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Experimental Investigation of Thermal Comfort in a Passenger Car under Driving Conditions

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HIGHLIGHTS

- Studied human thermal comfort in passenger car under actual outdoor driving conditions.
- Evaluated the non-uniform and unsteady thermal environment in the car.
- Found good correlation between the mean skin temperature and mean thermal sensation.

ABSTRACT

It is essential to quickly provide an acceptable comfort level in a car by automobile manufacturers during short commutes. Many previous thermal comfort tests for passenger cars were performed in laboratories or under parking conditions, where the thermo-fluid conditions and the driver's perception of thermal comfort may not have been the same as those under outdoor driving conditions. This study conducted tests under outdoor driving conditions, measuring the outside weather conditions, the air and surface temperatures inside a car, and the skin temperatures and thermal sensation votes of the driver under summer conditions. The results show that the air and surface temperatures in the car were non-uniform and decreased rapidly in the first 15 minutes after the air-conditioning system was switched on. In addition, the thermal comfort conditions in the car did not reach a steady state after two hours. Thus, a thermal comfort study in a car should be conducted under transient conditions. Reasonably good correlation existed between the mean skin temperature and mean thermal sensation. This study also found that the thermal sensation of the driver under outdoor driving conditions was different from that when the vehicle was parked.

Keywords: Non-uniform, Transient, Vehicle thermal comfort; Vehicle thermal environment; Subject test

1. Introduction

Increasing numbers of people in China are using passenger cars for commuting. It is essential to quickly provide an acceptable comfort level inside cars during short commutes so that drivers will be more focused and alert [1]. A comfortable thermal environment can also alleviate fatigue, reduce irritability, and improve driving safety [2]. Many studies have used standard EN ISO 14505 [3-5] from Europe and ASHRAE Standard 55 (2013) [6] from the United States to evaluate thermal comfort inside a car. These two standards employ predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) [3] or Standard equivalent temperature (SET) [4] to evaluate the thermal environment in a car. However, the two standards were intended for buildings, where the thermal environment is steady and uniform. Since the thermal environment in a car can change rapidly, the above standards may not provide objective evaluations of the thermal comfort level in this space.

The thermal environment inside a car is affected by a number of parameters, such as air supply temperature, flow rate, velocity, and direction from the air-conditioning system; enclosure surface temperatures; the intensity and incidence angle of direct, diffusive, and reflected solar radiation; clothing level; etc. [7]. When a driver turns on the air-conditioning system, the interior temperature and relative humidity change rapidly. Because of the confined and complex shape of the space in a car, the air distribution can also be highly non-uniform and transient. In addition, the driver must pay close attention to operating the vehicle. All of these conditions cause differences between the indoor environment in a car and in a building, which may lead to differences in psychological and physiological conditions between a driver and a building occupant. Thus, the key to achieving an acceptable thermal comfort level in a car is to understand the thermal environment, human thermoregulation, and perception of thermal comfort in the car environment.

Early studies focused on the environmental parameters in the car cabin. The effects of environmental conditions on thermal comfort were investigated by Burch et al. [8, 9]. Their experiment looked at the thermal comfort conditions in an automobile in a very cold winter season. They measured the changes in the air temperature inside the cabin and the temperatures of the solid surfaces contacting the human body during a standard heating process on a very cold day (-20^{o}C). The effects of heat loss from the body by conduction, convection and radiation on the thermal sensation (TS) were investigated. However, the heat loss from other body segments and their skin temperatures were not considered in these studies. Guan et al. [10] examined human thermal comfort experimentally under highly transient conditions in an automobile. They used an environmental chamber to simulate 16 typical sets of winter and summer conditions. Thermal sensation modeling was discussed in their companion paper [11]. Their mathematical model combined physiological and psychological factors, and both environmental and personal parameters were used as inputs to determine the physiological responses.

A number of other researchers have considered the effect of skin temperature on thermal sensation and thermal comfort. For example, Taniguchi et al. [12] studied effects of cold air on facial skin temperature in an environmental chamber, and [13] concluded that facial skin temperature and its rate of change could be used to predict thermal sensation. Zhang [14, 15] studied the vehicle cooling system. Most of their tests were carried out under typical summer conditions, and the subjects were engineers. Those subjects were fully aware of what the investigators were looking for, and this knowledge may have influenced their responses to the questionnaire [16]. Kilic and Akyol [17-19] investigated the effects of air intake settings (recirculation or fresh air) on thermal comfort under outdoor parking conditions. Their investigation found that the whole-body thermal sensation depended on local perceptions under highly transient and non-uniform environmental conditions. Zhang [20] investigated the environmental parameters inside and outside a parked vehicle for almost one year with four subjects. The study found that PMV can accurately predict thermal sensation in a car.

Most thermal comfort tests for passenger cars have been carried out in laboratories or outdoor parking conditions; few of them have been conducted under driving conditions [21-23]. Therefore, an objective evaluation of thermal comfort needs to be performed under realistic driving conditions. de Dear [24] expressed a number of reservations about the validity of the climatic chamber approach proposed by P.O. Fanger [25] and about the subsequent models. The first reservation related to the approach of judging thermal sensation by means of unnatural laboratory-type research.

The objective of this investigation was to conduct human subject tests for thermal comfort in a passenger car under driving conditions. As a comparison, the tests were also carried out under indoor and outdoor parking conditions. Our aim was to compare the results that were obtained under actual driving conditions with results from earlier studies of thermal comfort that were performed in a climatic chamber and under outdoor parking conditions. This paper reports our findings.

2. Research Method

To investigate human thermal comfort in cars, this study conducted human subject tests in actual vehicles. This section first analyzes the heat exchange between a human body and its surroundings in a vehicle to provide a theoretical basis for the subject tests. Next, the research design, experimental procedure, and studied parameters of the subject test are presented.

2.1 Heat exchange between a human body and its surroundings in a vehicle

The heat exchange between a human body and its surroundings in a car, as shown in Fig. 1, is more complex than the heat exchange that occurs inside a building. The use of automotive air conditioners and the impact of dynamic weather make the interior thermal environment of car non-uniform and transient [26, 27]. Therefore, before we present the details of the subject test, it is necessary to provide an analysis of the heat exchange in a vehicle. The heat transfer between a human body and its surroundings (Q_{sk}) consists of four parts, as expressed by Equation (1) [28-30]:

$$Q_{sk} = Q_{cv} + Q_{cd} + Q_r + E_{sk} \tag{1}$$

where Q_{cv} is convective heat transfer, Q_r radiative heat transfer, Q_{cd} conductive heat transfer, and E_{sk} evaporative heat transfer. Compared with a human body in an indoor environment, the human body under actual driving conditions may exchanges more heat by radiation [31-32] and conduction [8] in the case of intensive outdoor solar radiation. While a portion of solar radiation is reflected, the remaining solar heat enters the cabin either by transmission or absorption. The absorbed solar radiation enhances the long-wave radiative heat transfer on the human body by increasing the cabin surface temperature, while the transmitted short-wave radiation is directly received by the occupant. In addition, in an automobile, a significant portion (15–20%) of the body surface area is in contact with the seat, back support, and steering wheel [8, 9]. This portion of the body surface exchanges heat with the contacted surfaces by conduction.

