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QUalifying and Implementing a user-centric designed and EfficienT electric vehicle

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Publishable Executive Summary

Beside a summary of human thermo-physiology, the deliverable D2.1 of QUIET research project provides a comprehensive overview of subjective and objective methods of thermal comfort assessment in vehicles and amplifies the individual user needs with gender and aging society aspects.

Also, nowadays limits are described and a forecast to smart future technologies of air-conditioning is given as a suggestion to further research efforts in this field.

Moreover, the use case of the demonstrator vehicle Honda Fit EV is specified to the project partners.

At the end, global and local thermal comfort targets in vehicles are defined to support the comfort rating of the upcoming models and tests, which are going to be created or executed by the project partners within this research project.

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Abbreviations and Nomenclature

Table 1: List of Abbreviations and Nomenclature.

Symbol or Shortname	Description
ADAS	Advanced Driver Assistance Systems
AER	All Electric Range
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BEV	Battery Electric Vehicle
BMI	Body Mass Index
BMR	Basal Metabolic Rate
BW	Body weight
CO	Cardiac Output
CAE	Computer-Aided Engineering
CFD	Computational Fluid Dynamics
DTS	Dynamic Thermal Sensation
ECU	Electronic Control Unit
ET	Equivalent Temperature
EV	Electric Vehicle
HMI	Human Machine Interface
HVAC	Heating, Ventilation and Air Conditioning
IAV	"Ingenieurgesellschaft Auto und Verkehr" (IAV automotive ingineering)
LMV	Local Mean Vote
MTV	Mean Thermal Vote
OEM	Original Equipment Manufacturer
PMV	Predicted Mean Vote
PPD	Percentage of Persons Dissatisfied
RST	Resultant Surface Temperature
SET	Standard Effective Temperature
WP	Work Package

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1. Introduction

Key target of the QUIET research project is the increase of BEV's driving range under real-world driving conditions by an efficient energy management. Mobile HVAC as a main energy consumer hereby becomes the focal point of interest for optimization.

The first known mobile HVAC-systems in an automobile were applied by the manufactures Nash and Studebaker in 1938 [1]. Due to the fact that mobile HVAC-systems were inspired by air conditioning of buildings, for 80 years now these systems still try to condition the whole space of the vehicle cabin instead of trying to reach thermal comfort of each individual passenger. Fortunately, actual trends in automotive industry like hybridization, electrification and autonomous driving will revise the mobile HVAC concepts and push the spotlight more and more to the occupants by user-centric designs.

Aim of WP2.1 is to find out, what the user needs and expectations are with regards to thermal comfort including aging and gender aspects. This question closely involves the following questions: How is thermal comfort defined in general and how can it be assessed in particular?

Within this document we will answer the questions mentioned above first and try to find common target values of thermal comfort in vehicle compartments afterwards with the help of literature research. Hence, all project partners will get an indication how to judge their technological improvements with regards to thermal comfort of the human occupants. Taking into account that different engineering methods will be used by each project partner in the QUIET project for concept evaluation and product optimization, which range from user studies and real car HVAC tests up to full vehicle simulations.

Finally, the main project goal of 25 % AER increase has to be reached at least at the same thermal comfort level (which is hard to achieve simultaneously) as in the initial Honda Fit EV demonstrator, as determined in D1.1 by HRE-G.

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2. Thermal Comfort in Vehicles

The research for comfort optimization in general also lasts more than 60 years now. Starting from the first simple definition of Herzberg in 1958 [2], that "comfort is the absence of discomfort", nowadays the definition of comfort is much more complex and diverse. The third international dictionary of English language from 1981 for example defines comfort as a state of relief, encouragement and enjoyment. By this definition, comfort is very subjective and therefore hard to measure. The only gaugeable quantity in science is discomfort as it depends on physiological and biomechanical factors and processes. Moreover, a comfort level can only be reached when all disruptive environmental impacts are minimized and personal aesthetics, luxury and enjoyment is maximized in parallel. Furthermore, there are many environmental discomfort factors possible, which can be detected by human senses like light, sound, smell, vibrations or temperature. Based on Maslow's hierarchy of needs, Bubb [3] created the pyramid of comfort (see Figure 1). Following this hierarchy model, comfort deficits will only become aware if subjacent needs are fulfilled. In addition, this model shows that thermal comfort is just a small part of all environmental needs and by the way not the one with the highest priority of necessity.

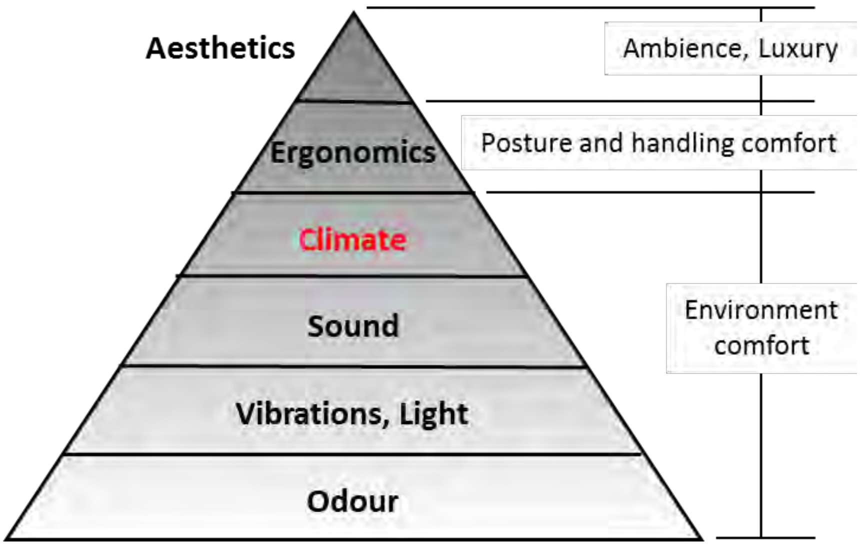

Figure 1: Comfort pyramid of Bubb (taken out of [4])

Nevertheless, the high rate of mobile HVAC configuration in new cars of round about 75 to 80 % affirm the important role of thermal comfort requirements in vehicles, which stand for stress-free and safe driving.

The scientific research of thermal comfort started in building industry and was transferred to the automotive industry later. Within the following sub-chapter, a short review of the thermal comfort development is given to understand the basics of thermo-physiology and the differences between human thermal sensation and thermal comfort.

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2.1. A Short Overview about Thermal Sensation and Thermal Comfort Developments

Strictly speaking the history of thermal comfort dates back into the year 1775 when Blagden [5] evaluates the ability of people to withstand high temperatures in a heated room. Between 1923 and 1932 different tries of thermal index definitions were made like "corrected effective temperature" [6] and "standard effective temperature" [7], which consider the environmental effects of air temperature, humidity and thermal radiation. In 1948 Pennes invented the bio-heat transfer equation [8], which became a standard model for predicting temperature distributions in living tissues for more than a half century and set the baseline for considering the thermoregulatory mechanism of human beings in future models. So that at the beginning of the 70s Fanger [9] and Gagge et al. [10] start to include human physiological parameters like metabolism, clothing and activity into their thermal comfort models. Those models are so-called global comfort models as they calculate an overall thermal comfort index for the whole human body. Another classification of such thermal models is one- or two-node model. A one node model (e.g. [9]) uses empirical equations to predict thermal responses based on correlations that were derived from experimental conditions. Whereas a two-node models (e.g. [10]) splits the human body into core and skin to model thermoregulatory control in the core layer and the heat exchange from the core to the environment and vice versa by the skin layer.

