The Application of Thermal Simulation Techniques for Seat Comfort Optimizations

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Executive summary

The seat is the most important interface between human and passenger car. It has a major influence on comfort or discomfort - especially on longer trips. Comfort optimization is the main driver for technical advancements in modern vehicle development. Interior comfort has become a key differentiator of premium class vehicles.

The following demonstrates the possible applications of simulation to correctly predict temperature and humidity in the contact zone, with a view to improving comfort by optimizing them. Seating comfort is discussed only in relation to microclimate. First, it will be shown how the moisture transferred by the body to the seat depends on the climatic conditions inside the vehicle. The simulation is carried out by coupling a finite-element-based thermal solver with a thermo-physiological manikin FIALA-FE [1]. This manikin is based on the internationally recognized publications by D. Fiala in [2-4]. New in this approach are the thermal coupling of the manikin with the interior climate (respiration, evaporation, convection, radiation, etc.), the use of the thermal manikin in contact and the consideration of local clothing size parameters in the simulation. When designing ventilation systems, which aim to dissipate moisture and thereby improve the "microclimate", it is essential to have knowledge based on physiological findings regarding the localized moisture created in contact with the seat. Simulation support is also required for the hardware dummies already used by industry to optimize seating comfort, when it comes to correctly reproducing the moisture given off by humans.

The second part of the document discusses the issue of seat comfort optimization. First, the ideal state of thermal neutrality is briefly described. Then the basic problem of localized warming in the contact zone is illustrated. Based on the concept of equivalent temperature, the thermal sensation experienced on the back in a range of real-life load cases is discussed and evaluated using a simple local comfort model according to DIN [5]. The simulation therefore opens up the possibility to contrast different concepts of seat heating and ventilation systems and to evaluate them locally in relation to thermal conditions. In conclusion, it is demonstrated on the basis of complex evaluation models by Zhang [6], that the optimization of thermal comfort in the contact zone cannot be achieved without

considering the global interior climate. This explains commonly known phenomena such as "a warm seat is only comfortable in a cold environment" and puts them into a formula-based context. The input parameters of the Zhang comfort model are skin temperatures, which are simulated with the manikin FIALA-FE. The paper concludes with a discussion of some concepts for intelligent control systems, based on the findings obtained in the simulation. In future, these systems could help to improve seating comfort founded on physiologically-based simulations.

1. Introduction

By definition, comfort is the absence of discomfort. "Comfort" in passenger cars therefore means that drivers and passengers are not subjected to negative sensations. First and foremost, the objective is to protect the driver and passengers from unpleasant smells, sounds and vibrations. In addition, the interior climate must be suitable, depending on seasonal clothing. The interior temperature should therefore be slightly higher in summer than in winter. However, sweating should be avoided. As well as physically measurable factors, aesthetic impressions have a significant influence on the interior of a car, but these are not considered any further here.

1.1 Seat comfort - Overview

Because the seat represents the main interface between vehicle and passenger, special attention must be paid to seating comfort. In this context, we distinguish between different "dimensions", which are shown in Figure 1.

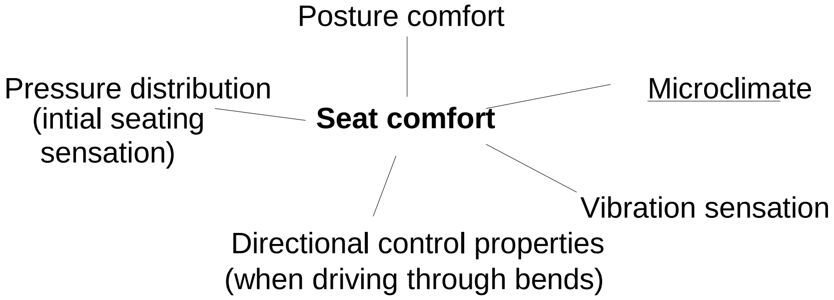

Figure 1: Dimensions of seating comfort

With the exception of the microclimate, all other comfort criteria can be evaluated using mechanical and ergonomic methods. In addition to the different dimensions, yet another review criterion is added in [7]: time. Initial seating comfort is evaluated during the first minute of contact. Short-term comfort relates to a period of up to 30 minutes, and everything above this falls within the definition of long-term comfort. A conflict of objectives can occur when one attempts to optimize pressure distribution and vibration sensation through thick layers of foam, but in doing so, at the same time creates such high thermal insulation that on longer journeys, the temperature in the contact zone becomes too high and the resulting moisture cannot be dissipated.

1.2. Microclimate and Sweating

"Microclimate" is a term frequently used in relation to seating comfort. It means the combination of humidity, diffusion, temperature and heat flows in the contact zone or in the seat. The heat given off by humans to their surroundings (80W in a resting state) can be considered as an approximate constant. This does not, however, apply to the amount of moisture. Sweating is the physiological response of humans to an environment perceived as too hot.

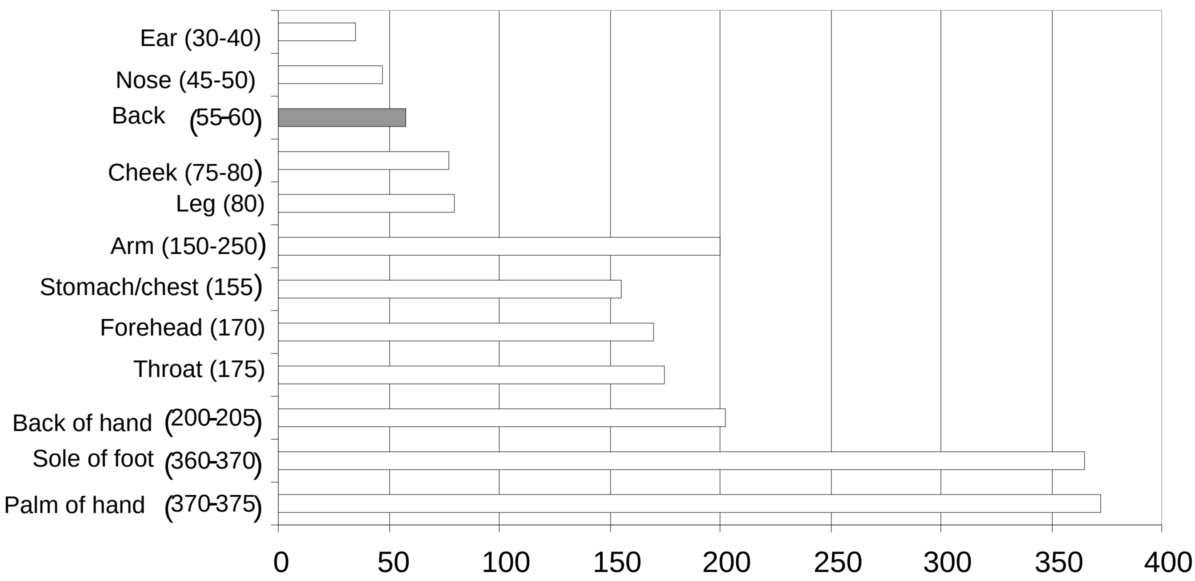

Figure 2: Localized differences in the number of sweat glands per cm^2, according to [8]

Apart from the above, the diffusion effects of moisture through the skin also have a role to play, but can largely be considered as constant, as shown in figure 3. The moisture transported from the inside of the body to the skin evaporates and thereby cools the human body. In this way, humans have a regulating effect on their own temperature balance through sweating, with the aim of maintaining a core temperature of 37°C and a mean skin temperature of 34°C. This temperature gradient (see Figure 10) is essential for the survival of the organism. When the core temperature is stable, it enables it to dissipate metabolic heat generated inside the body to its surroundings. Deviations from the ideal state are perceived as unpleasant. And humans automatically respond with changes of blood circulation in the skin, clothing, activity, shivering and sweating.

When sweating, sweat is transported to the skin surface through a total of about $2*10^6$ sweat glands. There is great discrepancy in the way these glands are distributed locally, as shown in Figure 2. The back and buttocks are the main surface in contact with the seat. They have a relatively low distribution density of 55-60 sweat glands/cm^2. If this value is multiplied using a contact surface[1] of approximately 1800 cm^2 and the number of sweat glands on the back is viewed in relation to the total $*2^{10}6$, it follows that only about 5% of the global volume of sweat occurs in the contact zone:

$$60/cm^2 \cdot 1800cm^2/2 \cdot 10^6 \approx 5\% \qquad (1)$$

The maximum amount of sweat to be expected from a body with a total area of 1.8 m^2 is 27 g/m, as the human body can only produce (globally) a maximum of 15 g/min/m^2. But out of this total amount, only 5% is transferred to the seat in the contact zone. This corresponds to a (local) maximum amount of sweat of approximately 8 g/min/m^2 in a contact zone of 0.18 m^2.

The thermal regulatory purpose of sweating is satisfied if the moisture transported to the skin evaporates and thereby cools the body and protects it from external heat. This regulatory mechanism is disturbed when clothing or the seat obstruct the water vapour on its way from the skin to the ambient air, or when the water absorption capacity of the air is limited due to relative humidity and temperature, see Figure 3. At 85% humidity, for example, a human starts to sweat when the air temperature reaches 25 °C and the evaporation heat is then proportional to the moisture being released:

$$\frac{\partial Q}{\partial t} = \lambda\left(\frac{\partial m_{diff}}{\partial t} + \frac{\partial m_{sweat}}{\partial t}\right),\ \lambda = 2256 J/g \qquad (3)$$

When the temperature is increased further and reaches T_{crit}, a point is reached for the first time where the gradient of vapour pressure between the skin and surrounding air on different parts of the body is no longer sufficient for the sweat to completely evaporate through the clothing. As the room temperature rises further, more and more moisture is accumulated, which collects on the skin or is soaked up by clothing and seat. This leads to a further increase in the vapor impermeability of the clothing and soon a point is reached where ever larger quantities of sweat accumulate as "wetness". The cooling effect of sweating remains

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[1] The calculation of a contact surface of 1800 m^2 is based on the simulation of the seating process using a crash dummy, which reproduces the average dimensions of an adult.

largely absent, the body temperature rises and the body responds with even more sweat secretion, until in extreme cases the human body can reach a maximum value of 15 g/min/m^2 [2].

