by convectional air through the surrounding medium in the interior of the vehicle. More recently, vehicles have climatic control seat systems that are capable of providing comfort to occupants. The heating and cooling of the occupant by these systems is done through independent thermoelectrically energized units incorporated into a vehicle seat, or fans pushing or pulling air across the vehicle seats. The heating and cooling of a occupant in an automotive vehicle can be most effectively obtained by applying the thermal conditioned air directly to the human being, thus making the vehicle climatic control seat an effective thermal instrument to provide occupant comfort.

SEAT HEATING/COOLING TECHNOLOGIES

There are currently three main types of seat heating and cooling technologies in the automobile market. A brief description of their functions and components is as follows.

The first type of seat heating or cooling technology consists of Peltier element or thermoelectric module with a fan embedded in the seat. These units typically consist of one or more thermoelectric (TE) modules, heat exchangers, and fans, and are operated by allowing the fan to blow cabin air over the hot and cold sides of the thermoelectric, resulting in heat being absorbed from the air on the cold side and released to the air on the hot side. The cooled air is directed through or over the seat to the occupant's body surface, whereas the warmed air is rejected into the vehicle cabin, for instance under or behind the seat. As with all the seat technologies, the blowing of air across the human occupant causes an evaporative effect at the skin surface producing a cooling effect. Because these thermoelectrically climate controlled seats use cabin air as the medium, which generally is initially cold in heating mode and warm in cooling mode, there is necessarily a deliberate transient thermal response of the seating system.

The second type of seat heating or cooling technology is to draw cabin air through an occupant-to-seat surface. This technology draws air away from the occupant causing the evaporative effect and cooling the human body. The pulling of air across the human body is the most effective way of evaporating moisture at the occupant's surface. However, this system still relies upon the unconditioned air of the cabin. The heating portion is done through conventional resistance techniques or with a carbon-fiber heating element, film, spacer fabric, fleece, and a snap connector within a three-dimensional air medium device.

The third method in the heating and cooling of an occupant's seat is to blow or push cabin air through the seat and back cushions. A motor driven fan pushes air into the top surface of the seat cushion. This technology also utilizes cabin air that has not been conditioned in any way. Also, it is not as effective in cooling as the pull system, as the evaporative effect is less. The heating portion is done through conventional resistance techniques or with a carbon-fiber heating element, film, spacer fabric, fleece, and a snap connector within a three-dimensional air medium device.

INNOVATIVE SEAT COOLING TECHNOLOGY

Applying the conditioned air directly to the human occupant attains the optimum comfort for an occupant in a vehicle. This is accomplished by flowing conditioned air to the occupant seat from a known source like the HVAC module or a thermoelectric cooler/heater dedicated to the seat, as illustrated in U. S. Patents Re. 38,128 to Gallup et al., 5,924,766 to Esaki et al., and 6,079,485 to Esaki et al., and PCT application WO 99/58907 to Bell.

However, the air from the HVAC module on initial startup is not thermally conditioned. In the case of heating, it takes time to warm the coolant due to the thermal inertia of the engine. In the case of cooling, it takes time for the A/C cycle to cool air. On the other hand, a dedicated thermoelectric device to heat or cool the ambient air from the vehicle cabin does not have the thermal capacity vis-à-vis the electrical power available to provide optimum comfort. In other words, the electrical power required to energize the thermoelectric heat exchanger for adequate comfort is quite significant and sometimes not practical. In the heating mode, the occupant is not satisfied with the level of warmth. In cooling mode, the occupant is not satisfied with the cooling effect and even feels clammy, because the thermoelectric does not dehumidify the air. The reason being is that the dew point temperature is below the thermoelectric cooling temperature and little to no dehumidification takes place. When the humidity is very high in the occupant cabin, the thermoelectric device will collect condensed moisture without being able to eliminate it.

This new innovative seat cooling incorporates thermally conditioned air to passages in a seat of an automotive vehicle having a HVAC module for supplying heating and cooling air to a cabin vent and is distinguished by exchanging heat with the heating and cooling air from the HVAC module in an auxiliary heat exchanger before delivery to the seat passages of the seat assembly, i.e., by an auxiliary air-conditioning device in the ductwork between the HVAC module and the seat passages of the seat assembly. Therefore, the new seat cooling system provides a thermoelectric device in series with thermally conditioned air from an HVAC module to provide the ultimate comfort to the occupant upon initial warm-up and cool down, and in steady state operation. The systems differ from the current systems by using preconditioned air from the HVAC module rather than unconditioned cabin air for the hot and cold side of a thermoelectric device. The placement of the thermoelectric device in series with the HVAC increases the effectiveness in cooling or heating the occupant and significantly reduces the initial time to reach the desired comfort level of the seat occupant, i.e., a faster cool-down in the cooling mode and/or warm-up in the heating mode of the vehicle seat than would otherwise be obtained using unconditioned air flows.

