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Evaluation of the thermal comfort for its occupants inside a vehicle during summer

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Abstract. Thermal comfort of occupants from the vehicle environment has gained more importance in the last decades because time spent by people in the vehicles is increasing. During each trip, driver's thermal comfort must be ensured to reduce both thermal stress (thus reduces the risk of accidents) and for a healthy state of the occupants. Given the fact that the vehicle environment is non-uniform and fast transient, and because the actual standard (ISO 14505) proposes comfort evaluation methods developed for the steady state conditions in buildings, the purpose of the study is to evaluate a vehicle environment using the three standardised method presented in the above standard. All the three standardized evaluation indices were achieved through standardised methods. The equivalent temperature (t_{eq}) index was assessed with an advanced thermal manikin and its values were compared with the survey answers given by people in questionnaires (TSV Thermal Sensation Vote index) and with Predicted Mean Vote (PMV) index values calculated with Comfort Sense standardized evaluation equipment. A first conclusion is that the results of the three evaluation indices are different. Air temperature is different from a zone of the car to another and the thermal evaluation must be done in the place of each passenger.

1. Introduction

Thermal comfort has been studied for a long time, research in this domain leading to the emergence of several indices to assess the thermal comfort. These indices were developed initially for the buildings in a uniform controlled and steady environment in research laboratories. Although the comfort evaluation indices were developed for the steady-state environments, the same indices were adopted to evaluate the transient and non-uniform thermal environments as in the vehicle interior case. Contrary to the case of building, assessing thermal comfort in vehicles has several particularities [1]. The effect of solar radiation, poor interior insulation, the non-uniformity of the average radiant temperature, a very short time to ensure the comfort parameters are some of the characteristics of an automotive environment. Indoor Environmental Quality in buildings has gained importance in the last decade and now is developing a new direction of research, the environmental quality in vehicles. The ambience quality is an important criterion in marketing this type of products. It influences not only the thermal comfort inside the car, but it also reduces the risk of accidents [2-4] by reducing the driver's thermal



stress and ensuring a good visibility (through avoiding the fogging phenomena), which leads to a safer trip.

The thermal comfort inside the vehicle is more difficult to be evaluated and controlled than in a building due to the increase influence of the heat exchange through convection, conduction, radiation [5-8]. Also, other influences are the environmental parameters and the non-uniformity of the vehicle environment resulted by the heating, ventilating and air conditioning system. Thus, ensuring and maintaining the thermal comfort inside the vehicle is one of the most important challenges for the researchers, designers and manufactures in the automotive industry.

The actual standard which, is proposing comfort evaluation methods for vehicles environment is ISO 14505 [9-11] standard "Evaluation of thermal environments in vehicles" being structured into three parts: 1. Principles and methods for assessment of thermal stress [9]; 2. Equivalent temperature determination [10]; 3. Evaluation of thermal comfort by the human subjects [11].

In the first part of the above-mentioned standard, is presented a comfort evaluation method based on the PMV and PPD model developed in the 1970 professor Fanger [12]. This comfort evaluation model was developed using data collected from human subjects evaluated in controlled laboratory conditions. Fanger's PMV and PPD indexes were adopted by international standardization organization such as ISO 7730 [13] and ASHRAE 55 [14]. Unfortunately, from the equations used for the calculation of these two indices we can observe that the results are generated particularly for homogeneous environments like the environments inside buildings.

The second part of the standard is presenting the t_{eq} index – the equivalent temperature index. This is a local and global index proposed by Nilsson following his PhD thesis [15-18]. The equivalent temperature uses the same method of calculation as the operative temperature for ambient air velocities under 0.1 m/s. This represents the average of the mean radiant temperature and the air temperature weighted respectively by the convection and radiation heat transfer coefficients for the occupant inside the vehicle. For values of the ambient air velocities greater than 0.1 m/s, the equivalent temperature is expressed as a function of the air temperature, the mean radiant temperature, the air speed and the thermal resistance of clothing [19-21].