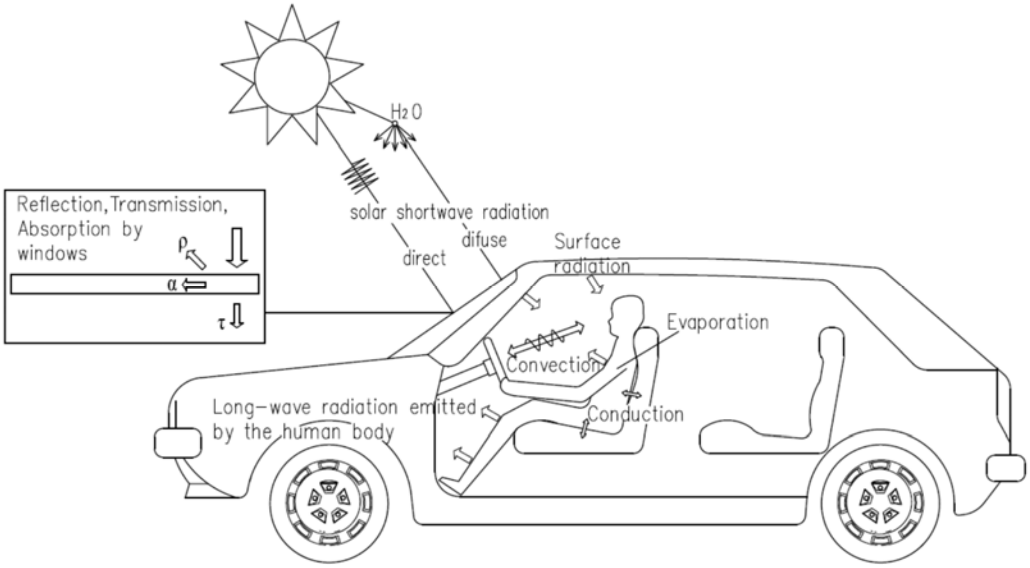


Fig. 1. Heat transfer between a human body and its surroundings in a car.

In addition to radiation, conduction and evaporation, an important form of heat transfer between a human body and its surroundings is convection. The level of convection depends on the air velocity and the temperature difference between the human surface and the air [35]. In an automobile, because the air inlets are close to the driver, an operating air conditioning system creates heterogeneous air temperature around the driver. Thus, the level of convection varies among body segments. Furthermore, conduction only occurs at several parts of the human body. Meanwhile, because of the directionality of direct short-wave solar radiation, this radiation is only received by certain body segments. The non-uniformity of direct short-wave solar radiation also leads to differences in interior surface temperature, which create a non-uniform long-wave radiation field around the human body in a vehicle.

2.2 Experimental design

The thermal environment and the state of the occupants inside an actual commuting passenger vehicle are significantly different from those in a parked car. In addition, whether a car is parked in a garage or exposed to the outdoor sun and wind can greatly influence the thermal environment in the vehicle cabin. Therefore, we conducted tests under three sets of conditions: (1) indoor parking conditions with relatively stable outside thermal environment, and subjects in sedentary states in the car; (2) outdoor parking conditions with transient but not rapidly changing outside thermal environment, and subjects in sedentary states in the car; (3) outdoor driving conditions with rapid change in inside and outside thermal environments caused by driving direction and changes in speed, and subjects engaged in real driving activities who must pay attention to road conditions. Our main emphasis was on the outdoor driving conditions, and the tests in indoor and outdoor parking conditions were conducted for the purpose of comparison.

Since the high outdoor air temperature and intense solar radiation in summer may cause great thermal discomfort to vehicle occupants, this investigation focused on summer conditions. To cover a wider range of environments, the test was conducted six or seven times for each of the three sets of conditions. In total, this study conducted 19 tests, where Tests 1-6 were conducted under indoor parking conditions, Tests 7-13 under outdoor parking conditions, and Tests 14-19 under outdoor driving conditions. The outdoor air temperatures under the outdoor parking and driving conditions were above 30°C.

According to EN ISO 14505-3 [5], at least eight subjects should be used to evaluate thermal comfort in a vehicle. Following the recommendation, this study recruited 16 subjects (8 males and 8 females) to assess thermal comfort in a car. They were residents of a subtropical region. Some of them had driving experience of five years or more. Each subject participated in the tests two times under different conditions. All the subjects were paid for their participation in the research. Eight subjects (two males and six females) with an average age of 33 (standard deviation = 9) participated in the tests under indoor parking conditions (Tests 1-6), 14 subjects (six males and eight females) with an average age of 34 (standard deviation = 10) took part in the tests under outdoor parking conditions (Tests 7-13), and ten subjects (eight males and two females) with an average age of 34 (standard deviation = 11) participated in the tests under driving conditions (Tests 14-19). In six of the 19 tests, only one subject sat in the driver's seat, and in the remainder of the tests, two subjects sat in the driver's seat and in the front passenger seat, respectively. In the tests under outdoor driving conditions, the subject who sat in the driver's seat actually drove the car.

2.3 Experimental procedure

The subject tests were conducted in a Nissan Tiida passenger car (2014 model) from July 17, 2017, to September 14, 2017, in Tianjin, China. In each test, one or two subjects were seated in the front seat(s) of the car. Before the start of each test, the car was parked under indoor or outdoor conditions to reach a thermal state that was in equilibrium with the surroundings.

Before the subjects entered the vehicle, they were taken to a preparation room with an ambient temperature close to the neutral level (26°C) and remained in the room for 30 minutes to achieve a neutral thermal state. During their stay in the room, all the subjects gave consent prior to their participation in the experiment and were briefed on both the withdrawal criteria and the experimental procedure. When the subject(s) entered the car, the air-conditioning system was turned on immediately to cool the interior space using the recirculation mode. The subjects stayed in the car for two hours. Since 85% of trips are between 15 and 30 min in duration [37], a two-hour test not only allowed us to capture the transient features of the thermal environment and thermal comfort in the car during typical short commutes, but also enabled us to study thermal comfort during long-distance trips.

To avoid the effect of drafts on subjects' judgment about thermal comfort, the fan speed was set at the medium level with an airflow rate of 0.12 m^3/s. The cabin air temperature was set at 26°C, that is, the temperature value of the return air should be up to 26°C by using the control logic of the car air conditioner. The supplied air was directed toward the face(s) of the subject(s) for cooling purposes [33].

2.4 Parameters collected

Fig. 2 illustrates the procedure for our study of thermal comfort and the parameters collected in this investigation. The thermal environment outside the vehicle and the cabin air conditioning system influence the thermal environment inside the vehicle cabin. Heat exchange between the human body and the cabin thermal environment results in a certain skin temperature level. The thermoreceptors in the skin perceive the skin temperature and send a signal to the brain, which interprets the signal as the thermal comfort level.

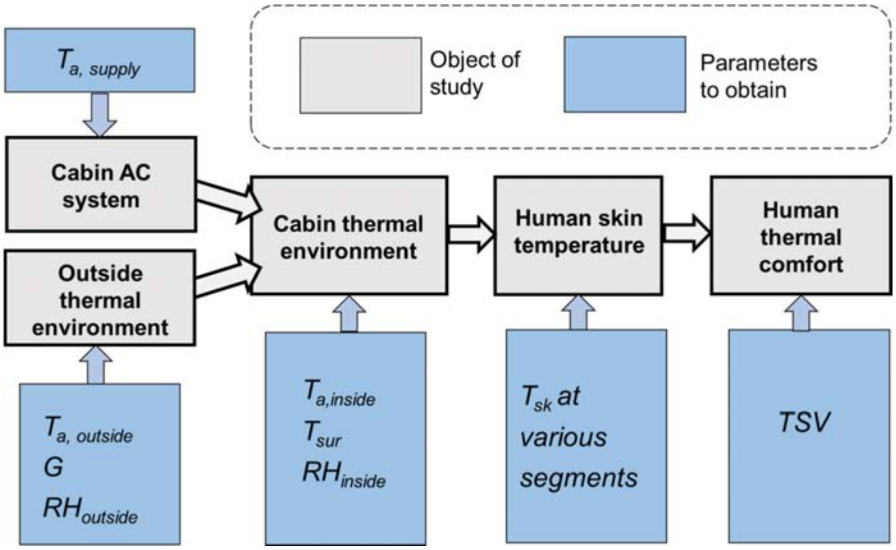


Fig. 2. Flow chart for studying human thermal comfort in vehicles and the parameters collected for the study. ($T_{a, supply}$ = supply air temperatures, $T_{a, outside}$ = outdoor air temperature, G = total radiation, $RH_{outside}$ = outdoor relative humidity, $T_{a, inside}$ = indoor ambient air temperature, T_{sur} = surface temperature, RH_{inside} = indoor relative humidity, T_{sk} = skin temperature, TSV = thermal sensation vote.)

