Development of a human thermal model to predict seat occupant thermal comfort

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Abstract While heated and cooled seats used to be integrated only in luxury cars, a wider range of carmakers proposes now such seats for their midrange market too. The design of heated or cooled seats, as well as their optimization to effectively increase the thermal comfort of the occupant, is very complex. Each of the interactions between the occupant, the seat cover, the cushion foam, and the heating or ventilation systems has to be taken into account, as the thermal comfort feeling of the occupant, which is highly subjective.

The use of virtual seat prototyping to predict the thermal comfort of a driver seating in a heated or cooled seat enables to answer effectively such a car interior design challenge. However such simulations require the use of digital human models including human body thermal behavior and objective thermal comfort criterion.

This paper presents the latest developments performed on Virtual Seat Solution Human Models to include human thermal modeling and thermal comfort criteria. The developed human model is then used with a virtual seat prototype equipped with heating pad to predict the thermal comfort of the occupant in various configurations.

Keywords: Thermal comfort, Human model, Virtual Seat Prototype, Heated, Ventilated, seat, Simulation

1 Introduction

This paper investigates how virtual seat prototyping and digital human thermal models can be used to find the right car interior design, optimizing both the energy consumption of an electrical vehicle and the comfort of the driver. After a brief description of ESI digital thermal human model and virtual seat model, it will be shown how to predict accurately the thermal comfort of a car seat occupant. Then a case study based on a car cabin temperature decrease, to improve an electrical car range, will be performed to investigate the effects on the thermal comfort of the seat occupant, with and without using seat heating system. The impact on the energy consumption and range of an electrical vehicle will be highlighted.

The paper will then show how digital human model combined with virtual testing can be used to optimize seat heating system to improve the thermal comfort of a seat occupant.

2 Thermal comfort of a seat occupant

2.1 Virtual seat and digital human model

2.1.1 Virtual Seat Prototype

A seat model is first created, with the objective of having a very realistic model, representing a behavior close to a real one: it contains all the seat components: frame, suspensions, foam blocks, heating pad, cover and padding with related attachment systems.

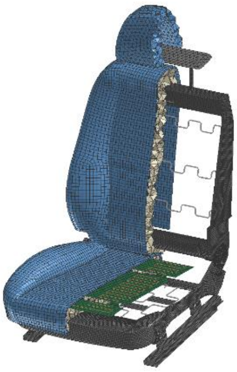


Figure 1. ESI's Virtual Seat Model

The frame is considered as rigid since the model will be used only for seating and thermal comfort simulation but all other components are deformable and connected the ones to the others through joints and contacts.
This modelling method has been extensively validated through comparison between simulations and real tests, regarding H-Point and pressure distribution measurements. [5] [6] [7] [8] [9].
Thermal material properties are added to the seat components, having a significant influence on the global thermal seat behavior, such as trim components (cover, foam and padding).
A heating system is incorporated inside the seat. The heating pad is modelled with beam elements representing the electrical wires, embedded in shell elements representing the unwoven fabric. A thermostat with sensors positioned on the cushion is added to the heating system.

2.1.2 Digital human model

Several human model anthropometries are available within the complete human model library of ESI's Virtual Seat Solution.

Figure 2. Examples of ESI's human models

For each finite element human model, an adapted thermal behavior has been integrated. It contains two main parts:

- A thermal passive system

The thermal passive system models the heat transfer conducted inside the body through conduction and blood circulation. It takes also into account the heat generation coming from the human basal metabolism or from the mechanical activity of muscle. Additionally the external heat exchanges through sweat evaporation, breath, convection, conduction and radiation are simulated, taken into account the clothes worn by the occupant.

- A thermal active system :

An active system representing the thermoregulation system of the human body (vasodilatation, vasoconstriction, shivering and sweating) is added to the human models. This thermoregulation is per nature transient and requires thus the direct coupling of the human model and the simulation of its environment: seat and air. The thermal behavior of the digital human models has been validated using data from independent experiments in literature (figure 3).