In the third part of the standard ISO 14505 a direct method for assessing thermal comfort in automobiles is presented, the main index being the Thermal Sensation Vote (TSV) of human subjects that are surveyed. This subjective method quantifies and records the response of people about their thermal sensation in an environment, on the same scale of values as for the PMV. The TSV only considers the psychological and physiological factors. A study using this method involves standardized questionnaires for a controlled and representative sample of population. By centralizing the obtained thermal votes, results the thermal sensation from the particular investigated situation.

This article is a part of a larger study, intended to deepen the knowledge on thermal comfort inside vehicles, the purpose is to evaluate a vehicle environment using the three standardized method presented in the above standard. All the three standardized evaluation indices were achieved through standardized methods. The equivalent temperature (t_{eq}) index was assessed with an advanced thermal manikin and its values were compared with the survey answers given by people in questionnaires (TSV Thermal Sensation Vote index) and with Predicted Mean Vote (PMV) index values calculated with Comfort Sense standardized evaluation equipment. A first conclusion is that the results of the three evaluation indices are different. Air temperature is different from a zone of the car to another and the thermal evaluation must be done in the place of each passenger.

2. Experimental set-up

The measurement campaigns presented in this study were performed in a Renault Megane vehicle. The evaluation was conducted in the hot season, in Bucharest. Outside, the air temperature was 35°C according to the National Institute of Meteorology. During the measurement's sessions, the vehicle was placed in a hall (see **Error! Reference source not found.**) in order to ensure as more as possible constant thermal conditions in the vicinity of the car. Totally, were made 12 measurement sessions, in 10 of them human subjects were placed in the driver seat. All the tests were made for the second

running position of the ventilation system Figure 1, this being the most used position in the summer conditions.

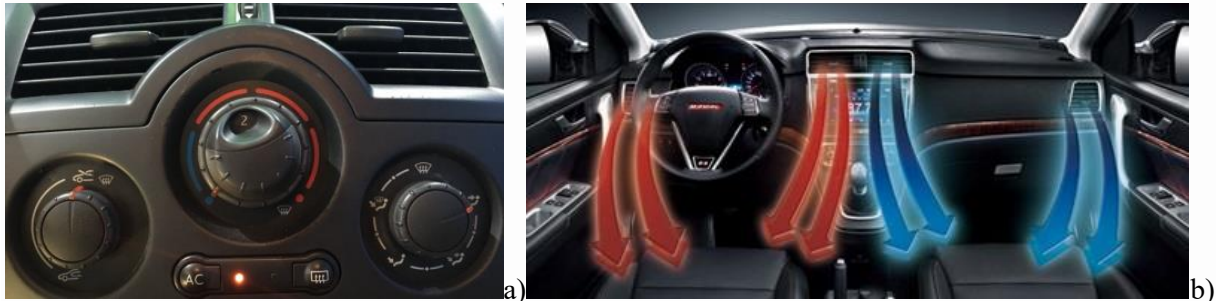


Figure 1. Ventilation/air conditioning system set-up.

The air was introduced in the vehicle only through dashboard diffusers as is showing in Figure 1. The air-conditioned system was turned on during all the tests. The mean velocity and the flowrates of the introduced air through the dashboard diffusers for this ventilation/air-conditioning running position are presented in Table 1.

Table 1. Values of the introduced air condition.