To study human thermal comfort in automobiles as shown Fig. 2, we needed to measure parameters for analysis of the impact of cabin thermal environment on thermal comfort. Sensors were installed on the top of the car to collect outside air temperature, relative humidity, wind speed, and horizontal solar irradiance data for the outside thermal environment. A radiation shield (with a sensor type RS3) was used to protect the air temperature and humidity sensor and ensure measurement accuracy. The wind resistance of RS3 can withstand a sustained wind speed of 80 km/h and a gust of 161 km/h. This study measured the supply air temperature of the air conditioning system because it affects the air temperature distribution in the cabin.

As demonstrated in Section 2.1, it was necessary to measure the air and surface temperatures surrounding the human body in the vehicle. This was achieved with the use of 17 thermocouples, as shown in Fig. 3(a). Thermocouples #1-#9 measured the interior air temperature, #10-#13 the surface temperatures in the car, and #14-#17 the temperatures of the surfaces contacting the human body. Following the recommendations in DIN 1946-3 [36], temperatures #3 and #4 were those of the lower legs/feet of the driver and passenger, respectively, and #5 and #6 were those of the heads of the driver and passenger, respectively. Temperature #1 was at face level, #2 at lower arm level, and #7 to #9 at upper arm level, so that the variation in air temperature between the human body and the surrounding environment could be determined. Temperature #10 was the windshield surface temperature, #11 the dashboard surface temperature, #12 the surface temperature of the driver's-side window, and #13 the ceiling surface temperature, as indicator of non-uniform long-wave radiation between the human body and the surroundings. Temperatures #14-#17 were those of the seat and back of the driver and passenger seats, which were in contact with human bodies. In addition to these air and surface temperatures, the outlet air velocity, V_a, and the relative humidity, RH, in the cabin were monitored.

To study the impact of cabin thermal environment on a human body, we used 10 thermocouples to measure skin temperature on different body parts of the subjects as shown in Fig. 3(b). The thermocouples were connected to a portable data logger. Table 1 provides the specifications of the instruments used in the subject tests.

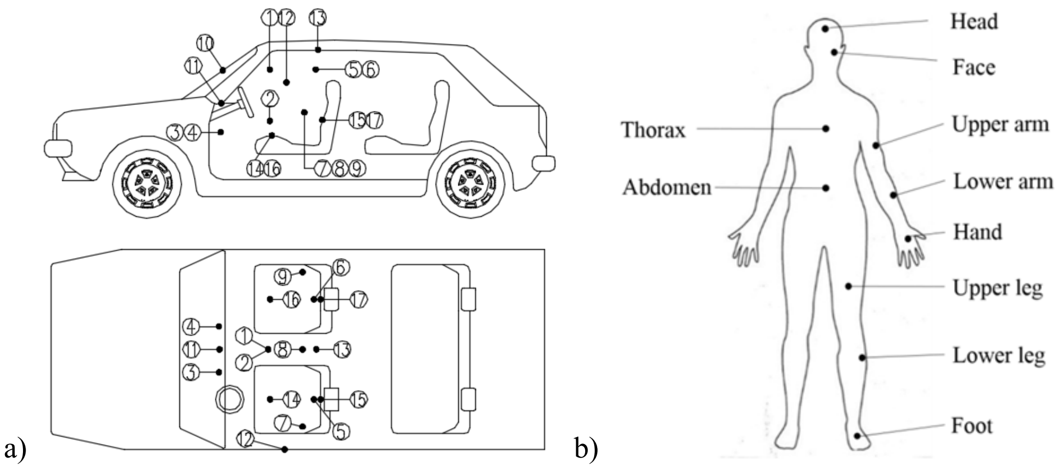


Fig. 3. Measurement positions of the thermocouples in the experiment: a) for interior air temperatures around the subjects (#1-#9) and for interior surface temperatures (#10-#17) and b) for skin temperatures of subjects.

Table1. Technical specifications of the sensors used to measure inside and outside environmental parameters and skin temperatures.

Parameter	Sensor type	Range	Accuracy	Measuring frequency
V_a, outside	S-WSET-A	0 to 45 m/s	±1.1 m/s	1 min.
G, outside	S-LIB-M003	0 to 1280 W/m^2	±10 W/m^2 or ±5%	1 min.
T_a, outside	S-THB-M002	-40 to 75°C	±0.2 K at 20°C	1 min.
RH, outside	S-THB-M002	0 to 100%	±3%	1 min.
T_{sk}	TT-K-30-SLE	0 to 350°C	±1.1°C or ±0.4%	1 sec.
T_a, inside	TT-K-30-SLE	0 to 350°C	±1.1°C or ±0.4%	1 sec.
RH, inside	HOBO U12	5 to 95%	±2.5% from 10 to 90%	1 min.
V_a, inside	AirDistSys 5000	0.05 to 5 m/s	±0.02 m/s ±1%	1 sec.
T_{sur}, inside	TT-K-30-SLE	0 to 350°C	±1.1°C or ±0.4%	1 sec.

In addition to our measurement of environmental parameters and skin temperature, the subjects voted for their thermal sensations by using the ASHRAE seven-point scale (−3 = cold, −2 = cool, −1 = slightly cool, 0 = neutral, 1 = slightly warm, 2 = warm, and 3 = hot). Typical summer clothing, which is a combination of short sleeve, shorts, underwear, socks and sneaker, with a clothing thermal resistance of 0.56clo. The subjects voted every minute during the first five minutes, and then every five minutes thereafter for the two-hour measurement period. The subjects were asked to report their personal information, including sex, age, health condition, and clothing, before the start of the experiment.

3. Results

This section first shows the outside environmental parameters of the 19 tests. Next, we analyze the supply air temperatures, the air temperatures around the subject, and the surface temperatures in the vehicle under different conditions to demonstrate the transient and non-uniform thermal conditions in the vehicle. Finally, the results for skin temperature and thermal sensation are presented.

3.1 Outside environmental parameters

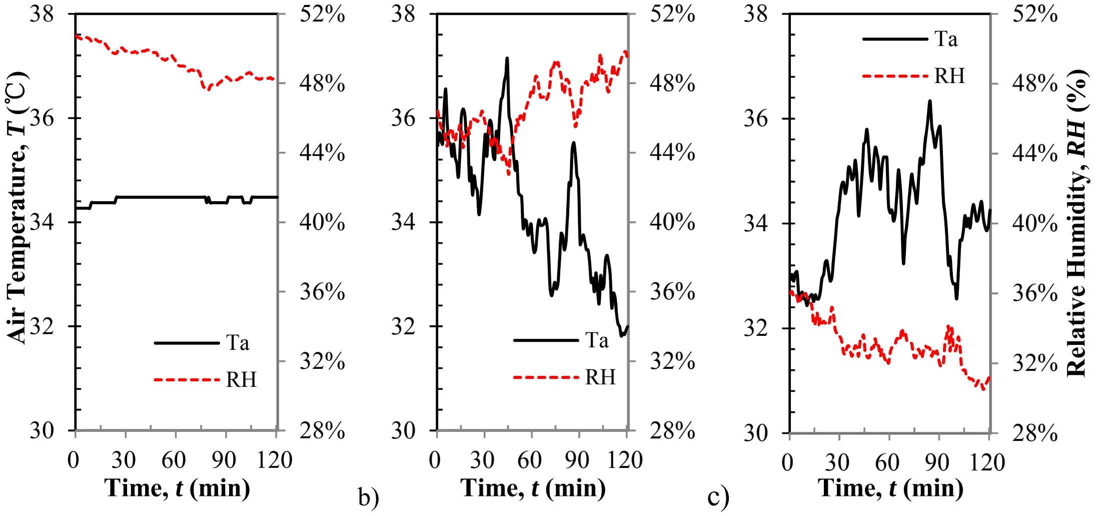
Table 2 shows the outside environmental parameters, in each case using the mean and standard deviation to represent the changes in the meteorological data during the experiment. The average outside air temperature for indoor parking conditions (Tests 1 to 6) was 30.3°C; for outdoor parking conditions (Tests 7 to 13) it was 32.4°C; and for outdoor driving conditions (Tests 14 to 19) it was 33.7°C. The average solar intensities were 0, 273.5, and 342.8 W/m^2, respectively, and the average relative humidity levels were 60.6%, 61.4%, and 46.7%, respectively.

The environmental parameters outside the vehicle were virtually unchanged under the indoor parking conditions during the two-hour experimental period. In contrast under outdoor conditions, the solar radiation intensity changed greatly, mainly because of the overcast sky.

