The evaluation of the overall thermal comfort inside a vehicle

Neacsu, Catalin*, Tabacu, Ion, Ivanescu, Mariana Vieru, Ionel

1 S.C. Automobile Dacia SA
2 University of Pitesti, Romania
catalin.neacsu@renault.com

Abstract. The thermal comfort is one of the most important aspects of the modern vehicles that can influence the safety, the fuel consumption and the pollutions regulation. The objective of this paper is to compare the global and absolute thermal comfort indexes for two vehicles with different distribution air systems inside the car cockpit, one using only front air vents, and the other using both front and rear air vents. The methodology of calculus consists in using the 3D model of the interior vehicle, generally in a CAD format. Then, using a meshing software to create the finite element model of the interior surfaces inside the cockpit and the volume of internal air. Using the obtained finite element geometry, there will be conducted a Theseus FE calculus using the given boundary conditions. The results of the numerical simulation are presented in terms of graphs and figures and also PMV, PPD and DTS thermal comfort indexes. With the obtained results, we will then create the graphs that allows us to evaluate the global and absolute thermal comfort indexes. The results of the evaluation show us that the use of the method allow us to evaluate with a greater accuracy the thermal comfort for the whole vehicle, not only for each passenger, like the standard methods. This shows us that in terms of general and absolute thermal comfort, the vehicle that use front and rear systems is better than the version that use only a front system. The thermal comfort is an important aspect to be taken into account from the beginning of the design stage of a vehicle, by choosing the right air conditioning system. In addition, by using the numerical simulation, we are able to reduce the time needed for preliminary tests and be able to provide the vehicle to the market earlier, at a lower development cost.

1. Introduction
Due to increase demand of new vehicles [1], and taking into account the fact that thermal comfort is a must in the modern cars, all the manufacturers have to offer to their clients’ cars equipped with efficient HVAC systems. This need for efficient HVAC systems has determined the R&D departments to develop new tools to predict the passenger’s thermal comfort.

Tools that few years ago were used only for state of the art applications today represent the standard in the automotive industry. Therefore, the use of numerical simulation has reduced the time needed for the development of a new product or improving an existing one. The main advantages of these tools are represented by the speed, the reduced cost and one of the main aspects is the reliability of the results.

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[9]. This is described and evaluated by the following indices: DTS (Dynamic Thermal Sensation), TS (Thermal Sensation), PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied). The two first 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 [7].

In this paper, the authors will evaluate the overall thermal comfort inside a vehicle General Thermal Comfort Index (GTCI) and General Absolute Thermal Comfort Index (GATCI), presented in [2], [3]

2. Thermal comfort basic considerations

Human body's thermoregulatory system allows adjustment of physiological heat load and thermal comfort of the body in different conditions, in figure 1 being presented the processes that characterize the heat transfer between the human body and the environment. We can state that the three existent types of heat transfer affect the thermal comfort: conduction, convection and radiation.

There are six parameters that influence the thermal comfort and they can be split into environmental and personal factors [5],[7].

There is a variety of thermal comfort indexes, but the most used in the industry are PMV (Predicted Mean Vote), PPD (Predicted Percentage of Dissatisfied), DTS (Dynamic Thermal Sensation). These indexes are calculated by taking into account the parameters that influence the thermal comfort.

In [2] and [3], the authors present the development of the GTCI and GATCI indexes, that are used to evaluate the thermal comfort for the entire vehicle. So far, the thermal comfort was evaluated only for each occupant using in most of the cases the PMV, PPD, DTS and Equivalent temperature [8], [9], [10], [11]. The newly developed indexes are directly linked with the existing indexes PMV, PPD and DTS.

3. The use of the newly developed overall thermal comfort indexes

To use the newly developed thermal comfort indexes we have decided to realize a numerical simulation scenario, using a vehicle fully loaded with five occupants (four adults and one child), and this being something new in the field of the numerical simulation. In generally, the numerical simulation is conducted using only two occupants, generally placed on a vehicle diagonal (driver in front and right rear passenger).

We have chosen to use five manikins because, in the real life, the sun is not placed directly over the vehicle, but at a given angle.