Diffusers/parameter	Mean velocity [m/s]	Temperature [°C]	Q [kg/s]
Central diffuser	3.29	13	0.0316
Right side diffuser	1.58	9.4	0.0152
Left side diffuser	1.19	14	0.0114

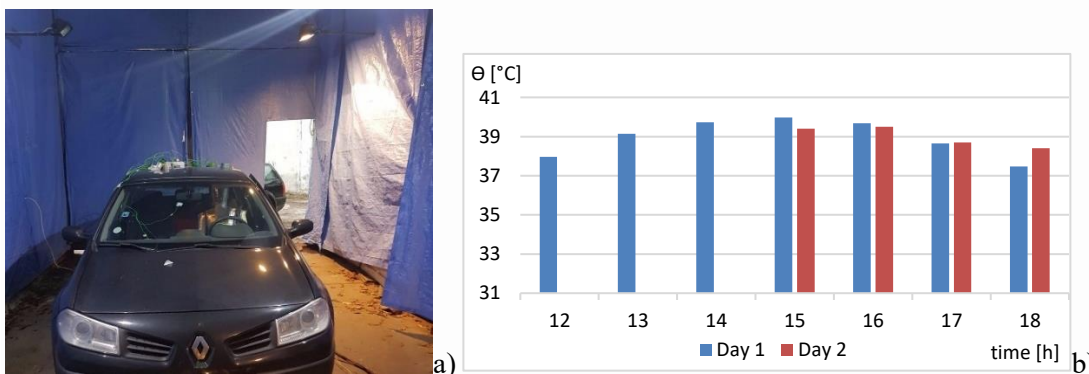


Figure 2. a) experimental test car in the hall; b) temperature variation in the hall during the experimental tests.

2.1. Thermal environment assessment

To monitor temperature on the interior surfaces a network of 11 thermocouples was placed on different surfaces as is shown in Figure 3. Three thermocouples were placed in the inlets: one in the centre (T19), one on the left side diffuser (T18) and another in the right-side diffuser (T20). Another nine thermocouples were placed on the interior surface: dashboard (T17), windshield (T16), sides windows (T21 and T22), ceiling (T24), floor (T23), top of the trunk (T25) and rear window (T26). These were connected to 4 data loggers manufactured by Ahlborn: two Almemo 710 each with 10 sensor connecting available ports.

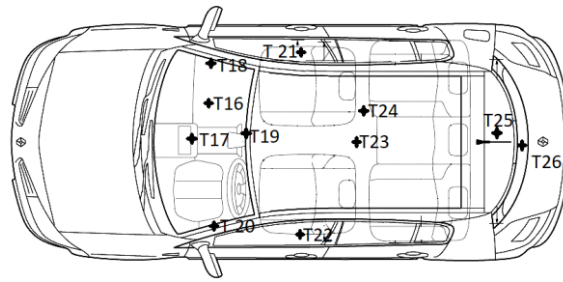


Figure 3. a) K-type thermocouples distribution on the surfaces.

Another 15 pieces of AX-DT 200 temperature and humidity wireless sensor (Figure 4 a) were placed in the places where are zones of the human body. For these, we built some special supports presented which can be seen in the following pictures. These zones are: foot, knee, abdomen, chest and head, five for each of the places of the other passengers. The distribution of all the AX-DT 200 sensors is presented in Figure 4. The temperature values were recorded after each minute.