Also during this time period, the very first thermal comfort standard from the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE 55) was published in 1966 and revised several times from 1974 to 2013 [11]. Fanger's well-known Predicted Mean Vote (PMV) index was integrated into this standard and was the basis for the first European standard of thermal comfort DIN EN ISO 7730 [12], which is still the most common standard of thermal comfort in building industry. Fanger's Dissertation [9] postulates that human satisfaction or dissatisfaction with the thermal environment is a result of the combination of the following six variables:

- Ambient air temperature;
- Relative air humidity;
- Mean radiant temperature;
- Relative air velocity;
- Activity level / metabolic rate;
- Thermal resistance of the clothing.

By this it can be easily seen that thermal comfort is not only just a matter of environmental conditions but also of physiological parameters of the occupants, which makes comfort assessment so complex as each individual is different. The data basis for Fanger's overall model comes from experiments in climate chambers where participants had to evaluate their thermal sensation in near-sedentary activity and in almost steady-state conditions. However, unfortunately the environment in a car cabin is highly inhomogeneous and often transient.

In response to these findings, the development of thermo-physiological models has gained more and more importance in the science of last 20 years. These so called multi-node models are able to predict the skin temperatures for different regions of the human body and the body's core temperature by including thermal control mechanism of human beings. The very first 25-node thermo-regulation model was developed by Stolwijk [13] for NASA during the Apollo program in order to create a mathematical model that can predict thermal responses of astronauts while performing their activities in space outside a spacecraft. This model is the "mother" of all modern thermo-physiological models like Fiala [14], UC Berkeley [15], Tanabe [16], ThermoSEM [17] and others. Such thermo-physiological models have in common a passive system and an active system.

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The controlled passive system simulates the physical human body parts and balances the heat transfer within the body parts, and between all body parts and their environment. Body parts represent blood circulation, bones, muscles, fat, skin layers, clothing, tissues etc. The active systems of such models hold the thermo-regulatory control reactions and responses of human beings. These are for example sweating, shivering, vasoconstriction, vasodilation, metabolic heat production, respiration, neurophysiological skin blood flow etc. In a nutshell, the advanced multi-node thermo-physiological models or even more sophisticated multi-element models (e.g. Wissler [18], Ferreira et al. [19]) will be able to predict human thermal responses in different thermal environments and simulate local body temperature distribution in detail, which reflects the thermal sensation of occupants in thermal environments. Figure 2 gives an overview of in and outputs of thermo-physiological models.

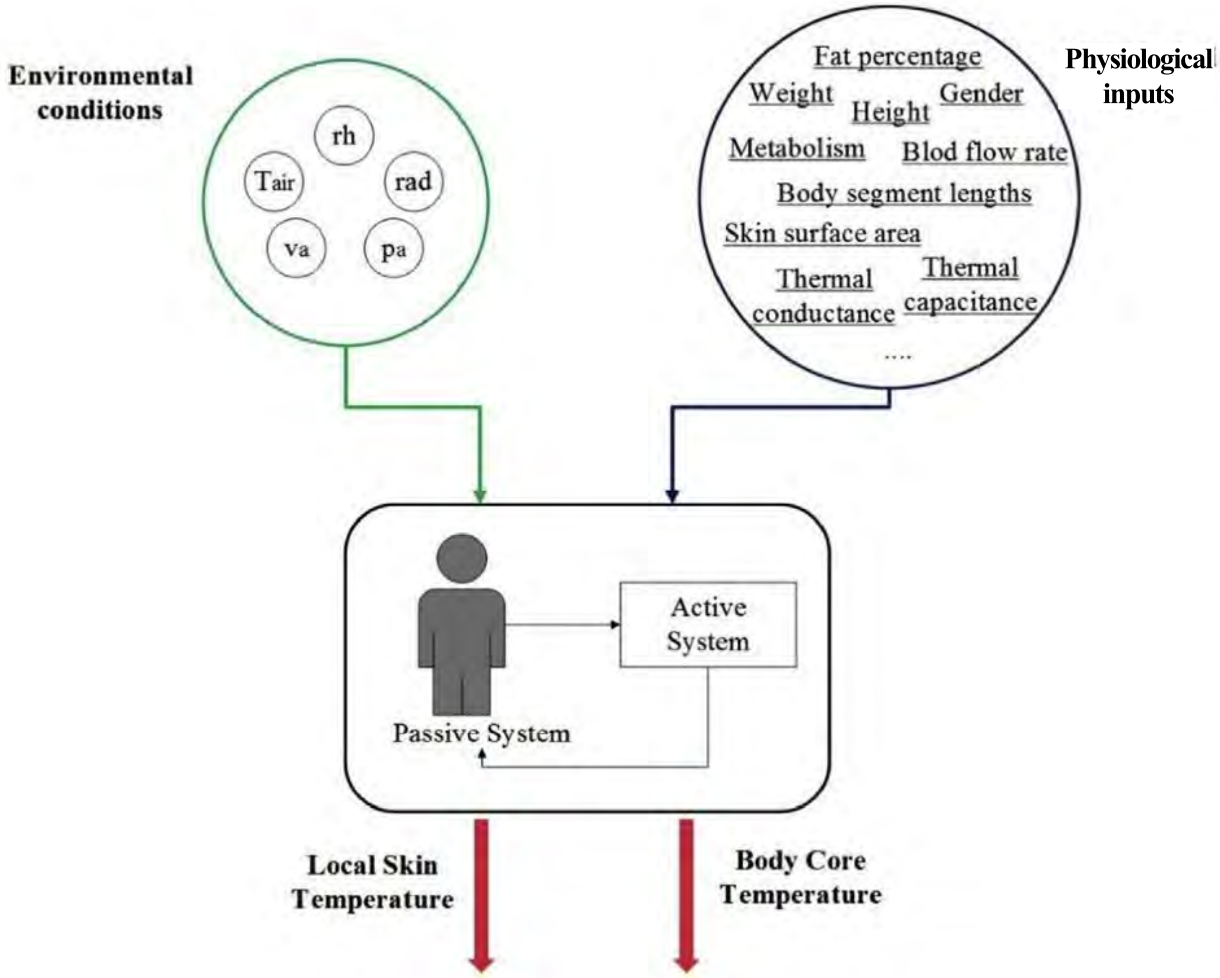

Figure 2: Schematic view of the inputs and outputs for thermo-physiological model [20]

In parallel to the development of theoretical thermo-physiological models during the Second World War in the 1940s the development of physically based thermal manikins by the US Army take place. A thermal manikin or thermal dummy is a human model designed for scientific testing of thermal environments without the risk or inaccuracies inherent in human subject testing. They are primarily used in automotive, indoor environment, outdoor environment, military and clothing research.

