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THE HUMAN THERMAL COMFORT EVALUATION INSIDE THE PASSENGER COMPARTMENT

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ABSTRACT - As many people spend several hours a day in cars, buses or trains, it is important to provide a good thermal environment, which gives comfort and optimizes performance for both drivers and passengers.

The thermal comfort sensation is assured by the factors that depend on the heat exchange between the human body and the ambient environment.

It is well known that one of the requirements to be fulfilled is that a person to be in thermal neutrality according to the comfort equation. This is described and evaluated by the following indices: DTS (**D**ynamic **T**hermal **S**ensation), TS (**T**hermal **S**ensation), PMV (**P**redicted **M**ean **V**ote) and PPD (**P**redicted **P**ercentage of **D**issatisfied).

This paper shows the influence of the different parameters and situations on the thermal human comfort prediction of passengers' compartment starting from the body's energy balance based on Fiala's manikin (which provides all the thermo-physiological effects of the human body model) by THESEUS-FE software.

On the other hand, this simulation is likened to the temperature values which are measured in four different points of passenger compartment (two airzones) that were obtained by experimental way.

Consequently, this paper will presents the different aspects of the global and local thermal comfort prediction, based on mathematical models from literature, as well as using simulated skin and cloth temperatures result to a quite simple-to-use method of assessing local thermal comfort at given boundary conditions, typical for a vehicle simulation.

Nomenclature

F_{cloud}	-	cloud cover factor
H	-	Dry Heat Loss. Heat loss from the body surface through convection, radiation and conduction. [W/m^2];
I_{cl}	-	Thermal insulation of clothing, [m^2 °C/W]; I_{cl} =0 to 0.310 m^2 K/W (0 to 2 clo)
M	-	The metabolic rate of body surface area [met, W/m^2]; M = 46 ÷ 233 W/m^2 (0,8 to 4 met)
p_a	-	Partial water vapour pressure in the air [Pa]. One recommands p_a= 0 ÷ 2700 Pa (and relative humidity must be between 30 to 70 %
DTS	-	Dynamic Thermal Sensation
PMV	-	Predicted Mean Vote
PPD	-	Predicted Percentage of Dissatisfied
TS	-	Thermal Sensation

T_{hy} hypothalamus temperature [°C]
$T_{sk,m}$ mean skin temperature [°C]
$\bar{t}_r$ - Mean radiant temperature [°C]
$T_{ambient}$ - Ambient temperature [K]
T_{dew} - dewpoint temperature [K]
W - The external work, (equal to zero for most activities) [W/m^2];

Greek symbols

α angle between the geographical south and the highway
ε_s - sky emissivity
φ - Relative humidity, [%];
φ_{aziTH} Azimuth angle used in Theseus [degrees]
φ_{aziS} - Sun azimuth angle according to South axis [°]

INTRODUCTION

Lately, most of the automotives manufactures have focused on the increasing human thermal comfort. To achieve a high thermal comfort, most manufacturers provide a system for their cars to ensure ventilation, heating and cooling air in the passenger compartment.

The interaction of convective, radiation and conduction heat exchange in a passenger's compartment is very complex. The varying radiation from the sun and the influence of inhomogeneous air temperature and air velocity from the vehicle's ventilation or air conditioning system creates a climate that may vary considerably in space and time.
The efficiency of the HVAC system is evaluated by taking into account the equivalent temperature and the surface temperature of clothing of the passengers [2, 3, 14].

The level of thermal comfort is highly dependent on the local environment. Human beings respond differently to local heat transfer in different parts of their bodies. It is suggested for that reason that local results from manikins should be presented in new clothing independent comfort zone diagrams [13, 14, 16].

In this paper the authors evaluate the human thermal comfort in the two airzones of passenger compartment (both for driver and the back passenger car). This is described and evaluated by the following indices: DTS (**D**ynamic **T**hermal **S**ensation), TS (**T**hermal **S**ensation), PMV (**P**redicted **M**ean **V**ote) and PPD (**P**redicted **P**ercentage of **D**issatisfied). The first two indices depend of the hypothalamus temperature and the mean skin temperature and PMV - PPD indices take into account the following six parameters: activity, clothing, air temperature, mean radiant temperature, air velocity and humidity (ISO 7730) [4, 5, 23, 24].

The numerical simulation was done for a car stationed 3600 seconds, following a period of the 1800 seconds with air conditioning start-up, both for city traffic and the highway traffic. Also by numerical simulation we can observe the distribution of the temperature in time depending on the sun position.

The obtained data by numerical simulation was likened with the results obtained on the experimental way in these conditions. This numerical simulation helps us to determinate the comfort indices in every moment, for different conditions and situations.

MANIKIN FIALA-FE

The new manikin FIALA-FE provides all the thermo-physiological effects of the human body model published in the frequently cited PhD thesis of 1998 [5].
From a mathematical point of view, the human organism can be separated into two interacting systems of thermoregulation: the controlling active system and the controlled passive system. The active system is simulated by means of cybernetic models predicting regulatory responses, i.e., shivering, vasomotion, and sweating, as discussed in [24]. The passive system is modelled by simulating the physical human body and the heat transfer phenomena occurring in it and at its surface.
The physical body consists of body elements that are approximated as cylinders or sphere (head), they are separated into sectors and subdivided into material layers: skin, fat, muscle, bone. [5,19,24].