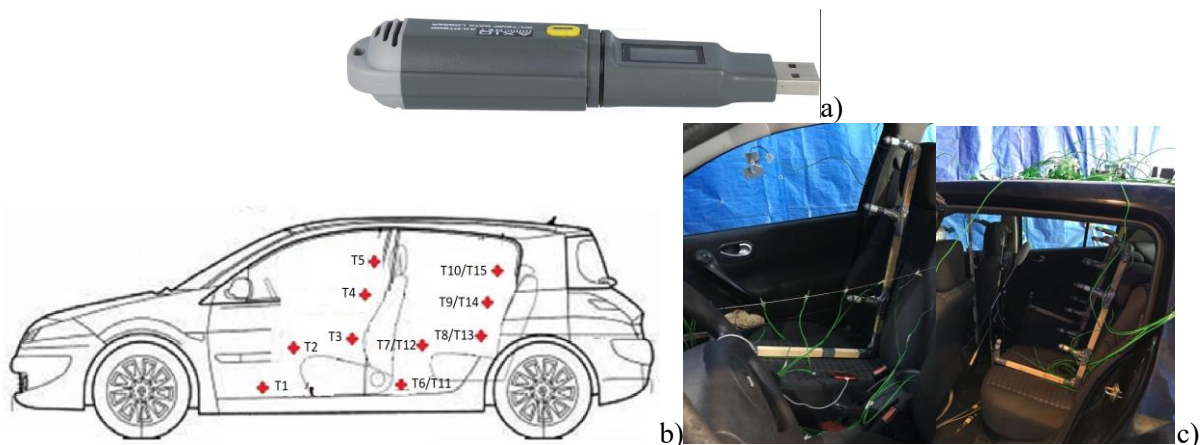


Figure 4. a) AX-DT 200 wireless sensor; b) sensors map distribution; c) images during measurement session.

2.2. Thermal comfort evaluation using PMV/PPD model – first part of ISO 14505

PMV and PPD indices are proposed by Fanger [12] over 30 years ago, and they are the result of a study in which subjects that had "standard" clothes performing a „standard" activity. During the assessment, the persons were exposed to various thermal conditions. According to the felt sensation, the subjects assessed the condition using a sensation scale with seven values (-3: cold, -2: cool, -1: slightly cool, 0 neutral, 1: slightly warm, 2: warm, 3: hot) [14]. Knowing the clothing insulation and metabolic rate resulting from the activity and introducing the external physical quantities that influence the phenomena of heat transfer (air temperature, radiant mean temperature, partial pressure of water vapor and relative air velocity) in the thermal equilibrium relationship of the human body, the PMV index is resulting from the equation:

$$PMV = (0.303e^{0.303} + 0.028) \{ (M-W) - 3.05 [5.73 - 0.007(M-W) - p_a] - 0.42 [(M-W) - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a) - 3,96 \cdot 10^{-8} f_{cl} [(t_{cl} + 273)^4 - (t_{mr} + 273)^4] - f_{cl} h_c (t_{cl} - t_a) \} \quad (1)$$

where:

$$t_{cl} = 35.7 - 0.0275(M-W) - I_{cl} \{ (M-W) - 3.05 [5.73 - 0.007(M-W) - p_a] - 0.42 [(M-W) - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a) \} \quad (2)$$

M - the metabolic rate, in watts per square meter [W/m^2];

W - effective mechanical power, in watts per square meter [W/m^2];

- t_{cl} - clothing surface temperature, in degrees Celsius [$^{\circ}\text{C}$];
 p_a - water vapour partial pressure, in Pascal [Pa];
 t_a - air temperature, in degrees Celsius [$^{\circ}\text{C}$];
 v_a - relative air velocity, in metres per second [m/s];
 I_{cl} - clothing insulation, in square meter Kelvin per Watt ($\text{m}^2 \text{K/W}$);
 f_{cl} - clothing surface area factor;
 t_{mr} - mean radiant temperature, in degrees Celsius [$^{\circ}\text{C}$];
 h_c - convective heat transfer coefficient, in watts per square meter Kelvin [$\text{W/m}^2\text{K}$]

NOTE: 1 metabolic unit = 1 met = 58.2 W/m²; 1 clothing unit = 1 clo = 0.155 m² °C/W

The PPD index (Predicted Percentage of Dissatisfied) is associated with the *PMV* and is indicating the percentage of occupants under thermal discomfort. A value of 10% of the *PPD* index corresponds to the interval between -0.5 and +0.5 for *PMV* on Fanger's scale. Even for the *PMV*=0, about 5% of occupants are in discomfort.

$$PPD=100-95\exp[-(0.03353PMV^4+0.2179PMV^2)] \quad (3)$$

In our study the *PMV/PPD* indexes were calculated with a Comfort Sense measurement tool. It has various sensors which are measuring air temperature and velocity, relative humidity, operative temperature. Adding to this the clothing insulation and metabolic rate, the device is calculating automatically the values of *PMV* and *PPD*. For our study we imposed a value of 0.7 clo for the clothing insulation and 1.2 met for the metabolic rate. The Comfort Sense probes were placed on the driver place as is shown in Figure 5.

