03 DHM-12

Experimental Study and Thermal Modeling of an Automobile Driver with a Heated and Ventilated Seat

G. Karimi, E.C. Chan, and J.R. Culham
Department of Mechanical Engineering

University of Waterloo

Waterloo, ON, N2L 3G1, Canada

ABSTRACT

This paper presents mathematical models of thermal interactions among an automobile passenger, the cabin environment, and a heated/ventilated seat. The model, which has the ability to predict the transient response of a driver in a highly non-uniform thermal environment, has been tested against subjective evaluations under simulated winter and summer driving conditions. The good agreement between model predictions and experimental measurements suggests that such a model can be a useful predictive tool in the design of a passenger thermal comfort system.

INTRODUCTION

The cabin temperature of an automobile can exceed 80°C on a hot summer day due to incident solar radiation, while during harsh winter conditions, ambient temperatures can drop below -30 °C. Under this extreme range of ambient conditions, automobile passengers can experience painful localized heating or cooling, as exposed body surfaces (15 to 20%) make contact with the seat, back support and steering wheel. Although the heating and air-conditioning systems within an automobile attempt to respond to the comfort needs of passengers, the thermal capacity of most cabin components limits the timely response of these heating and ventilation systems, resulting in passenger discomfort for extended periods.

The cabin air temperature is an important factor in determining the level of thermal comfort however, conductive heat transfer from the body due to contact with a seat that is initially very cold or very hot plays a significant role in influencing the thermal sensation of an automobile passenger.

The ability to reach thermal neutrality over the contact area during the cold season can be expedited by incorporating resistive heating elements into the seat to augment the standard engine-coolant-based heating system. A possible strategy to improve the cooling process is to ventilate the seat with ambient air from the passenger compartment. This technique can substantially reduce the time lag between heat transfer from the ambient air to the seat contact area. Furthermore, it can enhance the comfort level in the microclimate in the contact area.

A commonly used system evaluation procedure, which involves measuring the rise/drop in compartment air temperatures at selected locations during the warm-up/cool-down process may not be adequate to assess a driver's thermal comfort because a significant amount of heat is exchanged in the contact areas. A more fundamentally sound, albeit expensive and time-consuming procedure is to use test subjects to evaluate thermal comfort under simulated winter/summer driving conditions. In this procedure, teams of test subjects sit on fully equipped seats while they subjectively evaluate thermal sensation associated with the applied conditions. The test subjects must account for variations in local and overall thermal sensations produced by non-uniform thermal conditions.

The body of literature on theoretical and experimental human thermal comfort analysis is vast. Most of the prior studies have been limited to uniform thermal conditions, representative of a building environment. Fanger (1967, 1970) was the first person to give complete quantitative information on calculating the heat exchange between people and the environment. Comprehensive reviews can be found in Hwang and Konz (1977), Haslam and Parsons (1988), and Lotens (1988), among others. A combined experimental and theoretical study of thermal comfort in a tractor cab under summer conditions was reported by Kaufman *et al.* (1976). Air temperature, air velocity, and radiant temperature in the cab were measured under steady-state conditions and used in Fanger's comfort model to predict the associated thermal sensation of an occupant. The predictions were found to compare fairly well with subjective comfort rating by a 16-person jury under the same conditions. Madsen *et al.* (1986) used Fanger's model to predict the time required to reach thermal comfort in an automobile in both severe winter and summer conditions. A comprehensive thermal model was developed by Burch *et al.* (1992) for prediction of the thermal sensation of automotive passengers under severe winter conditions. Model predictions were in good agreement with jury evaluations obtained during standard warm-up tests as well as in tests involving supplementary electric heating. A three-dimensional clothed human thermal model developed by Shoji and Nakajima (1997) to predict the physiological response to temperature and humidity by considering the thermal properties of fabrics, and clothing ensembles. The performance of the model was experimentally verified using simulated heat and moisture mass transfer. A new numerical system and experimental evaluation method was developed by Kataoka (2001), to predict and evaluate an occupant's thermal sensation in a non-uniform, transient passenger compartment. Good agreement between the theoretical and experimental results was reported. A thermal model of the dynamic interaction between an automobile passenger, the cabin environment, and a heated/ventilated seat was recently developed by Karimi *et al.* (2002). The model considers the human body as being made of 21 distinct segments and three-layers. Simple mathematical models were used to simulate heating and ventilation of cool air through a seat. The model has the ability to predict the transient response of a driver in a highly non-uniform thermal environment in terms of local and overall thermal comfort levels.

The purpose of the present investigation is twofold: (a) to evaluate a heated and ventilated seat performance in bringing thermal comfort to an automobile passenger by conducting experiments under simulated winter and summer conditions, and (b) to develop a method to predict thermal response of a vehicle occupant based on fundamental heat transfer equations.

EXPERIMENTATIONS

An understanding of ergonomics is a necessity in automobile design, which requires information of human physiological capabilities, limitations, and environmental interactions. Automobile seat ergonomics can be studied through experimental simulations where certain variables are isolated and accurate representations created to simulate actual field conditions.

EXPERIMENTAL PROCEDURE

In the present study, a set of experiments was devised to investigate the effects of seat heating and ventilation on a passenger's level of comfort. A total of 26 individuals, half of them male and half female, with different ages, weights, genders, and body types were engaged to undergo experiments for a period of 2 ½ hours. The experimental program was carried out in a large, windowless classroom 6.0 m wide and 8.0 m long, with ceiling height of 2.8 m. Experiments were performed during the month of August; so all subjects were clothed in cotton shirts and shorts or trousers and sandals. Pilot experiments were initially conducted on the first 6 subjects to determine the optimum experimental conditions. The room temperature and relative humidity were maintained constant at 22.5 °C and 55%, respectively, by a central air-conditioning system.

