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To cite this article: P A Danca *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **664** 012064

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Thermal comfort evaluation inside a car parked under sun and shadow using a thermal manikin

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Abstract. During the summer, vehicle passengers may reach a comfort state, if the sun direct solar radiation do not affect them. Human body parts exposed to the sun, experience a high uncomfortable state which have a direct impact to the global sensation of the all body. The purpose of this study is to deepen the knowledge about the thermal phenomena that occur in cabin and its effects to the thermal state experienced by the driver during a summer sunny. This way we compare temperatures, humidity and Equivalent Temperature (t_{eq}) index acquired with an advanced thermal manikin for 3 scenarios. Results reveals that for a direct solar radiation of 500 Wm^{-2} temperature inside of the car rise with 10°C . Also, the values of t_{eq} for the manikin parts exposed exceed value of 36°C leading to a very hot thermal state for all body.

1. Introduction

The most common comfort evaluation index was developed by Fanger [1] and results from equation with six parameters (air temperature, air velocity, mean radiant temperature, relative humidity, clothing insulation and metabolic rate). From these air temperature is considered to be the most influent. Situation change when human body is exposed to the solar radiation. Direct solar radiation is potent determinant of comfort. In winter it may, on balance, result in a pleasant sensation if the ambient air temperature or MRT is low. In the summer, solar radiation falling directly on a person significantly affects their perception of thermal comfort [2]. One of the situations where people are exposed frequently to the solar radiation is when they are using vehicles. Adding to this other aspects as lack of space, asymmetry of radiation, low temperature and high velocity introduced by the ventilation system make vehicle environment far complex than those from the buildings. In the last years were performed many studies with this thematic. One of these was made by Hodder [3], he performed investigation of the solar radiation effects over the thermal sensation votes of the human subjects. They were exposed to four levels of simulated solar radiation: 0, 200, 400 and 600 Wm^{-2} . Results reveals that with every increase of simulated solar radiation, the value of thermal comfort increase with a point on PMV scale, after 30 minutes of exposure. There was a tendency for the lower legs and feet to be slightly cooler than the upper regions of the body. This could be due to these parts of the body being shielded from the direct radiation.



In the summer, direct solar radiation can create asymmetry radiation by heating some of surfaces from car as, dashboard, seats, steering wheel.

Our research team has performed different experimental numerical studies [4-13] in order to deepen the knowledge of the phenomena that occur inside the vehicle cabin, and to show the effects of different setups over the thermal state. Based on the previous experiences, in this study we intended to show the effects of solar radiation over cabin environment and over the manikin thermal state

2. Measurement protocol and equipment

Three measurement sessions were performed inside of Renault Megane hatchback car from Figure 1 as following: session I in a hall to avoid solar radiation; session II outside at the shadow; and session III in full sun. Used vehicle have an air conditioning system with manual control system. Conditioned air was introduced by the dashboard diffusers. Each measurement lasting 45 minutes and the inlet air flowrate was change as following: first 15 minutes a total mass flow rate of 0,033 kg/s, after 15 minutes with a total mass flow rate of 0,052 kg/s and during the last 15 minutes total mass flow rate of 0,067 kg/s of cold air. These three value of mass flow rate correspond to the first three positions of the air speed regulator of the ventilation system. More details of the determination of these values can be seen in [12, 13]. Outside, experimental car was placed with the front to the west, front seats and left side of the car being exposed to direct sun radiation.