Below, in figure 1, is a schematic of the system and components included in the system. First, air is delivered from the automobiles HVAC system to a seat mode case. Next the air is distributed based upon the occupant's selection of whether they want the system on or off. If the system is selected "on", the air is then delivered through a series of ducts to a thermoelectric in the bottom of the seat and a thermoelectric in the back of the seat. After being further conditioned by the thermoelectric, the air is delivered to the occupant's seat.

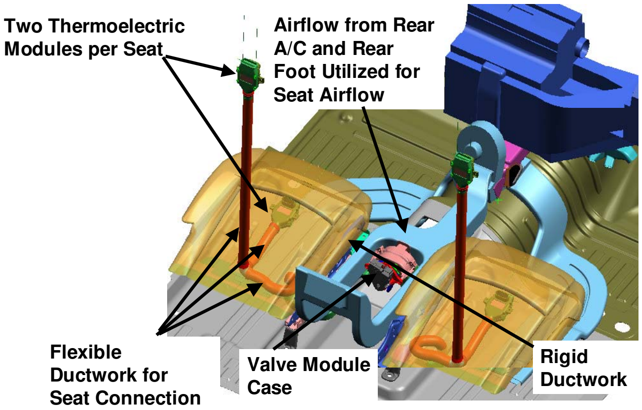

Figure 1. Augmented Heated and Cooled Seats

VIRTUAL THERMAL COMFORT ENGINEERING

Occupant thermal comfort is an important concern in the design of a vehicle. However, vehicle styling, tightening fuel-economy constraints, heated/cooled seats, the change to environmentally friendly refrigerants, and reduced condenser air flow, particularly at idle, are significant challenges to the ability to achieve occupant thermal comfort. As a consequence, it has become necessary to develop occupant thermal comfort model, 1) to predict the impact of various design choices on occupant thermal comfort, and 2) to maximize thermal comfort by optimizing the cooled/heated seat control algorithm. Predicting the thermal comfort in a vehicle is very complex due to the fast transient behavior of cool-down after a hot soak, and the non-uniform thermal environments, such as cooled/heated seats and radiation (solar) heat flux from surrounding interior surfaces. Analysis tools for the temperature and velocity distributions in occupant compartments coupled with thermal comfort predictions can evaluate design options during the early stage of the product development process [1, 2, 3, 4, 5, and 6].

Delphi Virtual Thermal Comfort Engineering (VTCE) [3] was developed jointly with UC Berkeley to predict the occupant compartment thermal environment and occupant thermal comfort. We employed this technology to design and develop our augmented heated and cooled seat technology. The key elements of VTCE process will be described in the following sections.

Vehicle Compartment Model

The geometry of the occupant compartment for the purpose of VTCE can be described by key design parameters that can be carefully selected from early stage vehicle architectural design parameters. The Delphi compartment model can potentially cover a wide range of vehicle shapes and sizes, from small sedans to full-size SUVs. The key design parameters, such as A/C outlet location and size, windshield angle, body vent locations, and many other parameters can be varied easily to accommodate potential design changes. Once the compartment model is available, the benefits of the model for developing the HVAC system design are tremendous. Due to readily available water-tight surface geometry from the Delphi compartment model, the mesh generation time can be drastically reduced compared to the traditional CFD process. The Delphi compartment model for a van baseline case is shown in Figure 2.