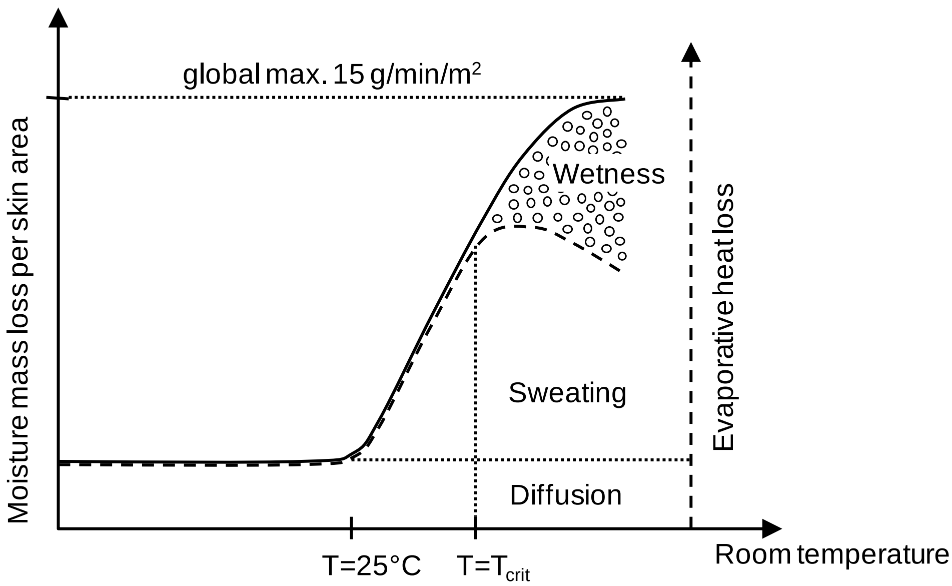

Figure 3: Sweating and evaporation after 3 hours at 85% relative humidity

The entire volume of moisture secreted by the human body through sweat pores can be calculated using mathematical models. The thermo-physiological manikin designed by D. Fiala [2-4] has become particularly popular in recent years, having been validated by means of a range of test persons and physiological tests. Fiala specifies a function for the global amount of sweat, which is based on tests and measurements:

$$\begin{aligned} Sw = & \left[0.65 \cdot \tanh\left(0.82 \cdot \Delta T_{sk,m} - 0.47\right) + 1.15\right] \cdot \Delta T_{sk,m} \\ & + \left[5.6 \cdot \tanh\left(3.14 \cdot \Delta T_{hy} - 1.83\right) + 6.4\right] \cdot \Delta T_{hy} \quad \text{in [g/min]} \end{aligned} \tag{4}$$

According to D. Fiala, multiplying the average skin area of 1.8 m^2 with the previously discussed maximum value of 15 g/min/m^2 results in an upper limit of $Sw_{max} \approx$ 30g/min for the function shown in (4). Regression analyses in [2] have shown that the variables $\Delta T_{sk,m}$ und ΔT_{hy} provide a particularly good means of modeling the measured sweat functions. They are changes to the current average skin temperature $T_{sk,m}$ and the hypothalamic temperature T_{hy} in relation to the (ideal) state of thermal neutrality[3]:

[2] A doubling of the specified value is possible in case of extreme athletes.

[3] See also section 2.1.

$$\Delta T_{sk,m} = T_{sk,m} - 34.4°C \; ; \; \Delta T_{hy} = T_{hy} - 37°C \qquad (5)$$

Since sweating only occurs in warm environments, negative values for $\Delta T_{sk,m}$ und ΔT_{hy} are always set to 0 in (4).

The central nervous system of the human body handles two essential input values: on the one hand the core temperature (at the hypothalamus), for which only minimal fluctuations can be allowed, and on the other hand the temperature of the envelope (skin). As an interface to the environment, this allows the organism to draw important conclusions on external thermal boundary conditions. The weighting factors $a_{sk,i}$ are used in [2] to calculate the average skin temperature $T_{sk,m} = \sum a_{sk,i} \cdot T_{sk,i}$. They are shown in Figure 4 and have a total of 1. It is apparent that the greatest physiological influence comes from precisely those parts of the body that are in contact with the seat (marked in grey here). It follows that the contact zone to the seat has a substantial influence on the thermal global perception of humans. It must therefore be treated with high priority, in particular for thermal comfort analysis.

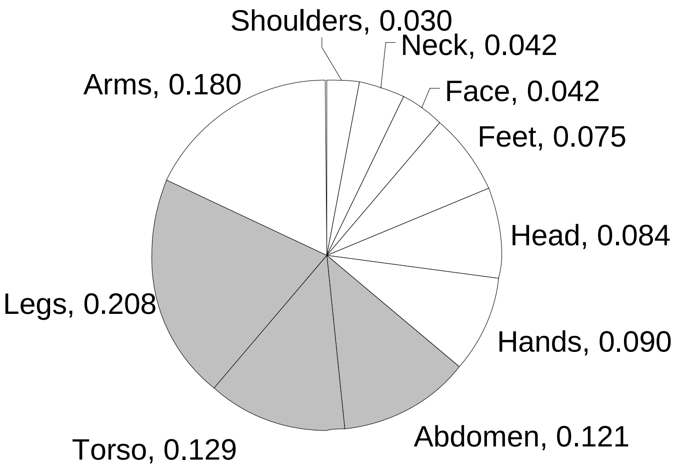

Figure 4: Local weighting factors $a_{sk,i}$ for calculation of average skin temperature. $T_{sk,m}$

The practical applicability of the sweating function (4) is limited, due to the fact that human body temperatures (T_{sk} und T_{hy}) are often not available in practice or can only be measured with extreme difficulty. Simple formula-based correlations that predict the amount of sweating subject to external boundary conditions would be more helpful, for example when designing hardware dummies. In fact, a range of external influences must be considered in order to predict human body temperatures. The most important parameters are air temperature, duration of exposure or previous history, radiation boundary conditions, air velocity and clothing. The influence of humidity only becomes apparent at high values of >80%, see Figure 3. Added to this is the level of activity, which determines metabolic heat production in humans. When driving a car, it can be set as an approximate constant of 1.2 met[4]. If the air velocity in the simulation is set to approximately 0.1 m/sec and if inhomogeneous radiation influences (sun) are omitted, exposure time and clothing remain.

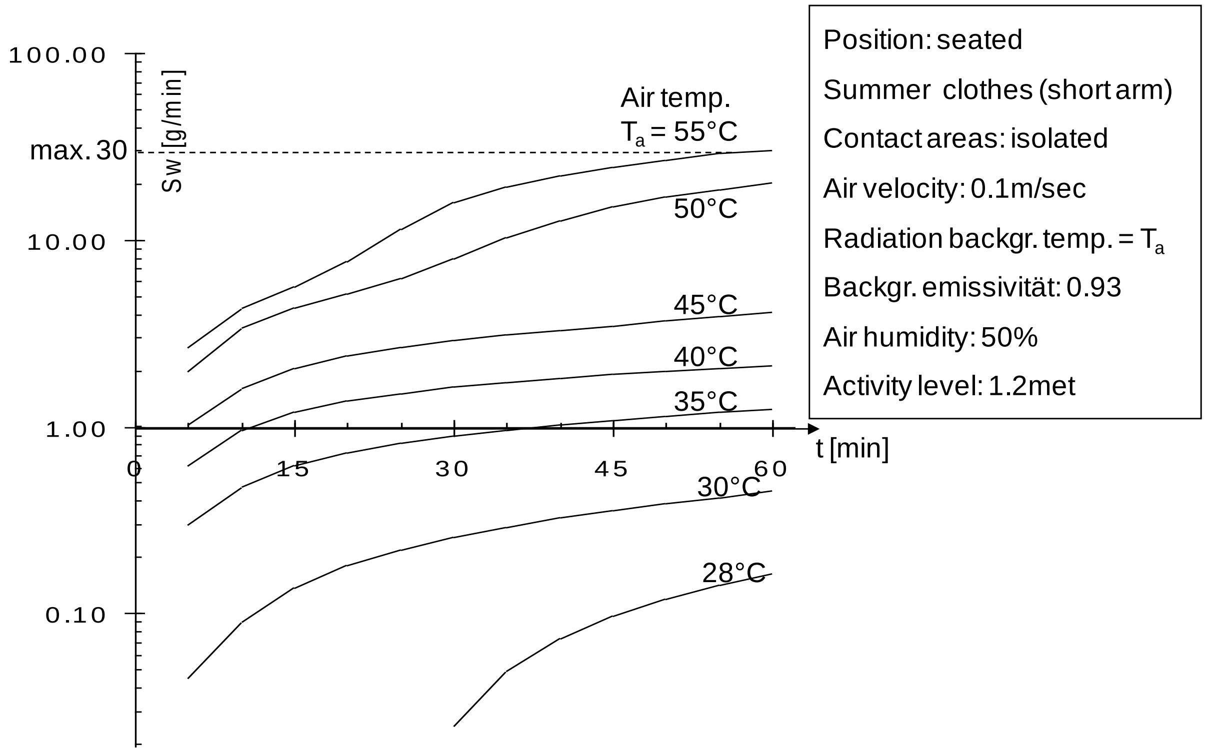

Figure 5: Simulated sweating rate Sw as a function of exposure time and air temperature T_a

Figure 5 illustrates the dynamic simulation results at different air temperatures for a person wearing summer clothing and when using thermally insulated contact surfaces. The air temperatures T_a were kept at a constant level during the simulation.

It is apparent that the maximum sweating rate $Sw_{max} \approx$ 30g/min can only be reached within the simulated time if air temperatures exceed >50°C. Irregularities in the course of the upper two curves are the result of the influence of hypothalamic temperature, which further increases the sweating rate. Sweating only occurs immediately at the start of the simulation if T_a = 30°C or higher. At 28°C, sweating only occurs after approximately 30 minutes. As

[4] At the activity level, the unit met represents 58W/m^2. 1.2met then refers to 1.2*58W/m^2*1.9m^2 = 132W of internal heat generated.

discussed earlier, one can assume that on average, only 5% of the global volume of sweat occurs at the point of contact (seat).

1.3. Thermal manikin FIALA-FE

According to [9], thermal manikins have been used in research and development for over 60 years, to analyze the thermal interface between the human body and its environment. In recent years, increasingly complex manikins have been developed. As shown in [2-4], they can be used under time-varying boundary conditions and can even provide a good model of sweating and breathing. Of course, individual differences in human thermoregulation cannot be replicated. However, a series of tests with several test subjects of both genders show that it is possible to calculate average human body temperatures (also locally).