Figure 1 Vehicle placed inside and outside during the measurement sessions

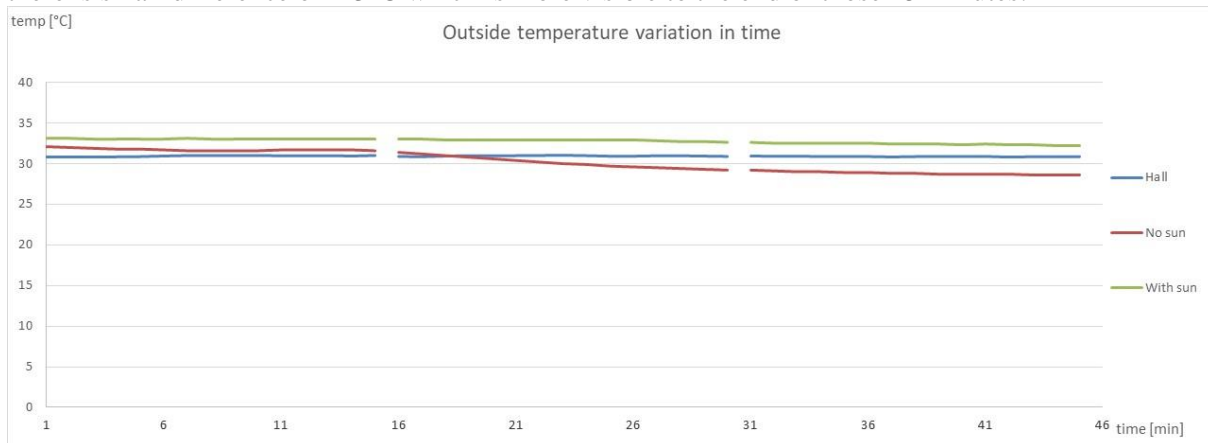
Inside of the car 8 thermocouples was placed on the following surfaces: driver side window, passenger side window, windshield, dashboard, center outlet, left side outlet, ceiling and floor. In cabin center temperature and humidity was recorded with a FHA646-E1 probe manufactured by Ahlborn. Another two AX-DT200 wireless probes were placed at the chest level of the back passengers.

Solar radiation was recorded with a Pyranometer Almemo FLA 628S probe, placed on the car during the acquisition. More details of used probes and data loggers are in Table 1

Table 1 Equipment used during the measurement sessions

Equipment	Parameter	Range	Accuracy
Data logger Almemo 710	-	-	- AA precision class
Data logger Almemo 2690	-	-	- AA precision class
Pyranometer Almemo FLA 628S	Global radiation	0 to 1500 W/m ²	- cosine effect <3% of measured value (0 to 80 ° inclination) - azimuth effect <3% of measured value temperature influence <1% of measured value (-20 to +40 °C)
AX-DT200 AXIOMET	Temperature Humidity	-20...70°C 0...100% RH	- ±0,3°C - ±2%
Thermocouple type K	Temperature	-60 to +175°C	±0.1°C
Capacitive humidity sensor Type FHA646-E1	Temperature, Relative Humidity	-20 to +60°C 5...98% RH	± 2% RH at nominal temperature

Before each measurement session, vehicle engine was turned on for 30 minutes to warm up it. Even the three measurement sessions were performed in external uncontrolled conditions, outside temperature variation during the three measurement sessions is presented in Figure 2. It can be observed there is small difference of 2-3°C which is more visible to the end of those 45 minutes.

**Figure 2** Exterior temperature variation

In our study, the teq values are calculated with an advanced thermal manikin with 79 zone independently controlled and neuro-fuzzy control. The manikin was developed in our laboratory with the support of Mechatronics Department of the National Institute of Aerospace Research Elie Carafoli. The thermal manikin was designed for both seated and standing postures. The size of the manikin is defined by the standard skin surface of a human of 1.8 m² [14, 15]. The equivalent temperature that represents an indication of thermal comfort is obtained by evaluating the power consumption of a region of the manikin (see equation 1). Due to the pwm (pulse with modulation) control signal which commutes on and off between maximum and minimum voltage, the power consumed by the thermostatic system was calculated by creating a calibration slope between pwm duty-cycle and the power calculated as a point by point mean of a single pulse period. The voltage drop on the patch was calculated differentially by measuring with the Hantek DSO5102P oscilloscope the voltage drops on the whole circuit from which it was subtracted the voltage drop on the transistors. The current consumed by the patch was measured with TH5A current transducer.

$$\theta_{ech} = \theta_{reg} - \frac{P}{S \cdot h_{cal}} \quad (1)$$

where:

θ_{ech} - equivalent temperature;

θ_{reg} - mean temperature of surface region calculated using a sliding average over a pre-set period;

S - surface area of manikin's region;

P - mean power consumption calculated using a sliding average over a pre-set period;

h_{cal} - convection coefficient calculated with equation (4) at constant environment temperature (θ_{ech}) of 24 °C and manikin's surface temperature controlled at 34 °C.