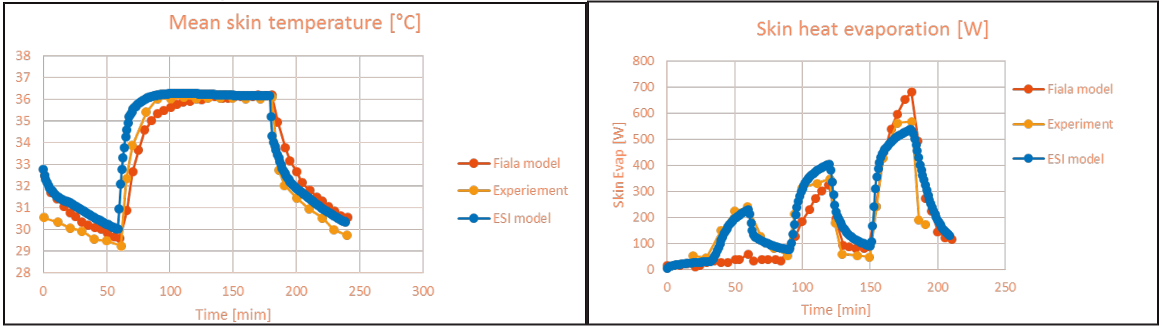


Figure 3. Example of comparison between thermal behavior of ESI's human models, Fiala model and experimental results.

The complete results comparison campaign showed good correlation with measured data.

2.2 – Virtual seating of human model

An exact prediction of the contact area between the seat and the occupant is important to calculate accurately the heat conduction between the seat and the human body (figure 4).

Figure 4. Seating of occupant and contact area Simulated with ESI Virtual Seat Solution

Similarly the simulation of the local pressure mapping and foam deformations under seated occupant (figure 5) enables a precise calculation of the heat conduction inside the seat, as it has been shown in previous paper [3].

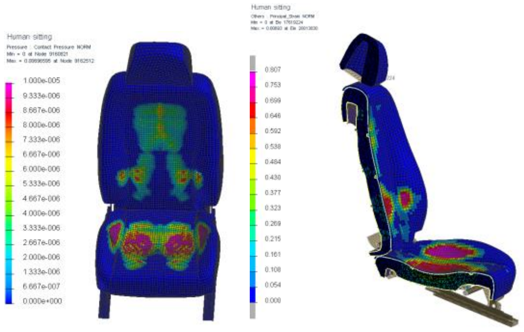


Figure 5. Seat pressure and foam deformation Simulated with ESI Virtual Seat Solution

2.3 - Thermal comfort criterion

The objective of defining a thermal comfort criterion is to have an objective criterion to support the design of seat heating and cooling system or global thermal management of the car cabin. The thermal comfort criterion which has been developed is partially based on the work of Zhang at UCB (University of California Berkeley). Based on experimental data, Dr. Zhang has established a direct relationship between objective values (skin temperature, skin temperature variation…) and the subjective feeling of comfort/discomfort.

The developed comfort criterion is not only adapted to transient environment, but also to non-uniform environments. This second point is very important in the car cabin environment, as for instance the seat introduces a high asymmetry between the heat transfer in the front of the occupant (convection) and the back of the occupant (conduction with seat). To take into account the asymmetry, the human body is divided into many parts, each part being divided into two to three sectors, having a local thermal value.

To calculate thermal comfort, Zhang has introduced the thermal sensation, which is easier to understand. In an environment where the temperature is far below (or above) the temperature needed for neutral sensation, one will feel cold (or hot) and in a discomfort situation.