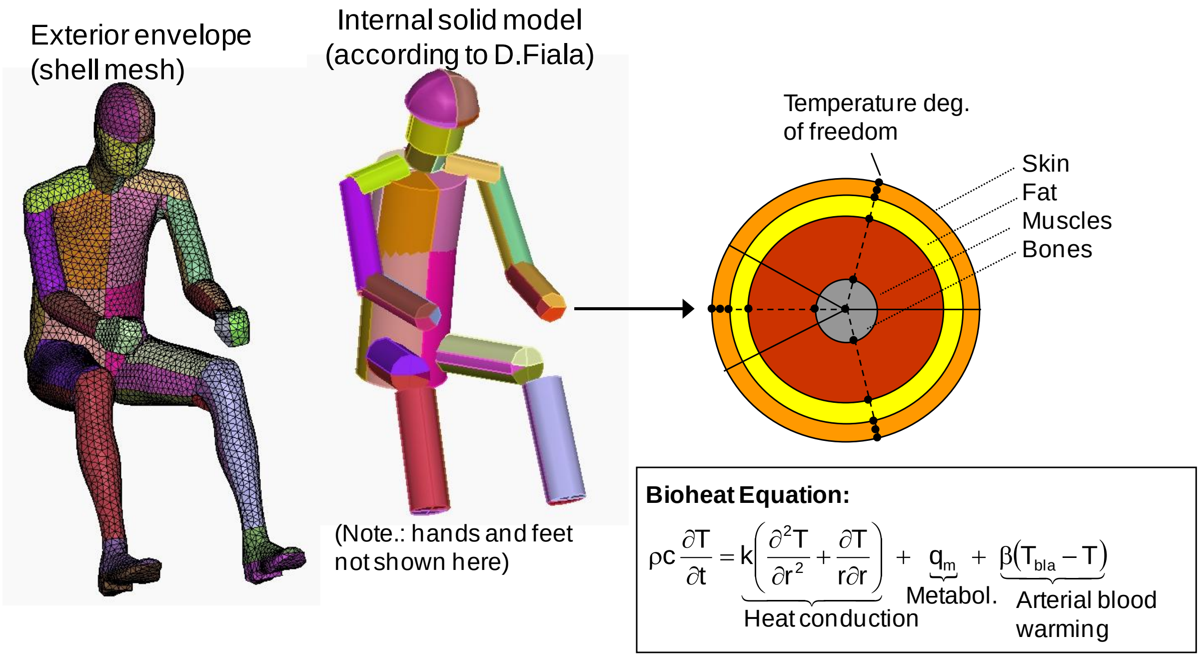

Figure 6: Manikin FIALA-FE

All simulation results shown here were created using a thermal manikin, as published by D. Fiala for the first time in 1998 in [2], see Figure 6. Based on this, a finite-element manikin (FIALA-FE) was integrated in the thermal solver THESEUS-FE for the first time in 2007. The FIALA-FE manikin was developed in close collaboration with D. Fiala. It is not possible within the scope of this document to provide a comprehensive overview of the physiological principles and mathematical methods, measurements and validations used in the implementation of the manikin. In relation to the above we refer to the technical literature [1-4].

It is possible to perform dynamic analyses coupled with the environment (e.g. car interior) when using this manikin integrated in THESEUS-FE. The manikin, which is based on physiological functions, serves to depict the thermal reactions of the human organism to a wider range of different external boundary conditions. It does so as close to reality as possible. Convection, radiation and evaporation are considered along contact heat flows and respiration. Internal heat exchange takes place by means of blood circulation and heat conduction through different material layers (skin, fat, muscle, bone, etc.). The active system, as used by Fiala, describes the reactions of the organism to external heat and cold: Vasoconstriction and dilation, shivering and sweating are phenomena that have different local effects. The associated weighting factors were derived in [2] using complex regression analyses from a range of experiments and test subjects. This is precisely why this manikin seems particularly suited to the realistic modeling of local skin temperatures and heat flows, which are essential for comfort analyses of the seat.

The physically correct modeling of locally different clothing layers together with the air enclosed in them, is of particular importance for the temperature balance in humans. The following are modeled at a local level: a resistance value against heat loss I_{cl} und evaporation i_{cl}. For this purpose, D. Fiala derived databases for local clothing outfits (winter/summer) on behalf of the P+Z Engineering GmbH, using measurement data available in THESEUS-FE. Depending on the degree of discretization, such a manikin has a relatively low number of 500-1000 temperature degrees of freedom. If the manikin is not coupled with its surroundings (decoupled mode), the computation times is less than 1 minute even for transient simulations. In coupled mode, any number of people can be simulated at the same time within a vehicle. These then exchange heat with the remaining system through convection (with cabin air), radiation, respiration, evaporation and contact.

2. Simulation of local thermal comfort

2.1 Thermal Neutrality

In a simulation, all temperatures on the surface and inside the manikin typically start in a state of thermal neutrality. This refers to an idealized state where a person rests naked in the shade at an ambient temperature of 30°C (act = 0.8met). According to the definition, a person is then in a state of global thermal well-being. The person experiences this state as typically 'neutral' - neither too hot, nor too cold. The core temperature T_{hy} is 37°C and the average skin temperature approximately 34.4°C. The corresponding local skin temperatures can be calculated by means of a quasi-static simulation in decoupled mode.

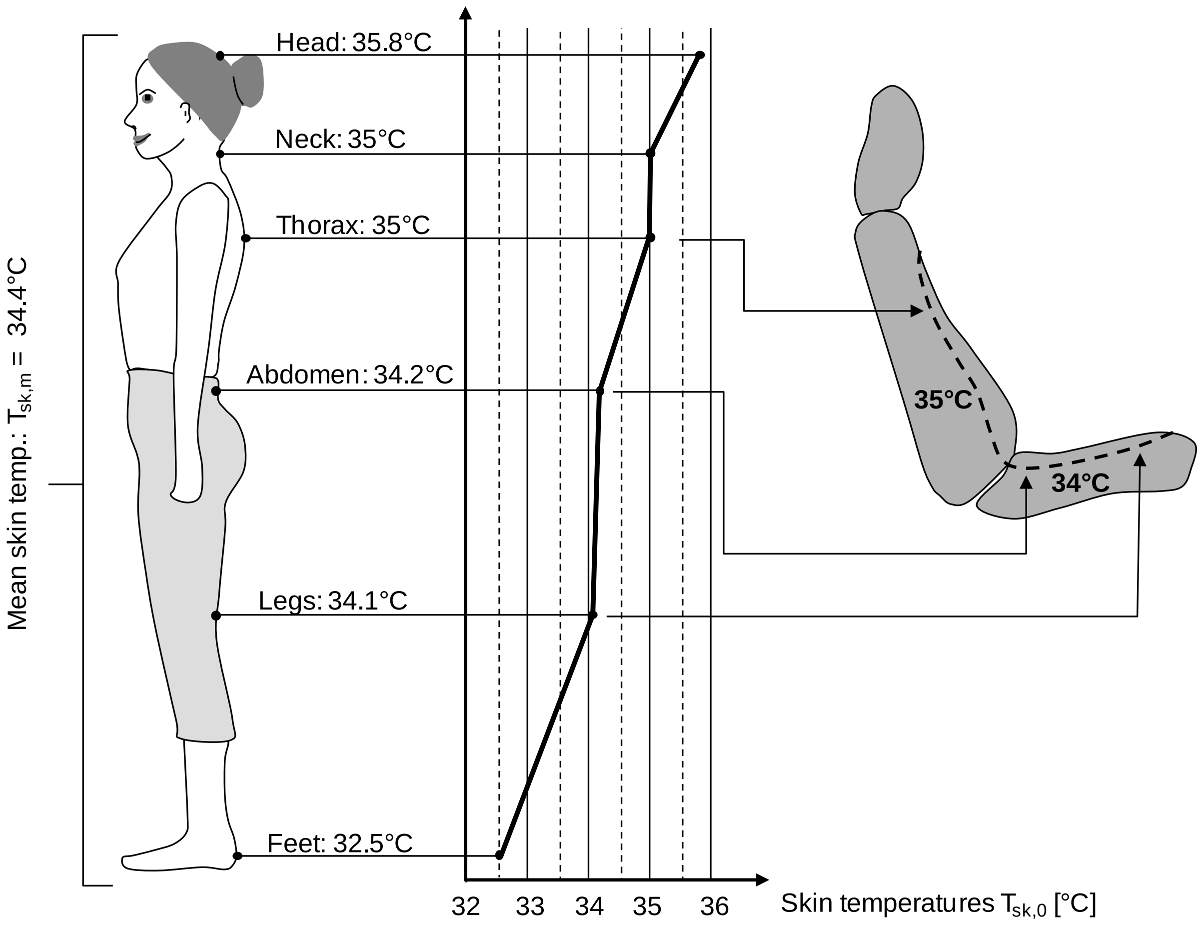

Figure 7: Local skin temperatures in a state of thermal neutrality

The ideal skin temperatures in the contact zones - 35°C for the upper seating shell and 34°C for the lower seating shell - are calculated by transferring the thermally neutral skin temperatures $T_{sk,0}$ of the upper body, abdomen and legs to their respective contact zones on the seat, as shown in Figure 7. For a local comfort evaluation according to Zhang (see section 2.5), these local neutral temperatures must be known in advance. This is required, for example, to calculate changes in current skin temperatures in contact with $\Delta T_{sk} = T_{sk} - T_{sk,0}$, compared to the state of neutrality. In order to capture dynamic effects in thermal sensation, temporal changes $\dot{T}_{sk} = \partial T_{sk} / \partial t$ were also incorporated into the Zhang model (see Figure 15).

2.2 Description of Simulation Model

All following simulations were carried out in coupled mode. A manikin dressed in summer clothes is placed on a seat. A contact algorithm ensures that temperature degrees of freedom within a defined search radius are automatically connected right at the beginning of the calculation. Seat and manikin are enclosed in a ventilated room (2.7m^3). Depending on the load case, either warm or cold air with a defined volume flow is blown into the room.

