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Coupling Human Models, Virtual prototypes of heated Seats and HVAC fluid behaviour to both improve the passenger thermal comfort and reduce the energy consumption of electric vehicles

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Summary

As mobility is transforming, most automotive manufacturers are either developing or commercializing electric vehicles (EVs). The range of these electric vehicles is a critical hurdle in broadening their adoption. The paper particularly focuses on an innovative solution coupling virtual seat prototypes behaviour, human model and HVAC through computational fluid dynamic. This smart embedded solution enables interior and seat engineers to replace real tests with virtual tests and reduce the cabin energy consumption, while improving the thermal comfort of the car occupants

In this paper, we will first present ESI's human models, virtual seat prototype, and virtual cabin modelling. Then different test cases, initiated in the frame of the OPTEMUS project "Optimized Energy Management and Use" (Horizon 2020 European Union for Research and Innovation funded project) will be presented, showing the coupling and interactions between these different models. These test cases aim at demonstrating how the usage of seat heating pads while reducing the HVAC system contribution can support cabin energy consumption reduction and thus increase the range of electrified car.

Contents

1 Introduction

Over the past few years, most of the automotive manufacturers have developed and commercialized electric vehicles. Last year, for the first time, global sales of new electric vehicles passed 1 million units, according to McKinsey's Electric Vehicle Index. Under the current growth trajectory, EV producers could almost quadruple that achievement by 2020, reaching 4.5 million units, around 5% of the overall global light-vehicle market. However, their low range and their cost prevent them to be adapted largely by the customers. Nowadays efficient electrified vehicles have an autonomy between 300 and 400 km. This performance is obtained when the HVAC system is off. Its activation reduces the range of the car, in severe condition by 40%. There is a clear need to reduce the thermal energy consumption and thus to improve the car range without impacting the level of the occupant's thermal comfort.

To overcome this challenge, interior and seat engineers must iterate quickly on different scenarios without impacting the final delivery schedule. With ESI's virtual prototyping solutions for seats and interiors, engineering teams test occupant thermal comfort, considering heated seats and the overall cabin HVAC system, for both nominal and in-operation conditions.

The paper presents a smart approach that is used to replace real tests with virtual tests and reduce the cabin energy consumption.

2 Virtual Seat Prototype

2.1 Mechanical Behaviour

The objective is to have a very realistic model, representing a behaviour close to a real one: it contains all the seat components: frame, suspensions, foam blocks, heating pad, cover and padding with related attachment systems.

The frame is considered as rigid since the model will be used only for seating and thermal comfort simulations, but all other components are deformable and connected with each other 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 [1] [2] [3].

In addition to the mechanical properties defined here before, some thermal material properties must be added to simulate the heat transfer phenomena. Two main parameters are fulfilled for the thermal properties of the seat materials, the conductivity and the specific heat capacity, as defined by the Fourier's law:

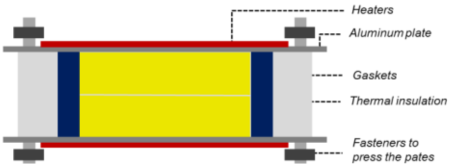

Figure 1: Heating pad positioned on the foam skin ESI Copyright

$$\rho C \frac{\partial T}{\partial t} = div\left(\lambda \overrightarrow{grad}(T)\right) \quad (1)$$

$$\begin{cases} \rho \text{ is the mass density} \\ C \text{ is the specific heat capacity} \\ \lambda \text{ is the conductivity} \end{cases}$$

Both can be set as constant or temperature dependent in ESI Virtual Seat Solution. Conductivity can also be made dependent on the level of compression reached by the material after an occupant is seated. This is what is done especially at the foam level in the seat model. [4][5][6][7]

2.2 Heating Pad Modelling

The heating pads are modelled as beam elements representing the electrical wires, embedded in shell elements representing the unwoven fabric.

2.3 Conduction Modelling

As indicated previously, contacts are defined between the different sub-components: foam, heating pad and cover. Again, these contacts are defined to manage the mechanical interaction, but also for the thermal interaction defined through a conductance value which is a function of the distance between the two interfaces. If those two interfaces are in contact, the heat is transferred without loss and, the more the two interfaces are distant, the less heat is transferred.

2.4 Convection Modelling

The loss of heat by convection with air is modelled through a constant coefficient applied on all external surfaces of the seat.

Figure 2: ESI's Virtual Seat Model with heating pad

3 Human Model

Several human model anthropometries are available within the complete human model library of ESI's Virtual Seat Solution. These human models have been developed for seat comfort evaluations, such as seating posture, pressure maps and dynamic comfort evaluation.