THESEUS-FE uses two different models for the new manikin FIALA-FE for pre- and post-processing (figure 1).

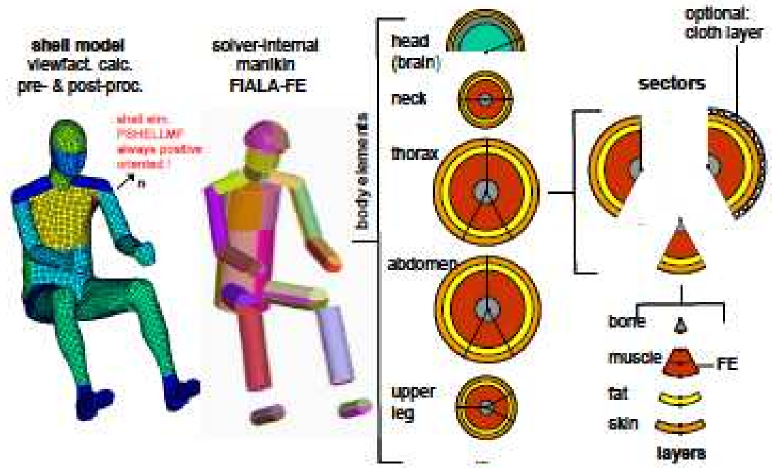


Figure 1: Discretisation of the thermo-physiological manikin FIALA-FE

THE HUMAN THERMAL COMFORT ANALYSIS

The human thermal comfort prediction was done depending on the different indices.
DTS and PMV index are both thermal comfort indices related to the global state, whilst the equivalent temperature can be derived for each body element sector of a human body [5, 24].

Dynamic Thermal Sensation (DTS) and the Thermal Sensation (TS) indices

One part of the post-processing in THESEUS-FE is the evaluation of the dynamic thermal comfort index DTS, as defined by Fiala in [24]. The index had been validated under dynamic conditions with suddenly changing environmental temperatures and more steady-state-like conditions, like 1hr exposure, or 3hr exposure.

Thermal comfort experiments typically run with test persons that mark the actual (subjective) state of thermal sensation on a 7-point ASHRAE scale (figure 2).

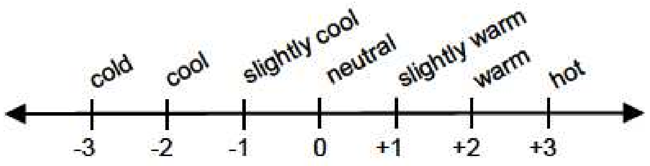


Figure 2: The 7-point ASHRAE-scale

The DTS index is a functions which takes in the calculation the hypothalamus temperature T_{hy}, the mean skin temperature $T_{sk,m}$, and the gradient $dT_{sk,m}/dt$).

$$F = F\left(T_{hy}, T_{sk,m}, \partial T_{sk,m} / \partial t\right) \qquad (1)$$

The DTS index combines 3 sub-functions:

$$\mathrm{DTS} = 3 \cdot \tanh\left(f_{sk} + \phi + \psi\right) \tag{2}$$

f_{sk} is a function that depends exclusively on the mean skin temperature derivation towards the set point:

$$\begin{aligned} f_{sk} &= 1.026 \cdot \Delta T_{sk,m} \quad \text{for} \quad \Delta T_{sk,m} > 0 \\ f_{sk} &= 0.298 \cdot \Delta T_{sk,m} \quad \text{for} \quad \Delta T_{sk,m} < 0 \end{aligned} \tag{3}$$

while φ contains the hypothalamus temperature too:

$$\phi = 6.662 \cdot \exp\left(\frac{-0.565}{\Delta T_{hy}}\right) \cdot \exp\left(\frac{-7.634}{5 - \Delta T_{sk,m}}\right) \tag{4}$$

$$\Delta T_{hy} \le 0 \Rightarrow \phi = 0\,, \quad \Delta T_{hy} \ge 5 \Rightarrow \phi = 0$$

Dynamic components in the DTS index are collected in ψ.

So, for cooling $$\psi = \frac{0.114 \cdot \dfrac{\partial T_{sk,m}}{\partial t}}{1 + \phi} \tag{5}$$

The thermal sensation index, TS, not contain dynamic terms it can combines 2 sub-functions:

$$\mathrm{TS} = 3 \cdot \tanh\left(f_{sk} + \phi\right) \tag{6}$$

PMV and PPD Indices

The degree of the thermal comfort for a person is influenced by six parameters:

► Personal factors: Activity level, M (met, W/m^2); Thermal insulation of clothing, I_{cl} (clo, m^2°C/W)

►Environmental parameters: Air temperature, t_a (°C); Mean radiant temperature, $\bar{t}_r$; Air velocity, v_a (m/s); Humidity Ratio, RH (%).

According to ISO 7730, the combination of these six parameters determines the degree of general comfort and is expressed by the Predicted Mean Vote (PMV). The PMV is the mean vote of a large group of people on the seven-point thermal sensation scale.