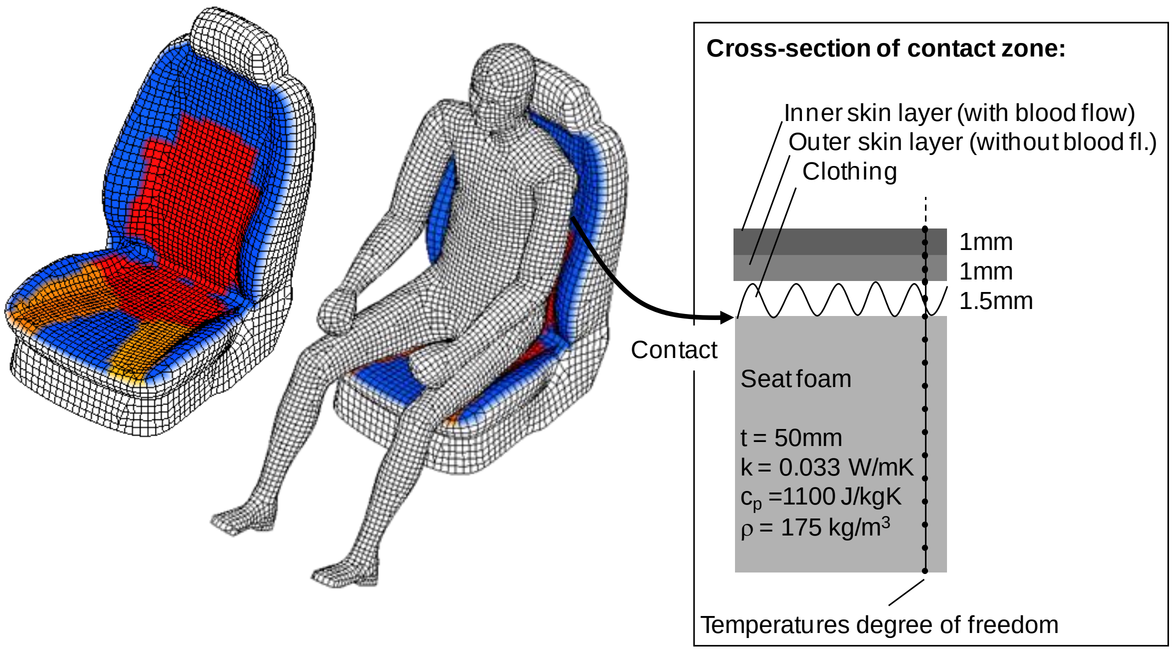

Figure 8: Finite-element model for the evaluation of seat comfort (+ contact temperatures qualitatively)

All calculations start with the person in a state of neutrality. The temperatures of the clothing are identical to that of the skin below at that point. For t = 0, seat and air temperatures are either constant at 60°C or 10°C. Immediately after the start of the simulation, contact is made between seat and clothing and very high (in terms of the amount) heat flows are transferred, which however quickly subside. At the same time, the interior air is adjusted to a comfortable

24-25°C within a few minutes, using a fan. The simulated real time was 2 hours throughout. This required between 5-10 minutes of computing time on a conventional PC. After 2 hours, it is generally noted that all temperatures in contact (skin, clothes, seat) approach a value of 37°C, see Figure 9:

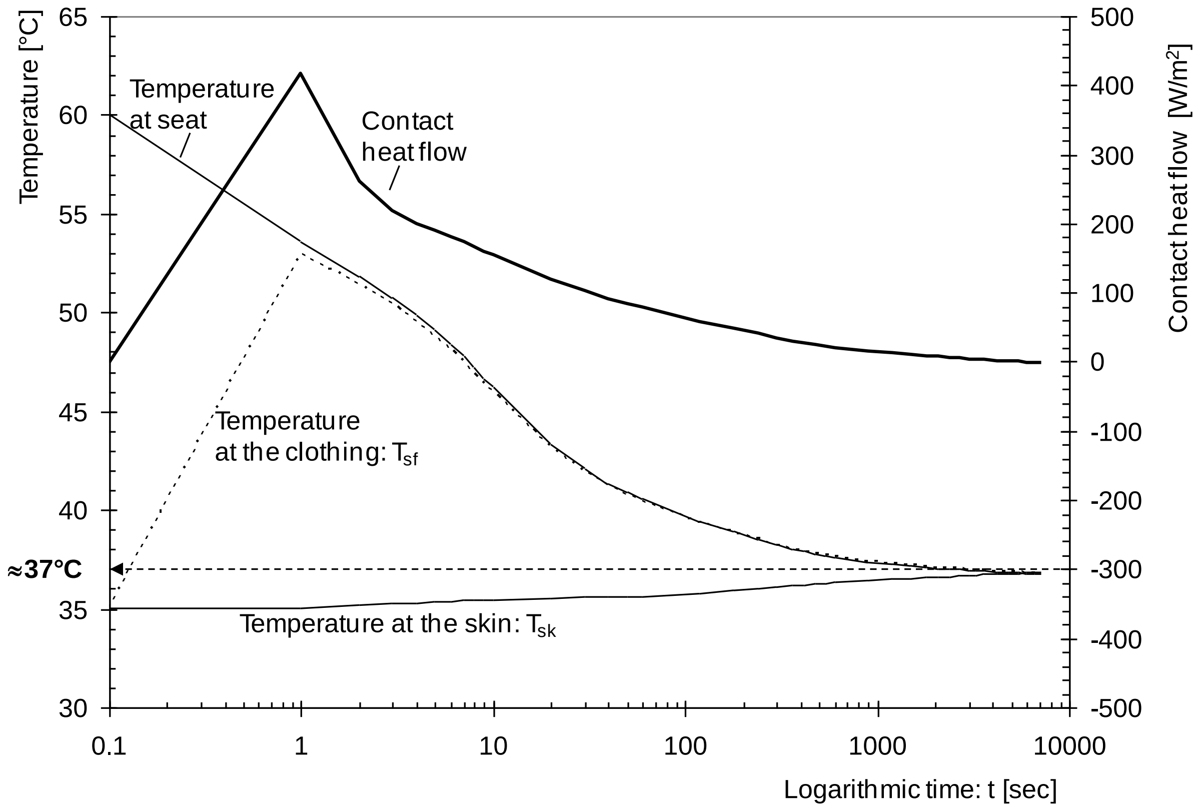

Figure 9: Temperatures and heat flow at the contact between the back and seat (Calculation starts at 60°C cabin temperature)

2.3 The Quasi-static Contact Temperature

37°C is exactly the skin temperature which occurs after prolonged sitting on a fully insulated (in the worst case scenario) seat. Everyone knows the slightly unpleasant feeling of "warmth" that occurs in the contact zone after one has been seated for some time. This phenomenon is caused by the strong insulation properties of the seat foam, which causes approximately adiabatic conditions after one hour $(\dot{Q} = 0)$. This may even lead to a turnaround, where the seat foam is then warmed by the human metabolism.

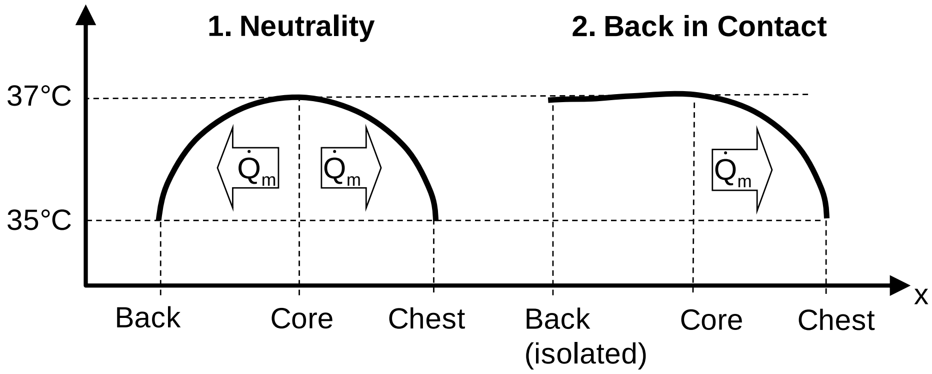

Figure 10: Quasi-static temperatures on average throughout the upper body (qualitative)

Figure 10 shows the (qualitatively) semi-circular temperature profile in the ideal state of neutrality. The gradient from the core to the exterior allows the "draining" of metabolic heat $\dot{Q}_m$ in the human body. If the back is thermally insulated by the seat foam, the temperature at the envelope rises from 35°C to 37°C in the long term, because the core temperature "spreads outwards". The internal heat can then no longer be dissipated at the back. This is perceived by the organism as unnatural (and dangerous), because this state can also lead to an increase in the core temperature, which results in sweating[5]. Ultimately, even sweating in the contact zone will not solve the problem, because the seat foam impedes the evaporation processes[6].

If one started the simulation with a cold passenger car, a similar picture would emerge: Ultimately, the simulation always shows that where highly insulated seats are involved, the temperature in the contact zone tends towards a value of 37°C in the long run.

[5] See formula (4).

[6] In extreme cases, all of the condensed sweat collects in the contact zone, as a consequence of vapour-impermeable seat constructions.

2.4 The Equivalent Temperature and its Evaluation According to DIN EN ISO 14505-2

The concept of equivalent temperature is based on accounting for the effects of external heat flows on the human body, in order to make statements about thermal comfort globally as well as locally[7]. Because heat flows have no real validity, a (real) external heat flow is extrapolated to a so-called equivalent temperature T_{eq}. The concept of equivalent temperature is similar to the idea of "perceived temperature", which is used in the evaluation of weather events in meteorology.

Using a current configuration (act) with known heat flows, T_{eq} is calculated using the following concept: The equivalent temperature is exactly the temperature of an imaginary space with identical wall and air temperature and very low air velocity, in which the human body exchanges the same amount of heat, as in the current configuration. While the global approach adds all heat flows affecting the human body to calculate T_{eq}, a local equivalent temperature is conceivable, which only evaluates the local heat flows (for example on the back) and derives T_{eq} from this. This approach to the issue of "comfort" has the advantage that inhomogeneous thermal boundary conditions, such as sun, high air velocities or thermal contacts can be reduced to a single temperature, which has a individual validity:

$$\begin{aligned} \dot{Q}_{act} &= \dot{Q}_{eq}\left(T_{eq}\right) \Rightarrow T_{eq} \\ \dot{Q}_{eq} &= A_{sf}\left(h_{convec} + h_{rad}\right)\cdot\left(T_{eq} - T_{sf}\right) \end{aligned} \tag{6}$$

In (6), A_{sf} refers to the surface (clothing or skin) and T_{sf} refers to the corresponding temperature. The convective heat transfer coefficient h_{conv} is calculated from the air velocity, which is set very low at with 0.1 m/s. Since the heat transfer coefficient of radiation h_{rad} stands in a non-linear relationship to T_{eq}, the equivalent temperature must be calculated by means of Newton's iteration method for a given heat flow of the current configuration $\dot{Q}_{act}$.

As a first step, the concept of equivalent temperature is applied to the simulation model described in section 2.2: A person dressed in summer clothes and in a state of neutrality, enters a hot passenger car which was previously exposed to the sun for an extended period. The air and seats in the passenger car are heated to 60°C at time t = 0. After the contact is closed, the interior air is cooled to a comfortable 24°C within a few minutes, using air conditioning and a fan.

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[7] Originally, the equivalent temperature was used to evaluate comfort on a global scale. But DIN EN ISO 14505-2 also describes the local applicability of this method.