Figure 3: Examples of ESI's human models ESI Copyright

Mathematical models aiming at predicting human thermal sensation rely on the computation of the body thermal balance. The human body can be considered as a combination of two thermoregulation systems: one active and one passive system. The active system model mimics the behaviour of the central nervous system which manages the temperature regulation, and the passive system simulates the heat and mass transfers within the body but also with the body environment, as described in the previous publication [4].

3.1 Human thermal behaviour: Passive System

The thermal modelling of the passive system is based on equations involving heat exchanges occurring inside and outside the body. Within the human body, a metabolic heat is produced. This heat is distributed amongst all body regions by conduction and convection (blood circulation). At the skin surface, heat is transferred inhomogeneously by conduction, convection, radiation and evaporation. Finally, a small amount of heat is exchanged through breathing.

A passive system, like Fiala's [8] on which ESI's model is based, relies on a model split in several segments enabling to capture the local specificities of the body on head, face, neck, thorax, abdomen, pelvis, shoulders and limbs: arms, forearms, hands, thighs, calf and feet.

In addition to this segmentation, some segments (such as limbs) may be divided into sectors, such as anterior, posterior and interior. The anterior and posterior sectors enable to differentiate for instance the surfaces in contact with the seat from those exposed to the air. The interior sector enables to account for the parts which are hidden, for instance the part of the arm close to the torso without radiation with the environment.

Finally, each sector is also constituted of several concentric layers of different tissues. Each of these layers contain specific thermal properties such as conductivity or heat capacity. These layers are different from one segment to another but usually contain a core layer, muscles, fat and skin. Based on the corpulence, the age and the physical condition of the individual to be represented, the thicknesses and the properties of each layer may differ.

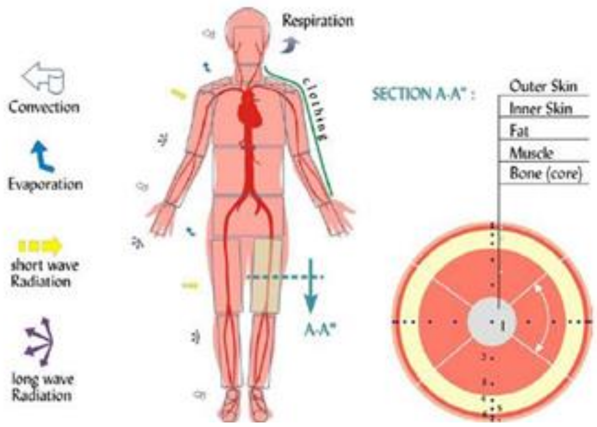

Figure 4: Human Body Parts Ref Fiala [8]

For instance, the heat transfer occurring within each layer is managed as follows in the Fiala model:

$$k\left(\frac{\partial^2 T}{\partial r^2}+\frac{\omega}{r}\frac{\partial T}{\partial r}\right)+q_m+\rho_{bl}W_{bl}c_{bl}\left(T_{bl,a}-T\right)=\rho c\frac{\partial T}{\partial t} \quad (2)$$

Where:

- 1^{st} $term$: $Conduction$ — k : $Conductivity$
- 2^{nd} $term$: $Metabolism$ — r : $Layer\ Radius$
- 3^{rd} $term$: $Blood\ Circulation$ — q_m : $Metabolic\ Heat$
- ρ : $Density$ — ρ_{bl} : $Blood\ Density$
- c : $Specific\ Heat$ — W_{bl} : $Blood\ Perfusion\ Rate$
- T : $Temperature$ — c_{bl} : $Blood\ specific\ Heat$
- t : $Time$ — $T_{bl,a}$: $Arterial\ Blood\ Temperature$

The ω parameter is equal to 1 for cylindrical segments such as legs and is equal to 2 for spherical segments such as head. The conduction heat transfer which is considered is one along the radial direction, by the temperature derivative respect to r. The values of some physiological parameters such as q_m and W_{bl} are influenced by the response of the active system. The metabolic heat q_m is influenced by several phenomena: basic metabolism, activity and sweating.

3.2 Human thermal behaviour: Active System

The active system model includes four thermoregulatory body responses from the central nervous system, their distribution within the body and their variation due to the local thermal influence: shivering, sweating, vasodilatation and vasoconstriction. These models have been developed based on simulations and statistical analyses:

- Vasoconstriction and vasodilatation reduce or increase the blood flow close to the skin
- Shivering generates heat from the muscles
- Finally, the variables involved in sweating are Average Skin temperature and its derivative, and Hypothalamus temperature

3.3 Thermal Comfort Score

The aim 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) [8]. 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 consider 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.