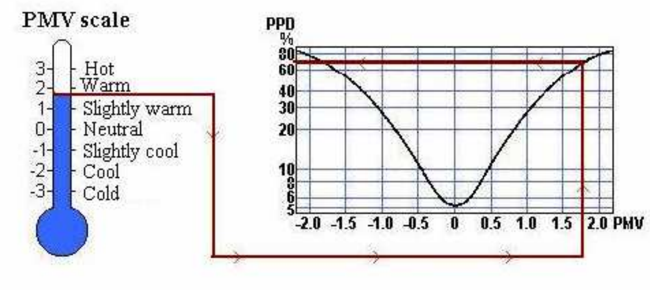


Figure 3. Thermal sensation scale PMV and the variation of PPD index depending on PMV

Thermal comfort values from the PMV index between -3 and +3 are related to the 7-point ASHRAE-scale (figure 3)

Negative values suggest that the occupant feels cold, positive values suggest that the occupant feels warm, and a value of 0 suggests that the occupant feels comfortable.

It is recommended that the PMV index be between -0.5 and + 0.5, which means that less than 10% will find the thermal environment unacceptable.

According to the value of the PMV index the discomfort percentage of a person by the PPD (Predicted Percentage of Dissatisfied) index can be determined graphically too. The minimum value of the PPD index is 5 % (figure 3).

The PMV and PPD indices are determined analytically with the following relations (ISO 7730, ASHRAE Fundamentals, 2001) [10, 21, 23].

$$\begin{aligned} PMV = (0{,}303e^{-0.036M} + 0.028)\{(M-W) - 3.05\cdot 10^{-3}\cdot[5733 - 6.99(M-W) - p_a] \\ - 0.42\cdot[(M-W) - 58.15] - 1.7\cdot 10^{-5} M(5867 - p_a) - 0.0014M(34 - t_a) \\ - 3.96\cdot 10^{-8} f_{cl}\cdot[(t_{cl}+273)^4 - (\bar{t}_r + 273)^4] - f_{cl}h_c(t_{cl} - t_a)\} \end{aligned} \tag{7}$$

$$PPD = 100 - 95\cdot e^{-\left(0.03353\times PMV^4 + 0.2179\times PMV^2\right)} \tag{8}$$

EXTERIOR BOUNDARY CONDITIONS

The exterior boundary conditions, the sun position on the sky, sky temperature and the solar radiation intensity used in the numerical simulation are presented in the table 1.

The solar radiation intensity values are taken from [25] and they represent the characteristic values for the month of July. They are presented in table 1 together with the values for sky temperature, ambient relative humidity and ambient temperature.

Table 1.

Sun load [W/m^2]	Ambient temperature [°C]	Relative humidity [%]	T$_{sky}$ [°C]	Azimuth angle [°]	Altitude [°]
1000	35	40	15.6	135	45

The sky temperature was estimated based on an algorithm using the following series of equations [26]:

$$T_{sky} = \varepsilon_s^{\frac{1}{4}}\cdot T_{ambient} \tag{9}$$

$$\varepsilon_s = 0.787 + 0.764\cdot\ln\left(\frac{T_{dew}}{273}\right)\cdot F_{cloud} \tag{10}$$

$$F_{cloud} = 1.0 + 0.24\cdot N - 0.035\cdot N^2 + 0.00028\cdot N^3 \tag{11}$$

where N is the “tenths cloud cover”, taking values from 0.0 to 1.0

In Theseus FE, the azimuth angle represents the angle between the sun direction and the Ox axis of vehicle, as we can see in Figure 4.

In the considered experiment, the angle between the Pitesti – Bucharest highway and the axis that represents the geographical South and can be represented as a straight line with an inclination about 135°, where the sun position on the sky, the azimuth angle being reported to the geographical South [17,24,25].

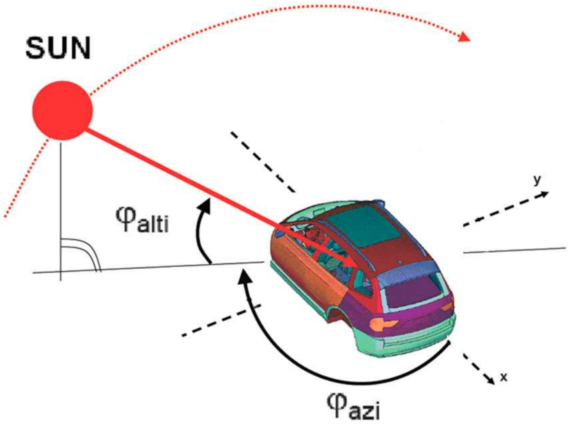


Figure 4. Sun position in Theseus FE

The equation used to calculate the azimuth angle needed for Theseus FE software is:

$$\varphi_{aziTH} = \pi - \left(\alpha - \varphi_{aziS}\right) \tag{12}$$

EXPERIMENTAL DATA AND RESULTS

The experimental tests have been done at an environment temperature of about 35^0C and a relative humidity of 40%. The car was stationed for 3600 seconds following a period of 1800 seconds with the air conditioning system opened in the city traffic and on the highway traffic. The two phases are also referred in the literature as soak, respectively cool-down.

The vehicle has got the following characteristics:
The engine is a Renault E7J and has a displacement of 1390 cm^3.

The position of the command:

Temperature: maxim cooling
Distribution: all aerators
Air flow range: medium (≈ 300 m^3/h)

Air-conditioning components:

Compressor: Sanden SD 7V16 30 SC;
Condenser: 390*310*16;
Evaporator: Valeo X65
Refrigerant: R 134a.

In order to measure the temperatures, eight thermocouples have been used (disposing in the head area and the feet area), each thermocouples was realised of chrome and constantan. The thermocouple used was type K with temperature ranges between -100 and 300°C.