Table2. Outside environmental parameters (numbers in parentheses are standard deviations) for the tests.

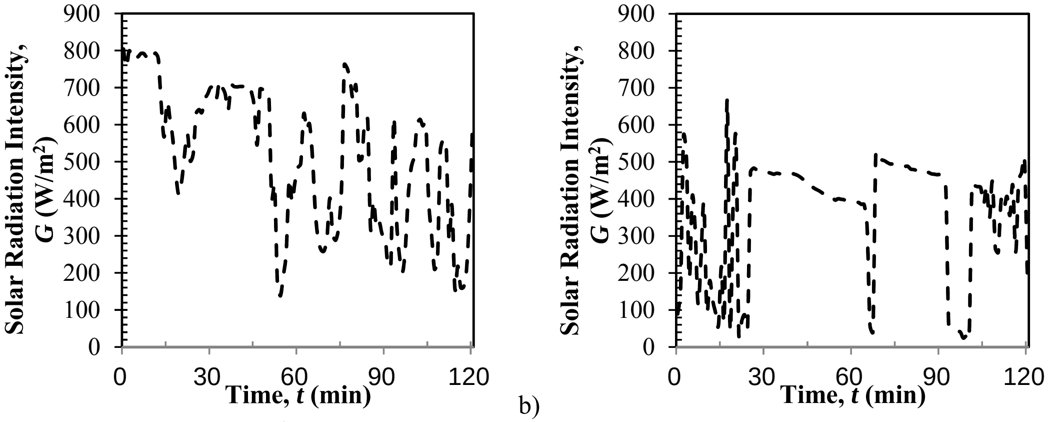
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18	Test 19
Number of subjects	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	1	2	1	2
Average outside air temperature (°C)	27.6 (0.1)	27.9 (0.1)	34.4 (0.1)	31.3 (0.1)	29.8 (0.0)	30.6 (0.0)	34.1 (0.6)	31.4 (1.5)	31.0 (0.5)	31.9 (1.2)	31.5 (0.6)	34.3 (1.3)	32.3 (0.9)	32.3 (1.3)	34.6 (0.7)	34.2 (1.0)	34.9 (0.6)	33.4 (1.2)	33.3 (0.6)
Average solar intensity (W/m^2)	0.0	0.0	0.0	0.0	0.0	0.0	462.9 (135)	191.7 (163)	240.7 (66.7)	247.1 (147)	112.3 (36.3)	518.9 (193.0)	141.1 (46.6)	210.8 (116.8)	319.2 (190.1)	361.4 (161.0)	503.8 (182.4)	213.1 (127.7)	474.4 (130.3)
Average relative humidity (%)	77.8 (0.4)	77.5 (0.4)	49.2 (0.9)	55.8 (0.3)	55.8 (0.3)	56.3 (0.3)	58.3 (0.9)	81.2 (4.4)	65.1 (0.86)	64.2 (3.0)	64.5 (1.3)	46.7 (1.7)	49.8 (1.8)	46.8 (1.4)	59.6 (1.7)	33.1 (1.4)	38.1 (3.2)	49.6 (2.9)	50.0 (1.1)

To further analyze the outside thermal environment, we selected three typical tests (Tests 3, 12, and 16) under indoor parking, outdoor parking, and driving conditions, respectively. These three tests had almost the same outside temperature (34.3±0.1°C). It can be seen in Fig. 4 that under the indoor parking conditions, the variations in the environmental parameters outside the vehicle were very small, whereas under the other two sets of conditions, the environmental parameters outside the vehicle changed significantly, especially the solar radiation intensity as shown in Fig. 5.



a) b) c)

Fig. 4. Outside air temperature (° C) and relative humidity (%) measured during a) Test 3 (indoor parking), b) Test 12 (outdoor parking), and c) Test 16 (outdoor driving)



a) b)

Fig. 5. Solar intensity (W/m^2) measured during a) Test 12 (outdoor parking) and b) Test 16 (outdoor driving)

3.2 Supply air temperatures

Fig. 6 depicts the temperature of the supply air from the air-conditioning system for the three typical tests (Tests 3, 12, and 16) under the indoor parking, outdoor parking, and driving conditions, respectively. The supply air temperature decreased rapidly in the first 15 minutes after the air-conditioning system was switched on. The supply air temperature in Test-3 decreased from 33.0ºC to 12.3ºC, in Test 12 from 51.7ºC to 13.5ºC, and in Test 16 from 41.7ºC to 10.7ºC. Since the outside air temperature was almost the same in the three tests, the differences in initial supply air temperature were due to solar radiation on the car. The supply air temperature stabilized at about 10ºC after 40 minutes and then remained the same until the end of each test. The changes in the supply air temperatures during the first 15 minutes were dramatic. As a result, more attention should be paid to dynamic thermal comfort and thermal sensation during this period, especially for short commutes. This result was consistent with that given in [34].

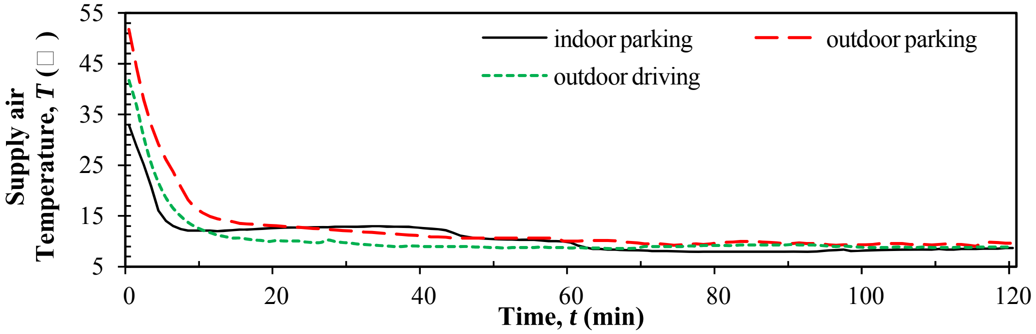
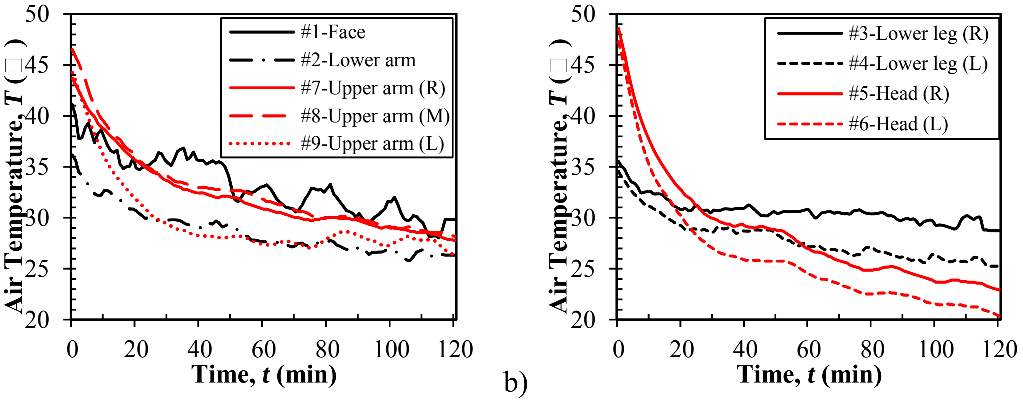


Fig. 6. Supply air temperatures from the air-conditioning outlets of the car for the three typical tests

3.3 Interior air temperature distribution around the subject

Fig. 7 shows the air temperatures around the tested subject at nine locations. Taking Test 12 as an example under outdoor parking conditions, the air temperatures around the subject decreased after the air-conditioning system was turned on. The change in air temperature occurred in two stages: (i) rapid change in the first 30 minutes and (ii) slow decrease afterwards. The air temperatures did not reach a steady state, even after two hours. Note that the air temperatures near the face (#1) and lower arm (#2) were also affected by outdoor solar radiation, as evidenced by their fluctuation.



a) b)

Fig. 7. Air temperature distribution inside the car measured during Test 12: a) in the horizontal direction and b) in the vertical direction.