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According to Wikipedia [21] “thermal manikins were developed by the US Army for the purposes of carrying out insulation measurements on the gear they were developing. The first thermal manikins were standing, made of copper, and were one segment, measuring whole-body heat loss. Over the years these were improved by various companies and individuals employing new technologies and techniques as understanding of thermal comfort increased. In the mid-1960s, seated and multi-segmented thermal manikins were developed, and digital regulation was employed, allowing for much more accurate power application and measurement. Over time breathing, sneezing, moving (such as continuous walking or biking motions) and sweating were all employed in the manikins, in addition to male, female, and child sizes depending on the application. Nowadays most manikins used for research purposes will have a minimum of 15 zones, and as many as 34 with options (often as a purchasable add-on to the base manikin) for sweating, breathing, and movement systems.”

However, reverse engineering of all human thermo-regulatory responses in hardware is still quite ambitious, so that most of the available thermal manikins are passive dummies equipped with measurement instrumentation and have a lack of active system control. In sub-chapter 2.2.2 a couple of thermal manikins will be introduced shortly, also FLATMAN, which is in use at HRE-G [22]. Due to reduced active systems in thermal manikins, sometimes their passive bodies are coupled with active systems of formerly described thermo-physiological models.

Although the ability to predict human thermal responses in different environmental conditions by thermo-physiological models or thermal manikins delivers local skin and segmented body core temperatures, both methods will only determine the thermal sensation of an occupant. But thermal sensation is just half the truth to a thermal comfort model, because how can all local model results be combined to a global or local comfort index?

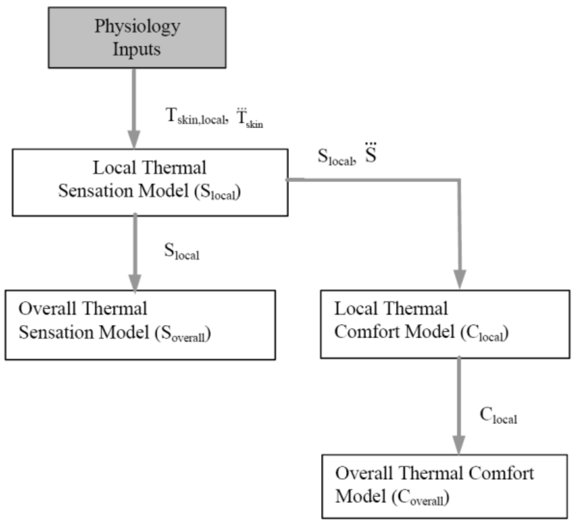

Figure 3: Flow chart from thermal sensation to comfort modeling [15]

The German Standard DIN EN ISO 14505-2 [23] try to find an answer to this problem by definition of the equivalent temperature. Thus, the equivalent temperature (ET) is defined as temperature of a homogenous room with mean radiant temperature equal to the air temperature and an air velocity of zero, in which the heat loss of a person by convection and thermal radiation meets the real heat loss under the existent conditions. With this method, a local comfort index for different body parts in summer and winter scenario can be calculated as written in the standard. Other possible comfort models are for example the Dynamic Thermal Sensation (DTS) from Fiala [14] or the most complex one from Zhang [15].

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2.2. Methods of Thermal Comfort Assessment

The mobile HVAC-system of Honda Fit EV uses a single temperature sensor in the cabin as an input parameter for the control strategy of the air-conditioning of the compartment, which outputs flap positioning, blower speed and cooling power for the AC system. Following the explanations of the previous chapter it is clear that individual thermal comfort cannot be achieved with that kind of sensor system. In small, compact and middle class cars this is todays standard of HVAC automatic temperature control and even high-class or luxury car cabins will only be equipped with additional (multi-directional) solar, fogging and in some cases additional humidity sensors. This is a first approach to detect and react to special environmental conditions, but of course still insufficient to satisfy the individual needs of the occupants. Further product developments like multi-zonal HVAC systems with 2 or 4 different air temperature regions, heated or ventilated seats and electrical heating of steering-wheels, are the actual attempt to increase the thermal comfort of the passengers.

Obviously, today's sensor technology in an interior of a car is still not smart enough to detect and establish the thermal well-being of the users. For this reason, currently three different methods are available to evaluate the thermal comfort sensation in vehicles. These are:

- Subjective user studies
- Objective rating with thermal manikins
- Objective rating with thermo-physiological models

The following chapters take a closer look to these three methods of comfort assessment and try to figure out some pros and cons.

2.2.1. Subjective Rating by Human Beings and Used Measurement Instrumentation

Thermal comfort application by ratings of skilled automotive test engineers during test drives is the most common method in automotive development of the OEMs all over the world. Moreover, in science human-subject studies are also quite common to get input data or for validation purposes of their thermo-physiological models.

In science, the big variety of individual thermal sensation in studies is intended to find generalities and exceptions. But in automotive development, where the target is to fulfill the thermal needs of a high rate of users, subjective rating by a single test person with individual preferences can generate a systematic error; e.g. a person who is feeling warm inside a cabin may enjoy a cool breeze from forced ventilation that cools exposed parts of the body. In other cases and cultures, the air speed might be a source of discomfort.

Moreover, most user studies in literature are generally focused on steady-state, uniform conditions of built environments. But people in vehicle compartments are probably more often exposed to spatially non-uniform, asymmetrical and time-varying temperatures than to thermal environments that are uniform and stable (see Table 2).

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Table 2: Comparison office environment versus vehicle compartment (according to [24])

Quantity	Office	Vehicle Compartment
Volume	Ca. 30 [m³]	Ca. 3 [m³]
Volume per person	Ca. 10 [m³/person]	Ca. 0,6 [m³/person]
Mode	Steady-state	Predominant transient
Air temperature	15 to 30 [°C]	-25 to 75 [°C]
Surface temperature	15 to 40 [°C]	-25 to 100 [°C]
Temperature field	Nearly homogenous	Inhomogeneous
Flow field	Nearly homogenous	Inhomogeneous
Radiation field	Nearly homogenous	Inhomogeneous
Solar radiation	Sun shade possible	Sparse protection possible
Approach velocity	Ca. 0.2 [m/s]	Up to 5 [m/s]
Distance to window	> 1 [m]	Ca. 0.2 [m]
Air exchange rate	2 – 8 [1/h]	10 – 200 [1/h]

Therefore, often the results of user studies do not apply to the thermal condition in vehicles or can be used only in a limited range. Sometimes these different conditions must be considered for the choice of measurement instrumentation, too, which are used in the study. In opposite to measurements in office rooms also the amount of test points is much higher in vehicle tests and due to the transient behavior, they have to be measured simultaneously with typical frequencies between 1 and 20 Hz. If local comfort assessment is required the number of measuring locations can even increase by a factor of 3.

Appropriate measurement equipment and sensor products are available for example from LumaSense Technologies Inc. [25], Ahlborn Mess- und Regelungstechnik GmbH [26], Dantec Dynamics A/S [27] and others.