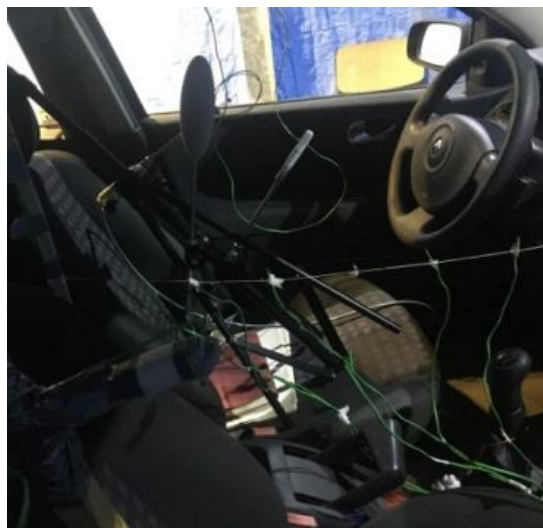


Figure 5. Comfort sense probes on the driver place.

2.3. Thermal comfort evaluation with t_{eq} index and thermal manikin – Second part of 14505

In our opinion the equivalent temperature is the most adapted for the evaluation in this environment. It offers the possibility to evaluate the thermal comfort at the local level taking into account the heat exchange between a specific body part with the surrounding environment. The equivalent temperature is using two relations function of the air velocity in the studied environment. In this case of velocities lower than 0.1 m/s, the equivalent temperature might be expressed as an average between the values of the air temperature and the radiant mean temperature weighted using the heat transfer coefficients (convection and radiation) between the occupant and the environment [22]. When the air speed values are larger than 0.1 m/s, the relation for the calculation of the equivalent temperature is:

$$t_{eq} = 0.55 \cdot t_a + 0.45 \cdot t_{mr} + \frac{0.24 - 0.75 \sqrt{v_a}}{1 + I_{cl}} (36.5 - t_a) \quad (4)$$

In our study, the t_{eq} 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 [23, 24]. 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 5). 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.

$$\theta_{ech} = \theta_{reg} - \frac{P}{S \cdot h_{calc}} \quad (5)$$

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

The 79 zones was grouped in 16 zones following the prescription of the standard [10]. 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 6. The imposed temperature of the manikin was 34 °C.



Figure 6. Thermal manikin placed in the driver place.

2.4. Thermal comfort evaluation using human subjects

The ISO 14505-3 gives guidelines and specifies a standard test method for the assessment, using human subjects, of thermal comfort in vehicles. The questionnaire used in our study made corresponding to from ISO 14505-3 and ISO 10551/2001 [25] which guide the construction and use of thermal sensation scales and proposes a set of specifications on direct assessment of thermal comfort/discomfort expressed by persons subjected to various degrees of thermal stress. In Figure 7 is presented an example of used questionnaires.