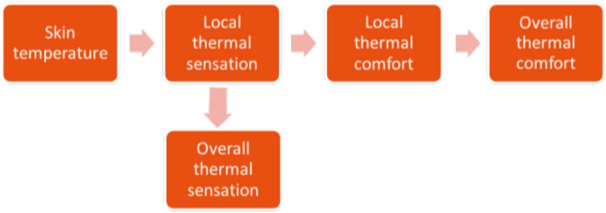
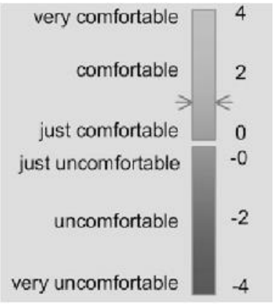


Figure 6- Model for prediction of Thermal Sensation and Comfort from physiological information e.g. skin temperature

Thermal comfort index and thermal sensation index are fixed by Zhang in a scale between -4 and 4. Figure 7 shows relation between each thermal sensation and its index value (from very hot to very cold sensation) and relation between thermal comfort and its index value.



Index value	Thermal sensation
4	Very hot
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold
-4	Very cold

Figure 7. Thermal comfort and Thermal sensation indexes

3 Effect of cabin temperature decrease on seat occupant comfort

3.1 Weather temperature and electrical vehicles range

To study a concrete example, let’s choose a standard electric vehicle with average range of 130 Km Nissan leaf 24kWh [4].

Information collected by society FleetCarma from Nissan Leaf users has shown that vehicle autonomy can decrease by over than 40% in cold weather (figure 8). The main reason of this, is energy consumption used on car cabin heating.

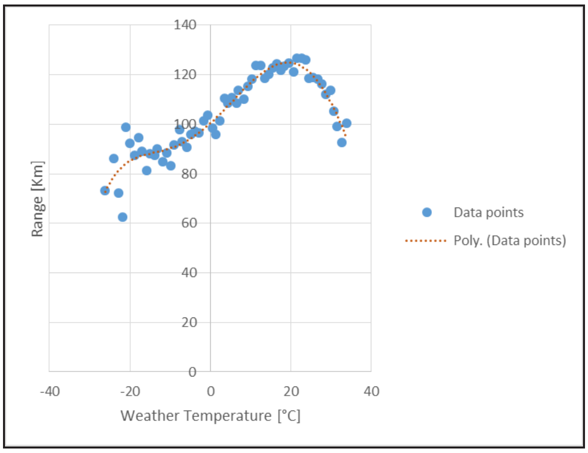


Figure 8. Nissan Leaf Energy consumption vs temperature

These results highlight the importance of optimizing the HVAC of electric vehicles, not only to optimize thermal comfort but also to minimize energy consumption and to increase electric vehicle's autonomy.
To minimize HVAC energy consumption in cold weather, it is possible to decrease the global car cabin temperature and add a seat heating system to compensate and maintain the thermal comfort of the occupant. Simulation can be used to test such scenario and find an optimum thermal management system.
Let's first investigate what happens on seat occupant when the car cabin temperature decreases from 18°C to 15°C.

2.2 Effect of a 3°C decrease in the cabin on seat occupant thermal comfort

To compare the influence of a decrease of 3°C in the car cabin on the thermal comfort of the seat occupant, the following scenario is simulated:

1. The human model is initially outside the car.

Outside temperature	-10 °C
Outside humidity	80 %
Outside Air velocity	10 m/s

He wears winter clothing, providing adapted insulation. He walks (from a building to the car) during 2 minutes with a moderated speed, which is equivalent to 2.5 met.

2. After he enters in the car, which is at -10°C, the HVAC is activated to reach 15°C or 18 °C after about 5 min.

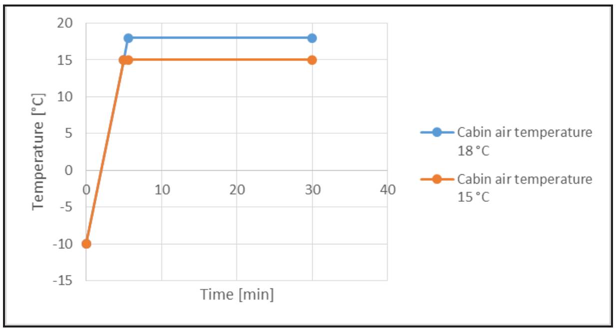


Figure 9. Car cabin air temperature vs time

Let's first compare overall thermal comfort and overall thermal sensation of the seat occupants in the two configurations (15°C and 18°C):