The acquisition of data was been done with WebDAQ/100 system and the processing them with the personal computer. To study the temperature-time dependence, the data transfer from the acquisition system to computer was made every 60 seconds.
In both situations were the AC system has been used, its parameters were identical (temperature, flow, type).

Table 2 shows the values of the temperature of the passenger compartment

Table 2

Environment temperature: 35°C								
Relative Humidity: 40 %								
Time [s]	*city traffic*				*highway traffic*			
	Front temperature [°C]		Back temperature [°C]		Front temperature [°C]		Back temperature [°C]	
	head	leg	head	leg	head	leg	head	leg
0	60.3	58.2	54	53.4	60.3	58.2	56	54.6
300	47.2	46	45.3	45.6	45.2	46	45.3	45.6
600	38	37.2	37.5	37.2	35.7	37.8	37.1	36.3
900	35.2	33.5	34.2	34.5	31.9	32.1	32.6	33.2
1200	29.8	29.9	31.8	31.1	27.8	29.4	29.8	31.6
1500	28.2	26.7	30.6	28.3	25.6	27.5	28.1	29.3
1800	26.2	25.7	29.8	26	23.1	24.9	27.2	27.1

NUMERICAL SIMULATION AND RESULTS

The software used for the numerical simulation was Theseus-FE 3.0; its benefits are represented by the short time needed to solve the problem, the good approximation of thermal comfort and heat transfer and the reliability of results [24].

Model creation

For the numerical simulation we used the CAD model of the vehicle used in the tests, but, because we wanted to evaluate only the temperature of the cabin, we kept just the elements that compose the interior of the car.

Meshing of the model was made by Beta CAE ANSA software, obtaining a number of about 48000 elements with an average size of 20 mm and distributed to 30 groups, each group being characterized by its material properties. The manikins are standard manikins used for the Theseus-FE software, each one having around 8350 elements, divided in 48 groups. A section in the thermal finite-element model is presented in Figure 5.

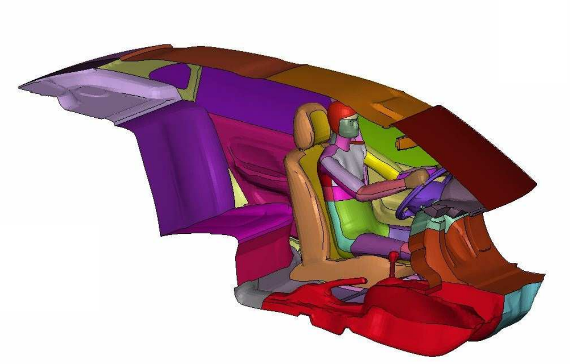


Figure 5. Section in the thermal finite-element model of the vehicle

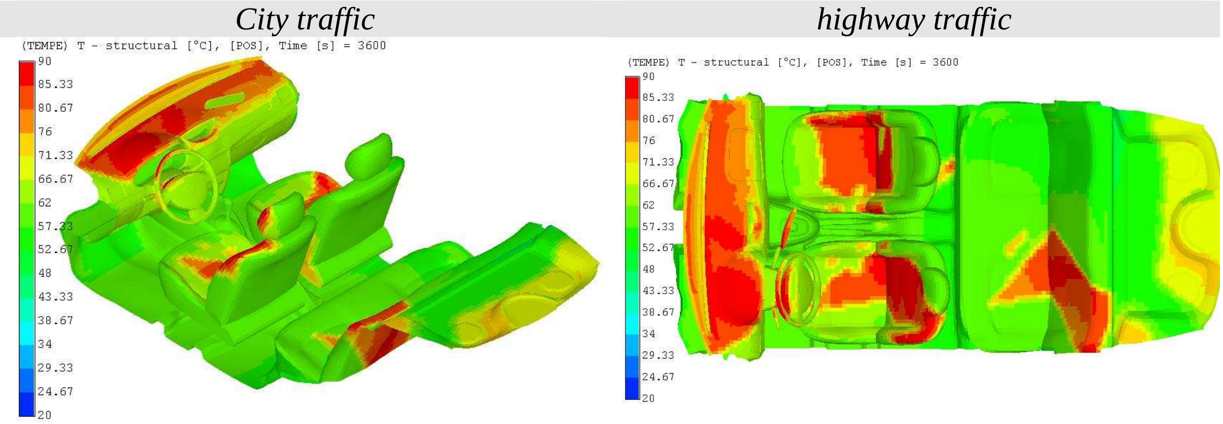
Simulation set-up

The thermal model of the car was divided in four airzones, two that represent the interior of the car and the other two that represent the dashboard and the trunk. The airzones initial conditions are presented in Table 3.

Table 3

Airzone		Volume [m^3]	Relative humidity [%]	Temperature [°C]
Interior	Front	1.5	40	35
	Back	1.25	40	35
Dashboard		0.51	40	35
Trunk		0.20	40	35

Figure 6 shows the distribution of the temperature on the passenger compartment both for city traffic and for highway traffic with a time step of 600s, with an air flow range 0.083 m^3/s for AC system the same experimental conditions.