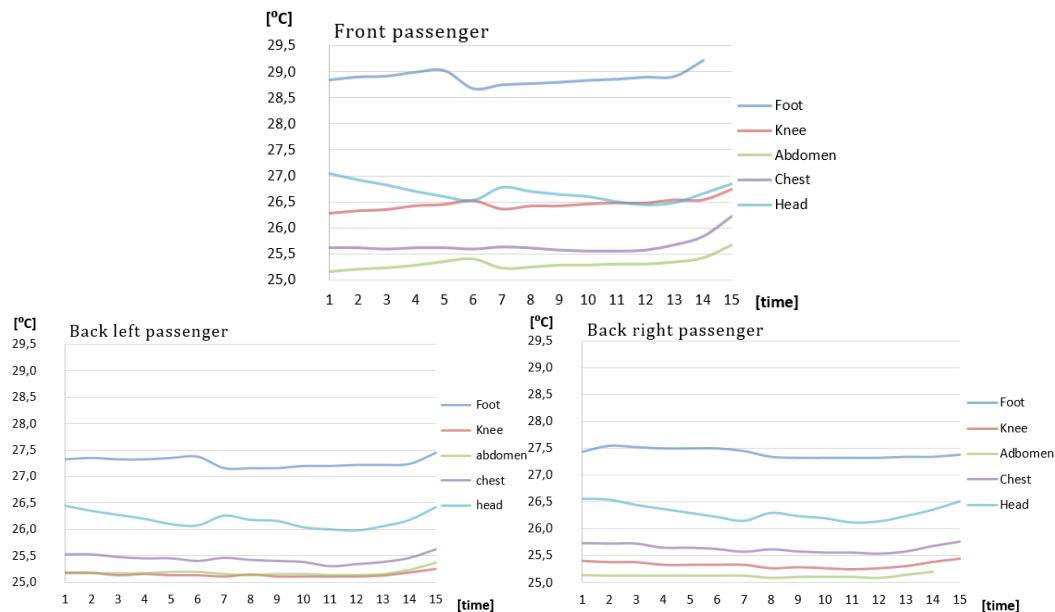


Figure 8. temperature variation in the place of the passengers.

Imposing the values of clothing insulation and of the metabolic rate and adding the measured values of the physical parameters, the PMV and PPD values were calculated. The mean value for each measurement session is presented in **Figure 9**. All the values are negative which means that there is a cold state tendency. An environment is considerate to be comfortable if the PMV values are within - 0.5 and + 0.5 range. In our case on the driver seat, 6 of the values are in the neutral limits, while 4 are near to the border of this state.

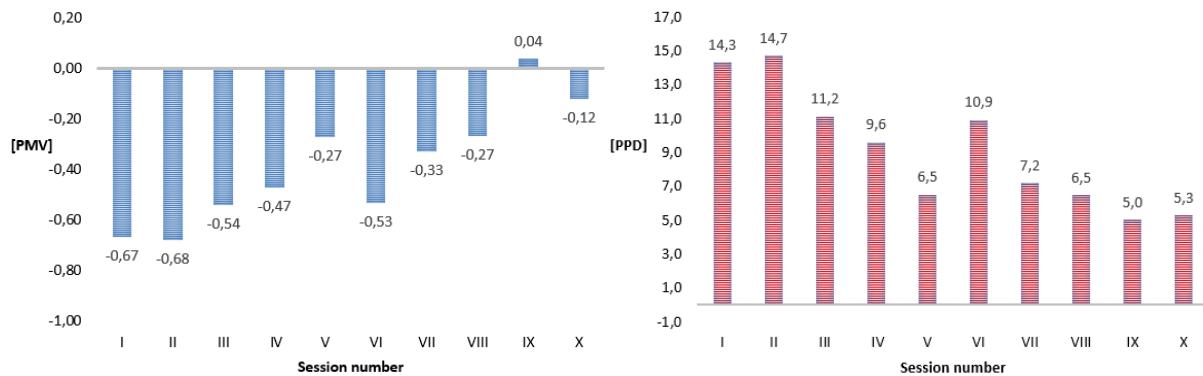


Figure 9. PMV and PPD values.

The results from the survey questionnaires study are presented in Figure 10. There are only three sensation voted by the volunteers. The highest percentages of the votes (80%) resulting from the questionnaires are in the neutral zone. The second biggest percentage from the votes (17%) are indicating that the passengers had a slightly warm sensation. While only 3% votes slightly cold. If we are going back to the PMV values we can see that excepting one vote, the values have negative values which means that there is a cold state tendency. From this we can see already a difference between the two indices, because their tendency is contradictory.

Comparing the TSV values at the local level we can note that for 6 of the persons surveyed voted a slightly cool sensation for the arms regions. This sensation may be produced by the cold air jets from the inlet diffusers which is passes near to these body parts. In fact, this is one of the observation of the volunteers.