The subjects were first instructed regarding the purpose of the study, the experimental procedure and the method of quantifying the thermal sensation. Then, their weights and heights were measured and their general information, such as age, body attributes, and general thermal comfort were collected. To monitor subjects' skin temperatures during the study, 10 thermistors (9.5 mm in diameter) were placed directly at different body locations; 4 on the back, four on the thigh, 1 on the neck, and one slightly below their navel as shown in Fig. 1. In addition, 9 T-type thermocouples were placed on the seat cushion and the backrest at the contact areas with the body to monitor the seat surface temperatures during each test.

Each session consisted of 8 experiments, 4 heating tests, and 4 ventilation/cooling tests. For heating tests, the seat was cooled to about –10~0 °C by covering it with frozen ice packs. For cooling tests, the seat was heated to about 60~80 °C by placing several bags of wheat heated in a microwave oven. Wheat was chosen because of its relatively high specific heat and its ease of use. For each experiment, a thermal blanket was used to cover the seat for a period of about 20 minutes to minimize the heat loss and to ensure a uniform temperature distribution with a reasonable penetration depth. During the seat preparation the seat surface temperatures were monitored to ensure temperature level and uniformity.

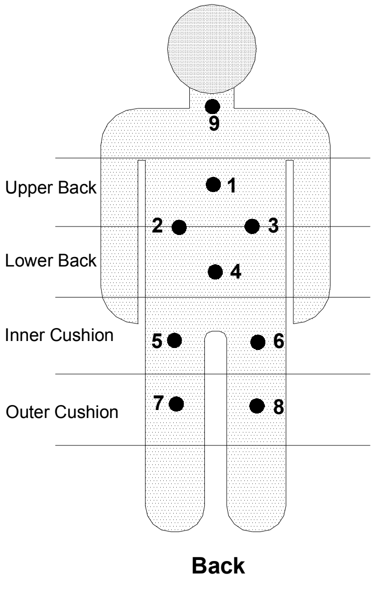

Fig.1: Approximate locations of thermistors on the participants' body (The 10th thermistor is attached to the participant's navel).

The seat was capable of providing heat and ventilated air to the body contact areas at low, medium and high rates to enhance thermal comfort. For heating experiments, heat was produced by passing electric current through a heating pad made of carbon fibers placed beneath the leather covering at a rate of up to 0.81 MW/m^3 depending on the seat setting. During ventilation, up to 3.8 L/s of ambient air was drawn into the seat using built-in fans, passed through a spacer material, heating mat, and eventually through the porous leather cover before coming in contact with the driver's body.

For each heating or ventilation test, subjects were asked to stand calm for about 10 minutes close to the seat. This period was necessary for the skin temperature to achieve thermal equilibrium. The seat covers as well as the ice packs/wheat bags were then removed, the seat setting was set and the subjects were immediately asked to sit on the seat. Heating and cooling tests were conducted sequentially however; the seat settings were chosen randomly to minimize subjective biasing. Subjects were allowed to perform quite activities such as reading and watching movies during the tests.

During each test, the participant's skin temperature, the seat surface temperature and the ambient temperature were collected and monitored using a data acquisition system. Information on local and overall thermal sensations was collected using a questionnaire. Subjects were asked to rank their thermal sensations at 4 body locations, upper back, lower back, inner cushion, and outer cushion areas (Fig. 1) as well as their overall sensations. The ranking was conducted in 2-minute intervals during the tests. When giving partial thermal sensation, the subjects were instructed to disregard as much as possible sensations at other places on their bodies.

Table-1 lists the statistics of the 20 subjects participating in the main study. Initial average skin and seat temperatures are given in Table-2.

Table-1: Statistics of participants

Participant	Average	STD
Age [year]	27.5	8.2
Height [cm]	173.3	10.1
Weight [kg]	75.0	22.3

Table-2: Initial average temperatures [°C]

Test	Seat	Skin
Heating:		
Cushion	-4.0	32.6
Backrest	-0.1	33.1
Ventilation:		
Cushion	73.7	33.2
Backrest	57.6	34.1

EXPERIMENTAL RESULTS

Local skin and seat temperatures were averaged to determine the regional temperatures at the participants' lower back, buttocks area, as well as the seat cushion and backrest surfaces in contact with the body.

Figure 2 displays time variations of averaged temperatures measured and thermal sensations reported during the heating experiments at different heat settings. Figures 2-a and 2-b show seat cushion and backrest surface (leather cover) temperatures as a function of time. From these figures, it is seen that steady-state temperatures are reached in approximately 10 minutes following the start of the experiment. Surface temperatures increase quickly regardless of the seat heat setting. The initial rates are estimated at 55 °C/min for the cushion, and 29 °C/min for the backrest, respectively. The high rate is due to the sudden contact of the cold seat with the participants' cloths, which were primarily at higher temperatures. During this period, the heat dissipated in the carbon fibers warmed up nearby regions and could not reach the leather surface. The lower rate in the backrest was due to the lower contact pressure or higher thermal resistance that existed between the participants' back and the backrest.

With the heating pad activated, heat was produced in the carbon fibers and transferred to the leather cover and eventually to the occupant's skin. The rate of heat transfer was so fast that the seat surface temperature exceeded the ambient temperature (22.5 °C) in less than a minute and stayed well above the ambient for the rest of the experiments. The electrical heater was shut down once the heating pad temperature exceeded a predefined value and reactivated if its temperature dropped more than 2 °C.