The numerical simulation is done in various stages starting from the car CAD geometry we will create a shell finite element model that comprises the car interior components. The obtained shell mesh will be used, as it is to realize the Theseus-FE calculus. We will use the material proprieties for the interior vehicle parts.

The aim is to first calculate the PMV, PPD and DTS indexes for each occupant, and then, using the values obtained for the indexes to evaluate the overall thermal comfort using GTCI and GATCI thermal comfort indexes.

3.1. Model discretization

The first step of the numerical simulation is to mesh the CAD model of the interior of the vehicle, using Beta CAE ANSA software. With this program, we will add to each part of the interior an ID, used after
to assign the material properties in the Theseus FE software. In figure 2, can be seen the finite element model of the interior of the vehicle.

![Finite element model of the vehicle](image)

**Fig. 2.** Finite element model of the vehicle

### 3.2 Boundary conditions

With the discretized geometry, we will conduct the Theseus-FE simulation. Because we want to observe the overall thermal comfort indexes, we will realize two numerical simulations, using different boundary conditions.

- **Soak:** the vehicle is placed under the environmental conditions without the AC on and without the manikins. Generally, this stage is about 3600-7200s.
- **AC simulation:** after the soak simulation, the manikins are placed inside the vehicle and the air conditioning system is turned on.

As exterior boundary conditions, we will use data from table 1. 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 3.

| Parameter                          | Case 1 | Case 2 |
|------------------------------------|--------|--------|
| Solar radiation intensity [W/m²]   | 850    | 1000   |
| Diffuse solar intensity [W/m²]     | 140    | 100    |
| Sun azimuth angle [°]              | 135    | 315    |
| Sun altitude angle [°]             | 63.5   | 78     |
| Ground reflectance                 | 0.2    | 0.25   |
| Environmental temperature [°C]     | 30     | 40     |
| Environment humidity [%]           | 40     | 10     |
| Sky mean radiant temperature [°C]  | 10     | 12     |
After the soak simulation, we will realize a simulation where we will start the HVAC system with five occupants inside the vehicle, as it can be seen in figure 4. The HVAC boundary conditions are presented in table 2.

| Time [s] | Temperature[°C] | Flow [m3/s] |
|----------|-----------------|-------------|
| 3600     | 36              | 0,125       |
| 3750     | 20              | 0,125       |
| 3900     | 15              | 0,125       |
| 4150     | 7               | 0,125       |

### 3.3 Results

Using the boundary conditions presented earlier, the obtained results for the simulations are presented in table 3 and in figure 5.

| Time (s) | Case 1 (°C) | Case 2 (°C) |
|----------|-------------|-------------|
| 0        | 30.0        | 40.0        |
| 600      | 37.1        | 47.5        |
| 1200     | 41.8        | 52.6        |
| 1800     | 44.9        | 56.0        |
| 2400     | 47.3        | 58.6        |
| 3000     | 49.0        | 60.5        |
| 3600     | 50.4        | 62.0        |
| 4200     | 20.1        | 23.4        |
| 4800     | 18.0        | 20.9        |
| 5400     | 17.3        | 20.0        |

As we can see from table 3 and figure 5, after the soak period, the temperature inside the car is 50.4°C for Case 1 and 62°C for Case 2. After starting the AC systems, in 10 minutes, we will have a drop in
temperature inside the vehicle over 30°C for both cases. This proves that the AC system, on the maximum speed helps reduce the temperature inside with a great amount. The downside of this, is represented by the noise produced from the fan on the highest setting.

In figure 6 are presented two images with the temperature on the vehicle components at the end of the simulation.

![Figure 6. Temperature distribution on the vehicle parts](image)

Althought, the exterior temperature and solar radiation intensity are bigger in the Case 2, compared to Case 1, the position of the sun at an altitude angle of 78° means that a bigger part of the radiation are received by the roof of the car, so that translates in a lower temperature on the interior at the end of the simulation.

The first evaluation of the thermal comfort is done by analyzing the local comfort indexes according to ISO 7730[7]. As we can observe from the figure 7, the majority of parts are placed in the thermal comfort neutrality, the only parts that presents some kind of discomfort are the ones placed in the direct sun via the glass surfaces.
Case 1
Figure 7. Local comfort indexes at the end of the simulations

The parameters that are needed to calculate the GTCI and GATCI are presented in Table 4 and in Figure 8.