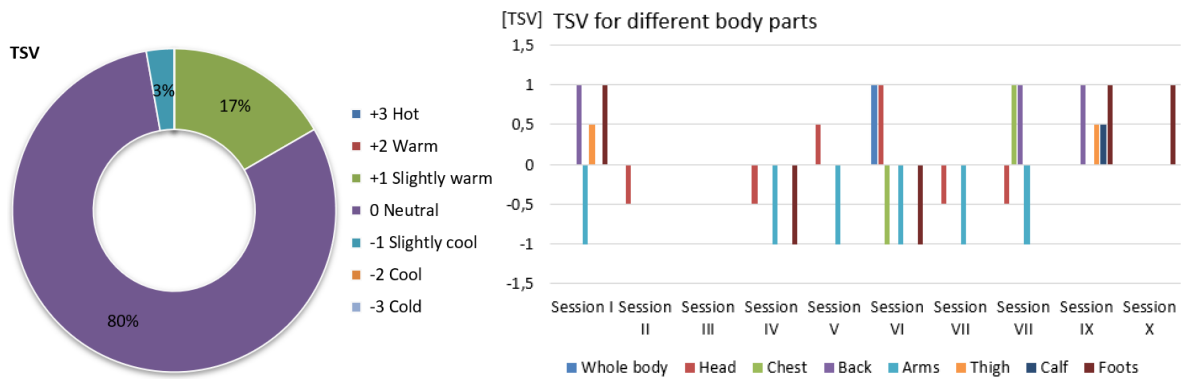


Figure 10. percentages of thermal sensations from the questionnaires.

Figure 11 shows better the differences of the two indices PMV and TSV. Although the majority of the votes of the two indices are showing a neutral thermal state, the majority of the TSV values are positive and the majority of the PMV values are negative.

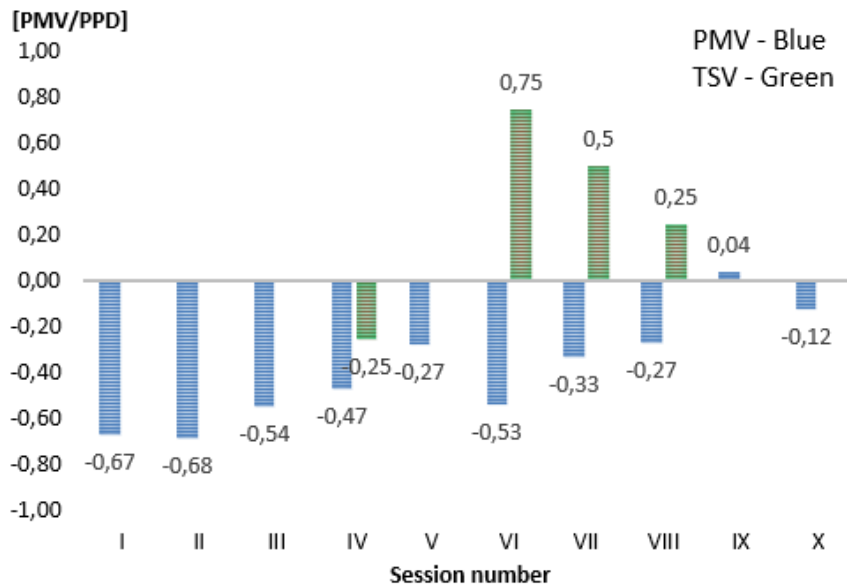


Figure 11. Comparison between PMV and TSV.

The results assessed with the thermal manikin are presented in Figure 12. In the shown 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 [10]. As it can be seen in Figure 12 the thermal manikin is assessing a high uncomfortable cold sensation for right upper arm placed in the direction of the inlet airflow which is coming from the central diffusers. Some of the regions as chest, left leg, left foot, right arm and left arm are near the region of cold sensation but still in the comfortable thermal sensation zone. The t_{eq} of the other body parts are in the zone 3 which is a neutral sensation.