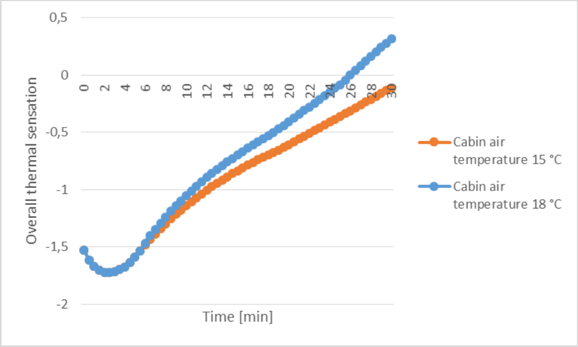


Figure 10 – Overall thermal sensation

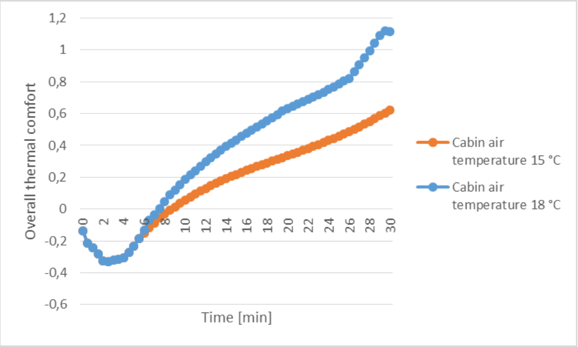


Figure 11 – Overall thermal comfort

The results for overall comfort & sensation (figures 10 and 11) are as expected: the occupant in the car cabin at 18°C feels more comfortable than the one in the car cabin at 15°C. To investigate if the difference is due to specific body parts or is the same in all body parts, it is interesting to analyze locally thermal comfort and sensation for all the body parts, focusing on those which show local comfort advantage at 18°C.
If we look at the local thermal comfort index, there are four parts having an index at 15°C below the index at 18°C: Arm, Foot, upper Abdomen and lower abdomen (figure 12).

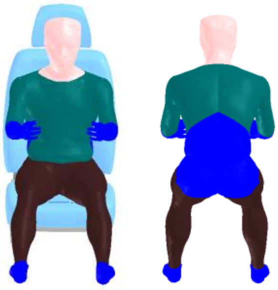


Figure 12. Highlighted in blue, parts where local comfort index at 15°C below the index at 18°C