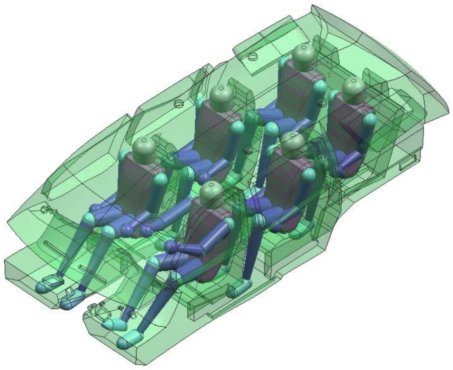

Figure 2. Van compartment model with six occupants

Solar Load

The solar load for the vehicle compartment is dependent on glass properties, solar incidence angle, and incident solar spectrum. The absorptivity, transmissivity, and the reflectivity of the glass vary depending on the incident angle of the sun and the wavelength distribution of the incident solar radiation. The solar intensity varies depending on the time, date, location, and vehicle orientation. The overall solar intensity can be obtained from the NREL's SOLPOS code [7] and NREL's hourly solar database. This solar load program keeps track of the reflection from the glass, absorption by the glass, transmission into the cabin, and also incident radiation on the occupants in the cabin. The amount of solar load absorbed by the occupant influences the thermal comfort of the occupant by increasing exposed clothing and skin temperatures. A database of various automotive glass properties has been incorporated in VTCE, which allows the effect of solar absorbing and reflecting automotive glasses on thermal comfort can be assessed. The accuracy of these simulations was described in our previous work [5].

Radiation Heat Load

Radiant heat exchange occurs between the occupant and its surroundings. During vehicle cool-down and warm-up processes, the radiation heat load has roughly the same influence as air temperature on occupant thermal comfort. Using a realistic 3-D model of the occupant, we calculate the view factors between the polygons that define the occupant and the cabin interior surfaces. The heat gain/loss by radiation from the occupant is computed using view factors between the occupant and the surrounding interior surfaces. The accuracy of these simulations was described in our previous work [5].

Refrigeration Cycle Analysis

The system airflow rate and the discharge air temperature for cool-down and warm-up analysis can be measured from tunnel test as shown in Figure 3 or can be specified from the simulation of the refrigerant cycle system [9]. The system airflow rate and the discharge air temperature at the A/C and heater outlets provide boundary conditions for 3-D flow and thermal analysis of occupant compartment.

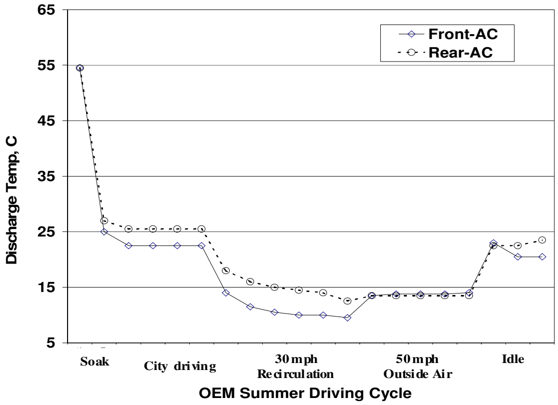

Figure 3. Typical discharge temperatures during the summer driving cycle

Cabin Thermal Environment

The cabin thermal environment can be computed directly from 3-D flow and thermal analysis. The compartment CAD geometry was generated directly from the UG model shown in Figure 2. This CAD geometry was directly imported to Gambit, the Fluent pre-processor, and the time and therefore, the effort for preparation of clean surface geometry for 3-D mesh generation was significantly reduced. For CFD analysis, the physical domain of the compartment was subdivided into finite volumes. Then, the Reynolds-averaged Navier-Stokes equations were solved simultaneously with the conservation of energy equation to predict airflow, temperature, and humidity distribution around occupants. CFD analysis provides detailed airflow distribution information for the cabin and around the occupants.

Figure 4 shows airflow distributions around the chest of an occupant and path-lines from the A/C outlets. Figure 5 shows the interior temperature distribution in a van cabin after 30 minutes of cool-down after a hot soak. To evaluate the cooled/heated seat, a given seat surface temperature profile can be defined during the simulation. The accuracy of these simulations for a simplified occupant compartment was described in our previous work [5].

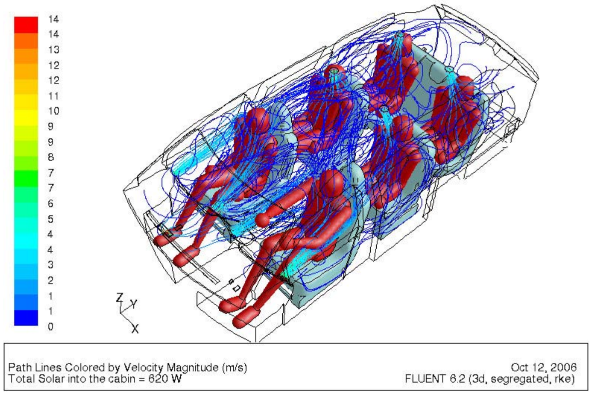

Figure 4. Air flow distribution in a van cabin.