Another important factor of human-subject studies is comfort questionnaire itself. As in every survey the result can be influenced by the questions. Therefore, DIN EN ISO 14505-3 [28] tries to standardize the evaluation of thermal comfort using human subjects and gives an example of comfort questionnaire. Another questionnaire example of Delphi can be found in Zhang's dissertation [15]. Figure 4 shows an exemplary comfort questionnaire from AVL qpunkt GmbH [29] that may be used in studies for comfort judgement in vehicle heat-up/cool-down tests.

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Comfort assessment scale: PMV-Index (predicted mean vote)	
hot	3
warm	2
slightly warm	1
neutral	0
sligthly cool	-1
cool	-2
cold	-3

Test number		
Name of test person		
Sex (male / female)	M/F	
Height and weight	m	kg
Clothing (type/color)		
Fan level		
Conv. heating power/level		
Set temp. of heated panel	°C	
Recirculation (yes/no/%)		

Assessment areas	after:	5 min	10 min	15 min	20 min	25 min	30 min	35 min	40 min	45 min	50 min	55 min	60 min
head, neck													
torso													
thighs													
lower legs													
left arm													
right arm													
Dissatisfaction due to: (mark x if applicable)													
draught													
vertical temperature differences													
cold or warm floor													
asymmetric radiation													

Remarks:	min:	
	min:	
	min:	
	min:	
	min:	
	min:	
	min:	

Result:	Comfort target reached after:	min	Date:

Figure 4: Example of a comfort questionnaire for IR-heating test of EV

Of confidentiality reasons, it is not possible to publish original test questionnaires from OEMs. But due to the fact that each OEM uses its own template and guideline, it would be useless anyway as there is no shared OEM standard available.

The project partner HRE will execute a human-subject study with Honda Fit EV later during QUIET research project to evaluate thermal comfort, usability and user acceptance including factors like accessibility/ergonomics and driver distraction.

Beside the high measurement efforts and costs that a thermal comfort user study will cause in many expensive climatic wind tunnel tests, the biggest challenge of this method is still the subjective rating, which requires a huge number of subjects to get a representative sample. Because it is in the interest of OEMs to create an objective measuring methodology of comfort assessment, which hit the collective liking.

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2.2.2. Objective Rating by Thermal Manikins

To objectify the development cycle described in 2.2.1, the market of today offers a variety of thermal manikins, some of them are "intelligent" and able to simulate thermal reactions of a human body (e.g. sweating).

Mentionable in this context is NREL's (U.S. Department of Energy´s National Renewable Energy Laboratory) thermal manikin called ADAM, which is an acronym for Advanced Automotive Thermal Manikin [30]. The technical data of this thermal manikin are: tall 175 cm, weight 61 kg, 126 elements of each ~120 cm² (see Figure 5).

Figure 5: Thermal Manikin ADAM

In comparison to other thermal manikins ADAM is not only a passive test dummy but also aware of an active system. Further advantages are:

- Self-contained power, water, and wireless communications for 2 hours of operation;
- High-spatial thermal, breathing and sweating resolution and control with 120 zones;
- Controlled by human thermal physiological model with iteration time of 2 min;
- Communicates with human thermal comfort model of the University of Berkeley.

Another well-engineered thermal manikin is P.A.Co. (= Perception Air Comfort), which was developed by Six Tau S.p.A. and Centro Richerche FIAT [31] (see Figure 6) and is an evolution of FIAT's EVA a female thermal manikin. P.A.Co. is accurate, very robust, extremely flexible, can communicate with CAN bus of the car and operates in a large range of environmental conditions e.g. -20 to 80 °C and air velocities up to 7 m/s.

Figure 6: Thermal Manikin P.A.Co.

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For this project, HRE intends to use FLATMAN from LumaSense/INNOVA, which is already described in [22].

More thermal manikins like DRESSMAN from Fraunhofer Institute, Thermal Mannequin Driver from PT-Teknik, NEWTON from Measurement Technology Northwest and SAM from EMPA ETH Zürich are described in detail in [32].

Most of them are passive dummies, which measure temperature, radiation, humidity and air velocity for different body parts and calculate PMV or equivalent temperature from a simple comfort model that includes clothing and activity factors.

Beside the high price of thermal manikins and the lack of active thermoregulatory systems, their use is often limited by sensor technology, fixed dimensions and improper thermal mass. Individual differences in human physiology (e.g. gender, age, body composition, etc.) are not considered. Moreover, most of them cannot handle conductive heat transfer, how it occurs for example in case of seat or steering wheel heating.

2.2.3. Objective Rating by Thermo-Physiological Models in CAE Applications

Another method of getting objectivity into thermal comfort rating is the virtual Computer-Aided Engineering (CAE) simulation of vehicle cabins with integrated thermo-physiological models. In chapter 2.1 the most important thermo-physiological models are already mentioned. Table 3 summarizes the main characteristics and constraints of recently developed advanced thermo-physiological models and should facilitate the selection process to identify which model fits best to the used simulation environment.

Table 3: Summary of the main attributes and constrains of selected thermo-physiological models [20]

Model	Attributes	Constraints
Gagge	- Whole body, single segment, two layers - Easy to implement - Short calculation time	- Only uniform conditions - Moderate activity level - One hour exposure time - No local body part outputs
Foda	- Two nodes: core and skin - 17 segments - Adjusted two-node model for individual body parts - Skin set-points based on neutral condition measurements	- Steady state conditions - Lower predictability at the limbs in extremely cold environment - Similar average of subjects - Normal office clothing - Sedentary activities
Stolwijk	- Local skin temperatures: six segments, four layers	- Constant environment - Assumes that every node of a segment has the same blood temperature - Prediction of the core temperature in the cold environment is less accurate
Tanabe	- Local skin and core temperatures: 17 segments - Validated for steady state and non-uniform transient conditions - Physical characteristics can be changed	- Based on set point temperatures of each segment
Berkeley	- Validated for steady state conditions, transient and non-uniform environment - Local physiological output possible of arbitrary number of segments - Each body segment can be exposed to different environmental conditions - Model structure is very flexible and the model can be modified and implemented easily - Individualization	- During transient conditions simulated arm temperature is lower than the measured one, but the final stable arm temperature has very good agreement
Fiala	- Extensive validation covering steady state and transient conditions, and various activity intensities - Environmental temperatures: 5 °C – 50 °C - Activity intensity: 0.8 met – 10 met - Average rms deviation of 0.7 °C and 0.9 °C for the mean and local skin temperatures for moderate, hot and cold stress conditions - Average of 0.2 °C rms deviation for body core temperature	- Lower predictability of skin temperatures during exercise in cold environments - Regression based
ThermoSem	- Local skin temperatures: 19 segments - Sub-division into sectors-asymmetric conditions possible - Based on neurophysiology - Individualization	- Validated for mild conditions

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Beside the thermo-physiological simulation models at least another tool is required to simulate the complex thermal conditions in a car cabin and deliver the transient environmental input values for these models. The Fiala model [14] was implemented in the thermal solver THESEUS-FE [33] that is used to solve steady state and transient heat transfer applying Finite-Element-Method (FEM). Another pair of linked tools is TAITherm [34], a thermal Finite-Difference-Solver, with integrated thermo-physiological model of the UC Berkeley [15]. Both tools use multi-layered shell meshes to discretise the geometry of the vehicle compartment, which on the one hand eases the modelling and the setup of the pre-processing (materials, boundaries, etc.) as well as speeds up the calculation times, but on the other hand both tools do not enable volume meshes for the air space in the cabin. Consequently, the simulation of the spatial distribution of the air flow is not possible.