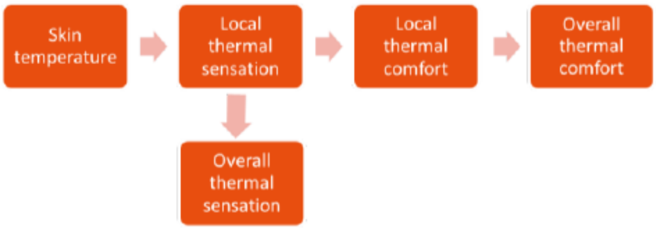

Figure 6: Sensation and comfort schema in ESI Virtual Seat Solution

Figure here below shows the relation between each thermal sensation and its index value (from very hot to very cold sensation) and the relation between thermal comfort and its index value.

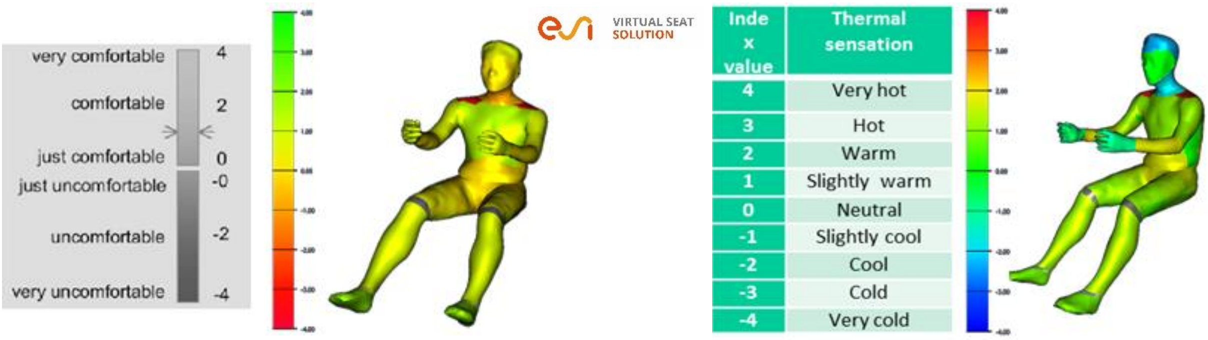

Figure 7: Thermal comfort and Thermal sensation indexes in ESI Virtual Seat Solution

3.4 Human Seating

As conduction depends on several mechanical phenomena, it is important for having accurate prediction of the thermal exchange, to consider all these phenomena during simulation. First the conduction between the seat and the occupant depends on the surface of contact between the human and the seat, but also on the distance between the human and the seat. The conductivity is also dependant on the strain conditions. So, to obtain accurate results through simulation, it is very important to perform a good seating simulation which will correctly predict the contact area between seat and human, the seat deformation and the associated mechanical interaction between the seat and the occupant.

Two simulations have been performed, one considering the conductivity dependence on the seat deformation and one considering an average conductivity [6]. The pictures here below, show the impact of seating calculation on thermal results.

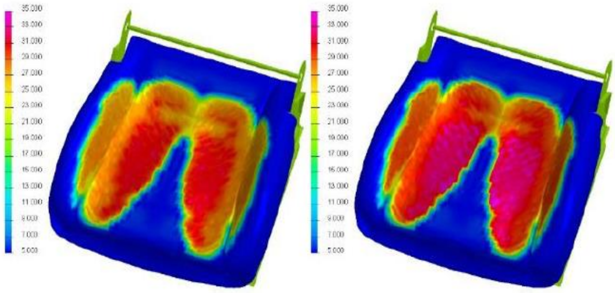

Figure 5: Results of thermal simulation done with ESI Virtual Solution
On the left with a constant average conductivity, on the right with a conductivity strain dependent

For the results show here after, the accuracy of the exchanges between seat and occupant is ensured by the fact that a preliminary finite element simulation of the seating of the occupant has been performed, and produced the right deformations of, and thus the right interactions between them.

4 Virtual Cabin Prototype

4.1 Coupling

In real conditions, air blows, air temperature and thermal management can fluctuate. For this reason, air dynamics are simulated using CFD techniques. It enables to make sure that the exchanges between air and human, or between air and seat are accurate. This resolution is transient, and computes simultaneously heat exchanges within and between all domains, making results more accurate.