Figures 2-c and 2-d show variations of local skin temperatures in contact with the seat cushion and the seat back, respectively. The skin temperatures decreased considerably during the first minute for all heat settings. With no heating, the skin temperature remained below the initial value and it took more than ten minutes to recover its original conditions. The slight increase in skin temperature was due to the heat generated in the contact areas by the body's internal thermo-regulatory system, which stimulates shivering. When the heating system was activated, it took about 4 minutes for the skin to get back to the initial temperatures and would exceed the initial values for the rest of experiment. The considerable delay observed between the seat and skin temperatures was due to the skin and the clothing heat capacities. Besides, the larger initial skin temperature drop as well as a higher skin temperature observed in the cushion side after 10 minutes were due to the larger contact pressure or the smaller contact resistance between the body and the seat in the cushion area than that in the backrest area.

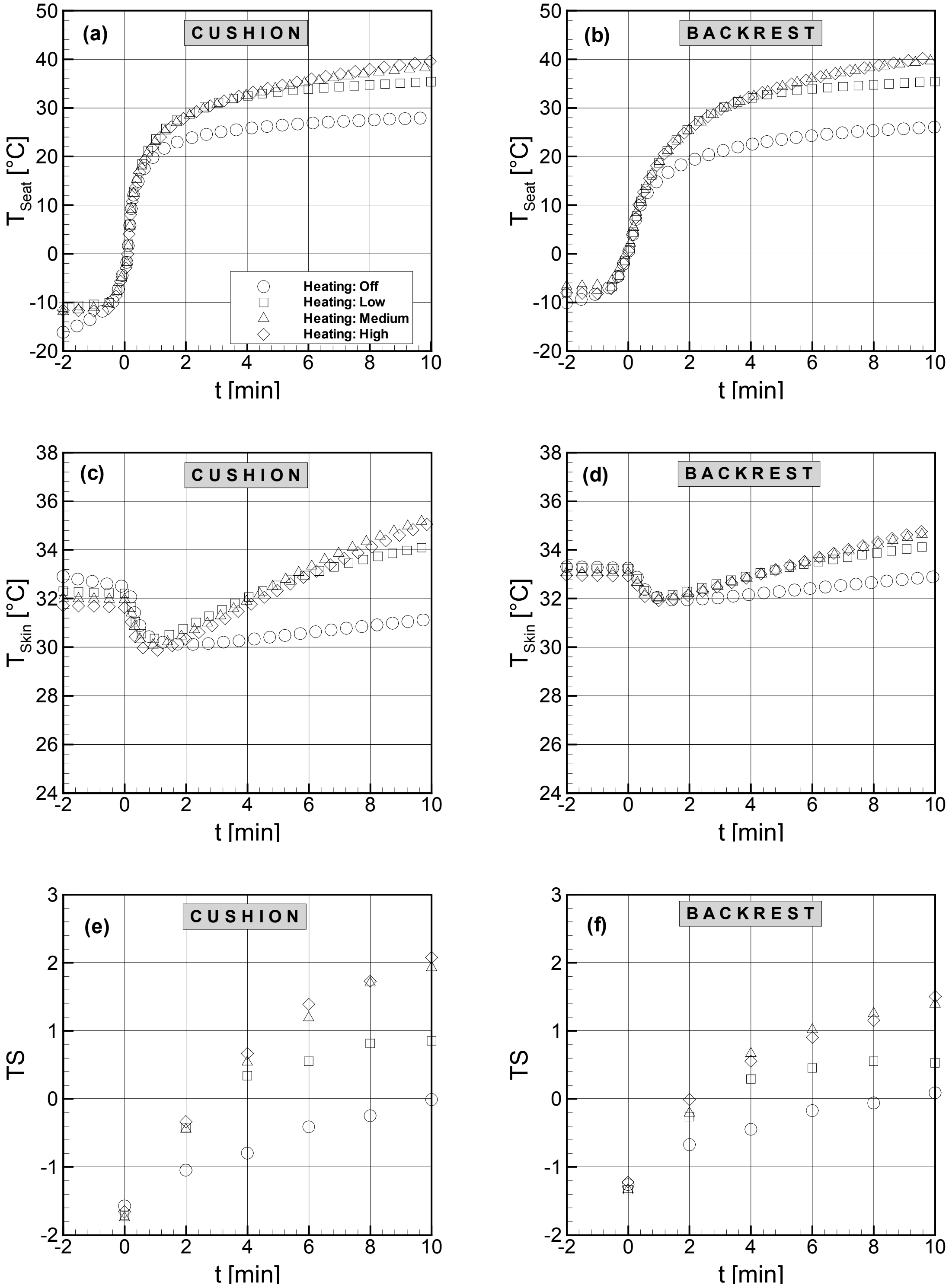

Fig. 2: Time variations of experimentally measured seat temperatures, local skin temperatures, and local thermal sensations as a function of heat settings under simulated winter conditions