For this reason, thermo-physiological models are also linked to CFD codes sometimes, which often have gaps to consider the multiple materials at the cabin walls and interior parts in an adequate way or only with an extreme modelling effort for multi-physics heat-transfer and very long calculation times.

The simulation of complete driving-cycles with permanent changes of the multiple boundaries with such complex 3D CAE models is almost impossible with regards to a reasonable cost-benefit ratio. Thus, occasionally 1D simulation tools are used, too, although the 1D approach of course neglect any local comfort aspects. This means, that they are mostly used to analyze the overall system of a vehicle and to determine energy flows or only global comfort indices. In terms of modelling HVAC control strategies, 1D simulation tools are nevertheless the first choice.

The benefits of linking different multi-domain simulation tools and subsystems into one so called co-simulation is obvious and practiced since more than a decade now. Multi-physics co-simulation frameworks like TISC [35], MpCCI [36], AVL Model.CONNECT [37] or ICOS [38] and many others provide an application independent interface for the direct coupling and data exchange of different simulation tools, sub-systems, test environments, devices, data and automation solutions, so that even the lines between the virtual and the real world are blurring. A linking of the HVAC control, thermal cabin simulation, aerodynamics, refrigerant and coolant cycles, vehicle dynamics and thermo-physiological models whether virtual or real is possible.

Figure 7 show exemplary results of a vehicle air conditioning co-simulation (top left: temperature stratification and free convection stream at the end of passive heating; top right: surface temperatures in the passenger cabin 10 min after start of active cooling; bottom left: skin and clothing temperatures of driver and air speeds and paths of recirculation air 20 min after start of cooling-down; bottom right: risk of draught according to ISO 7730 in the driver's region).

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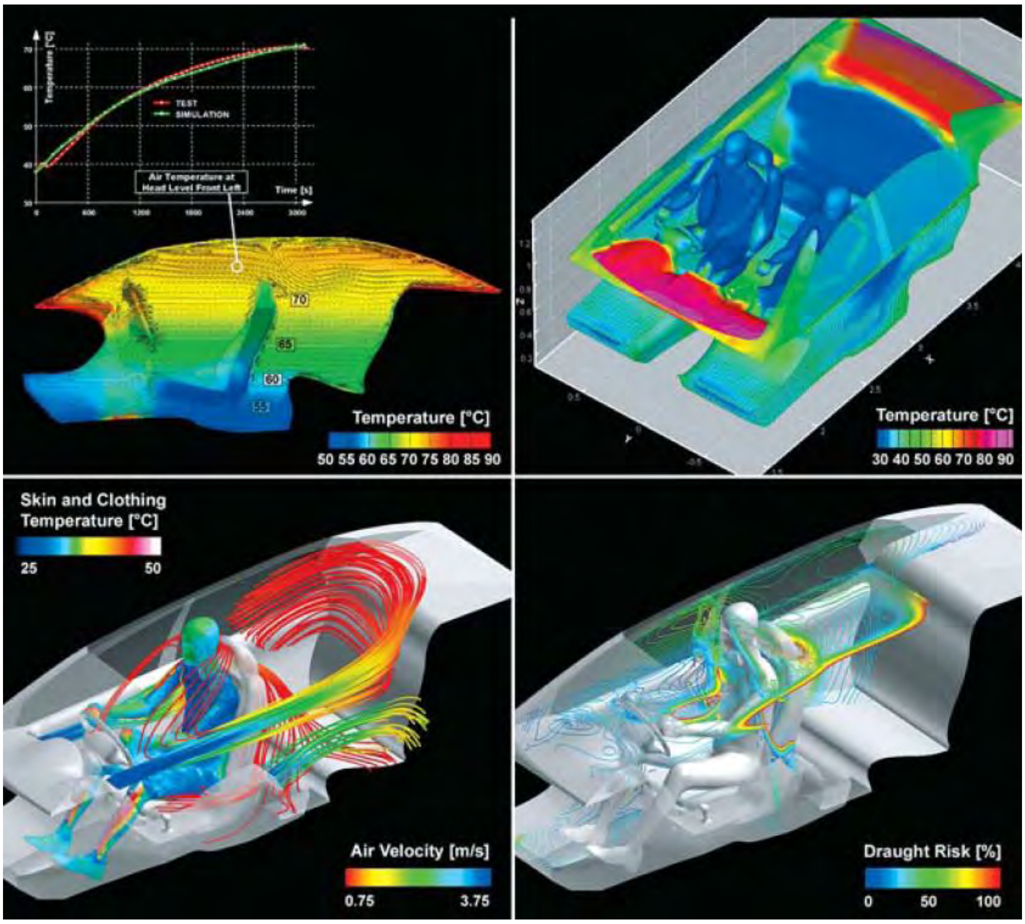

Figure 7: Exemplary results of a vehicle air conditioning co-simulation [39]

Beside local interior part and air temperatures, humidity, air velocities, convective, conductive and radiative heat and enthalpy balances, the thermal sensation and the local thermal comfort evaluation by equivalent temperatures at each body part according to DIN EN ISO 14505-2 can be derived (see Figure 8).

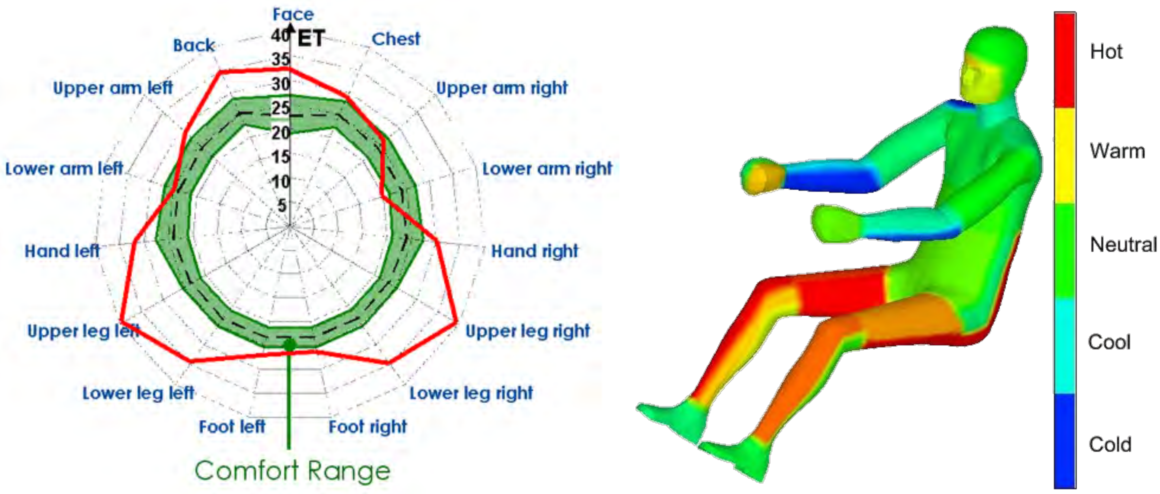

Figure 8: Local comfort assessment by CAE methods according to ISO 14505

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However, objective rating by thermo-physiological models in CAE applications still have two obstacles to overcome. The first obstacle is the huge amount of thermo-physiological and comfort models available, which cause different results of thermal comfort values and indices, so that a direct comparison in most cases is not possible and hence a common standard not available. The second obstacle is the correlation of the virtual CAE results to the subjective field test results of different individuals.