City traffic *highway traffic*

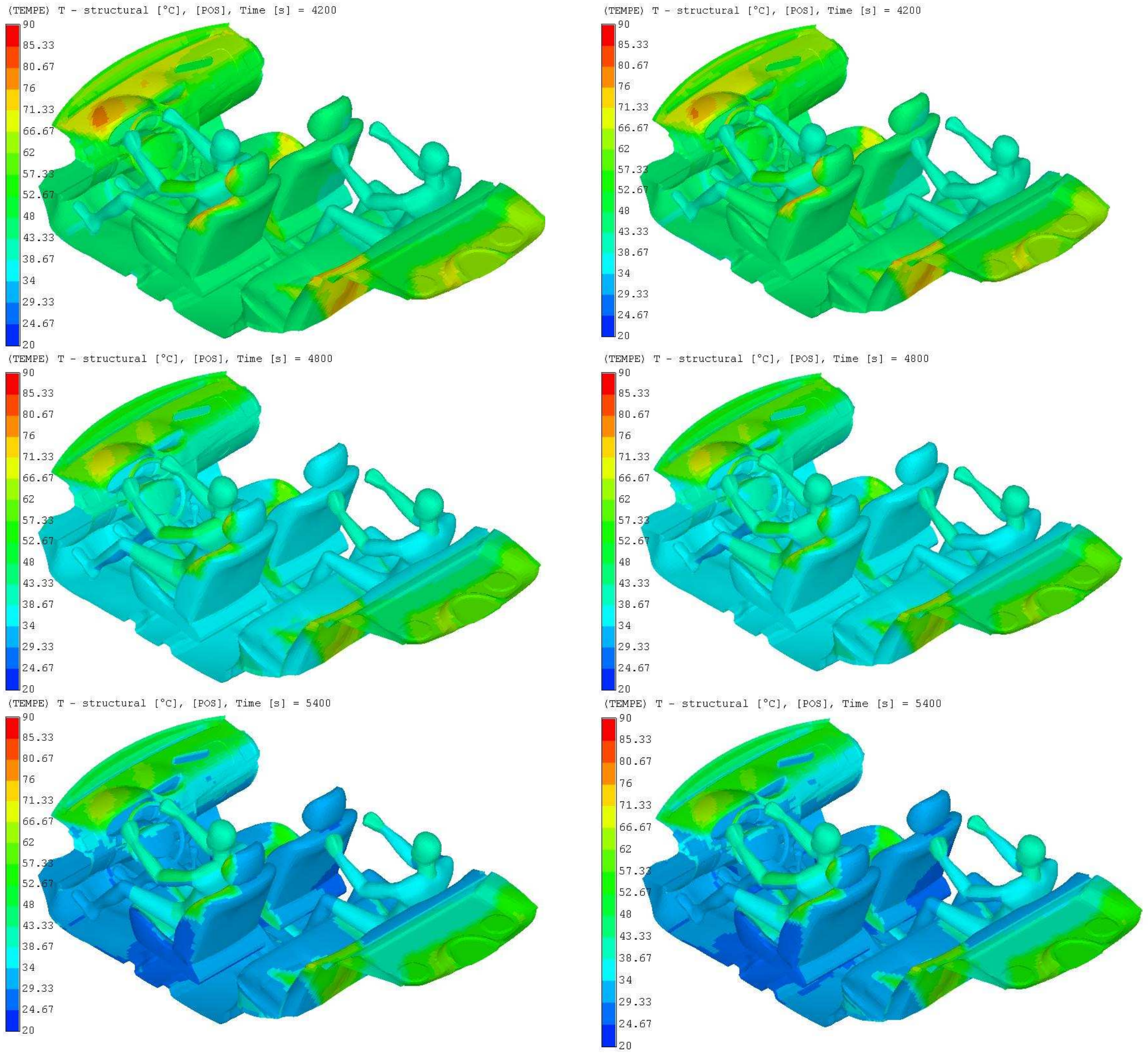


Figure 6. The distribution of the temperature depending on time for both cases

Figure 7 shows the distribution of the local equivalent temperature on each segment of manikin body after a period of time of 10 minutes, respectively 30 minutes from start-up air conditioning system.