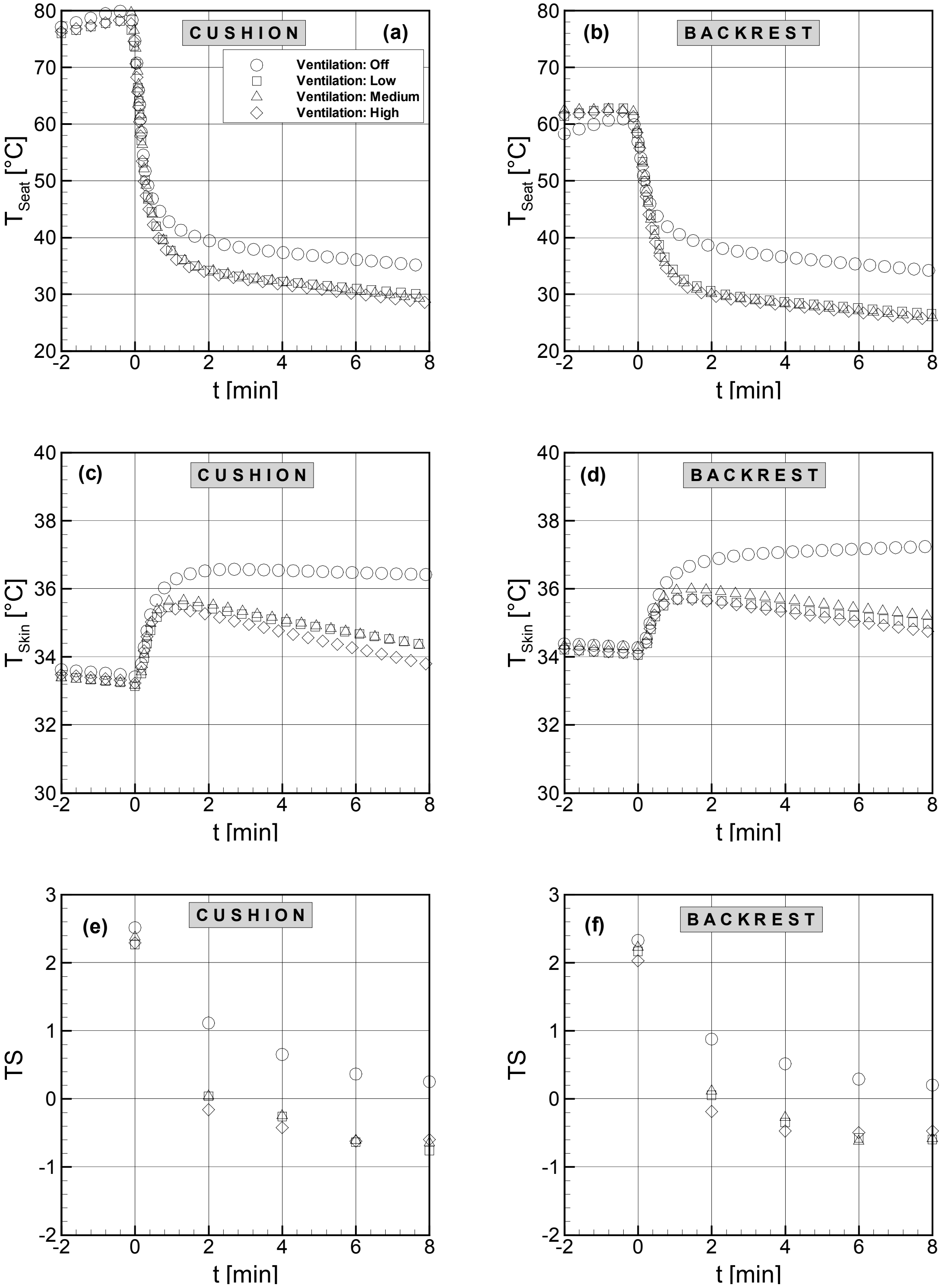

Fig. 3: Time variations of experimentally measured seat temperatures, local skin temperatures, and local thermal sensations as a function of ventilation settings under simulated summer conditions

Figures 2-e and 2-f show participants' local thermal sensations (TS) reported as a function of time. In the present study, Fanger's thermal comfort scale (Fanger, 1970) was used to evaluate thermal sensations. This scale uses 7 distinct numbers from –3 to +3 corresponding to very cold, cold, cool, neutral, warm, hot, and very hot, respectively. Participants were instructed to rate zero for their thermally neutral sensations. As shown in the figures, participants reported local sensations ranging from very cold (-3) to cold (-2) at the moment they sat on the seat. With an unheated seat, it took about 10 minutes for the participants to reach thermal neutrality at contact areas. On the other hand the body's internal heat generation due to metabolism and shivering was not sufficient to bring local thermal comfort in a reasonable period of time. When the heating system was activated, local thermal sensations increased quickly and the participants would feel warm after about 3 minutes. If the heating system is not shut down after this period participants will feel localized heating at the contact areas with the seat as shown in the figure. Again, the difference in thermal sensation ratings at the cushion and the backrest are due to different thermal capacities and thermal resistances from skin to the seat in contacted areas.

Ventilation/cooling tests were conducted by raising the seat temperature between 60~80 °C to simulate summer conditions. Participants were asked to sit on the seat while their local skin and seat temperature data were collected simultaneously as a function of time. Participants reported their thermal sensations in 2-minute intervals.

Figure 3-a and 3-b show variations of seat surface temperatures as a function of time. Experimental results revealed that the seat temperatures drop considerably during the first few seconds of experiments. The initial rate of temperature drop is independent of the ventilation rate. This is due to the sudden contact of the seat and the participants' cloths, which were at significantly lower temperatures. During this period, the ambient air ventilated through the seat has no contribution in lowering the leather cover temperature. On the other hand, the intake air leaving the seat would approach the leather temperature. Comparison of seat cushion and backrest temperatures indicates that the initial rate of temperature drop in the backrest area is smaller than that of the cushion area (-46 °C/min compared to –85 °C/min), which is due to different contact pressures as previously pointed out.

The effectiveness of the ventilation system becomes apparent after the first minute of operation. The seat temperatures decrease constantly due to the cooling effect of the ambient air and approach the ambient temperature as time elapses. Experimental results indicated minor differences in the steady-state temperatures for low, medium, and high ventilation rates as predicted by Karimi *et al*., 2002.