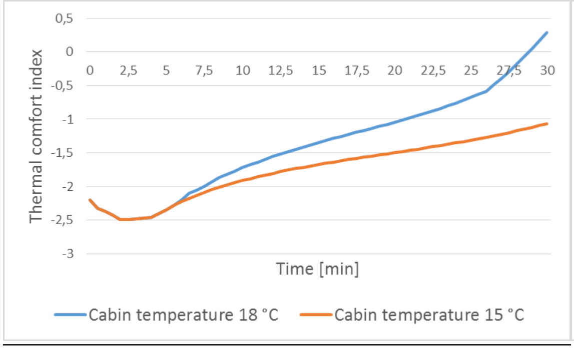


Figure 13a – Arm thermal comfort

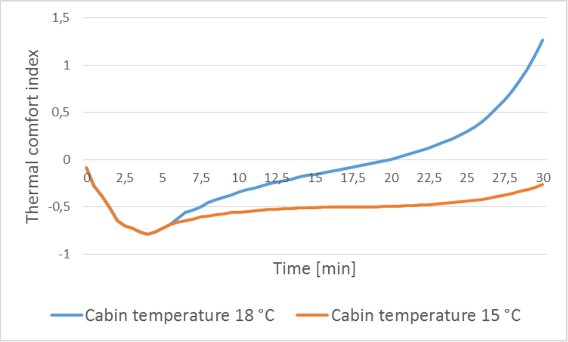


Figure 13b – Foot thermal comfort

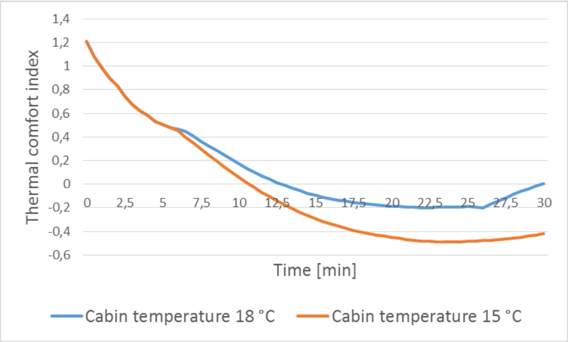


Figure 13c – Upper abdomen thermal comfort

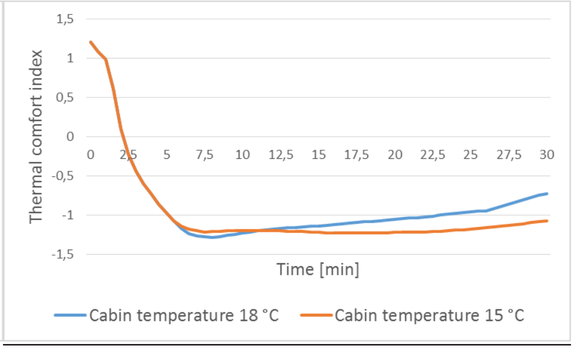


Figure 13d – Lower abdomen thermal comfort

The analysis of the simulation shows that in order to increase overall thermal comfort of the seat occupant in a car cabin at 15°C, local thermal comfort of these four body parts must be increased.
As the abdomen parts are in contact with the seat, it can be supposed that an active heating seat could impact positively the local and thus the overall comfort in a colder car cabin environment.

2.3 Use of heating system and effect on seat occupant thermal comfort

Based on the previous analysis, let's investigate how an active heating seat could contribute in keeping the same level of comfort for the occupant without increasing car cabin temperature. The study focuses on the improvement of local thermal comfort in the lower abdomen area, by activating a heating pad system in the virtual seat prototype.
The heating pad is piloted by a thermostat, used to control heating cycles (the on/off status) and maintain the temperature between two limit values. The heating pad stays ON until the seat has reached the maximum prescribed temperature and it is then turned off until the seat temperature is lower than the minimum temperature limit.
The same scenario than in previous paragraph is simulated, in a car cabin at 15°C with a heating pad, piloted by a thermostat with two temperature limits of 31°C and 33 °C measures by sensors on the seat cushion.