2.3. Thermal Comfort in Aspects of Individual Needs

Instead of offering customized products, which are adaptable to individual consumer needs, car manufacturers still try to achieve a high cumulative percentage of occupant thermal satisfaction by objectification and unification of the crowd with above mentioned optimization methods.

But individual differences in human physiology, gender, age, culture, Body Mass Index (BMI), fitness, personal mood and health, influence the thermal state of the body and physiological responses, thus creating possible differences in thermal comfort and thermal preferences of occupants. People from different climate regions and different ethnic background may experience thermal comfort and sensation differently in the same environmental conditions. Including physiological and psychological differences can provide more accurate thermal comfort assessment. These aspects will be examined in the next sub-chapters.

2.3.1. Use-Case of B-segment BEV

First, it is necessary to know, who the target group, owners and users of the product are. Based in Honda's internal market research, the typical European customers of B- and C-segment BEV were characterized. In courtesy of HRE the following use-case data is provided to QUIET.

Table 4: Use-cases of Honda Fit EV

Owner Items	Statistical User Data
Main user age	Mean age = 52 years, 75 % are between 35 and 65 years
Household type	~ 50 % without children
Usage Items	**Statistical User Data**
Commuting	~ 70 % daily
All seats occupied	~ 5 % daily and ~ 20 % never
Second row usage	~ 15 % daily and ~ 15 % never
Mileage per day	80 % under 70 km
Radiation field	60 % between 10 and 50 km
Holiday traveling	~ 75 % never

Browsing the data, the most frequent use-case is a 52-year-old single person, who rides almost daily short distances between 10 and 50 km. This brief analysis fits to the provided data of the operating profiles in the next Table 5.

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Table 5: Operating profiles of Honda Fit EV users

	Rarely (<5%)	Partially (6~50%)	Mainly (51~95%)	Exclusively (>95%)
City	4%	61%	31%	4%
Rural	9%	61%	28%	2%
Motorway	44%	50%	6%	0%

Most of the times the EV is used for city drives and short trips to rural areas. High-speed drives on motorways happen at rare intervals.

In summary, a B-segment BEV, like the Honda Fit EV is driven unhurried by elderly people in urban environment.

2.3.2. Age, Gender, Fitness and Other Aspects

To understand the individual factors and differences, it is necessary to take a closer look to the biological basics of human thermal sensation. Humans are not able to sense e.g. air temperatures directly, but the human thermoreceptors (i.e. the nerve endings) send signals to the hypothalamus at the base of the brain when stimulated by cold or warm stimuli. Three different types of sensory organs – cold receptors, warmth receptors and pain receptors – allow the body to discriminate gradations of cold and heat, ranging from cold to cool to indifferent to warm to hot. Thermoreceptors are located mainly in the skin and in the hypothalamus, but are also found in places such as the spinal cord, abdominal viscera, and in or around the great veins in the upper abdomen and thorax. The relative degrees of stimulation of the nerve endings determine the intensity of thermal sensation. As a result of this characteristic of thermoreceptors, a person feels much colder when the temperature of the skin is rapidly falling as when the temperature remains at the same level. Cold receptors are beneath the epidermis and the standard location of warmth receptors is within the upper layer of the dermis, so that the warmth receptors are in a deeper skin layer. Moreover, the number of cold thermoreceptors far exceeds the number of warmth receptors by round about a factor of 10. Figure 9 displays a mean distribution of cold receptor on a body, whereas Table 6 gives some typical values of cold and warmth receptors per body part.

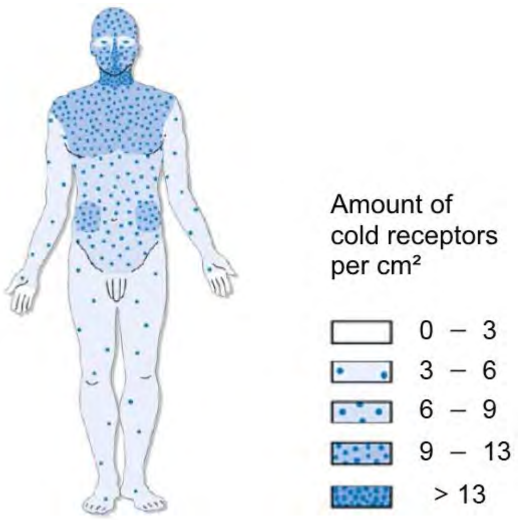

Figure 9: Mean surface distribution of cold receptors [40]

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Table 6: Density of thermoreceptors at various body parts [40]

Body parts	Receptor density [1/cm²]	
	Cold	Warm
Forehead	6.750	0.62
Nose	10.50	1.00
Thorax	9.00	0.30
Upper Arms	5.70	0.30
Lower Arms	6.00	0.40
Back of the Head	7.40	0.54
Thighs	5.85	0.39

Another factor is the individual anatomy, anthropometric shape and constitution, which often is expressed by the BMI. The ratio of musculature for women is relatively and absolutely lower compared to men. On average males have 5 % more muscles than females, i.e. 35 kg for men and 23 kg for women, if we assume a mean total weight for European males of 88 kg and 65 kg for females. On the other hand, females have more fat than males. Females have a mean body fat percentage of ca. 28 % compared to 18 % for males. Because both, muscles and fat, can be build or reduced by training and nutrition, thermal sensation also depends on personal fitness, also called Shape- or Tone-Index. Figure 10 show the body fat percentage of men and women in dependence of the BMI.

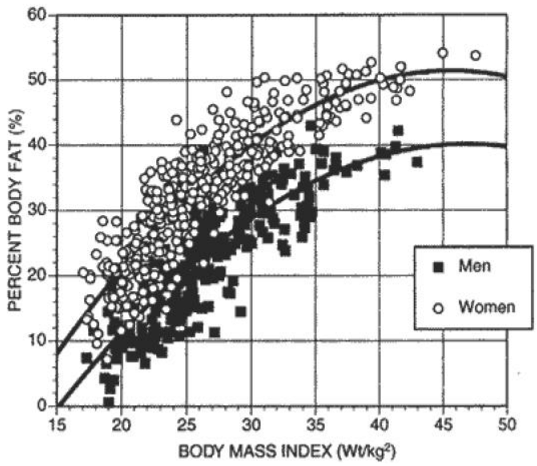

Figure 10: Body fat percentage versus body-mass-index [41]

Individual fitness often is also combined with health and it is obvious, that an ill person has a completely different heat balance, disordered thermo-regulatory system and therefore thermal sensation. Standard thermo-physiological models can also not be applied to pregnant women, to disabled or to individuals whose age is below fourteen or above sixty, which is considered the adult range. During childhood thermoreceptors must be developed first and trained later on. For this reason, children do not sense temperature very well.