Figure 3 Thermal manikin placed in the driver place.

The 79 zones were grouped in 16 zones following the prescription of the standard [16]. The manikin was placed on the place of the driver, with the left hand on the steering wheel and left hand on the gearshift as is showing in Figure 3. The imposed temperature of the manikin was 34 °C. In order to stabilize the temperature on the surface of the manikin, it was turned on around 20 minutes.

3. Results and discussions

When the car was placed on the hall, mean temperature measured in the center of the car is 25°C for the first 15 minutes, 23,5°C for the second 15 minutes and 20,5°C for the last 15 minutes. When the car was placed at the shadow temperatures recorded in center are with 5°C higher than from the hall. Sun presents increase temperature with 6-7°C in center of the car, comparing with the case with car in shadow. The difference of 5°C between the first two cases is explain by the fact that the car was placed in the son for some hours before the measurement.

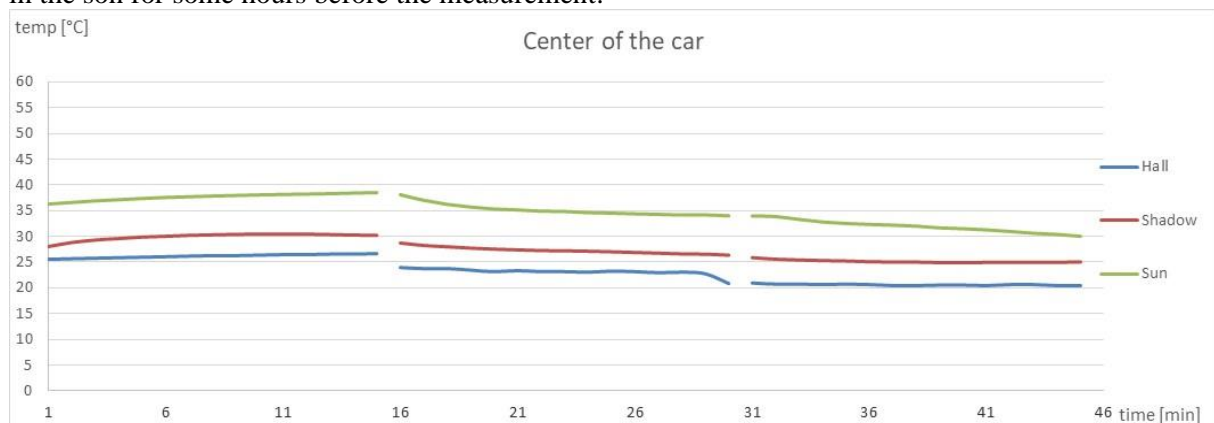


Figure 4 Temperature variation in center of the car

Passenger and driver windows temperature variation are drowned in Figure 5. Blue line is the window variation in hall. We choose to represent only the driver window, because there is no significant difference between the left and right window in hall. We can see there is a insignificant difference of windows temperatures at shadow. In session III driver window was exposed to direct solar radiation, that warming it to 55°C. In this case passenger window temperature was around 40°C. Comparing the two recorded temperature we can say solar radiation is leading to an asymmetric radiation inside cabin.



Figure 5 temperatures of the left and right windows when the car

Dashboard temperature reached the value of 40°C at the end of the second 15 minutes see Figure 6 with car exposed to sun. After another 15 minutes decrease to 35°C. There is a tendency to decrease dashboard temperature in the last 15 minutes when fan speed is on the third position and the airflow introduced by climatization system is 0,067 kg/s.