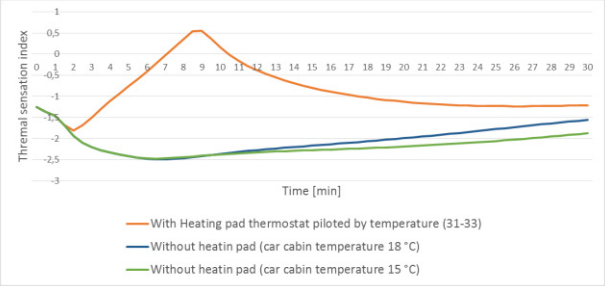


Figure 14a. Lower abdomen thermal sensation

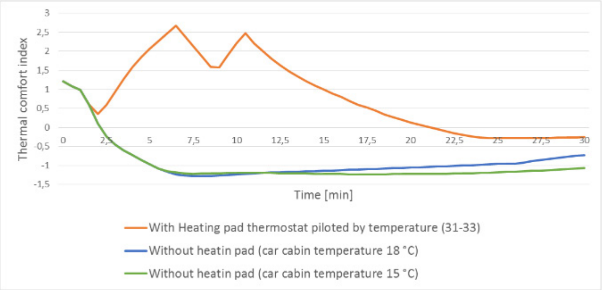


Figure 14b. Lower abdomen thermal comfort

The figure 14b shows that the thermal comfort in lower abdomen has increased and becomes even more comfortable than in a car cabin at 18°C. The same can be done for the upper abdomen part, by using a heating pad in the seat backrest.
The other body parts thermal comfort (arm and foot) could not be improved by seat heating system since there is no contact between them and the seat. Other local solution, such as radiation panels can be used.
The use of virtual seat prototyping with digital human model helps finding solution to reduce the cabin temperature (in this case of 3°C), without decreasing thermal comfort of the occupant. Such solution will contribute to reduce the car energy consumption and thus the range of electric car vehicle:
Applied on a car such as the one illustrated in paragraph 3, it can be calculated that:

- In cold weather, by activating the HVAC to maintain the car cabin temperature, the car loses more than 40 % of its autonomy, which is equivalent to 8 Kwh (in two hours if we suppose vehicle average speed is 45 Km/h).
- On the other hand heating pad with electric power of 40 W will consume 80 Wh in two hours, which represent 1% of the energy consumption of the global HVAC system. This value can even be reduced by half if we take into account the heating cycles of the heating pad (In two hours driving, heating pad will be on, only one hour).

This means that the car energy consumption by the HVAC system in electrical vehicles can be reduced by over than 10%, the vehicle range increased by 4%, all this without any thermal discomfort.

4 Heating system optimization

Let's now investigate how the simulation can help optimizing the heating system, described in the previous paragraph to maximize the thermal comfort of the occupant. A comparison of local comfort in the lower abdomen area will be performed between five different configurations:

- For four configurations, the heating system is piloted by a thermostat with a temperature sensor positioned placed on the seat cushion. Different intervals of temperature limits are defined for the thermostat, 31°C-33°C, 32°C-33°C, 32.5°C-33.5°C and 33.5°C-35.5°C.
- One configuration with a heating system piloted by the optimum occupant local thermal sensation index, close to zero.

The same scenario as in previous paragraph is used for the driver, the car and the outside conditions, with a car cabin warmed at 15°C.
The following results are obtained:

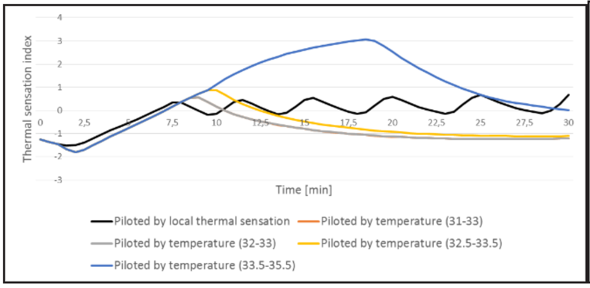


Figure 15a. Lower abdomen thermal sensation

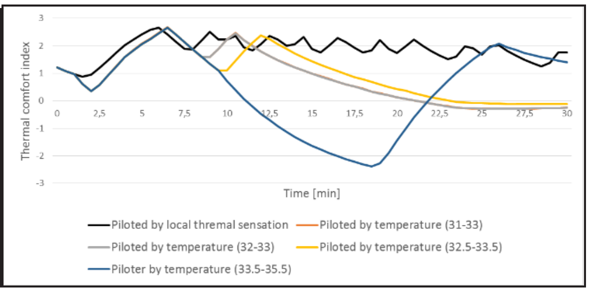


Figure 15b. Lower abdomen thermal comfort

Even if heating pads are supposed to improve thermal comfort, an incorrect definition of the heating cycle may lead to discomfort:
In figures 15, the heating pad piloted by temperatures interval does not enable to reach a good thermal comfort level:

- The temperature interval 33.5°C-35.5°C leads to over-heating, as shown by the sensation index superior to 1, until reaching the index 3
- The other temperature intervals lead to under-heating, with a sensation index close to -1, remaining at that level.