Table 4. Thermal comfort indexes at the end of the simulation

| Case | Driver | Front passenger | Rear left passenger |
|------|--------|-----------------|---------------------|
|      | PMV    | PPD(%)          | DTS                 | PMV    | PPD(%) | DTS     | PMV    | PPD(%) | DTS     |
| Case 1 | -0.1   | 5.4             | -0.8                | 0.0    | 5.0    | -0.7    | -0.4   | 7.9    | -1.2    |
| Case 2 | 0.7    | 14.0            | -0.1                | 0.3    | 7.5    | -0.4    | -0.3   | 6.4    | -1.1    |
|       |        |                 |                      |        |        |         |        |        |         |
| Rear center passenger | Rear right passenger |
| Case 1 | -1.0   | 25.0            | -1.7                | -1.1   | 29.6   | -1.8    |
| Case 2 | -0.2   | 6.0             | -1.0                | 0.2    | 5.7    | -0.6    |
Using the values presented in table 4 we will construct the diagrams for GTCI and GATCI index comfort. The diagrams are presented in figures 9 for GTCI and 10 for GATCI.

Calculating the surfaces under the figures, we will obtain the results presented in table 5.

| Case   | GTCI  | GATCI |
|--------|-------|-------|
| Case 1 | 2.801 | 1.756 |
| Case 2 | 2.003 | 0.414 |
| Target | 1.993 |       |
The results in terms of GTCI and GATCI are similar to those from the local comfort indexes. We can observe that for the Case 2, the GATCI value proves that all the manikins are near optimal thermal comfort.

In addition, another benefit of the newly developed index is represented by the GTCI index, that shows where, compared to the ideal condition, the vehicle is placed. In our case, we can observe that for the Case 2, all the passengers in the vehicle are situated near the optimal thermal comfort.

4. Conclusions
The thermal comfort is characterized by different indexes and we must define a link between those indexes and the general thermal comfort. The graphs are constructed taking into account the value of the thermal comfort indexes for all the vehicle occupants, and the GATCI and GTCI are defined by the area of the surfaces.

The use of those new thermal comfort indexes helps us to understand if all the occupants have reached optimal thermal comfort and also via GTCI and also compare two technical solutions for the HVAC systems by evaluating the GATCI.

Acknowledgement
This work was supported by a grant of the Romanian National Authority for Scientific Research, UEFISCDI, project number PN-II-PT-PCCA-2013-4-0569

References
[1] http://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_cars_in_the_EU
[2] Neacsu CA et al 2015 The Development of a New Thermal Comfort Indexes Proceedings of the European Automotive Congress EAEC-ESFA 2015 pp 703-714 - Springerlink
[3] Neacsu CA – 2011 – Contribuţii privind optimizarea confortului termic din habitaciu folosind simularea numerică - Teza de doctorat
[4] Paulke S (2008) Thermal comfort design and assessment of vehicle cabins with THESEUS-FE, HdT seminar. München (14.10.08)
[5] ISO/TS 14505-1:2007 (2007) Ergonomics of the thermal environment—evaluation of thermal environments in vehicles—part 1: principles and methods for assessment of thermal stres
[6] Neacscu CA et al 2009 The influence of the solar radiation on the interior temperature of the car - Proceedings of the European Automotive Congress EAEC-ESFA 2009
[7] ISO 7730 (1984) Moderate thermal environments—determination of the PMV and PPD indices and specification for thermal comfort. International Standards Organization, Geneva
[8] Baker, P, Jenkins, M., Wagner, S., Ellinger, M. - An optimised thermal design and development process for passenger compartments, European Automotive Simulation Conference, Munich, Germany, 2009
[9] Nilsson, H, Holmér, M., Bohm, O. - Definition and theoretical background of the equivalent temperature. Assessment of thermal climate in operator’s cabs - seminar in Florence 18 –19 November 1999
[10] Nilsson, H. - Comfort Climate Evaluation with thermal manikin method and computer simulation models, ISBN 91-7283-693-8, 2004
[11] Nilsson, H. - Thermal comfort evaluation with virtual manikin method, International Journal of Building and Environment, 2007