According to Fig. 7, the air temperature around the subject was highly non-uniform. For the driver, the air temperature difference between the head and calf was 13.1°C at the beginning of the test and -5.8°C at the end, while the difference between the left and right arms was 2.8°C at the beginning and 0.4°C at the end. For the passenger, meanwhile, the air temperature difference between the head and calf was 12.8°C at the beginning of the test and -4.9°C at the end, and that between the left and right arms was -0.5°C at the beginning and 1.3°C at the end. Their exposure to solar radiation was also highly non-uniform. In Test 12, the average radiation on the subject's face was 259.5 W/m^2, and it may have been zero on the lower part of the body, which were not exposed to solar radiation due to the occlusion of the vehicle and other body segments.

The air temperature distributions around the subject in other tests exhibited a similar inhomogeneous trend as that in Test 12. Table 3 lists the maximum vertical and horizontal temperature differences under various conditions at t = 0, 5, 10, 15, and 120 min. The differences were small under the indoor parking conditions because of the absence of solar radiation. As can be seen from Fig. 7 and Table 3, the temperature difference at the horizontal direction and the vertical direction were more than 6 ºC in the car during outdoor conditions, the subjects in the car experienced a non-uniform and asymmetrical air temperature compared with building occupants.

Table 3. Maximum changes in vertical and horizontal temperature differences measured under various conditions (ºC)

	Indoor Parking		Outdoor Parking		Outdoor Driving	
	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
t = 0 min	-0.1	0.4	9.2	2.1	5.2	-6.0
t = 5 min	-0.4	0.5	4.0	0.3	2.6	-6.8
t = 10 min	-0.4	0.1	-0.1	-1.3	-0.4	-7.3
t = 15 min	-0.5	0.2	-3.3	-2.2	-2.2	-6.1
t = 120 min	-4.3	-1.7	-12.6	-3.1	-7.0	-3.2

3.4 Interior surface temperatures

Fig. 8 illustrates the interior surface temperature distributions for the three typical examples. Under the indoor parking conditions, the air temperature and radiation outside the car exhibited negligible changes, which could correspond to changes in the lab environment. The temperatures of the interior surfaces exposed to air changed with the air temperature, but the changes were less than that of the air temperature because of interior surfaces' thermal mass. Under the outdoor parking conditions, the decreasing trends of the surface temperatures were the same as the trend for indoor parking conditions, but solar radiation caused small temperature variations. Under driving conditions, the rapid change in solar radiation led to large temperature variations on the interior surfaces exposed to the sun. In all three cases, the temperatures of the surfaces in direct contact with the subject's body (the seat cushion and back) were almost unchanged because of heat conduction.

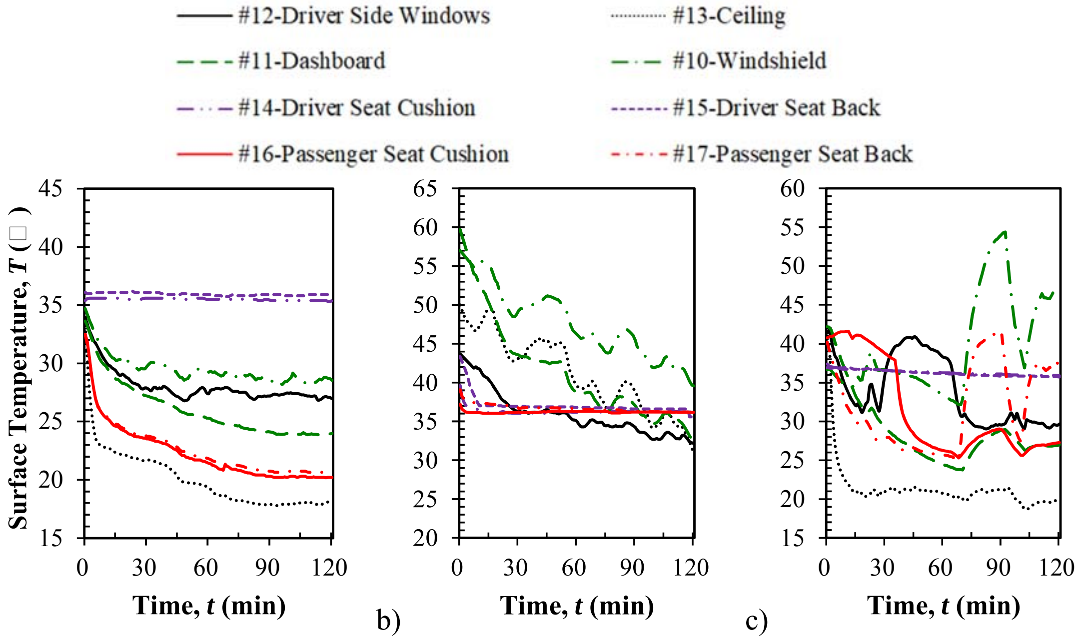


Fig. 8. Measured interior surface temperatures of the car during a) Test 3 (indoor parking), b) Test 12 (outdoor parking), and c) Test 16 (outdoor driving)

3.5 Mean skin temperature (MST) and thermal sensation vote (TSV)

According to our analysis of the subjects and the environment inside the car, the subjects experienced non-uniform and transient heat transfer conditions. Calculation of the heat transfer of the subjects should include different body segments. The two most commonly used thermal sensation models, the PMV model (Fanger 1970) and Standard equivalent temperature (SET) (Gagge, Stolwijk et al. 1972) [39], consider only uniform, steady-state conditions. They are not applicable to the environment in a car with transient, spatially non-uniform, and asymmetrical conditions. Therefore, we investigated the possibility of using mean skin temperature to evaluate thermal sensation in a car.

ISO 9886 [40] provides two formulas for calculating MST in warm/hot environment and in neutral/cold environment. For warm or hot environment, the MST is calculated as:

$$MST_1 = 0.28T_{neck} + 0.28T_{shoulder} + 0.16T_{hand} + 0.28T_{lower\ leg} \tag{2}$$

MST_1 is the mean skin temperature applying in warm or hot conditions. T_{neck}, $T_{shoulder}$, T_{hand}, and $T_{lower\ leg}$ are the skin temperature at the neck, shoulder, back of the hand and calf, respectively.

$$\begin{aligned} MST_2 = {} & 0.07T_{forehead} + 0.175T_{should} + 0.175T_{chest} + 0.07T_{upper\ arm} + 0.07T_{lower\ arm} \\ & + 0.05T_{hand} + 0.19T_{upper\ leg} + 0.2T_{lower\ leg} \end{aligned} \tag{3}$$

MST_2 is the mean skin temperature applying in conditions close to thermal neutrality and in cold environments. $T_{forehead}$, $T_{shoulder}$, T_{chest}, $T_{upper\ arm}$, $T_{lower\ arm}$, T_{hand}, $T_{upper\ leg}$ and $T_{lower\ leg}$ are the skin temperature at the forehead, shoulder, chest, upper arm, lower arm, back of the hand, upper leg and calf, respectively.

However, the environment inside the car is significantly non-uniform, the radiation is asymmetrical. Since there is no consensus on the specific weights for the sensitive parts, using area weighted values is a safe measure to consider the local skin temperature differences caused by non-uniform thermal environment. Thus, mean skin temperature (MST) is an area-weighted value, i.e.

$$MST = \int T_{sk} dA_{sk} / A_{Du} \tag{4}$$

where T_{sk} is the local skin temperature, dA_{sk} the corresponding local surface area on a body element of the human, and A_{Du} the Dubois area of the human, which is 1.86 m^2.

Fig. 9(a), (b) and (c) show that the mean skin temperatures of the subjects in the three tests decreased over time after the air-conditioning system was switched on. The change rate of the mean skin temperature under outdoor parking condition was the smallest, and for indoor parking conditions it was the largest. When coming to the change rate of TSV, the drop of TSV is 4.5 unit scale for the indoor parking condition, while the number is 2 unit scale for the outdoor parking condition, and 2.5 unit scale for the outdoor driving condition. This is because the solar radiation (an average of 518.9 W/m2 for outdoor parking conditions, 361.4 W/m2 for outdoor driving conditions, and 0 for indoor parking conditions) played a very important role in warming up the body. Fig. 9(d), (e), and (f) depict reasonably good correlations between the MST and the TSV, with $R^2 = 0.84$, 0.48, and 0.51 for the three cases, respectively. This suggests that the MST could be used to evaluate the TSV. However, the correlations for the outdoor parking and outdoor driving conditions are not high. The rapid change in solar radiation in the two cases would contribute to thermal sensation, but it was not reflected by the MST.