Figure 6 Dashboard temperature variation

In a previous study [12] we saw that the temperature at the inlets is different due to the heat exchanged through the pipes placed inside the dashboard, each pipe having different shape and length. These differences are more evident in Figure 7 and Figure 8 where are presented air temperatures introduced through left side and center inlet. The difference reach 15°C between cases in hall and outside, while between the two sessions made outside, the difference is insignificant. This is because the session with the car at the shadow was made after the car was placed in the sun for 3 hours.

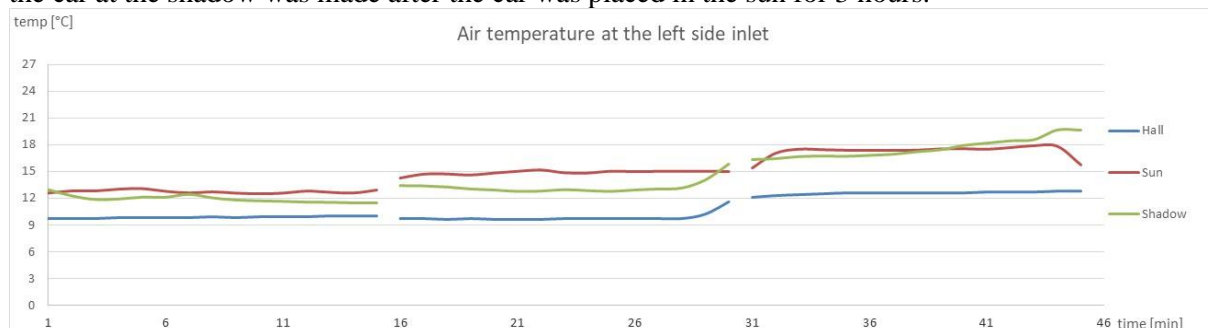


Figure 7 Air temperature at the left side inlet

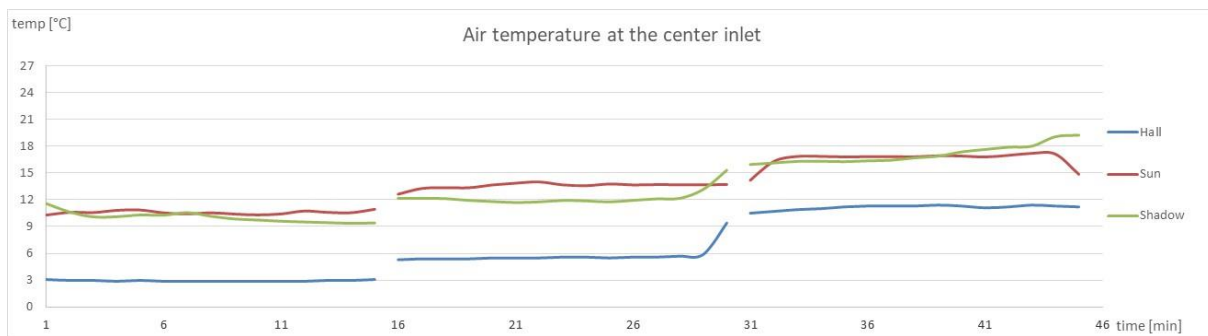


Figure 8 Air temperature at the center inlet

In Table 2 are presented t_{eq} achieved with the manikin. Can be notified that, although, at the shadow, cold air provided by ventilation system lead to a cool sensation for arms, with vehicle in sun it improves equivalent temperature value by decreasing it from 41,3 °C for V1 to 37,5 °C to V3. This decrease can be seen also at the level of chest, head, left hand and pelvic region. On a other hand, temperature of manikin's back remained stable, with a small difference between session I and other two. It may be explained by the temperature stored by the seat, from the sun prior measurement sessions.

Table 2 Equivalent temperature recorded with the thermal manikin.