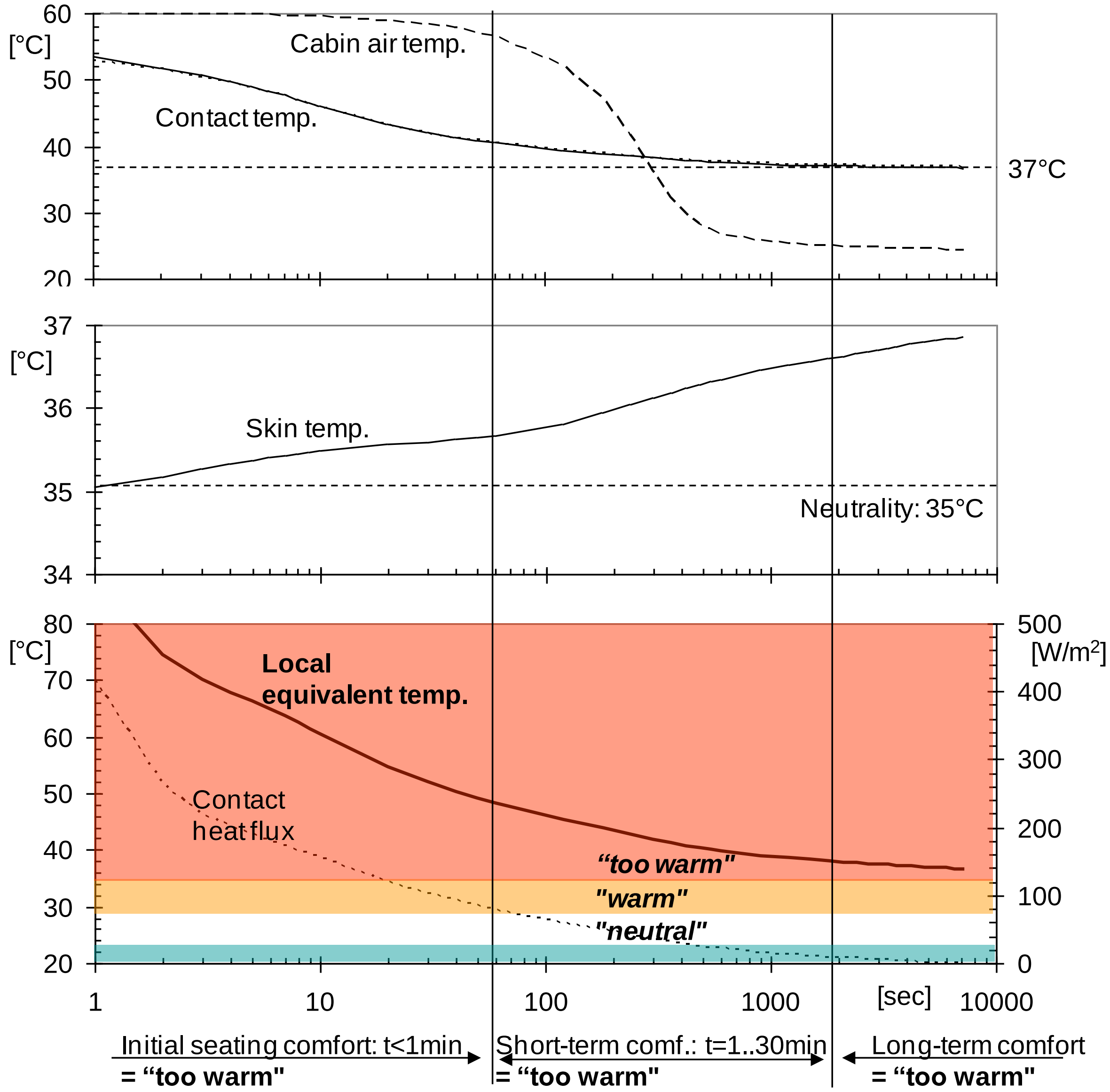

Figure 11: Temperatures and heat flow at the seat contact, inc. evaluation according to DIN EN ISO 14505-2 for load case "Entering a hot vehicle".

The application of a logarithmic time scale allows a visually differentiated view of the three standard temporal evaluation dimensions: Initial seating comfort (t<1min), short-term comfort (t=1..30min) and long-term comfort (t>30min). The equivalent temperature ranges, which can be associated with different thermal sensation on the back according to DIN EN ISO 14505-2, are marked in different colors in the diagram below: T_{eq}<17.3°C ⇒ "too cold",

$17.3 < T_{eq} < 23°C \Rightarrow$ "cold" $23 < T_{eq} < 28.6°C \Rightarrow$ "neutral", $28.6 < T_{eq} < 34.3°C \Rightarrow$ "warm" and $34.3°C < T_{eq} \Rightarrow$ "too warm". These temperature ranges explicitly apply for summer clothing.[8]
It can be seen that the skin temperature at the contact zone continues to increase, although the interior temperature has already been cooled down to a comfortable value of about 24°C after 8 minutes. In the long term this leads to an "unnatural" temperature profile which causes uncomfortable sensations - as shown schematically in Fig. 9. The contact heat flows are very high at the beginning. Applying formula (6) results in equivalent temperatures that are deep in the red range ("too warm"). The initial seating comfort is evaluated using T_{eq} values of over 50°C. It should be taken into account here that clothing still significantly attenuates the contact heat flows. On bare skin, much higher equivalent temperatures would occur within the first minute, because heat flows are not attenuated.
After a longer journey in a passenger car, the T_{eq}-values at the contact zone continue to fall, but never reach the "warm" or "neutral" range of sensation, even after several hours' drive. It is interesting to note that all three temperatures (seat, skin and equivalent temperature) asymptotically approach a quasi-static value of 37°C. As discussed in section 2.3, this is caused by the high insulation properties of the seat foam. This causes the core temperature to move towards the skin and the contact zone during longer journeys. When inserting the adiabatic boundary condition $\dot{Q}_{real} \approx 0$ achieved in the long-term comfort stage, $T_{sf} \approx 37°C$ requires that the equivalent temperature must also be $T_{eq} \approx 37°C$, so that the right side of formula $(6)_2$ is set to 0.
As a second step, a person dressed in summer clothes enters a passenger car that was cooled down beforehand (e.g. at night). The air and seats in the passenger car are cooled to 10°C at time $t = 0$. After contact is made, the interior air is heated to a comfortable 25°C within a few minutes.
Compared to the previous load case, we now see a turnaround of the contact heat flows. The minimum amount of heat drawn from the body is $-400W/m^2$ immediately after contact has been made. This results in T_{eq} values far below 20°C, therefore the initial seating comfort is rated as "too cold". Again, near static-adiabatic conditions are reached in the long-term (after a longer drive). However, the boundary case $\dot{Q}_{real} \approx 0$ is not reached within the simulated time of 2 hours. The heat flows still remain negative: Heat is still being discharged. Nevertheless, the long-term comfort must already be evaluated as a "warm" sensation in the contact zones, according to DIN EN ISO 14505-2. It is interesting to note in this context that

[8] A modified evaluation scheme can be found in the DIN when using winter apparel.

the human sensation "I feel warm" or even "I feel too warm" does not necessarily mean that the contact zone is being warmed by the human body. It suffices that the heat produced inside the human body cannot be sufficiently discharged locally.

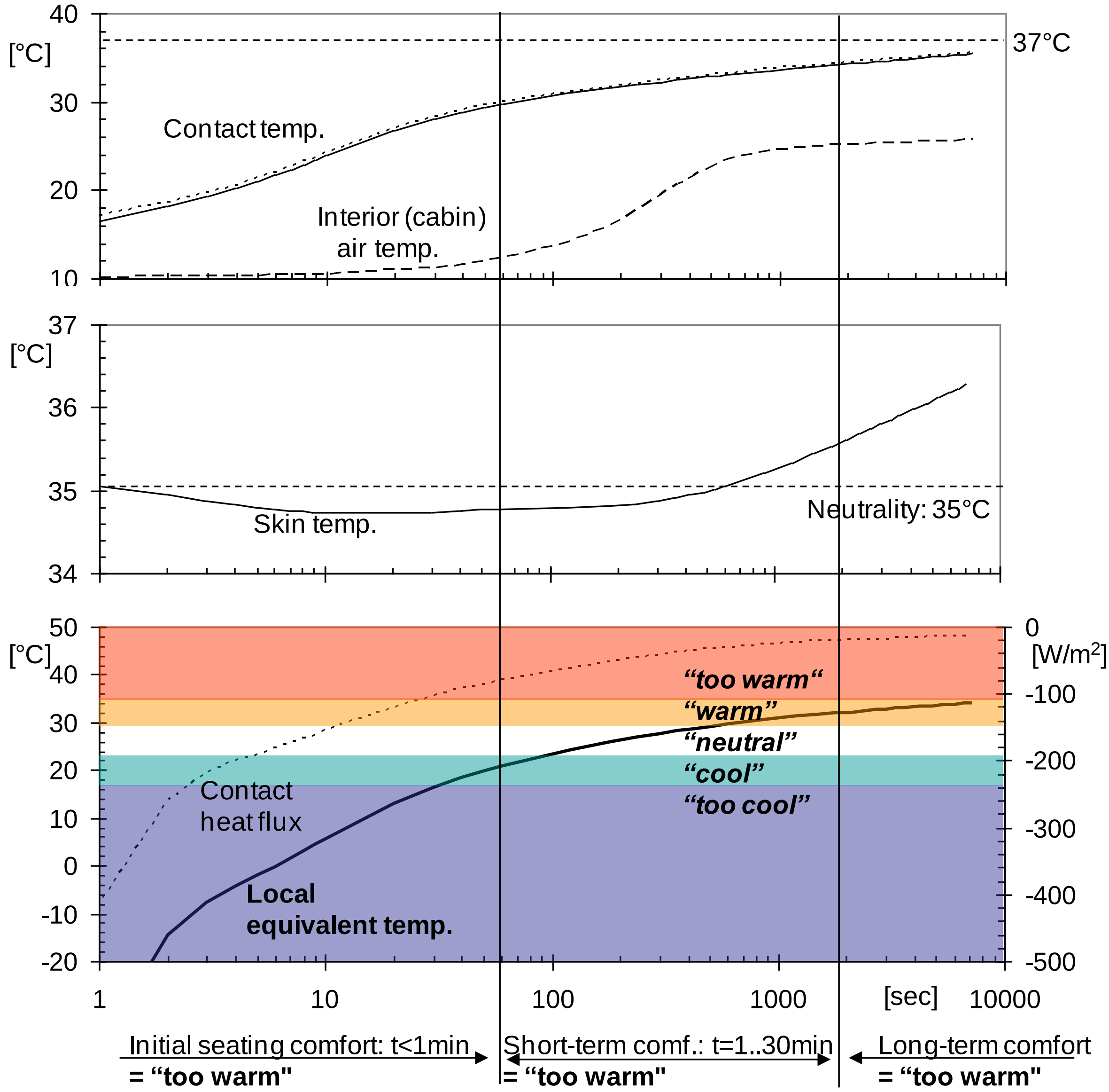

Figure 12: Temperatures and heat flow at the seat contact, inc. evaluation according to DIN EN ISO 14505-2 for load case "Entering a cold vehicle without seat heating".