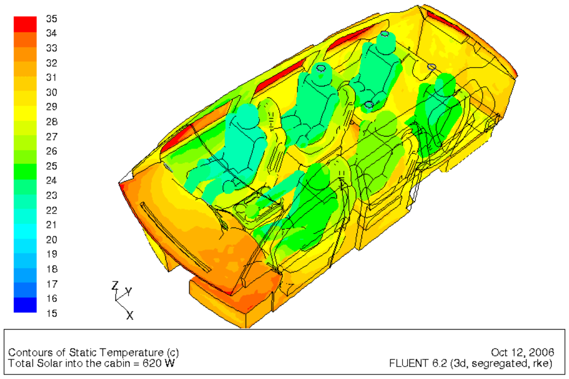

Figure 5. Surface temperature distribution in a van.

Physiological Model

When occupants perceive warmth or coolth, they do not actually sense the temperature around them, but rather the thermo-receptors send signals to the brain. The thermo-receptors are sensors that signal the conditions around us and permit us to feel those conditions as thermal sensations. The thermo-receptors are located in the intracutaneous region at an average depth of 0.15 to 0.17 mm for cold receptors and 0.3 to 0.6 mm for warmth receptors [17].

The current human physiology model can simulate an arbitrary number of body segments. Each of these segments consists of four body layers (core, muscle, fat, and skin tissues) and a clothing layer. A separate series of nodes, representing the arteries and veins, provide for convective heat transfer between segments and tissue nodes and the countercurrent heat exchange between the arteries and the veins. Human body thermal regulation is mainly achieved by regulating blood flow, so a realistic blood flow model is important for any dynamic model of human thermal comfort. The body uses vasoconstriction and vasodilatation to regulate blood distribution in order to control skin temperature through an increase or decrease of heat loss to the environment. Veins and arteries are paired, even down to very small vessels, and veins carry heat from the arteries back to the core. The details of this human physiology model are described in [10, 11]. The model is able to predict both core and extremity skin temperatures with reasonable accuracy under a range of environmental conditions. Detailed validations for transient conditions can be found in [12].

Clothing Model

The current model includes a clothing node to model both the heat and moisture capacitance of clothing. Heat capacity of the clothing is important when considering transient effects [13]. Moisture capacitance is important to correctly model evaporative heat loss from the body through clothing. The moisture model uses the regain approach [14] to calculate the amount of moisture that a specific fabric will absorb at a given relative humidity.

Contact Surfaces

In almost any environment, the body is in contact with solid surfaces and loses or gains heat via heat conduction. In the vehicle, the seat contacts a considerable fraction of the body and must be considered to accurately model the occupant. The current model includes a contact surface for each body segment. The thermal properties of the contact surface are used to simulate its surface temperature. Each body segment includes the fractions of exposed skin and clothed skin in contact with the surface.

Physiological Variation

Human physiology varies significantly among individuals, and these differences can affect perceptions of thermal comfort; e.g., higher metabolic rate or increased body fat can cause people to feel warmer. The present model in VTCE maps six descriptive characteristics of the human body (height, weight, age, gender, skin color, and body fat) to the physiological data used by the comfort model. The simulations show that a change in body fat from 14% to 28% can result in a skin temperature change of nearly 1°K. In the present study, a standard Stolwijk physiology model [10] was used for the human physiology with a metabolic rate of 60 w/m^2. Standard summer clothing (Clo=0.5) was specified for hot soak and cool-down simulations and standard winter clothing (Clo=1.0) was specified for winter warm up simulations.

Thermal Comfort Model

The human sense of thermal comfort is very complex, and involves both the physiological and the psychological states of a person under specific conditions. Bohm [15] accepted the 'Equivalent Homogenous Temperature' (EHT) proposed by Wyon [16] for assessing non-uniform environments and developed limits for thermal comfort. We calculate EHT for each body segment from the human physiology model and generate a diagram that plots these together with the comfort limits established for body segments by Bohm [15], as shown in Figure 6. A statistically determined comfort range between the cold and warm borderlines, in which 90% of the people would feel comfortable, is indicated by the bold lines shown in Figure 6 for 16 body segments.