As most published human subject studies are executed with adult, healthy, average test groups and not with above mentioned special groups, the VTT Technical Center of Finland used a thermo-physiological model to calculate the impact of individual characteristics on human thermal sensation [42].

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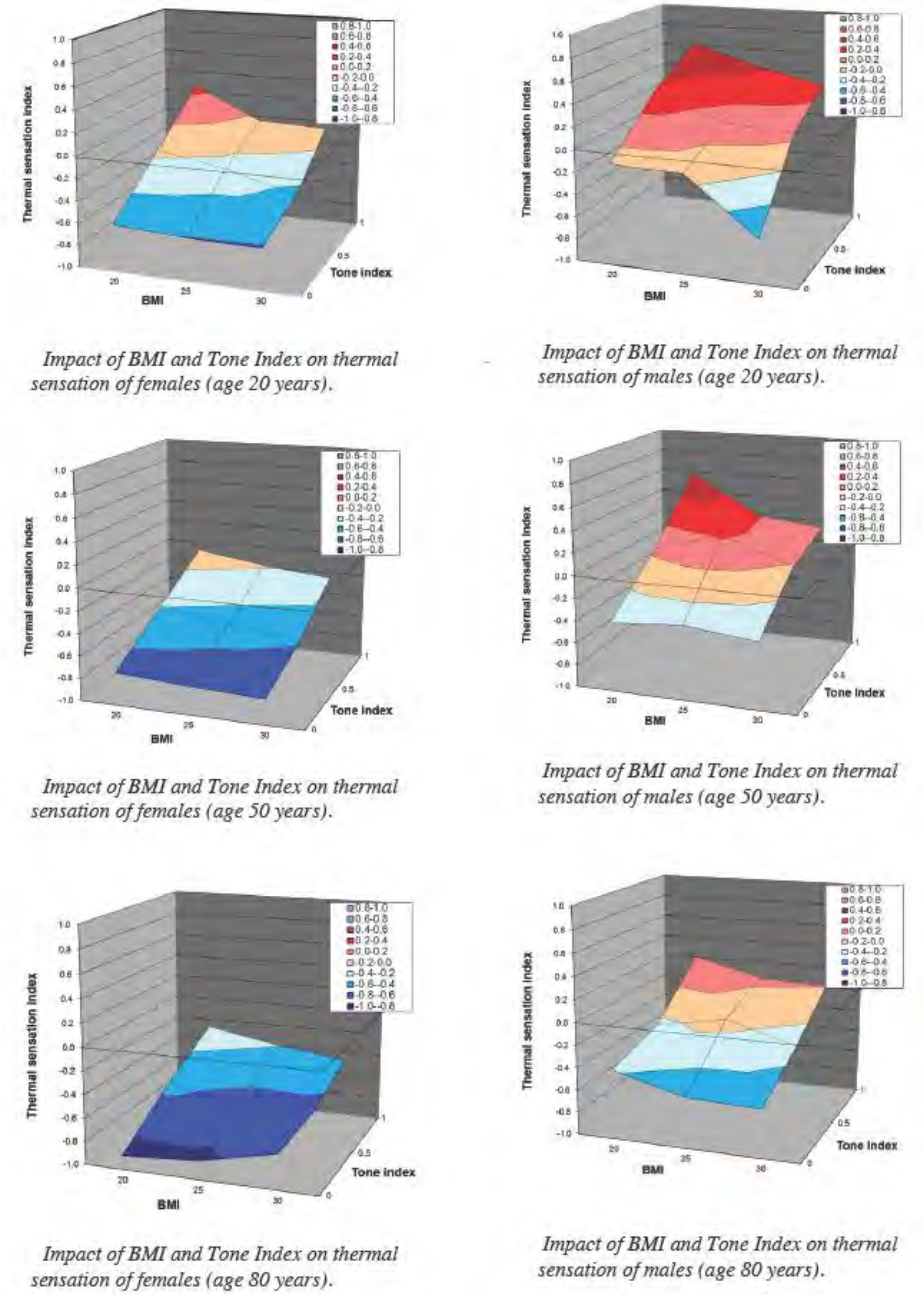
In this paper, they varied the BMI between 20 and 30, the age between 20 and 80 years and the Tone-Index between 0 (min. fat) and 1 (max. fat), within a simple thermal comfort simulation at steady-state, neutral conditions in a room of 22 °C air and wall temperature as well as 40% humidity. The results of this simulation variants are illustrated in the following Figure 11.



Impact of BMI and Tone Index on thermal sensation of females (age 20 years).

Impact of BMI and Tone Index on thermal sensation of males (age 20 years).

Impact of BMI and Tone Index on thermal sensation of females (age 50 years).

Impact of BMI and Tone Index on thermal sensation of males (age 50 years).

Impact of BMI and Tone Index on thermal sensation of females (age 80 years).

Impact of BMI and Tone Index on thermal sensation of males (age 80 years).

Figure 11: Age, gender, BMI and fitness impacts on human thermal sensation [42]

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Comparing the results of the female characteristics on the left-hand side, with the male characteristics on the right-hand side, and the increase of age from top to bottom, three clear trends can be evaluated:

- Increase in age result in a decrease of thermal sensation index values;
- Lower thermal sensation index values were obtained for females compared to males (with corresponding BMI and Tone-Index parameters);
- BMI values have a minor impact on thermal sensation compared to high Tone-Index values (individual fitness), which cause the most significant increase in thermal sensation index.

In 2010 Novieto and Zhang studied the possibility of adapting the Fiala model to an aged human body [43]. The authors focused on three parameters obtained from literature, playing a major role in terms of ageing effects. These parameters are basal metabolic rate, cardiac output and body weight. As a first approach, the authors varied each parameter separately in their physiological range of -20 % to +20 % compared to the standard human manikin model and calculated the ambient and mean radiant temperature, necessary for keeping the model in thermal neutrality (no intervention of the active system). In a second step, the authors focused on dynamic thermal sensation and thermal comfort prediction. The gained results reveal that the Basal Metabolic Rate (BMR) is the main responsible factor for changes in thermal comfort requirements. The combination of BMR, the Cardiac Output (CO) and the Body Weight (BW) show a high influence on local comfort concerning skin areas directly exposed to thermal ambient conditions.

Existing literature provides consistent evidence that sensitivity to hot and cold environment usually declines with age. There is also some evidence of a gradual reduction in the effectiveness of the body in thermo-regulation after the age of sixty [44]. For this reason, seniors prefer warmer temperatures than young adults.

In terms of gender thermal comfort preferences between sexes seems to be small, but there are some differences. Studies have found males report discomfort due to rises in temperature much earlier than females. Males also estimate higher levels of their sensation of discomfort than females. Often, females feel cooler than male persons in the same environment and will prefer higher temperatures. But while females are more sensitive to temperatures, males tend to be more sensitive to relative-humidity levels [45] [46].

Since anthropology varies between ethnic groups, thermal comfort is also affected by cultural and regional climate influences.