Figures 3-c and 3-d show a variation of local skin temperatures as a function of time and the level of ventilation. As expected the local skin temperatures increased initially due to the large temperature difference in the contact areas however, the rate of increase in temperature would diminish substantially as the temperature gradients were decreased with time. Ventilation of ambient air through the seat would quickly reduce the skin temperatures back to the initial values. Again, the temperature of the skin in contact with the cushion cooled down at a higher rate due to a better local contact there. Figures 3-c and 3-d clearly show that there is virtually no difference between the performance of the low, medium and high ventilation rates.

Local thermal sensation values at different ventilation settings are shown in Figs. 3-e and 3-f. As seen from the figures, local thermal sensations start between very hot (+3) and hot (+2) territories. With no ventilation, all participants reported warm sensations for the duration of the experiment. Seat ventilation would bring thermal neutrality in 2 minutes and caused an unpleasant feeling (-1) in all participants for the duration of the tests. Thermal sensations reported are almost identical for both medium and high ventilation rates.

THERMAL MODELING

In the present work, physical models are developed to predict thermal interactions between a typical driver, and a heated or ventilated seat. The numerical predictions are compared with the ergonomic data under simulated winter and summer driving conditions.

DRIVER'S THERMAL MODEL

Thermal response modeling accounts for the heat exchange processes between the body and the surrounding environment in order to estimate the rate of heat storage and body temperature. The human thermal response model developed in this work (Karimi *et al.* 2002) considers the body to be made of three layers: core, skin and the clothing worn, and 21 distinct segments. The selection of body segments provides local as well as overall thermal response estimation of the human body over a wide range of clothing and environmental conditions. In addition, the effect of heating or ventilation through the driver seat, the steering wheel, and local air velocity can be investigated.

Based on this model, heat (per unit area) is generated in the body by normal metabolic performance (and possibly shivering), Q_{MT}, and could be lost to the environment by conduction, Q_{CN}, convection, Q_{CV}, radiation, Q_{RD}, respiration, Q_{RS}, and evaporation of sweat from the skin, Q_{EP}. The rate of heat storage in a body segment, Q_{ST}, is the difference between the rate of heat generation and the rate of heat loss to the environment as given in Eq. 1

$$Q_{ST,i} = (m \cdot C_P)_i \frac{dT_i}{dt} = Q_{MT,i} - (Q_{CN} + Q_{CV} + Q_{RD} + Q_{RS} + Q_{EP})_i \qquad i = 1,2,\cdots,N \tag{1}$$

where subscript, i, denotes an arbitrary layer in a body segment (*e.g.* core, skin or clothing) under consideration and N is the total number of body segments.

Fundamental heat transfer principles can be used to evaluate the dry heat loss (conduction, convection and radiation) in terms of skin temperature, thermal resistances, and environmental conditions. Skin temperature as well as evaporation and respiration heat fluxes are dependent on complex thermo-regulatory functions of the body including sweating, shivering, and the control of the blood flow through vascular constriction and dilation. In general, these thermo-regulatory functions vary over the body in response to changing rates of heat loss due to thermal transients and non-uniformity in clothing, temperature, and air velocity.

The equations for each of the heat gain/loss terms are used and heat balances are made on every layer of each segment to develop equations for estimating local temperatures as a function of time. If the initial core, skin and clothing temperatures and ambient conditions are given, subsequent values can be calculated from the heat rate terms and heat capacities by solving the system equations.

HEATED/VENTILATED SEAT

The Total Comfort Seat System (TCSS^{TM}) under investigation is intended to augment the standard engine-coolant-based heating system in winter and to provide ventilated cool air to the contact surfaces during the summer to provide a higher level of comfort. Heat is produced in the heating pad electrically and ambient air is ventilated through the seat before coming in contact with the driver's body. The schematic of the seat under ventilation condition is shown in Fig. 4.

Although heat transfer in the seat is a complex three-dimensional phenomenon, simple transient, one-dimensional thermal models are developed to predict the time variation of temperature in the seat during the heating and ventilation processes. The governing equations are:

Heating:

$$\frac{\partial^2 T_j}{\partial x_j^2} + \frac{\dot{Q}_j}{k_j} = \frac{1}{\alpha}\frac{\partial T_j}{\partial t} \qquad j = 1,2,\cdots, Number\ of\ seat\ layers \tag{2}$$

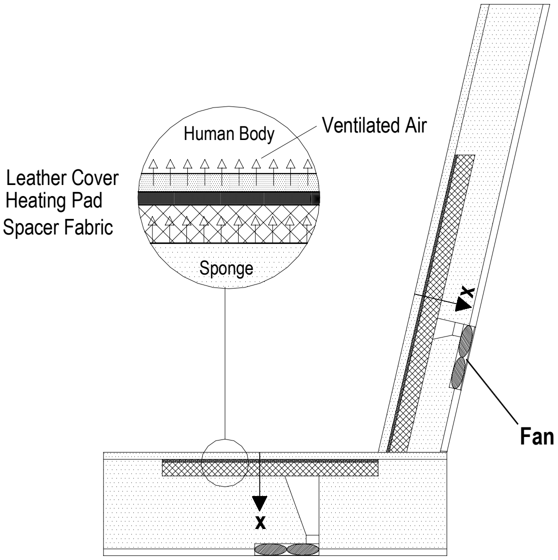

Fig. 4: Schematic of the TCSS^{TM} and air velocity vectors

Ventilation:

$$\frac{T_{Out} - T_{In}}{T_{t=0} - T_{In}} = e^{-\beta t} \quad , \qquad \beta = \frac{(\dot{m}\, C_P)_{Air}}{(m\, C_P)_{Material}} \tag{3}$$

Equation 2 shows the time variation of temperature, T, across the seat materials, x. $\dot{Q}$ is the heat generation per unit volume of the heating pad and is zero for other seat materials. k and α are thermal conductivity and thermal diffusivity ($k / \rho C_P$) of the seat materials, respectively.