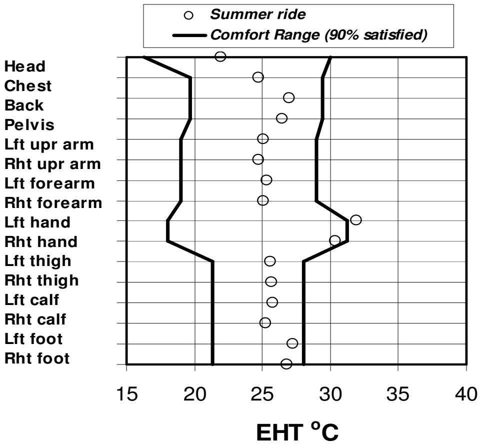

Figure 6. EHT index for 16 body segments for the baseline case near the end of the summer comfort ride

Each body segments weight differently to the overall comfort. For instant, back and pelvis have strong weight on overall comfort. To integrate the weighted segments comfort, we developed a model to correlate the overall EHT scale to a particular OEM's comfort rating [4]. This OEM's comfort ratings are based on a scale from 1 to 9 as shown in Figure 7.

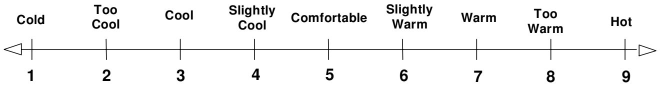

Figure 7. OEM's comfort scales (1 is cold, 5 is comfortable, and 9 is hot)

Utilizing this model, we are able to develop seat cooling strategy with control algorithm and provide occupants with optimum comfort.

THERMAL COMFORT SEAT COOLING CONTROL STRATEGY

According to our thermal comfort model, 65% of the occupant's comfort is from the effective air around occupant, 22% is from the seat back, and 13% is from the seat bottom, the equation (1) has been developed to determine comfort temperature:

$$T_{set}'=0.65*T_{eff}+0.22*_{Tseat,back}+0.13 * _{Tseat,\ bottom} \qquad (1)$$

The model for effective temperature can be derived as:

$$T_{eff} = 0.8 * T_{cabin} + 0.2 * T_{mr} \qquad (2)$$

Where,

T'_{set}= calculated effective occupant setting for comfort
T_{cabin}= air temperature within the vehicle
T_{eff}= calculated effective temperature in the cabin
T_{mr},= mean radiant temperature

T_{mr} is "the uniform surface temperature of an imaginary enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space. The equation for the calculation of T_{mr} is:

$$\overline{T}_{mr} = \sqrt[4]{\sum_{n} F_{p-i}(T_i + 273)^4} - 273 \qquad (3)$$

Where Ti is the surface temperature of surrounding surface, i, and $F_{p\text{-}i}$ is the view factor between the person and surface, i. The mean radiant temperature uses traditional techniques by calculating the radiant factors from all the surfaces.

Additionally,

$T_{seat,\ back}$= seat temperature desired back setting
$T_{seat,\ bottom}$= seat temperature desired bottom setting

So,

$$T_{seat} = T_{seat,\ back} = T_{seat,bottom}$$

Substituting in T_{seat} into Eq. (1), Eq. (4) can then be rewritten as

$$T_{set}' = 0.65 * T_{eff} + 0.35 * T_{seat} \qquad (4)$$

It has been discovered that T_{seat} is dependent upon T_{set}, T_{mr}, and a K factor. The equation is as follows.

$$T_{seat} = T_{set} - 0.1 * T_{mr} + K \qquad (5)$$

Where,

T_{set}= occupant setting for comfort

K is a direct seat coefficient and is dependent upon the T_{mr} and T_{cabin}, and therefore, can be equal to 0 or can be equal to K'

K' factor is determined as follows:

T_{mr} Range	K'
<18	7
18-27	8
>27	9

The condition to determine K is based upon when $T_{set}' = T_{set}$. This will determine the equation for T_{seat}. T_{cabin} can be obtained by solving equations (1), (2), (4), and (5).

Also,

$$T'_{cabin}= 1.25 * T_{set} - 0.1825 * T_{mr} \qquad (6)$$

Where,

T'_{cabin}= fictitious value within the vehicle to determine the temperature regime

Using the equation (6), we can determine the seat temperature for any condition. It is as follows:

$$T_{seat}= T_{set} - 0.1 * T_{mr} \qquad T_{cabin} > T'_{cabin} \qquad (7)$$

$$T_{seat}= T_{set} - 0.1 * T_{mr} + K' \qquad T_{cabin} < T'_{cabin} \qquad (8)$$

$$T_{seat}= T_{set} - 0.1 * T_{mr} + K'/3 * (T'_{cabin} - T_{cabin}) \qquad T'_{cabin} > T_{cabin} > T'_{cabin} - 3 \qquad (9)$$

This is based upon the thermal comfort zone in a vehicle cabin which can be defined as:

$$0.5 \geq | 0.2 * T_{set} – 5.0 | \qquad (10)$$

Figure 8 is an example of seat control temperatures for T_{mr}=32.2℃, under different T_{set}'s and T_{cabin}'s.