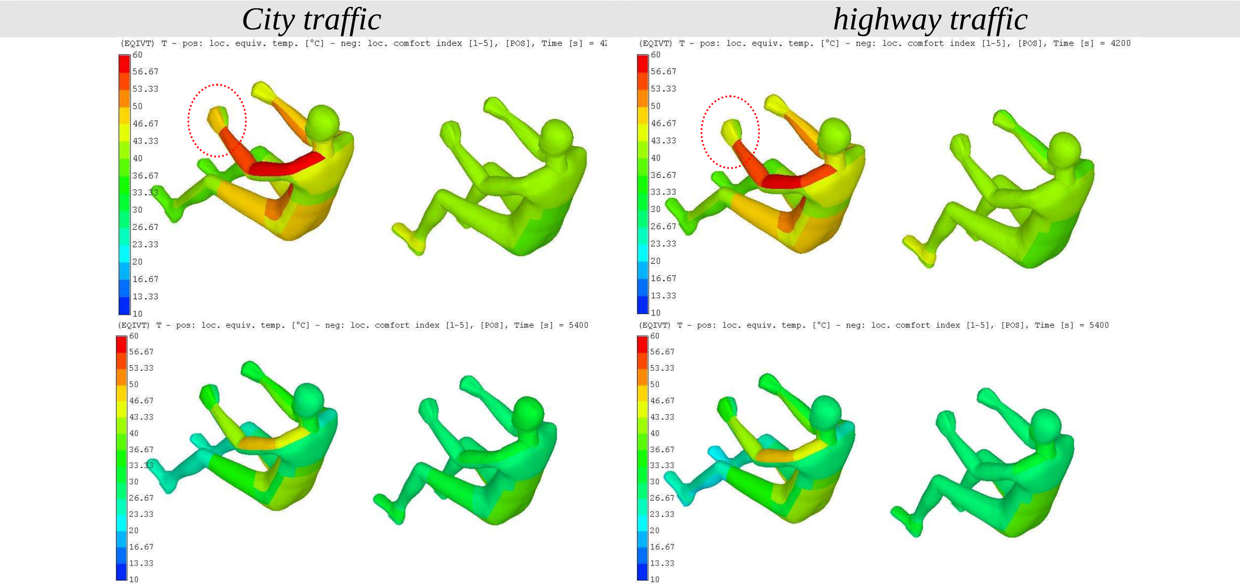

City traffic *highway traffic*

Figure 7: The distribution of the local equivalent temperature on each segment of manikin body

The Theseus-FE software has integrated functions that help finding directly the comfort indices: DTS, TS, PMV, PPD which are showed in table 4 and figure 8 for driver and table 5 and figure 9 for back passenger car when the car moving on the highway traffic. Also, in both cases are given the hypothalamus temperature T_{hy} and the mean skin temperature $T_{sk,m}$, used to calculate DTS and TS indices.

Table 4

time [s]	DTS	TS	PMV	PPD	T_hy	T_sk,m
3600	0	0	3	100	36.9048	34.4205
3900	2.95788	2.68133	3	100	36.8465	35.8244
4200	2.58996	2.69475	3	100	36.8569	35.8465
4500	2.28321	2.5709	3	99.9667	36.885	35.6698
4800	1.73285	2.31714	2.40282	91.1702	36.9184	35.4207
5100	1.25381	1.94711	1.67373	60.3405	36.9485	35.1745
5400	0.664175	1.47209	1.06144	28.7767	36.9688	34.9437

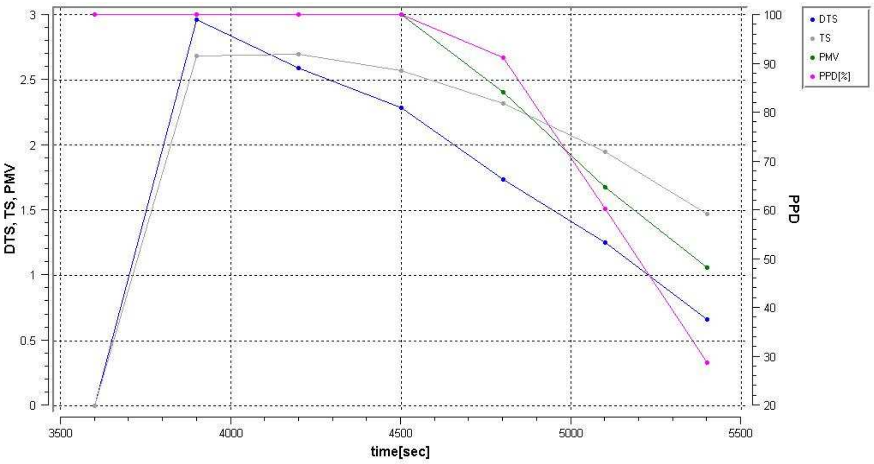


Figure 8: The variation of the comfort indices depending on time for driver

Table 5

time [s]	DTS	TS	PMV	PPD	T_hy	T_sk,m
3600	0	0	3	100	36.9048	34.4205
3900	2.89995	2.28849	3	100	36.86	35.398
4200	2.09647	2.28471	3	99.9971	36.8707	35.3951
4500	1.56807	2.05008	2.62463	95.6867	36.8921	35.2347
4800	0.843176	1.63319	1.61028	56.9046	36.9103	35.0154
5100	0.254449	1.09515	0.918628	22.8217	36.9207	34.7935
5400	-0.37798	0.486746	0.353006	7.59296	36.9234	34.5801

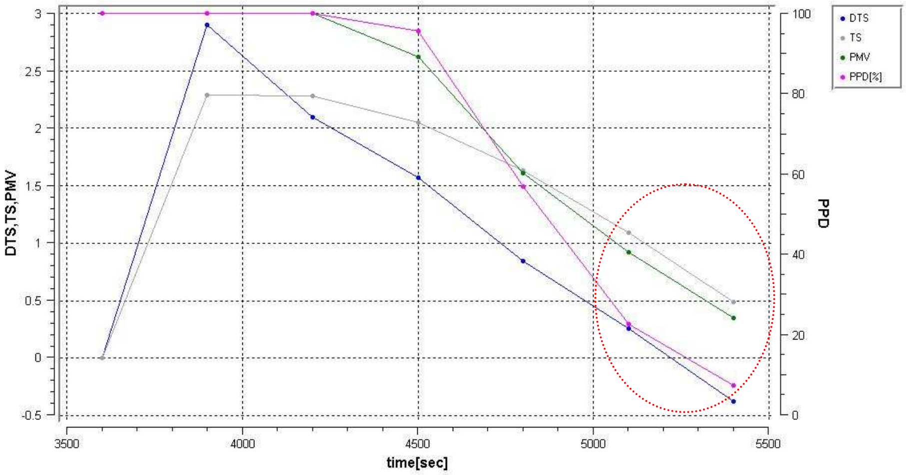
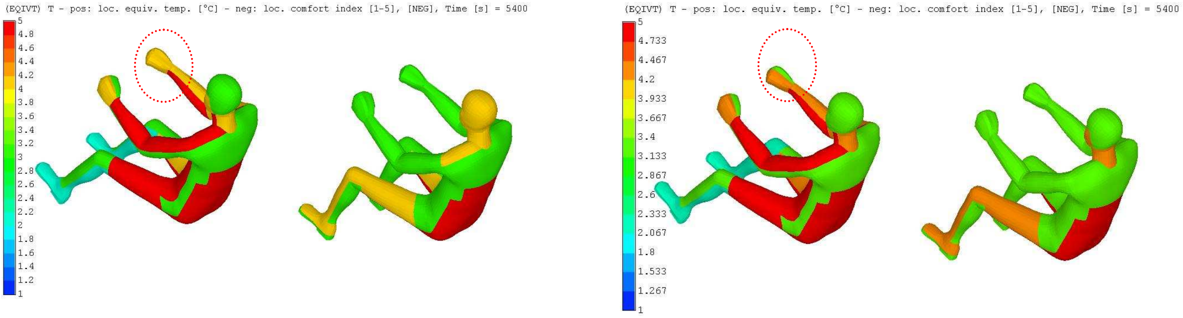