The skin temperature drops only slightly at the beginning of the simulation (initial seating comfort) by 2-3 tenth °C and reaches thermal neutrality again after about 10 minutes. The subsequent further warming of the skin is accompanied by T_{eq}-values >30°C, which are rated by human beings as "warm". This is still within the comfortable range, according to DIN. For the back, the extreme ranges "too cold" (T_{eq}<17.3°C) and "too warm" (T_{eq}>34.3°C) are considered to be uncomfortable.

In a next step, a heat source below the seat surface is added to the simulation. It is turned on when contact is made and reaches its full power of 500W/m^2 within 5 seconds. This is comparable to the effect of the midday sun on an inclined surface. After one minute, the seat heating is switched off completely.

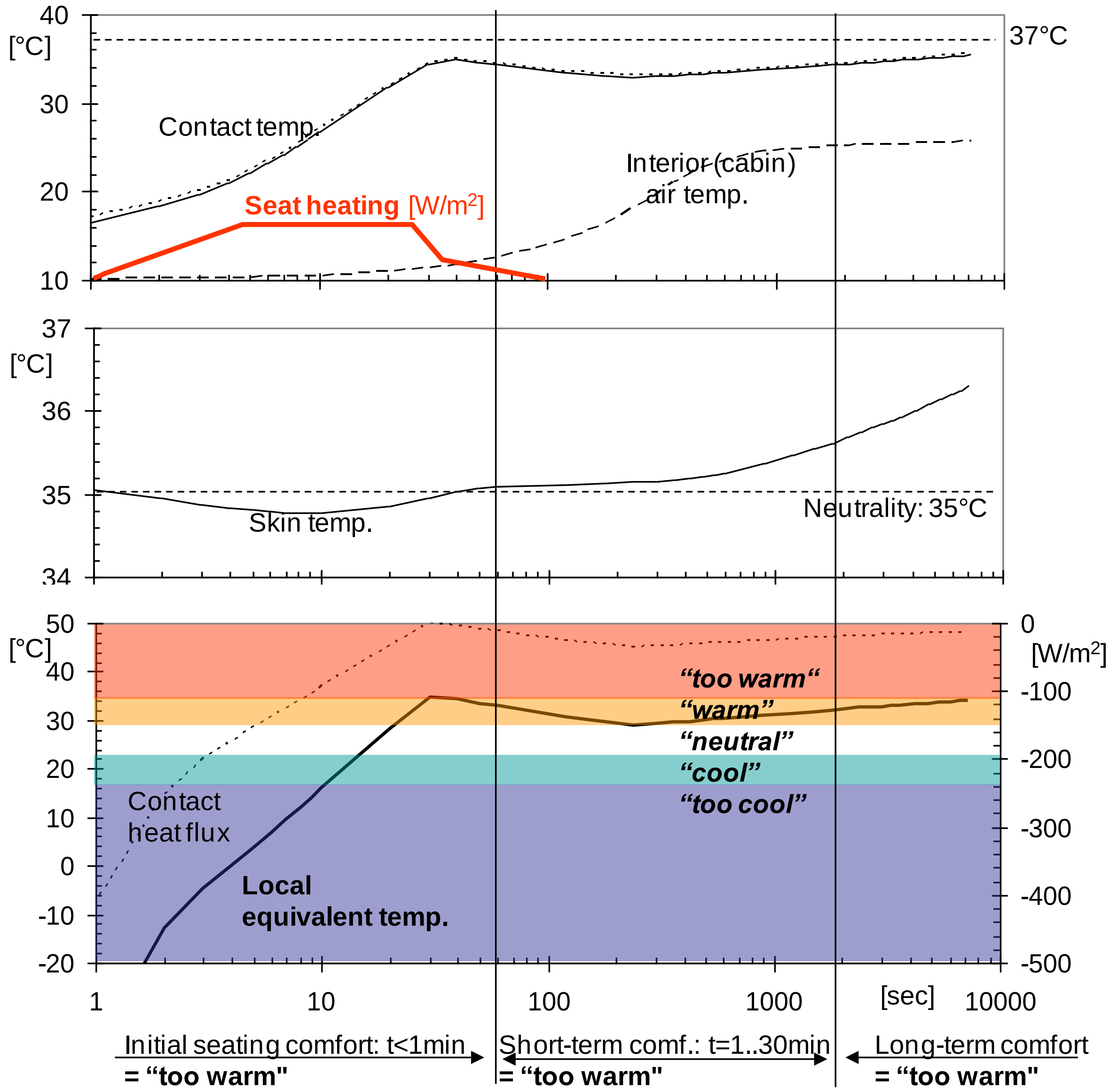

Figure 13: Temperatures and heat flow at the seat contact, inc. evaluation according to DIN EN ISO 14505-2 for load case "Entering a cold vehicle with seat heating".

As shown in the comparative Table 1 (below), the equivalent temperature of the initial seating comfort rises from the original value $T_{eq,max}$ = 20°C (without seat heating) up to 34°C

(with seat heating). The associated thermal sensation "warm" in the contact zone is welcomed by the passenger. It counteracts the global sensation of cold in the passenger car caused by the 10°C interior air temperature. A mathematical model [6] that calculates thermal comfort as a function of global and local sensations is discussed in the next section.
A comparison of Figure 12 and Figure 13 shows the following results in relation to initial seating comfort: The contact temperature rises as high as 35°C with seat heating, compared to 30°C without seat heating. The seat heating now allows the skin temperature to return to neutrality within approximately 1 minute, compared to 10 minutes without heated seats. At the same time, the equivalent temperature rises as high as 34°C, which is still rated as comfortably "warm". Overall, the use of seat heating results in a significant improvement in thermal sensation during the period "initial seating comfort" (t<1min).
When comparing the effect of seat heating on short-term comfort, it can be seen that the equivalent temperatures which are higher at the start (with seat heater) are evaluated as "warm" throughout, which does not necessarily mean that they are uncomfortable. In contrast, when there is no seat heating, the evaluation passes through the stages "cool" – "neutral" – "warm". It is not possible to come to a clear decision which load case performs better in relation to short-term comfort. There are only marginal differences in long-term comfort.

Table 1: Comparative evaluation at the seat contact according to DIN EN ISO 14505-2

Load case	**Initial seating comfort**	**Short-term comfort**	**Long-term comfort**
Fig.11: Entering a hot vehicle	“too warm" (T_{eq}=80..48°C)	“too warm" (T_{eq}=48..38°C)	“too warm" (T_{eq}=38..37°C)
Fig.12: Entering a cold vehicle	“too cold" .. “cool" (T_{eq}=-20..20°C)	≈ "neutral" (T_{eq}=20..32°C)	"warm" (T_{eq}=32-34°C)
Fig. 13: Entering a cold vehicle with seat heating (1min, 500W/m^2)	“too cold" .. "warm" (T_{eq}=-20..34°C)	"warm" (T_{eq}=28..33°C)	"warm" (T_{eq}=33-34°C)

An evaluation based on equivalent temperature therefore shows that the use of a seat heater significantly improves thermal sensation, especially during the initial seating comfort period[9].

[9] Significant, positive effects of seat heating for the time period short-term comfort (1..30min) can not be shown at this point, but will follow in the next section as part of an evaluation of the Zhang model.

However, two potential risks can be identified: 1. If the seat heater performs at a higher level, the T_{eq} curve in Figure 13 extends into the range "too warm", which is perceived as unpleasant. 2. If the seat heater is not switched off again quickly, the values for both short-term comfort and long-term comfort may permanently remain in the range "too warm", which is perceived as unpleasant.

The use of cooling seat ventilation systems is desirable, specifically for the summer load case when a warm vehicle is entered. This will not only avoid the sensation "too warm" on the back when entering the vehicle, but also during the entire journey. Regardless of the load case, there is a general tendency in relation to long-term comfort for temperatures in the contact zone to rise to 37°C. The most efficient method of avoiding this are cooling ventilation systems in the seat.

A conceivable improvement for seat heating systems would be to switch on the heating at the earliest possible point to further optimize initial seating comfort, e.g. at the same time as operating the door lock. It also seems reasonable to automatically switch off the seat heater after a few minutes. The aim is to avoid that skin temperatures continue to rise above the neutral level and that the sensation "too warm" becomes dominant in relation to short-term and long-term comfort. In order to coordinate such measures in a useful way, the global sensation experienced by the human body must also be included in the studies, because it is apparent that local comfort not only means the absence of discomfort, but is also a reaction to global sensation. It is well known in this context that a warm back is only experienced as pleasant in a cold global environment - in that case, however, it is even regarded as very pleasant. Such complex, combined comfort ratings, which create a relationship between global and local sensation, can be depicted using Zhang's comfort model.

2.5 Zhang's Local Comfort Model

Zhang's comfort model is based on 109 climate chamber test cases at the University of California (Berkeley). Humans were tested under dynamic and inhomogeneous thermal boundary conditions. During several years of research, Hui Zhang developed mathematical models based on these test cases, which are used for the evaluation of local and global thermal sensation as well as the thermal comfort derived from this. In 2003, Ms. Zhang published these models in the context of her dissertation in [6]. Zhang distinguishes 19 parts of the body in relation to local thermal sensation or comfort (one of these is the back). Their specific model parameters were published in tables.

Model inputs consist of measured or simulated skin and core temperatures, which must be known in advance. Their influence can frequently be neglected, because the core temperature T_{hy} is subject to only very small fluctuations under a relatively moderate thermal load. In order to evaluate a current configuration in terms of local comfort, given values must exist for the current skin temperatures T_{sk} as well as the gradient $\dot{T}_{sk} \approx \Delta T_{sk} / \Delta t$, which allows dynamic evaluation. The model can be "fed" with either measured or simulated skin temperatures. The Fiala human model currently represents the most recognized simulation tool for the calculation of local skin temperatures. The combination of the Zhang and Fiala models in order to create a purely simulative method for local comfort evaluation is therefore an obvious step.