Fig. 10 shows the relationship between the subjects' TSV and the average skin temperature in all the tests under summer conditions. The green triangles represent TSVs under indoor parking conditions, mainly between -2 and 1. Several votes were for “warm sensation,” and were provided by subjects when they entered the car and the interior air temperature was still high. The blue diamonds represent TSVs under outdoor parking conditions, primarily between -2 and 3. The red squares represent TSVs under outdoor driving conditions, mainly between -1 and 3.

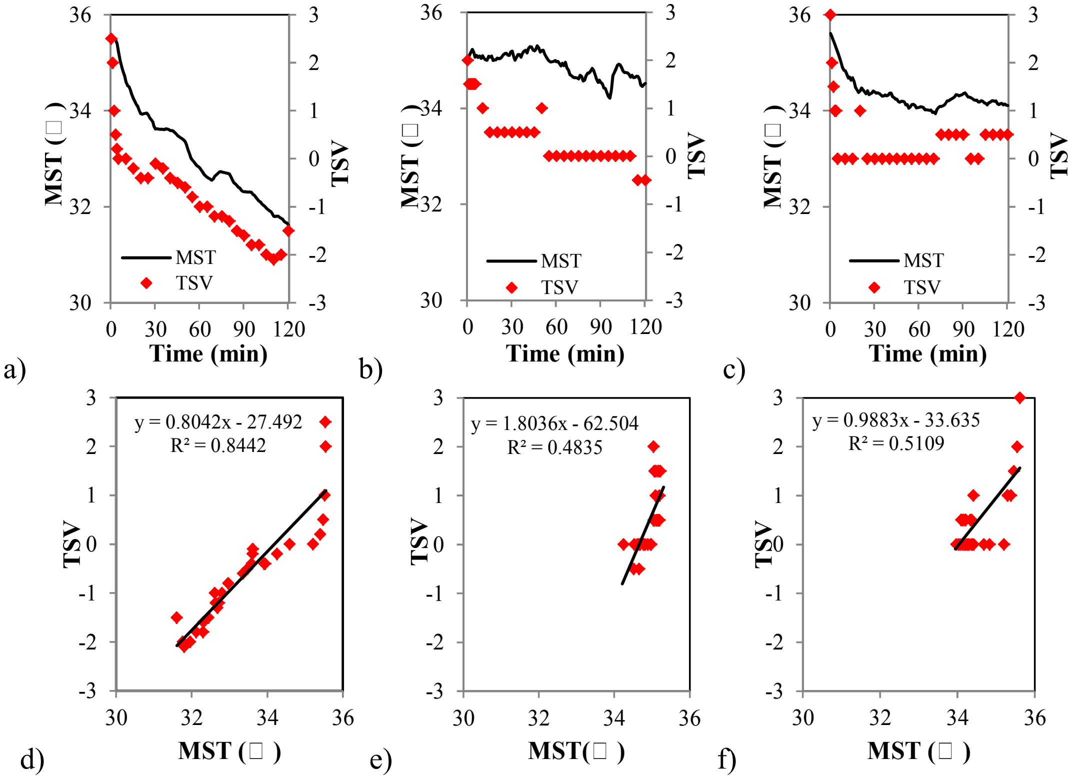


Fig. 9. MST and TSV changes over time obtained during a) Test 3, b) Test 12, and c) Test 16, and the correlation between MST and TSV for d) Test 3, e) Test 12, and f) Test in16.

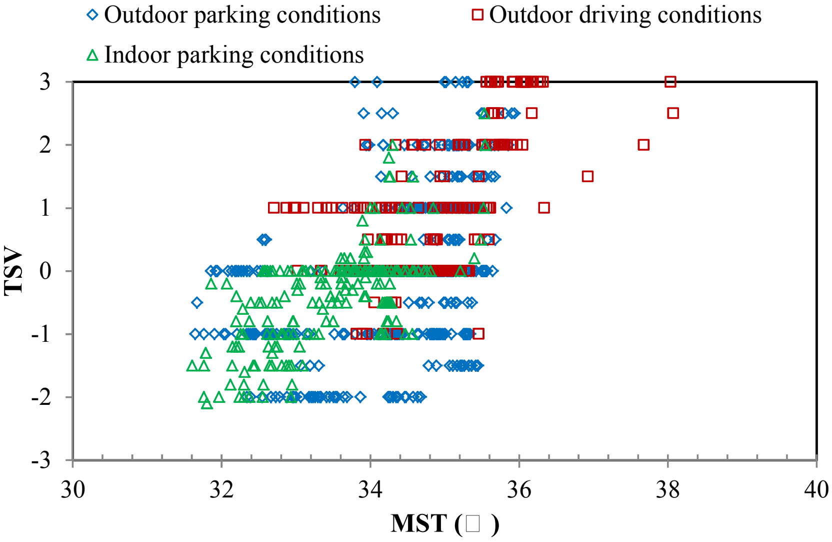


Fig. 10. Scatter plot of relationship between MST and TSV found in the tests.

The data in Fig. 10 also shows that the MST and TSV varied significantly because of individual differences. For different subjects with the same skin temperature, the thermal sensations given were quite different. The initial MST and corresponding initial thermal sensation may have influenced the variation. For example, in Fig. 9(a), the subject in Test 3 had an initial MST of 35.5 and an initial TSV of 2.5. In contrast, in Fig. 9(c) the subject in Test 16 had an initial MST of 35.6 and an initial TSV of 3.

To reduce the influence of initial skin temperature on thermal sensation, we calculated the arithmetic averages of TSV and MST, namely, $\overline{\text{TSV}}$ and $\overline{\text{MST}}$, as shown in Fig. 11. The correlations in Fig. 11 (d) to (f) are better than those in Fig. 9 (d) to (f).

The first three plots in Fig 11 clearly show that the first 30 minutes of MST & TSV is quite different from the latter 90 minutes. In the first 30 minutes, with the operation of the car air conditioning system, the air temperature and surface temperature in the car changed drastically, which led to a sharp drop in TSV. The $\overline{\text{TSV}}$ had dropped from 0.94 to -0.17 for the indoor parking condition, from 2.13 to -0.22 for the outdoor parking condition, from 2.81 to 0.69 for the outdoor driving condition during the first 30 minutes. While during the next 90 minutes, for the indoor condition without solar radiation, the $\overline{\text{TSV}}$ dropped from -0.17 to -1.08, with a reduction of 0.9 units; for the outdoor conditions with solar radiation, the decreases in air temperature and surface temperature were small compared to the first 30 minutes, and the $\overline{\text{TSV}}$ fluctuated within a small range. The $\overline{\text{TSV}}$ dropped from -0.22 to -0.63 for the outdoor parking condition, and from 0.69 to 0.16 for the outdoor driving condition, with a reduction of 0.4-0.5 units.

The three typical examples for different conditions each had a slope (d (TSV)/d (MST)) that was similar to the average of their corresponding conditions. It is interesting that the slopes in Figs. 9 and 11 were similar. The slopes were 0.80 for Test 3 and 0.84 for the average indoor parking conditions; 1.80 for Test 12 and 1.76 for the average outdoor parking conditions; and 0.99 for Test 16 and 1.13 for the average outdoor driving conditions.