Velocity step	V1			V2			V3		
Mass flow rate introduced	0,033 kg/s			0,052 kg/s			0,067 kg/s		
Body part	Hall	Shadow	Sun	Hall	Shadow	Sun	Hall	Shadow	Sun
1. Right foot	22,7	27,7	28,3	21,3	25,5	28,1	21,4	25,2	28,3
2. Right leg	17,6	36,4	37,3	18,6	35,7	37,0	18,7	35,1	36,6
3. Right thigh	22,5	32,4	33,9	22,6	31,5	34,9	23,2	31,0	33,9
4. Left foot	22,8	26,3	27,6	21,3	24,5	27,4	22,9	26,3	27,7
5. Left leg	21,6	30,3	31,8	21,8	29,3	31,5	22,2	28,6	30,8
6. Left thigh	22,8	33,7	38,2	23,1	31,2	38,6	23,3	31,1	36,1
7. Right hand	22,9	34,2	35,1	21,1	33,5	36,7	22,0	32,0	35,6
8. Right arm	21,2	31,1	33,8	22,1	30,3	36,0	23,6	26,6	33,5
9. Right upper arm	18,0	25,4	35,7	16,6	23,9	34,9	18,6	20,0	31,7
10. Left hand	19,8	34,1	38,6	10,0	32,0	39,1	9,5	30,7	36,3
11. Left arm	23,8	32,2	36,1	23,4	30,7	36,7	23,5	28,8	35,0
12. Left upper arm	21,1	35,2	41,3	20,4	33,2	39,2	21,1	31,1	37,5
13. Head	23,7	34,4	41,1	23,4	27,3	38,4	23,1	24,3	34,3
14. Pelvic region	25,6	32,6	35,1	22,2	32,2	34,8	18,2	31,8	33,8
15. Chest	24,1	33,6	40,7	20,5	29,8	39,2	18,6	29,1	36,2
16. Back	28,9	34,4	35,0	28,6	34,1	35,0	27,7	33,5	34,6

These results are presented in another format in Figure 9. In these diagrams with 1, 2, 3, 4 and 5 are represented comfort sensations corresponding to too cold, cold but comfortable, neutral, warm but comfortable, too hot thermal sensations. To each sensation is corresponding different ranges of t_{eq} values specific for each zone. This ranges are presented in ISO 14505-2 [16]. When experimental car was placed at the sun (session III), left hand, left upper arm, head and chest, have the highest t_{eq} due to the solar radiation “falling” on these parts. At the shadow (session II), after the car was parked in the sun, t_{eq} values of those parts decrease, but remain still greater compared to session I. The principal reason is higher temperature recorded in air and on the surfaces.

We can see that during the first session majority of the equivalent temperatures achieved shows a comfortable or cold but comfortable thermal state. There is an exception in case back part due to seat isolation, this sensation is maintained also in the other two sessions. When experimental vehicle was placed in the sun, we have tattily different thermal state. Recorded t_{eq} value reveals a “to hot” thermal sensation. This conclusion is similar with Hodder [3]. According to his study, after 30 minute of exposure to a solar radiation of 600 Wm⁻², subjects vote was “hot” on a Thermal Sensation Vote scale, with the remark, solar lamps was turned on at the beginning of data acquisition. However, for the third fan velocity position, body parts exposed to sun have a tendency of decreasing if t_{eq} values.

Equivalent temperatures at the foot and calf do not have a significant changes, and high values recorded during sessions II and III are based on the high temperature of the air from cabin. Footh and lower legs are the only parts where the solar radiation does not” fall”. For all the other body parts we can note great differences from a session to another.