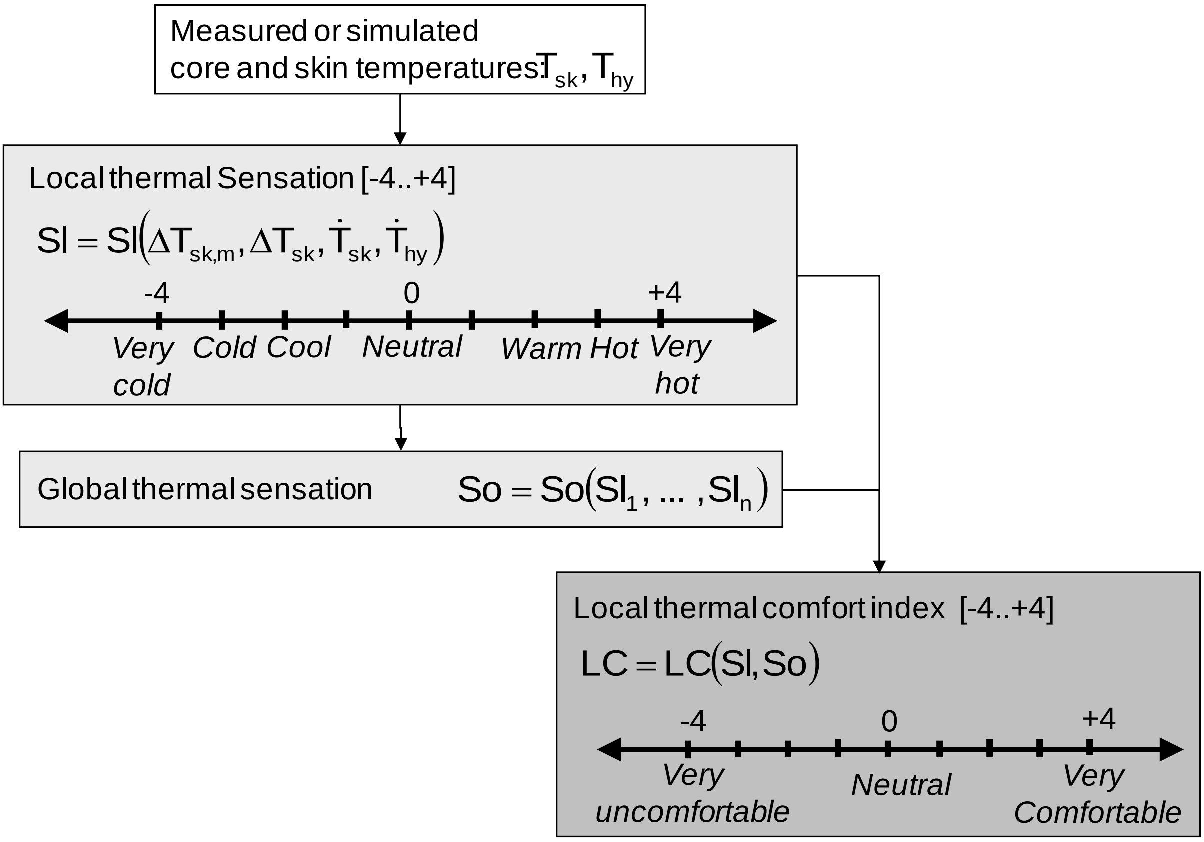

Figure 14: Zhang's comfort model (general)

If skin temperatures are known, then the local thermal sensation SL (Sensation local) is calculated as a first step. In order to achieve this, ΔT_{sk} is used to implement changes in skin temperatures in relation to neutrality, see also (5). $T_{sk,m}$ represents the average skin temperature. The value range of thermal sensation lies in the range from -4 (= very cold) up to +4 (very hot). This applies to the local sensation Sl as well as to the global sensation So (Sensation overall), which is calculated from all local SL values of the body.

Once local and global sensations are known, local comfort is calculated with function LC=f(Sl,So). The value range again lies between -4 ("very unpleasant") and +4 ("very pleasant"). Figure 15 shows the formulas and their corresponding parameters for the back. It is noteworthy that the maximum value of the comfort function depends on the global sensation.

$$LC_{max} = 2.22 + 0.74 \cdot |So| \quad \text{in a cold environment (So<0)}$$
$$LC_{max} = 2.22 \quad \text{in a warm environment (So>0)} \tag{7}$$

It follows that a comfort value of +4 is only possible in a cold global environment (at So≤-2.4). On the other hand, the Zhang model shows that it is not possible to reach a very pleasant (LC=+4) thermal sensation on the back through cooling in a warm global environment. This also seems to be comprehensible in reality.

Zhang model for local thermal sensation:

$$Sl = 4\left[2/\left[1+\exp\left(-C_1 \cdot dT_{sk} - K_1\left(\Delta T_{sk} - \Delta T_{sk,m}\right)\right)\right]-1\right] + C_2 \cdot \dot{T}_{sk} + C_3 \cdot \dot{T}_{hy}$$

Parameters for the back: $K_1 = 0.1$, $C_3 = -4054$, $\Delta T_{sk} < 0 \Rightarrow C_1 = 0.3$ else: $C_1 = 0.7$

$\dot{T}_{sk} < 0 \Rightarrow C_2 = 88$ else: $C_2 = 192$

Zhang model for local thermal comfort:

$$LC = \left[\frac{le\_slope - ri\_slope}{\exp(5(Sl + offset)) + 1} + ri\_slope\right](Sl + offset)^n + LC_{max}$$

$offset = C_8 + C_4 \cdot |So|$, $LC_{max} = C_6 + C_5 \cdot |So|$

$le\_slope = \frac{4 + LC_{max}}{|-4 + offset|^n}$, $ri\_slope = \frac{-4 - LC_{max}}{|4 + offset|^n}$

Parameters for the back:

$n = 1$, $C_6 = 2.22$, $C_8 = 0$

$So < 0 \Rightarrow C_4 = -0.5$ $So > 0 \Rightarrow C_4 = 0.59$

$So < 0 \Rightarrow C_5 = 0.74$ $So > 0 \Rightarrow C_5 = 0$

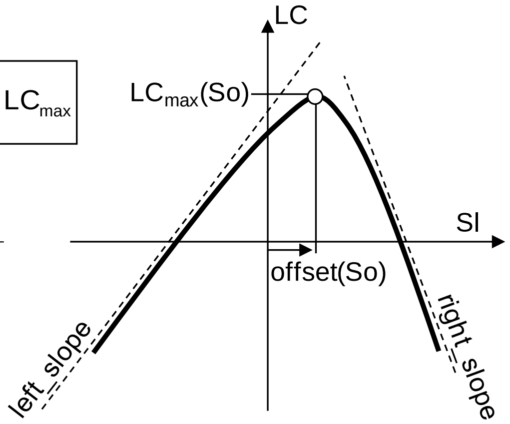

Figure 15: Features of Zhang's comfort model for the back

As a first step, the Zhang model for the back is now applied to the load case which was last evaluated using the equivalent temperature ("Entering a cold vehicle with seat heating"). The resulting developments for the local thermal sensation Sl and the local comfort LC on the back, as well as the global sensation So are shown in Figure 16. The maximum comfort value LC_{max} derived from Formula (7) is also depicted.

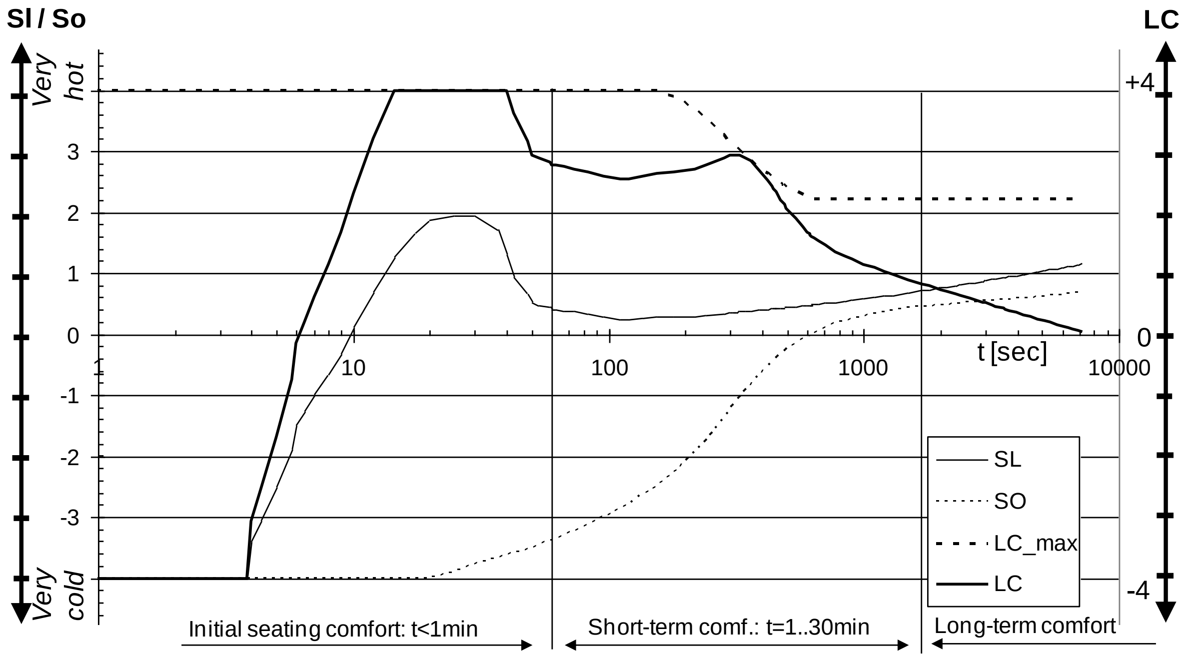

Figure 16: Thermal sensation and comfort index LC on the back according to Zhang, for load case "Entering a cold vehicle with 1 minute 500W/m^2 seat heating"

It is apparent that the thermal sensation on the back is evaluated as "warm" (SL = + 2) after the seat heating is switched on, which corresponds to the evaluation method according to DIN EN ISO 14505-2. In addition, the Zhang model also permits the evaluation of whether a person experiences the warm back as pleasant or unpleasant, when seen against the background of global sensation. In Figure 15, the local comfort index on the back rises to the maximum value of LC = LC_{max} = + 4, which means that the seat heating is adjusted optimally. After the seat heating is switched off, LC falls to values below LC_{max}. This leads to the conclusion that prolonged heating would lead to even higher levels of comfort. The global sensation So reaches the neutral area within a few minutes, as a result of warming the cabin air (to 25°C). At the same time, the back warms up again, but this is not a pleasant sensation any more: the local comfort index then decreases to values <0.

Finally, two variants are evaluated: first a doubling of the heat output to 1000W/m^2 (see Figure 17), then an extension of the heating period from one to 6-minutes (see Figure 18).