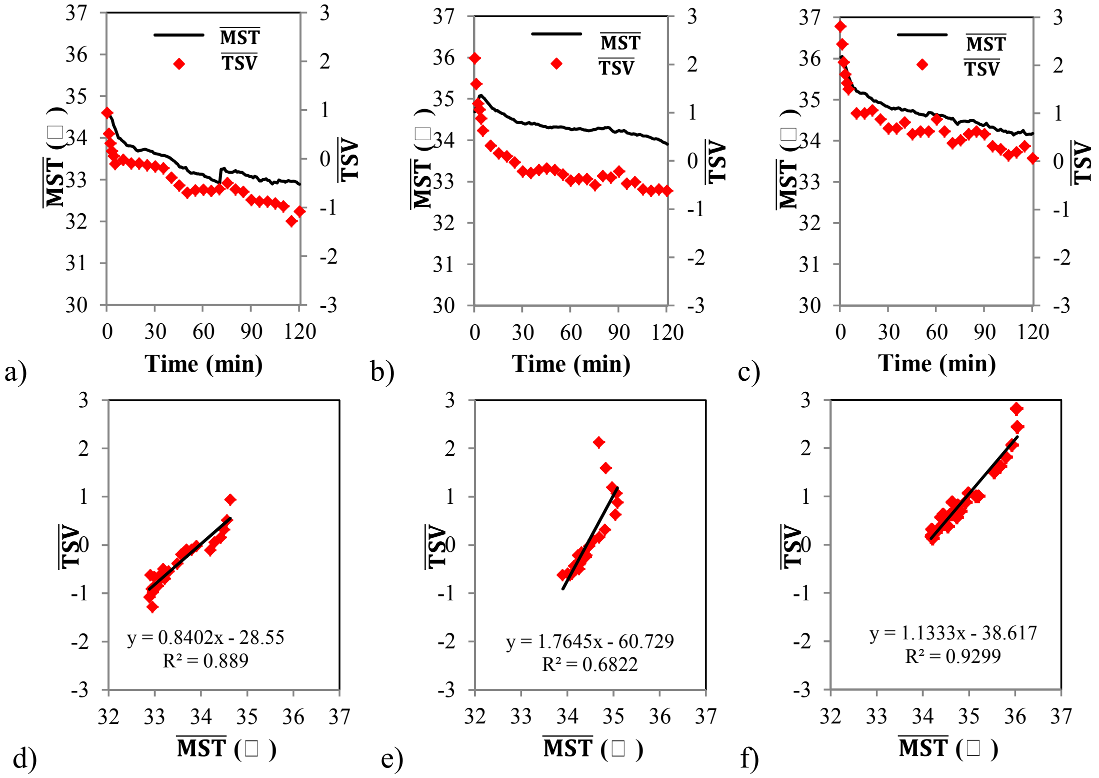


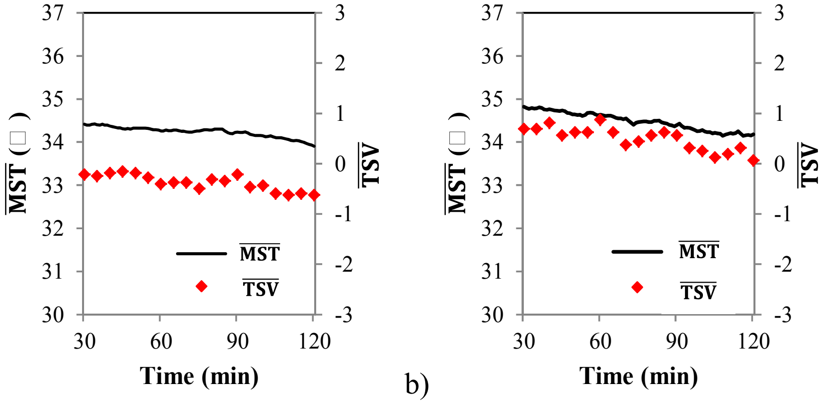
Fig. 11. Changes in $\overline{\text{MST}}$ and $\overline{\text{TSV}}$ over time during the tests for a) indoor parking, b) outdoor parking, and c) outdoor driving, and correlations between $\overline{\text{MST}}$ and $\overline{\text{TSV}}$ for d) indoor parking, e) outdoor parking, and f) outdoor driving.

It is also worth noting that the slope (d (TSV)/d (MST)) was larger for outdoor parking conditions than outdoor driving conditions, indicating that with the same level of change in mean skin temperature, the TSV of outdoor parking conditions had larger change than that of the outdoor driving conditions. It is possible that the subjects under outdoor driving conditions paid more attention to traffic conditions and thus were less sensitive to changes in mean skin temperature. As a result, the thermal sensations of the drivers under outdoor driving conditions were different from those under parking conditions. Evaluation of thermal comfort should therefore be performed separately for different sets of conditions.

4. Discussion

4.1 Influence of metabolic rate

Fig. 12 shows the changes in $\overline{\text{MST}}$ and $\overline{\text{TSV}}$ over time from t = 30min to t = 120min for outdoor conditions. We can see from Fig. 12, the mean $\overline{\text{TSV}}$ and standard deviation was -0.38 (0.15) for outdoor parking condition and 0.49 (0.23) for outdoor driving condition. Since $\overline{\text{MST}}$ for the outdoor parking and outdoor driving condition were nearly the same, $\overline{\text{TSV}}$ were -0.38 for the outdoor parking condition, while 0.49 for outdoor driving condition. This may be due to the influence of metabolic rate, because the metabolic rate is 1.2-1.7 met under driving conditions, and the metabolic rate is about 1.0 met under sitting conditions [41]. That is, when metabolic rate increases from 1.0 met to 1.2-1.7 met (1 met equals to 58.2 W/m^2), it can result in approximately 0.87 unit scale of TSV difference. Since human metabolism has been recognized as a basic and key indicator of thermal comfort prediction, we can't ignore the metabolic rate difference between the driving subjects and the sedentary subjects.



a) b)

Fig. 12. Changes in $\overline{\text{MST}}$ and $\overline{\text{TSV}}$ over time from t = 30min to t = 120min for a) outdoor parking, and b) outdoor driving condition.

4.2 Practical implications

The design of air conditioning system in vehicle is conducted on subjects in laboratory test under parking condition. From our results, the TSV under driving conditions is higher than the TSV under parking conditions, which could be caused by the difference in metabolic rate and in attention to real road conditions. So the thermal comfort needs found under laboratory parking conditions may underestimate the driver's requirements for the interior thermal environment.

4.3 Limitations and future challenges

The subject sample size was somewhat limited, and it did not encompass a wide variety of ages, weights, or other factors. Indraganti [42] found that thermal sensitivity changed with age, gender and economic group.

Our investigation primarily monitored the air temperature from the air diffusers in the car, the air temperature around the human body, the wall temperature, the outdoor weather parameters, and so on. We did not measure the flow field in the car or the relative humidity distribution around the subjects because it is not safe under driving conditions, whereas the German standard for automotive air-conditioning, DIN 1946-3 [36], recommends the measurement of the non-uniform air velocity distribution inside a car. We examined the impact of vapour pressure on thermal sensation but only minor influence was found. As a result, we did not elaborate more on vapour pressure.

We found that the relationship between mean skin temperature and TSV is not strictly linear as depicted in Fig, 9 and 11. This may be due to the effects of sweating, as sweating causes the skin temperature to drop while the corresponding TSV does not change. The sweating rate of the human body may be an important physiological parameter that influences thermal comfort under hot condition. But the difficulties in measuring it prevented us from studying its impact in this study. We used averaged values when correlating TSV and MST. Because the averaging process can reduce the uncertainties caused by differences among individual subjects, the R^2 may be overestimated.

The adaptive thermal comfort model [43, 44] suggests that comfortable temperature changes with the outdoor climate condition. Although the adaptive thermal comfort theory is based on data from free-running built environment, it is possible that it applies to vehicle thermal comfort as well, especially for transition season when air conditioning system is not commonly used in the cars. However, our experiment data was obtained only in summer in Tianjin, China. It is worthwhile to collect more field data of vehicle thermal comfort in other climate regions to test the validity of adaptive thermal comfort.

5. Conclusions

This study experimentally investigated thermal comfort in a passenger car under indoor parking, outdoor parking, and outdoor driving conditions in summer. The investigation collected a large amount of experimental data concerning outdoor environmental conditions, air and surface temperature distributions in the car, skin temperatures of the subjects in the car, and the subjects' thermal sensation votes. The study led to the following conclusions:

The interior air and surface temperatures in the car were transient and non-uniform. The changes in surface temperatures under outdoor driving conditions were greater than under the other two sets of conditions because of the rapid change in solar radiation.