Figure 9: The variation of the comfort indices depending on time for back passenger car

Figure 10 shows the distribution of the comfort index for each segment of manikin body.



city traffic *highway traffic*

Figure 10: The distribution of the comfort index

Opening the scalar results file one can obtain the temperature values for head area and leg area, for both cases.

Figure 11 presents the date obtained on the experimental way and the numerical simulation date for city traffic.

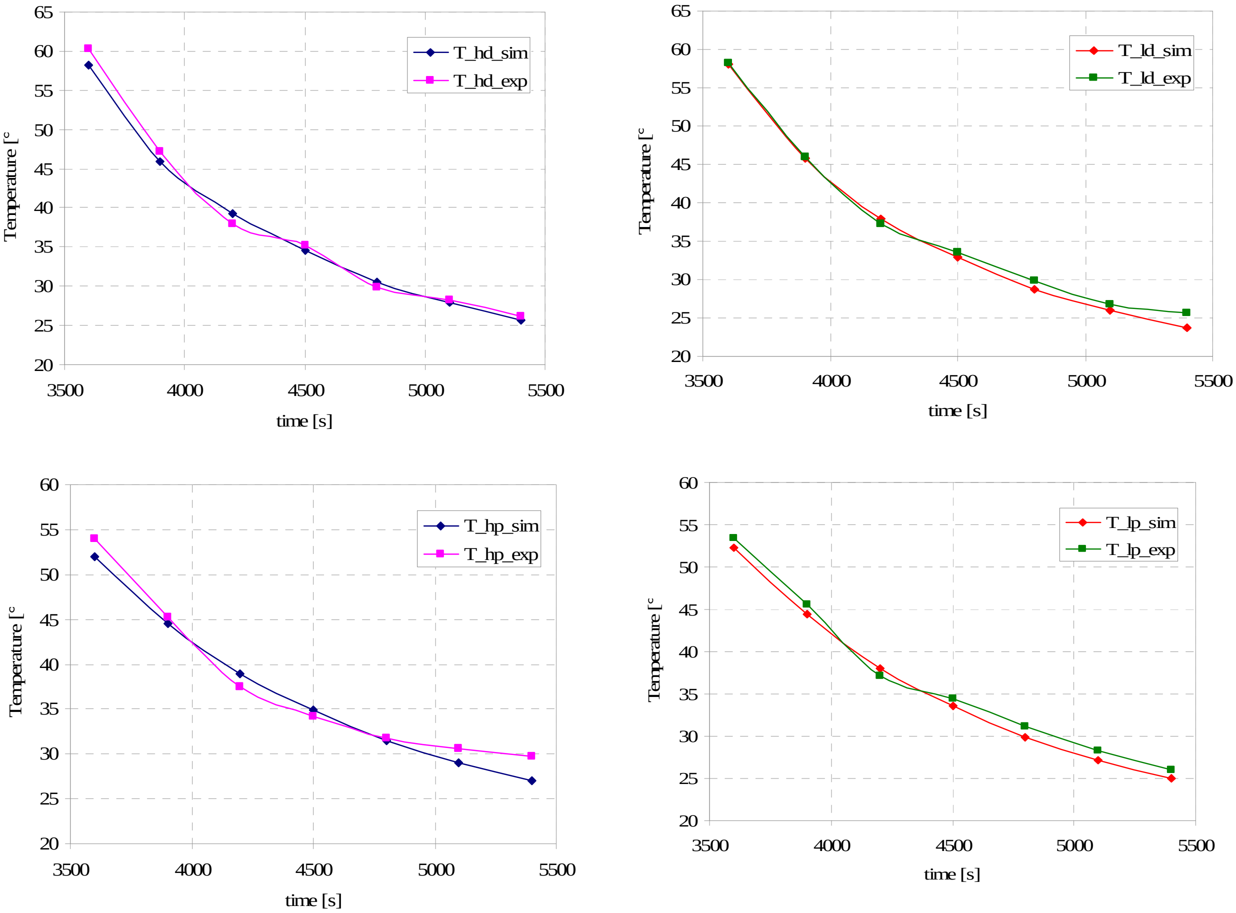


Figure 11: Temperature values for head/leg areas depending on time (city traffic)

Also, figure 12 presents the date obtained on the experimental way and the numerical simulation date for highway traffic.