Equation 3 is obtained based on a lumped heat capacity approach. In this equation T_{In} and T_{Out} are the air temperatures drawn into and leaving an arbitrary control volume, respectively as illustrated in Fig. 5. $T_{t=0}$ represents the initial temperature of the control volume. m is the mass of the seat material in the control volume, $\dot{m}$ is the mass flow rate of ventilated air, and C_P is the specific heat. This equation was derived based on the following assumptions: (a) heat transfer occurs only perpendicular to the seat surface, (b) the conduction term is negligible compared to convection, (c) the mass of air trapped in the material is negligible in comparison to the mass of the material, and (d) a thermal equilibrium is reached between the air and the material when air leaves the control volume.

Winter simulations are obtained by applying initial and boundary conditions. Equation 2 is discretized implicitly using a finite difference scheme. The resulting set of algebraic equations forms a tri-diagonal matrix, which is solved using a Thomas Algorithm. The seat temperature distributions are updated with time.

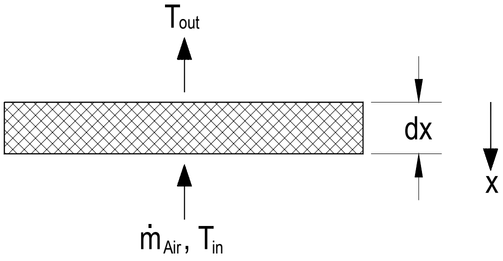

Fig. 5: Control volume used for ventilation

Transient temperature profiles due to ventilation are obtained by dividing the seat layers into small control volumes. Calculations are started from the beginning of the spacer material where air is introduced and continued upward to the leather cover. The temperature profiles in the sponge and the leather on the seat back are still governed by conduction and obtained by solving Eq. 2.

Figure 6 shows time variations of seat and local skin temperatures predicted by the thermal models under the same experimental conditions (Table-2). Figures 6-a and 6-b display variations of the seat cushion and backrest surface temperatures with an average driver (75 kg and 173 cm) at different heat settings as a function of time. As expected, the seat surface temperatures increase rapidly in the first two minutes due to the large temperature difference at the contact areas. The rate of temperature increase is diminished with time as temperature gradient decreases and as controller regulates the electrical current fed to the heating pad. It is seen from the figures that with no heating the seat temperature is always lower than the local skin temperatures causing a continuous heat loss from the skin to the seat surfaces. Numerical predictions of the seat temperatures show maximum average errors of –14.1% and +11.2% for the cushion and backrest, respectively

Time variations of local skin temperatures as predicted by the physical model are shown in Figs. 6-c and 6-d. The thermal model predicts the initial reduction in skin temperature followed by an increase in local skin temperatures. The maximum average errors observed are 5.2% for the seat cushion and –9.4% for the backrest.

Figure 7 shows time variations of seat and local skin temperatures predicted by the thermal models under experimental summer conditions. Figures 7-a and 7-b show variations of seat surface temperatures as a function of time. The thermal models predict instant drops in seat temperatures followed by small kinks for ventilated seat. The initial drops in temperatures are due to the sudden contact of the driver model and the seat with relatively large temperature differences. The existence of the kink in temperature profiles can be attributed to the heat, which is delivered to the seat surface by the heated ambient air. On the other hand, the seat cooling starts at the spacer material where air is initially introduced and moves upward to the seat surface. As ambient air is moving towards the surface, it removes heat from the seat materials (initially at high temperatures) and its temperature rises. The heat delivered to the surface is governed by force convection, and is capable of preventing a temporary drop in surface temperature. The increase in local clothing temperatures also contributes to the size of the kink. A better contact in the cushion results in a larger clothing temperature, which in turn forms a wider kink. This phenomenon occurs in a very short period of time (about 30 seconds) and the kink quickly vanishes as cool air reaches the seat surface. While thermal models consider a uniform initial temperature throughout the seat, one possible motive for not seeing such bumps in experimental results is the short penetration depth during the initial heating of the seat.

Although the thermal model predicts reasonably the sudden drop in seat temperatures, there is a maximum average of +6.0% error in steady-state predictions. In addition, numerical results show minor differences in seat steady-state temperatures for all ventilation rates.

Figures 7-c and 7-d show variation of local skin temperatures as a function of time and ventilation rate. As expected the local skin temperatures increase initially in the contact areas, however, the rate of increase in temperature will diminish substantially as temperature gradients are decreased with time. Ventilation of air through the seat would cause the local skin temperatures to drop quickly and efficiently to the initial values. The change in the local skin temperatures occur with a few seconds of delay with respect to the seat temperatures due to the thermal heat capacities of the clothing and the skin. Thermal models predict the skin temperatures with maximum average errors of –1.6% and -10.1% for the cushion and the backrest, respectively.

Details of average errors observed for all simulation cases are listed in Table-3 and Table-4.