A reasonably good correlation existed between the mean skin temperature of the subjects and their thermal sensation. Therefore, mean skin temperature is an important factor in determining the thermal comfort level in a car. Under indoor parking, outdoor parking, and outdoor driving conditions, the correlation coefficients were 0.89, 0.68, and 0.93, respectively. Subjects were found to be more thermally sensitive to the environment in the car under parking conditions than under driving conditions.

Due to limited space of this paper, we could not provide the details of the original data obtained. However, the authors would be happy to provide the data to readers upon their requests.

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References

[1] Norin F, Wyon DP. Driver vigilance—The effects of compartment temperature. SAE Technical Papers 1992, International Congress and Exposition.
[2] Szczurek A, Maciejewska M. Categorisation for air quality assessment in car cabin. Transport & Environment 48 (2016) 161–170.
[3] ISO/TS 14505-1:2007. Ergonomics of the thermal environment—Evaluation of thermal environments in vehicles—Part 1: Principles and methods for assessment of thermal stress. Switzerland.
[4] ISO/TS 14505-2:2006. Ergonomics of the thermal environment — Evaluation of thermal environments in vehicles - Part 2: Determination of equivalent temperature. Switzerland.
[5] ISO/TS 14505-3:2006. Ergonomics of the thermal environment — Evaluation of thermal environments in vehicles - Part 3: Evaluation of thermal comfort using human subjectsSwitzerland.
[6] ASHRAE. 2014. ANSI/ASHRAE Standard 55-2014. Atlanta: ASHRAE, Inc.
[7] Danca P, Vartires A, Dogeanu A. An overview of current methods for thermal comfort assessment in vehicle cabin. Energy Procedia 85 (2016) 162-169.
[8] Burch SD, Ramadhyani S, Pearson JT. Experimental study of passenger thermal comfort in an automobile under severe winter conditions. ASHRAE Transactions 97 (1991) 239–246.
[9] Burch SD, Ramadhyani S, Pearson JT. Analysis of passenger thermal comfort in an automobile under severe winter conditions. ASHRAE Transactions 97 (1991) 247–257.
[10] Guan Y, Hosni MH, Jones BW, Gielda TP. Investigation of human thermal comfort under highly transient conditions for automotive applications—Part 1. ASHRAE Transactions 109 (2003) 885–897.
[11] Guan Y, Hosni MH, Jones BW, Gielda TP. Investigation of human thermal comfort under highly transient conditions for automotive applications—Part 2. ASHRAE Transactions 109 (2003) 898–907.
[12] Taniguchi Y, Aoki H, et al. Study on car air conditioning system controlled by car occupants' skin temperatures - Part 1: Research on a method of quantitative evaluation of car occupants' thermal sensations by skin. SAE Paper Series (1992) 920169.
[13] Taniguchi Y, Aoki H, et al. Study on car air conditioning system controlled by car occupants' skin temperatures - Part 2: Development of a new air conditioning system. SAE Paper Series (1992) 920170.
[14] Zhang H, Arens E, Huizenga C, Han T. Thermal sensation and comfort models for non-uniform and transient environments: Part I: Local sensation of individual body parts. Building and Environment 45 (2010) 380–388.
[15] Zhang H, Arens E, Huizenga C, Han T. Thermal sensation and comfort models for non-uniform and transient environments, Part III: Whole-body sensation and comfort. Building and Environment 45 (2010) 399–410.
[16] Zhang H. 2004. Human thermal sensation and comfort in transient and non-uniform thermal environments. Ph.D. Thesis. University of California at Berkeley, CA, USA.
[17] Kaynakli O, Pulat E, Kilic M. Thermal comfort during heating and cooling periods in an automobile. Heat Mass Transfer 41(2005) 449–458.
[18] Kaynakli O, Kilic M. Investigation of indoor thermal comfort under transient conditions. Building and Environment 40 (2005) 165–174.
[19] Kilic M, Akyol SM. Experimental investigation of thermal comfort and air quality in an automobile cabin during the cooling period. Heat Mass Transfer 48 (2012) 1375–1384.
[20] Zhang W. 2013. Study on the key technology of thermal environment and occupant's thermal comfort in vehicles. Ph.D. Thesis. South China University of Tech, Guangdong, China.
[21] Alahmer A, Mayyas A, et al. Vehicular thermal comfort models: A comprehensive review. Applied Thermal Engineering 31 (2011) 995–1002.
[22] Croitoru C, Nastase I, et al. Thermal comfort models for indoor spaces and vehicles—Current capabilities and future perspectives. Renewable and Sustainable Energy Reviews 44 (2015) 304–318.

[23] Chothave A, Mohite Y, Poal V, Pamarthi P. A method to evaluate passenger thermal comfort in automobile air conditioning systems. SAE Technical Paper (2017) 2017-26-0150.

[24] de Dear RJ and Fountain ME. Field investigations on occupant comfort and office thermal environments in a hot-humid climate. ASHRAE Transactions 100 (1994) 457–474.

[25] Fanger PO. 1970. Thermal Comfort. Copenhagen: Danish Technical Press.

[26] Silva M. Measurements of comfort in vehicles. Measurement Science & Technology 13 (2002) 41–60.

[27] Pala U, Oz, H. Ridvan. An investigation of thermal comfort inside a bus during heating period within a climatic chamber. Applied Ergonomics 48 (2015) 164–176.

[28] Peri G, Sambandan S, Sathish KS. Cool down analysis of an HVAC system using multi-zone cabin approach. SAE Technical Paper (2017) 2017-01-0182.

[29] Marcos D, Pino FJ, Bordons C, Guerra JJ. The development and validation of a thermal model for the cabin of a vehicle. Applied Thermal Engineering 66 (2014) 646−656.

[30] Lai D, Chen Q. A two-dimensional model for calculating heat transfer in the human body in a transient and non-uniform thermal environment. Energy and Buildings 118 (2016) 114–122.

[31] Lai D, Zhou X, Chen Q. Modelling dynamic thermal sensation of human subjects in outdoor environments. Energy and Buildings 149 (2017) 16–25.

[32] Lai D, Zhou X, Chen Q. Measurements and predictions of the skin temperature of human subjects on outdoor environment. Energy and Buildings 151 (2017) 476–486.

[33] Lee DW. Impact of a three-dimensional air-conditioning system of thermal comfort: An experimental study. Automotive Technology 16 (3) (2015) 411−416.

[34] Han T, Huang L. A sensitivity study of occupant thermal comfort in a cabin using virtual thermal comfort engineering. SAE Paper Series (2015) 2005-01-1509.

[35] Imai K, Kataoka T, Masuda T, Inada T. New Evaluation method of transient and non-uniform environment in a passenger compartment. SAE 5 (2) (2012) 2012-01-0633.

[36] Deutsches Institut für Normung e.V., DIN 1946-3, "RaumlufttechnikTeil 3: Klimatisierung von Personenkraftwagen und Lastkraftwagen," 2006.

[37] Cisternino M. Thermal climate in cabs and measurement problems. Paper for the CABCLI seminare EC Cost Contract No SMT4-CT98-6537 (DG12 BRPR), 1999, Dissemination of results from EQUIV e EC Cost Contract No SMT4-CT95-2017.

[38] Alahmer A, Omar M, Mayyas AR, Qattawi A. Analysis of vehicular cabins' thermal sensation and comfort state, under relative humidity and temperature control, using Berkeley and Fanger models. Building and Environment 48 (2012) 146–163.

[39] Gagge AP, Stolwijk JAJ, Nishi Y. An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Transactions 77(1) (1971) 247–262.

[40] ISO. EN ISO 9886: Ergonomics - Evaluation of thermal strain by physiological measurements. International organization for Standardization, Geneva (2004).

[41] ISO. EN ISO 8996: Ergonomics of the thermal environment—Determination of metabolic rate. International organization for Standardization, Geneva (2004).

[42] Indraganti M, Rao KD. Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations. Energy and Buildings 42 (2010) 273–281.

[43] de Dear R, Brager GS. Developing an adaptive model of thermal comfort and preference. ASHRAE Transctions 104 (1998) 145-167.

[44] Nicol JF, Humphreys MA. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and buildings, 34 (6) (2002) 563-572.