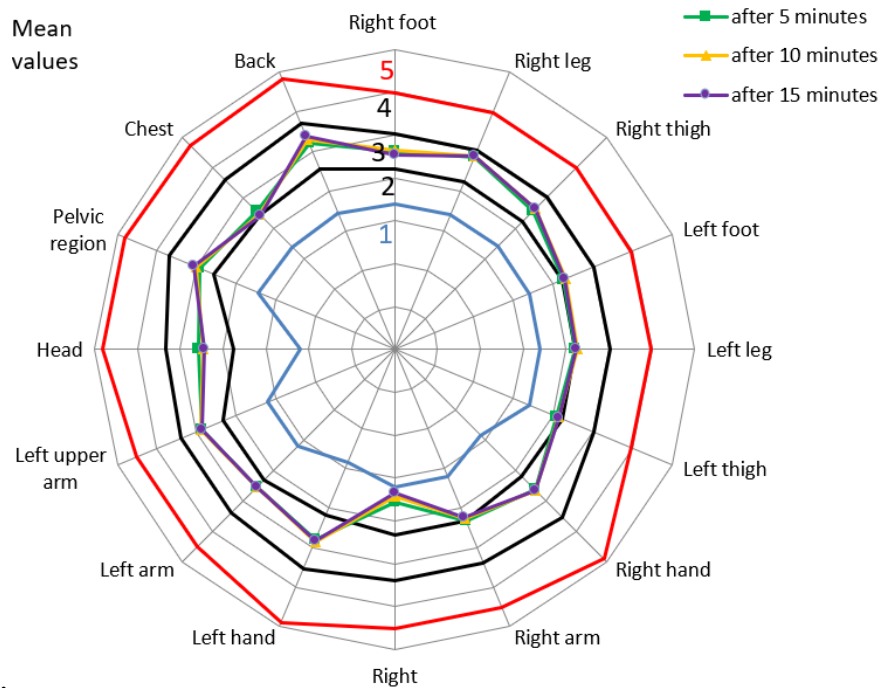


Figure 12. Distribution of the mean t_{eq} values.

In Table 2 are exposed mean values of the standardized indexes. The results of evaluation with all three standardized methods are predicting that most of the persons which are entering in the car should feel a comfortable thermal state. Although, the majority of the votes of the three indices are showing a neutral thermal state, the majority of the TSV values are positive and the majority of the PMV values are negative. Thermal comfort assessment at the local level highlights that there are different thermal states felt for different body parts, for example arms which are in a cold thermal state due to the air jets from the inlet diffusers.

Table 2. Values of thermal comfort evaluation indexes.

Index	t_{eq} [°C]	TSV [-]	PMV [-]
V2	22.80 (cold but comfortable)	0.14 (neutral)	-0.41 (neutral)

4. Conclusions

This paper is focused on the comfort assessing in a transient non-uniform environment inside a vehicle. Determination of the vehicle occupants thermal comfort is very complicated due to the transient nature and non-uniformity of the vehicle interior. More than this, the actual standard is proposing three evaluation indexes and was developed for steady state and controlled conditions and some of the indexes are not adapted to this complex environment.

In this article are compared the values obtained for the three standardized indexes in term of thermal comfort, in a vehicle passenger in summer season.

The results are showing that the mean values PMV/PPD model calculated in a single point with Comfort Sense equipment are far from the TSV mean values resulting from questionnaires survey with human subjects, while the t_{eq} index calculated with an advanced thermal manikin reveals thermal states similar to the survey questionnaire study (TSV). This may be explained by the fact that the TSV and t_{eq} consider the sensation for each body part at the local level.

Another conclusion may be, that for a correct evaluation of thermal comfort in non-uniform and transient environments like in the vehicles, measurement of the physical parameters in a single point from the environment is not relevant.

The main conclusion is that the PMV/PPD indexes are not very well adapted to the vehicle environment.

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