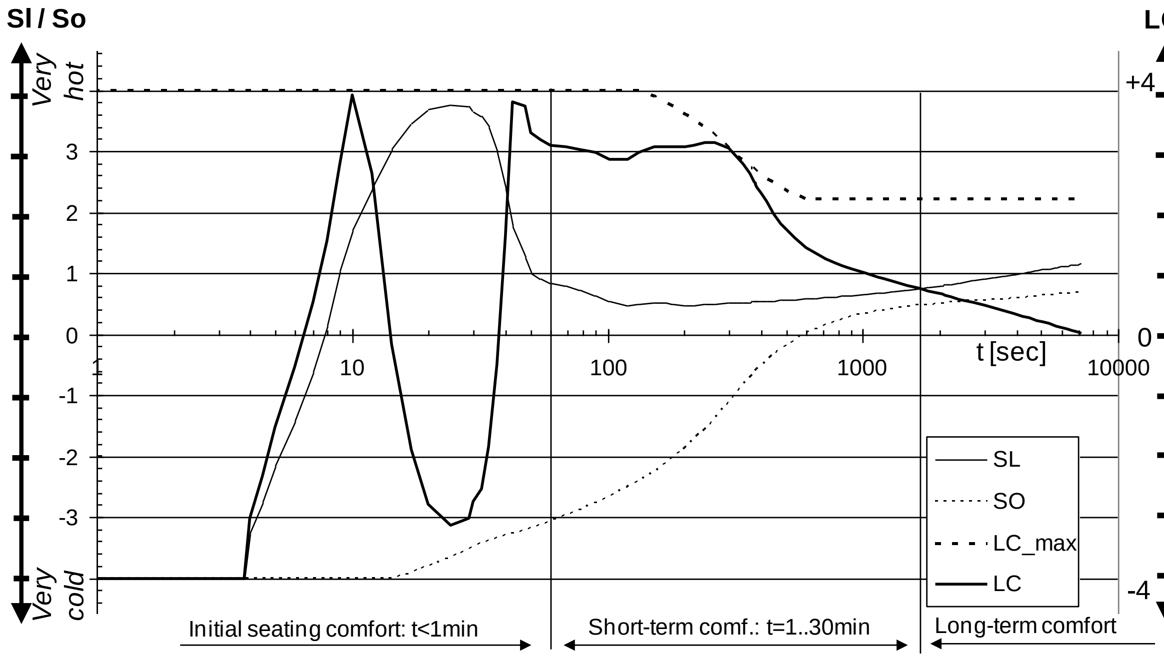

Figure 17: Thermal sensation and comfort index LC on the back according to Zhang, for load case "Entering a cold vehicle with 1 minute 1000W/m^2 seat heating"

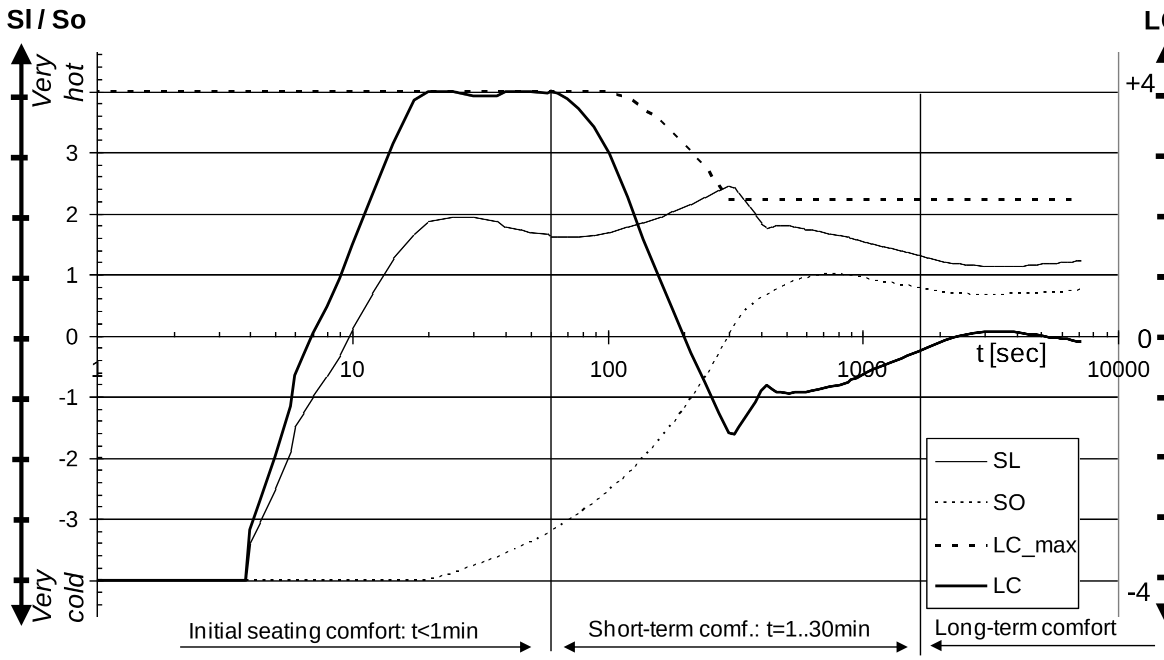

Figure 18: Thermal sensation and comfort index LC on the back according to Zhang, for load case "Entering a cold vehicle with 7 minute 500W/m^2 seat heating"

It is evident that even a doubling of the heat output in the simulation drives up the thermal sensation SI so strongly (close to values of +4), that human beings experience it as unpleasant: the local comfort index drops to LC=-3.
Initially, extending the heating phase of the seat from 1 to 6 minutes creates an extension of the very pleasant LC=+4 phase. However, it then strongly decreases the local comfort index on the back. Due to simultaneously rising interior air temperatures, the back is already perceived to be too warm, and therefore no longer comfortable.

2.6 Measures for Comfort Optimization

The dotted LC_{max} curve in Figure 18 shows what could be achieved through comfort optimization. It would be conceivable to have intelligent control systems, which couple the heat output of the seat with a measured interior temperature. Automatic activation of the seat heating could already take place when the door lock is operated, in order to optimize initial seating comfort. After some minutes, the heat output would then need to be reduced further and further, linked to the interior temperature. This would maintain the short-term comfort in the contact zone at the highest level, (=LC_{max}). The seat heating should then be deactivated completely, because further heating does not make sense once the comfort temperature set by the driver has been reached.
As already discussed in the previous sections, balanced cooling through the use of seat ventilation systems (see Figure 19) makes sense particularly with regard to long-term comfort, in order to avoid an increase in skin temperature. Such ventilation systems not only serve to improve long-term, but also short-term comfort in the context of the summer load case. Too much cooling in the contact zone should be avoided, however, as skin temperatures below neutrality are detrimental to local comfort (according to Zhang).
Ventilation systems have another advantage - the removal of moisture caused by sweating[10]. This not only improves comfort, but in the long-term it also prevents unpleasant odors in the interior.

[10] Under summer load case conditions, sweating is unavoidable immediately after entering a heated vehicle. If a pleasant temperature can be achieved in the interior and at the contact zone within a short time, the amount of sweat quickly returns to 0.

3. Conclusions

Simulations in the field are a great rarity in the area of thermal seating comfort. The thermodynamic interaction with people is generally not considered in simulations today, if they are carried out at all in this area. An example of this is the design of ventilation systems, as shown in the picture below from the Johnson Controls Company in [10].

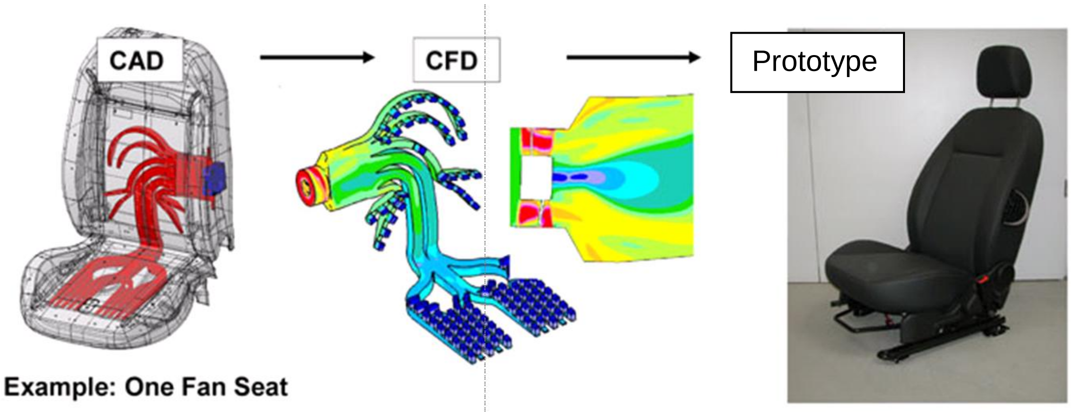

Figure 19: Design of seat ventilation channels [10]

The major advantage resulting from a thermally coupled simulation (manikin-seat), as demonstrated here, lies in the calculability of skin temperatures and with this, the localized values "thermal comfort" and "thermal sensation". Separate configurations of an existing simulation model (for example seat heating in section 2.5) can be evaluated very quickly in relation to their thermal comfort properties. Simple questions can be answered quickly, such as "Is a certain heat output still tolerable?" or "When does cooling at the back make sense?" Moreover, it is possible to design intelligent control systems that gradually turn down the seat heating when the temperature inside the vehicle comes closer and closer to the comfort temperature.

The alternative to the simulation-supported comparison of variants is the time-consuming and costly comparison of concepts in trials. Here, it is not possible for one single test person to be the reference for thermal comfort or discomfort. Rather, a large number of test persons must be questioned. This is because using the individual perception of one person as a benchmark is one of the dangers in the evaluation of concepts.

In contrast, the models of Fiala and Zhang are based on a large number of experiments and test subjects. They thereby represent (by definition) the benchmark for the average thermal sensation of human beings. A professional use of manikins in practice does not necessarily mean however, that one must resign oneself to already existing simulation tools. Rather, it makes it possible to adjust the model parameters (see Figure 15) to allow future adjustments to the simulation, for example by letting differences in sexes become part of the simulation. As an example, individually customized seat heaters for women or children are one possibility in this context.

While it is easy for any engineer today to gain insight into mechanical systems, the evaluation of thermal sensation and comfort is a topic that seems reserved for physicians and physiologists on the one hand, but on the other hand also includes thermodynamics. The use of simulation can create transparency in this area and reveal relationships that can otherwise only be guessed at. A deeper understanding of thermo-physiological processes can therefore promote technical advancements and reveal potential for optimization.

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