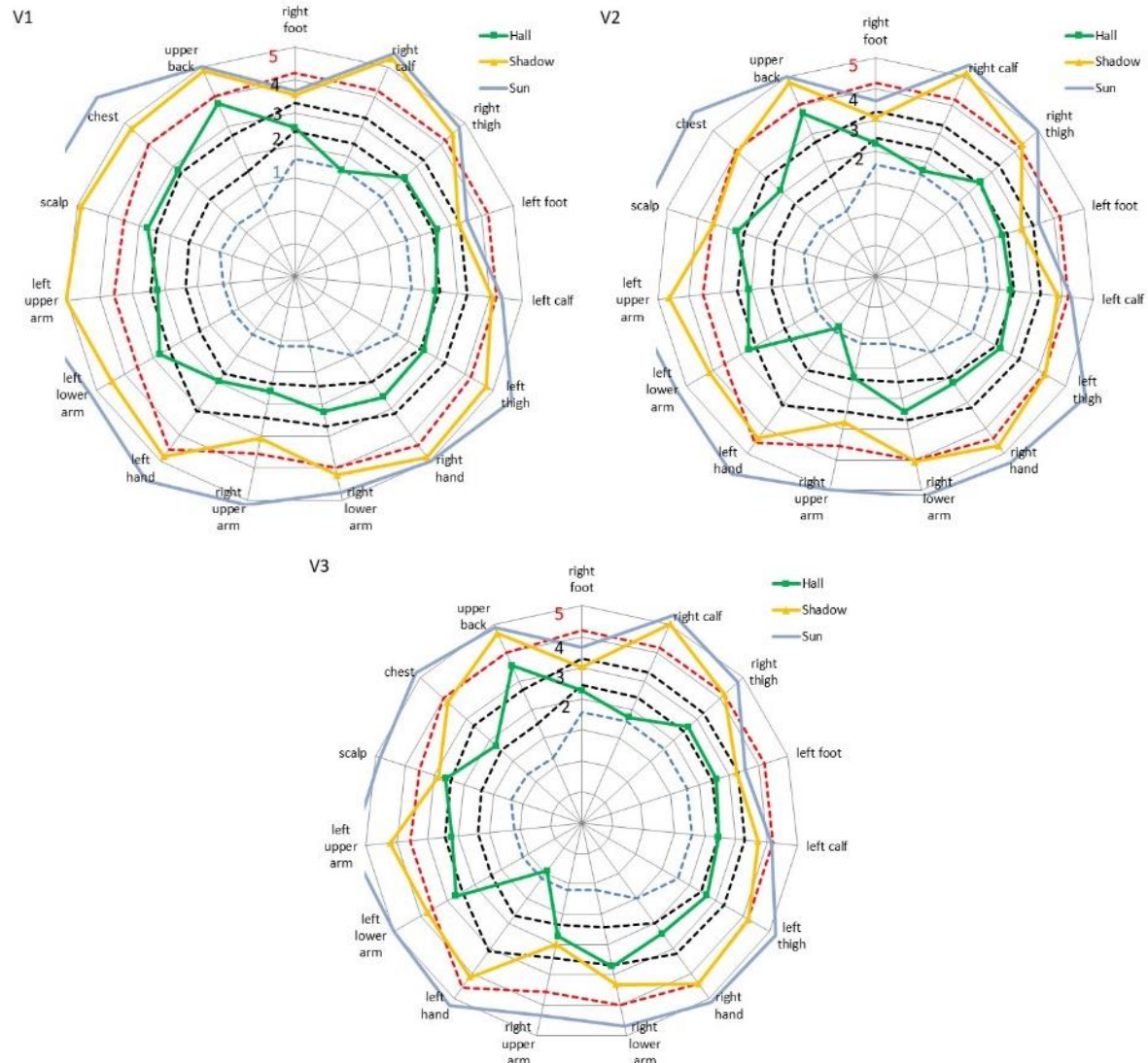


Figure 9 t_{eq} votes recorded and the comfort zones conform to the standard ISO 14505-2[16]

4. Conclusion

Solar radiation is a very important factor which affects directly thermal sensation of the human body parts who are exposed, and indirect the other parts by heating some of the vehicle elements leading to a high air temperature and a different temperature of the interior element of the car. A secondary effect is related to the temperature introduced by the ventilation system. Direct solar radiation heats the dashboard. Conditioned air passes through the ducts from the dashboard, taking a part of the heat. It may make the conditioning system more inefficient and lead to a longer time until the comfortable thermal state is reached.

Acknowledgement

This work was supported by the grant Innovative system to extend the range of electric vehicles at improved thermal comfort – XTREME, PN-III-P2-2.1-PED2019-4249 and by a grant of the Romanian National Authority for Scientific Research, CNCS, UEFISCDI, Project code: PN-III-P2-2.1-PTE-2019-0394.

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