Table-3: Estimated average errors for different simulated heating cases (%)

Location	**HEATING**			
	Off	**Low**	**Med.**	**High**
Cushion surface	-14.1	+4.8	+10.8	+6.4
Backrest surface	-1.1	+0.5	+7.0	+11.2
Skin at cushion	-1.6	+2.7	+4.0	+5.2
Skin at backrest	-9.4	+2.7	+6.5	+6.9

Table-4: Estimated average errors for different simulated ventilation cases (%)

Location	VENTILATION			
	Off	Low	Med.	High
Cushion surface	+21.3	+5.2	-2.3	-7.3
Backrest surface	+15.8	-5.0	-5.4	-6.3
Skin at cushion	-1.6	+0.1	-1.4	-1.5
Skin at backrest	-0.1	-8.1	-10.1	-10.1

CONCLUSION

A transient physical model was developed to simulate the thermal interactions between an automobile passenger, the cabin environment, and a heated/ventilated seat. The model takes into account the effect of heating and ventilation through the seat on the local and overall thermal responses. Experimental studies were conducted under simulated winter and summer conditions to evaluate the model predictions. It was found that low-power electric heating pads installed on the seat cushion and backrest greatly reduced the time needed to attain thermal comfort to the passenger in the contact areas which in turn enhanced overall thermal sensations. In addition, ventilation through the seat in the hot season can reduce the seat temperature quickly and efficiently and increase thermal comfort of the passenger.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of Materials and Manufacturing Ontario (MMO), the Natural Sciences and Engineering Research Council of Canada (NSERC), and W.E.T Automotive Systems Ltd.

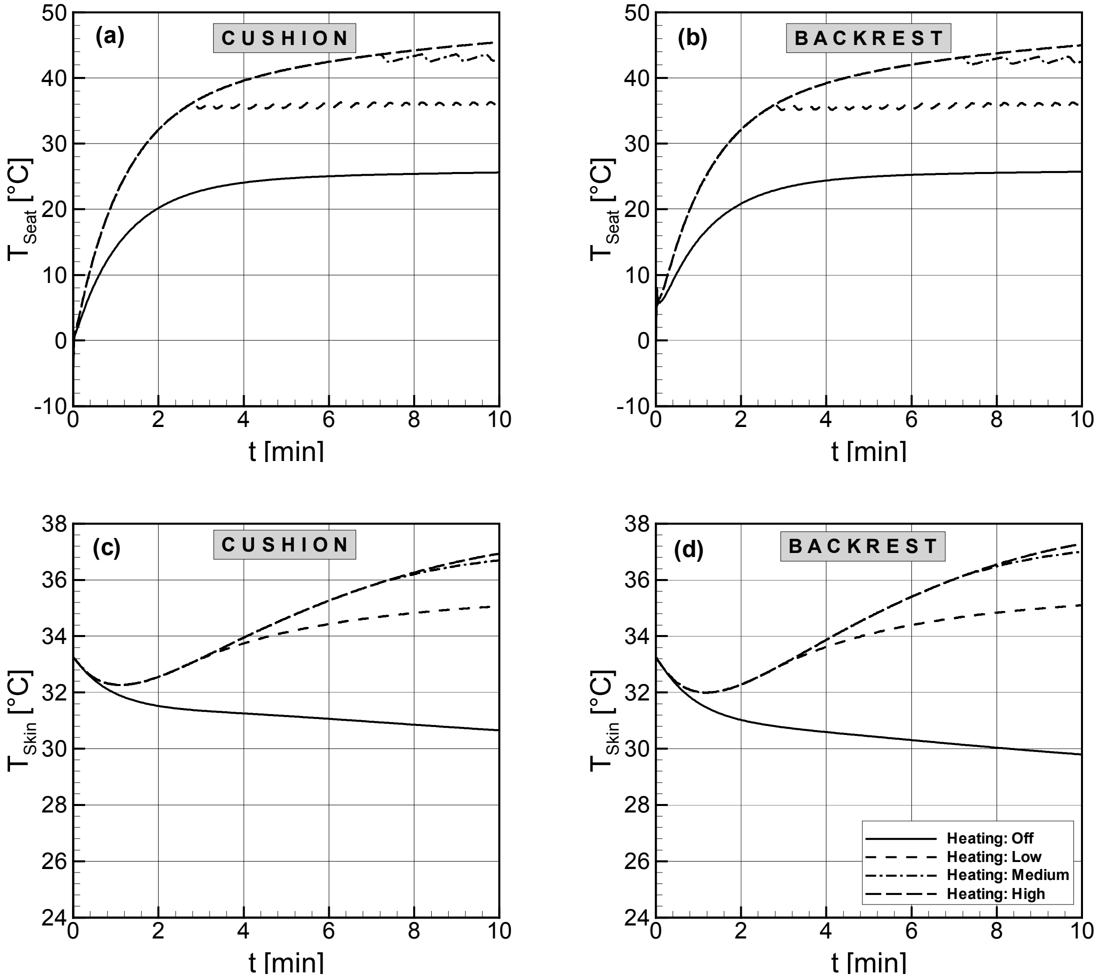

Fig. 6: Time variations of seat and local skin temperatures predicted by the thermal model under experimental winter conditions