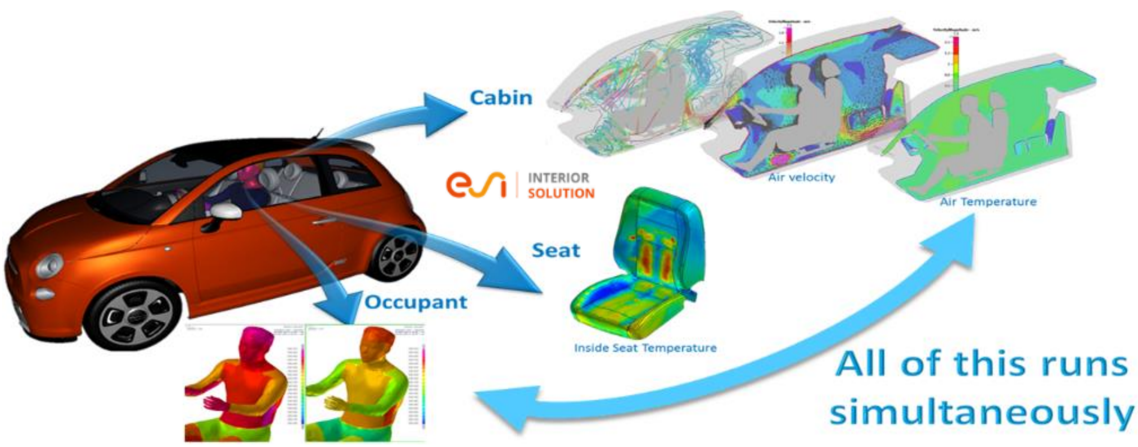

Figure 8: ESI Interior Solution results performed in the frame of OPTEMUS project

4.2 Cabin with seat and occupant thermal Simulations

To ensure that the heating or cooling system brings comfort in an efficient way and to reduce HVAC energy consumption, several scenarios have been performed, initiated during the Horizon 2020 European Union Funding for Research & Innovation project OPTEMUS “Optimized Energy Management and Use”.

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.

An active heating seat could contribute in keeping the same level of comfort for the occupant without having to increase the overall 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.

HVAC and seat heating systems are combined in the simulations defined here below, to both improve comfort and energy consumption:

Scenario	**Cabin Temperature**	Final Temperature	Heating Pad
①	Considered as uniform and imposed arbitrarily along time	15°C	On
②	Computed by a CFD computation with inlet imposed conditions	15°C	On
③	Computed by a CFD computation with inlet imposed conditions	18°C	Off

For each scenario, the outside temperature is 10°C with 30% of humidity. The driver is wearing winter clothing.

The aim of the comparison between the first and second scenario is to show the accuracy improvement when a detailed CFD computation is used to represent the HVAC system. The aim of the comparison between the second and the third scenarios is to establish the energy gain when adding a heating pad and diminishing the cabin temperature, which is a way of adapting the heating system to the car occupancy level.

4.2.1 Influence of simulating the HVAC system

Here below is a comparison between first and second scenarios. The first one considers the temperature map as constant and homogenous. It involves that the air velocity and the temperature are constant everywhere inside the cabin and they don’t have any influence on the thermal exchange coefficients. The second supposes that the temperature and the velocity can fluctuate inside the cabin. A CFD calculation is integrated in a coupling process enabling the calculation of the convection coefficient dependent on air velocity, air temperature and skin temperature. As expected, it can be observed that the temperature distributions inside the cabin are totally different between the two scenarios. The fact that the temperature is higher next to fans is more realist in scenario 2.

Figure 9: Temperature distribution results inside the cabin (ESI Interior Solution)
On the left the cabin temperature is imposed and constant, On the right, CFD is used for HVAC simulation

Consequently, the temperature distribution on the seat is also different. As we can see there is an asymmetry of temperature map distribution on the seat in the simulation including CFD coupling. It is due to differences of air properties along the seat and the driver.

Figure 10: Temperature distribution on the seat (ESI Interior Solution)
On the left the cabin temperature is imposed and constant, On the right, CFD is used for HVAC simulation

The temperature distribution on the human models is at the end also different between the two scenarios. As the thermal comfort depends on the temperature of the occupant, we don't have the same level of thermal comfort. This simple comparison shows how important it is to consider the CFD computation in a coupling process to ensure accurate results.

Figure 11: Temperature distribution on ESI human model (ESI Interior Solution)
On the left the cabin temperature is imposed and constant, On the right, CFD is used for HVAC simulation

4.2.2 Energy and comfort evaluation by adding a heating pad and diminishing the cabin temperature

The same scenario than in previous paragraph is simulated, in a car cabin at 15C° with heating pads, piloted by a thermostat with two temperature limits of 31C° and 33C° measured by a sensor on the seat cushion. The second test simulates a cabin at 18 C° without heating pads.