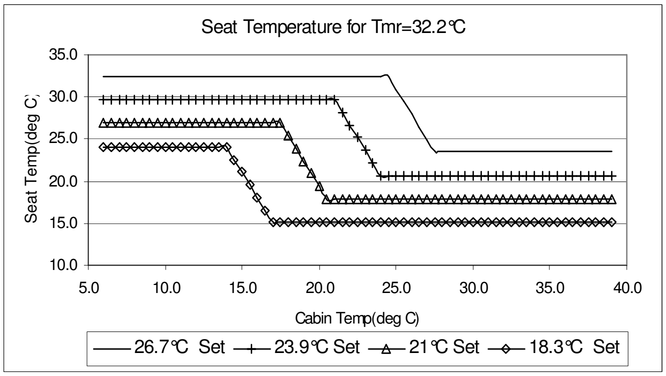

Figure 8. Seat Cooling temperature for T_{mr}=32.2℃

VALIDATION

To validate the current seat strategy, a standard vehicle was soaked to 40℃ x 40% rh, with a solar load of 850 W/m^2 for 1 hour. The vehicle was then started and run for 30 minutes with several occupants, and the average time to comfort was determined. Figure 9 are the results of the average time to comfort for a baseline system, a system with thermoelectric seats alone, a system utilizing just the HVAC air, and a system utilizing the augmented HVAC system with thermoelectrics.

The Virtual Thermal Comfort Seat Strategy System is utilized to compare results back to the vehicle test. The results have accuracy greater than 17%, as shown in Figure 10.

The methodology used in the Virtual Thermal Seat Strategy accurately predicts an occupant's comfort versus time for different seat climatic cooling systems.

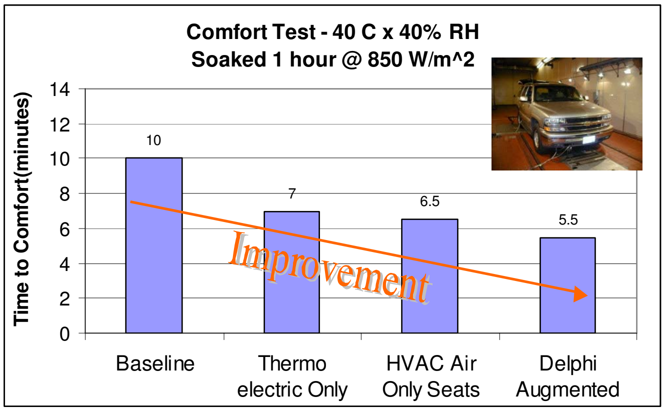

Figure 9. Vehicle Test of Time to Comfort with different seat climatic systems.

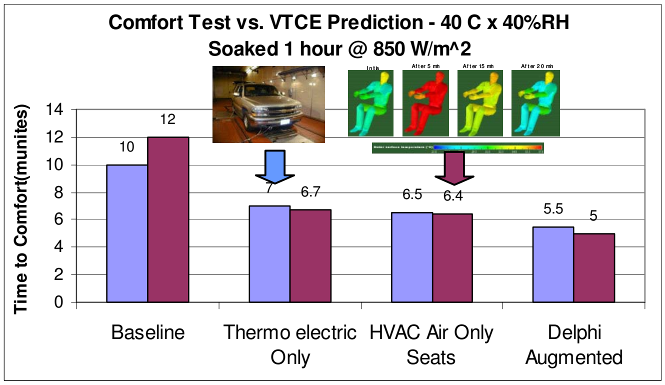

Figure 10. Comparison of Vehicle Test to Virtual Thermal Seat System Strategy

CONCLUSIONS

The optimum effect of providing comfort to an occupant is attained by applying the conditioned air as directly as possible to the human occupant. Seat cooling provides rapid time to comfort versus baseline systems, with the Delphi Augmented system shown to be the best versus the known other seat cooling technologies.

An accurate model has been developed to predict the complex human sense of thermal comfort involving both physiological and psychological states of a person under specific conditions. Through vehicle occupant type testing this model has been validated.

Subsequent to the validation of the model, a control algorithm has been developed. This algorithm accurately predicts the human comfort and optimizes the seat conditions based on a vehicle's conditions and occupants' inputs.

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