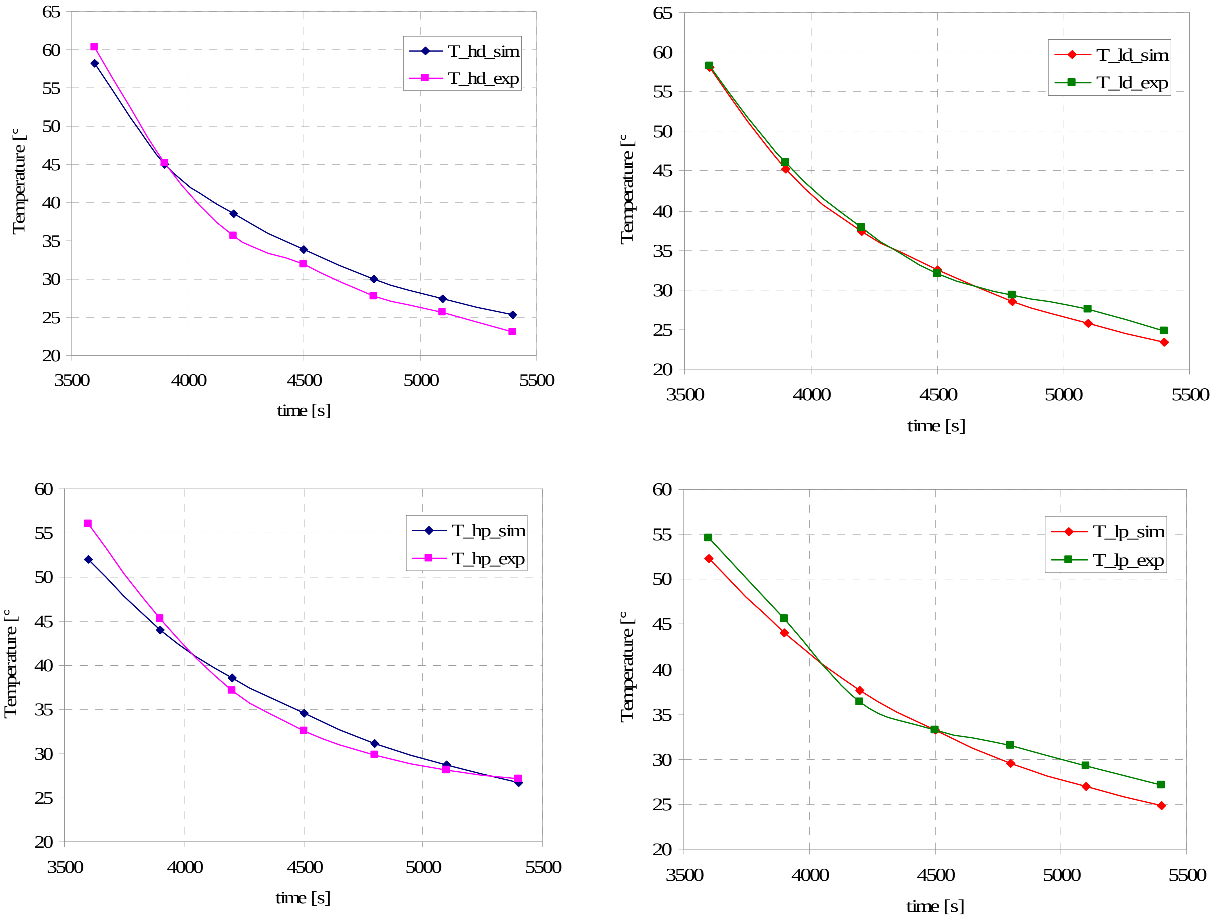


Figure 12: Temperature values for head/leg areas depending on time (highway traffic)

CONCLUSION

The climate in the passenger compartment is very inhomogeneous. The varying radiation from the sun and the influence of inhomogeneous air temperature and air velocity from the vehicle’s ventilation or air conditioning system creates a climate that may vary considerably in space and time.

Analyzing the cartographies we can observe also the influence of the sun position on the temperature of the interior components, and also on the car occupants. Analysing the figure 6 we can see that the temperature of the interior components that are in direct contact with the back passenger(rear seat) are lower that those of the components that are in contact with the driver (front seat).

From figures 8 and 9 we can observe that the back passenger reach a better thermal comfort state earlier than the driver. After 20 minutes the PMV index is about 1.06 for passenger and the value obtained of the driver is after 25 minutes. Also we can observe, comparing the obtained results with the values given in Figure 2, that after whole simulation completed, the back passenger is in the neutral thermal comfort zone, while the driver feels slightly cool.

The efficiency of the HVAC system is evaluated by taking into account the equivalent temperature, the sun position, the air velocity and the surface temperature of clothing of the passengers etc.

This numerical simulation helps us to determinate the comfort indices: DTS, TS, PMV and PPD in every moment, for different conditions and situations. Those indices are dependent of all parameters that influence the climate inside the car cabin.

Thus, we can determine the comfort indices in any given situation. The numerical simulation is a tool that can be used from the early phases of the product and help in choosing the right HVAC system for a given car.

Accurate predictions of temperature distributions in the cabin are crucial to the success of numerical simulations. The full analysis of the soak and cool-down simulations demonstrated agreement with experimental data.

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