In these two cases, we have run a CFD calculation to update the air velocity and the air temperature during the simulation. We can observe that there is again a no-symmetry of the temperature distribution on the seat in the two cases.

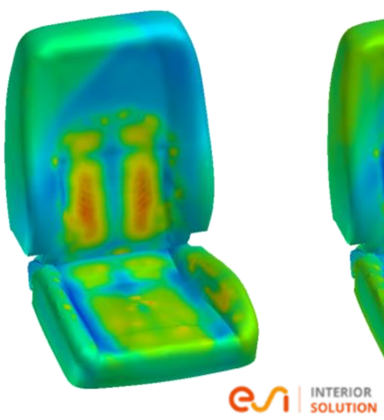

Figure 12: Temperature distribution: On the left the heating pad is ON and the air temperature is 15C°, On the right the heating pad is off, and the air temperature is 18C°

As expected, we don’t have the same temperature distribution on the seat. When the heating pad is ON, we can observe that the temperature is high, whereas when the heating pad is off, the temperature is coolest on the backrest. It could be explained by the fact that at the beginning of the simulation, the seat is not heated. This difference of temperature distribution on the seat impacts the thermal comfort of the occupant.

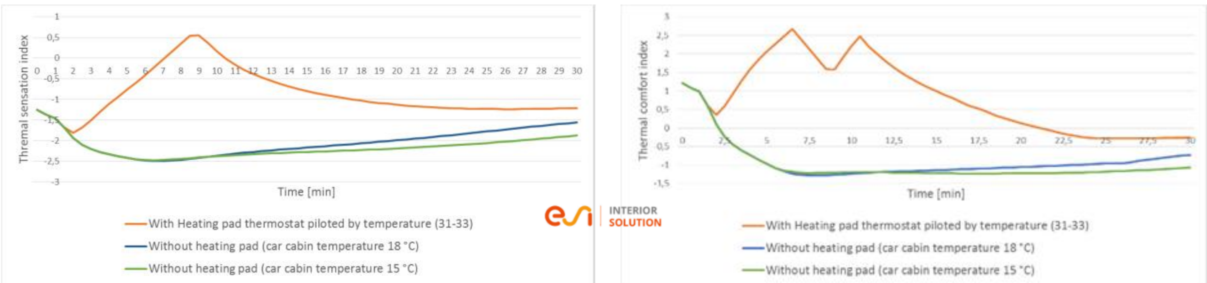

Figure 13: ESI Interior Solution simulations results: On the top the temperature distribution

On the bottom Lower abdomen thermal sensation & comfort

The thermal comfort in lower abdomen has increased and becomes even more comfortable than in a car cabin at 18°. The other body parts thermal comfort (arm and foot) cannot be improved by seat heating system since there is no contact between them and the seat. The use of virtual seat prototyping with digital human model helps finding the 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 Nissan Leaf, it can be calculated that:

- In cold weather, by activating the HVAC to maintain the car cabin temperature, the EV car loses more than 40 % of its autonomy, which is equivalent to 1 kWh.
- On the other hand, a standard heating pad with electric power of 40 W will consume 80 Wh in 2 hours, thus much less than the saving performed with the cabin global temperature diminution.

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

We have shown that we can improve the thermal comfort. Nevertheless, it remains negative. The goal is now to investigate how the simulation can help optimizing the heating system to maximize the thermal comfort of the occupant. The piloting of the heating pad by sensation index, enables to maintain a neutral sensation (this was the setpoint) and consequently, to reach a good thermal comfort level along time. Simulations and results are presented in the following paper [4].

Conclusion

With ESI's seat and interior solutions, seat and interior engineers can test occupant thermal comfort, considering heated seats as well as the overall cabin HVAC system. These solutions, applicable from the early stage of the development cycle, supports designers and engineers in engineering the thermal equipment of the cabin and seat. This ensures that it is optimal in terms of passenger comfort in and to energy consumption, for both nominal as well as in-operation conditions. This solution is different from current methodologies by the fact of coupling all the necessary technologies to account for all phenomena: conduction in the seat, convection in the air, and human subjective feeling and comfort. The accuracy gained by this detailed modelling will enable to do the necessary finer evaluation of HVAC performance for electric vehicles. ESI Interior Solution offers a unique capability for interior engineers to virtually test and optimize innovative cabin layout of electric and autonomous vehicles, while contributing to the car range increase in real driving conditions.

You can handle iterations virtually to diminish the costs and enable many more variants, move the iterations upstream in the development process to anticipate potential issues, and manage simultaneously all performances to make the right trade-offs. You innovate in confidence and minimize the risk.

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