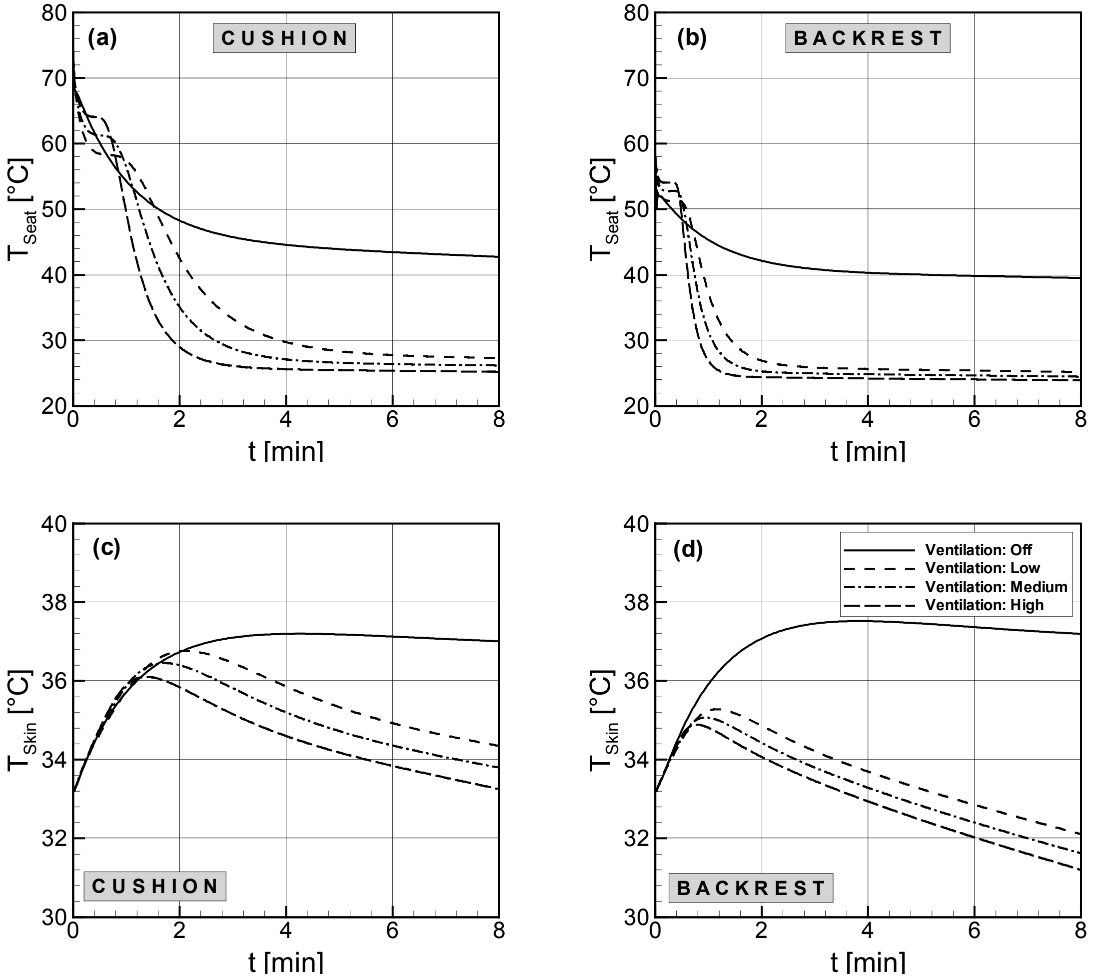

Fig. 7: Time variations of seat and local skin temperatures predicted by the thermal model under experimental summer conditions

REFERENCES

Burch, S.D., Ramadhyani, S., and Pearson, J.T., "Experimental Study of Passenger Thermal Comfort in an Automobile Under Severe Winter Conditions," *ASHRAE Transactions,* pp. 239-246, 1992.

Burch, S.D., Ramadhyani, S., and Pearson, J.T., "Analysis of Passenger Thermal Comfort in an Automobile Under Severe Winter Conditions," *ASHRAE Transactions,* pp. 247-257, 1992.

Fanger, P.O., "Calculation of Thermal Comfort: Introduction of a Basic Comfort Equation," *ASHRAE Transactions,* Vol. 73, No. 2: III.4.1, 1967.

Fanger, P.O., Thermal Comfort Analysis and Applications in Environmental Engineering. McGraw-Hill, New York, 1970.

Haslam, R.A. and Parsons, K.C. "An Evaluation of Computer-Based Models That Predict Human Responses to the Thermal Environment," *ASHRAE Transactions,* Vol. 94, Part 1, pp. 1342-1360, 1988.

Hwang, C.L. and Konz, S.A., "Engineering Models of the Human Thermoregulatory System: A Review," *IEEE Transactions on Bio-Medical Engineering,* Vol. BME24, No. 4, pp. 309-325, 1977.

Karimi, G., Chan, E.C., Culham, J.R., Linjacki, I., and Brennan, L., "Thermal Comfort Analysis of an Automobile Driver With Heated and Ventilated Seat," *SAE 2002 World Congress*, Detroit, MI, SAE Paper 2002-01-0222.

Kataoka, T., "Prediction of Occupant's Thermal Sensation Under the Transient Environment in a Vehicle Compartment," *SAE 2001 World Congress*, Detroit, MI, SAE Paper 2001-01-0586.

Kaufman, K.R., Turnquist, P.K., and Swason, R.N., "Physiological Responses and Thermal Comfort of Subjects in a Tractor Cab," Winter Meeting, ASAE, St. Joseph, MI., Paper 76-1577, 1976.

Lotens, W.A., "Comparison of Thermal Predictive Models for Clothed Humans," *ASHRAE Transactions,* Vol. 94, Part 1, pp. 1321-1341, 1988.

Madsen, T.L., Olesen, B., and Reid, K. “New Methods for Evaluation of the Thermal Environment in Automotive Vehicles,” *ASHRAE Transactions,* Vol 92, Part 1, pp. 38-54, 1986.

Shoji, Y., “A Three-dimensional, Clothed Human Thermal Model,” *Heat Transfer-Japanese Research*, Vol. 26, No. 8, pp. 554-566, 1997.

CONTACT

Gholamreza Karimi, Research Associate, Department of Mechanical Engineering, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada.

NOMENCLATURE

C_P	specific heat, J/(kg.K)
k	thermal conductivity, W/(m.K)
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
N	number of body segments
Q	total heat flow rate, W
$\dot{Q}$	heat generation per unit volume, W/m^3
t	time, s
T	temperature, °C
TS	thermal sensation
x	thickness/distance, m
α	thermal diffusivity, m^2/s

Subscripts

CN	conduction
CV	convection
EP	evaporation
i	body segment number
In	Inlet
j	Seat layer number
MT	metabolism
Out	outlet
RD	radiation
RS	respiration
ST	stored