The piloting of the heating pad by sensation index, enables to reach a good thermal comfort level along time. We can then use its heating time cycle, to pilot the thermostat.

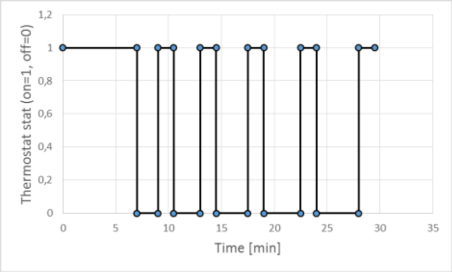


Figure 16. Heating cycle output form simulation with thermostat piloted by thermal sensation

The analysis of this heating time cycle shows that, after a heating period of 7 min, the heating system alternates between two states: off for 120 to 240 seconds and on for (90 seconds). An average heating cycle is then defined (figure 17).

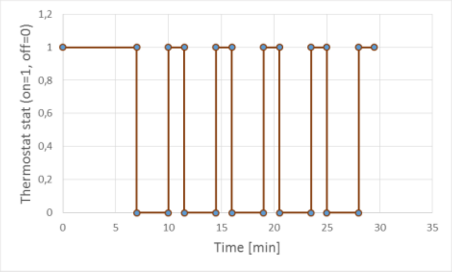


Figure 17. Heating cycle approximation of the heating deducted from thermal sensation

Figure 18.b, below, shows that with this new heating system a better level of comfort is reached. Such heating system definition and optimization by simulation could be performed for different scenarios (with different thermal conditions) and for different human anthropometries.

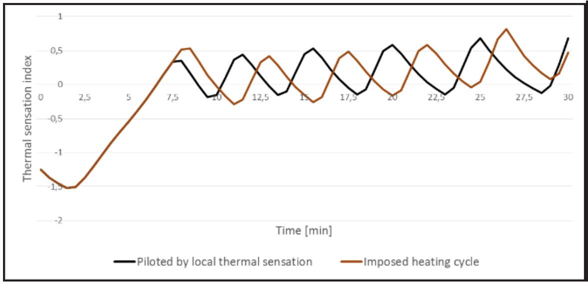


Figure 18a. Lower abdomen thermal sensation

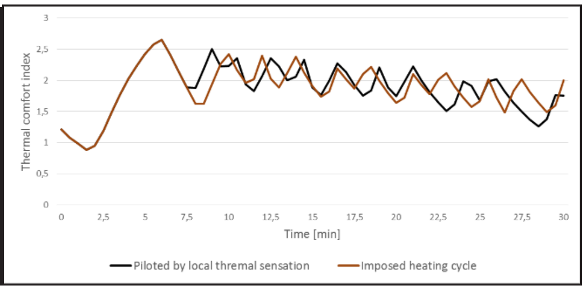


Figure 18.b Lower abdomen thermal comfort

Table 1 shows warm up duration, energy consumption and average thermal comfort, for the four heating thermostat piloted by temperature, the one piloted by thermal sensation, and the optimized heating system with imposed time cycle.

Heating system piloted by:	Warm up Duration [min]	Power consumption [Wh]	Mean Comfort
Thermal Sensation	15	5	1,87
Imposed	14.5	4.83	1.87
T [32,33]	9	3	0,82
T [32.5,33.5]	10	3,33	0,95
T [33.5,35.5]	19	6,33	0,42

Table 1. A comparasion between different heating systems

As mentioned previously, energy consumption of heating system embedded in car seat is negligible compared with energy consumption of the global HVAC system of an electric vehicle.

5 Conclusion

This paper shows with a simple example how the simulation coupling virtual seat prototype and human thermal model can support engineers in managing both the thermal comfort of the seat occupant and the electrical vehicle range. Next step is to add to this seat, human model and cabin environment coupling, the computation of fluid dynamics, both in seat-embedded ventilation systems and in the car cabin, as system management between the different possible heating systems (seat, HVAC…).

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