Finally, individual's comfort level in a given environment may change and adapt over time due to psychological factors. Subjective perception of thermal comfort may be influenced by the memory of previous experiences. Habituation takes place when repeated exposure moderates future expectations and responses to sensory input. Psychological factors also lead to the ‘hue-heat’ hypothesis, which states that an environment which has wavelengths predominantly toward the red end of the visual spectrum feels warm and one with wavelengths mainly toward the blue end feels cool. In latest research it was found, that these colors influence participants’ response speed [47], so that thermal sensation is delayed which changes subjective comfort ratings.

2.3.3. Future Demands and Individual Needs with Respect to New Technologies

The general lack of today´s AC-systems to take the passengers’ actual thermal sensation into consideration and the missing user-centric design, lead to some research in the fields of input handling and passengers’ well-being-detection. Another driving force are of course current technology trends like electrification of vehicles and autonomous driving. With the Advanced Driver Assistance Systems (ADAS) Level 5, the vehicle compartment will change to a “living space” and completely new HVAC concepts are required as the location of the passengers in the cabin are no longer fixed as well as the activity levels of the occupants. Therefore, in

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the future objective detection of occupants' comfort and activity state becomes a key role for many control systems to offer user-centric functions like specific air-conditioning, light and entertainment control, ADAS and safety systems etc. Following a very small selection of actual research topics, future technologies are spotlighted.

UC Berkeley published a paper [48] presenting the correlation between thermal comfort and temperature differences in different regions of the face, suggesting to use these results to control a HVAC system. The researcher equipped an eyeglass frame with infrared sensors to measure the temperature of ear, front face, nose and cheekbone (see Figure12). Fifteen test persons wore those eyeglass frames in an everyday office working environment, for at least 2 hours on four days. During testing, subjects were required to give feedback on thermal comfort with the following options: much too warm, uncomfortably warm, comfortably warm, comfortable, comfortably cold, uncomfortably cold and much too cold.

Figure 12: (a) infrared sensing locations, (b) sensing device with sensors [48]

The results of the UC research show clear correlation, valid for 95% of the testing group (see Figure 13):

- If the temperature of the nose is lower than the temperature of the front face / cheekbone, the test person will complain about cold stress;
- If the temperature of the ear is higher than the temperature of the front face / cheekbone, the test person will complain about warm stress;
- This correlation is seen with male and female test persons and again female values are even lower than male temperatures.

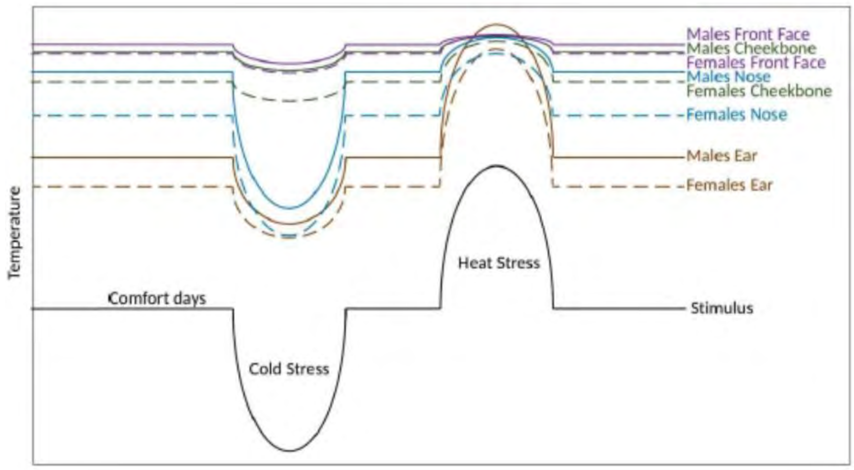

Figure 13: Schematic illustration of the observed physiological response [48]

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RWTH Aachen took these findings for a test [49], setting up a system with a thermographic camera by using a software to recognize different areas of the face including face tracking methods. In a single test feasibility it was shown, that the software was very well able to recognize face areas and to show temperature differences of these areas congruent with the results from UC Berkeley.

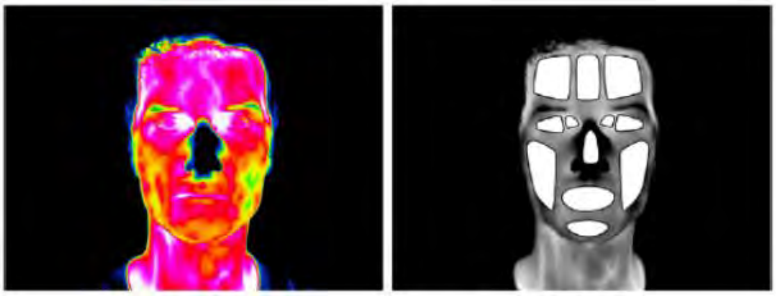

Figure 14: Exemplary thermal image and face regions as defined by RWTH [49]

As the human face is normally not clothed while driving, these systematics is highly likely to change future operating concepts and testing equipment for HVAC systems in cars.

Other thinkable influences can be additional sensors to the steering wheel (pulse, sweat) or the seat (weight, temperature) to gain further information about the passenger status, even the inclusion of wearables (e.g. fitness wristband, smart watches, etc.) could offer important information.

Combining these sensors with RWTH's capability of detecting facial zone temperatures and then using UC Berkeley study of comfort sensation (influencing facial blood flow) would offer a new approach to assess personal subjective sensation. RWTH Aachen already published a project combining all these techniques [50]. Multiple sensors focusing on thermal reactions of the passenger feed a model in real-time, allowing to control a HVAC system exactly to the needs of each passenger and created a new Modelica-based thermo-physiological model based on Stolwijk, Fiala and Tanabe called MORPHEUS [51], which is able to consider morphological and anthropometric parameters.

A sensor system published in an US Patent [52] (see Figure 15) with accessibility to the CAN-bus of the car, enables the system to interact with other functional actuators and control systems of the vehicle. The title "Biometric application of a polymer-based pressure sensor" is a little bit misleading, but the inventors describe a complete system of different sensors using every information to describe the passenger´s biometric state. The main aim is to increase safety and reaction time, but comfort functions, too.

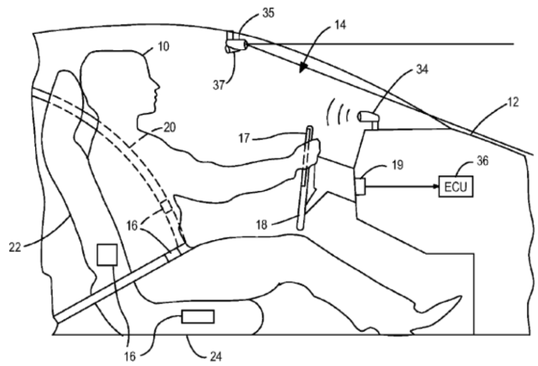

Figure 15: Cross-sectional view of applied biometric control system [52]

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The measured and collected data of such a system may be provided by car busses or even wireless (e.g. Bluetooth, NFC, Wi-Fi, etc.) to central control units of vehicles, so that different actuators are automatically triggered.

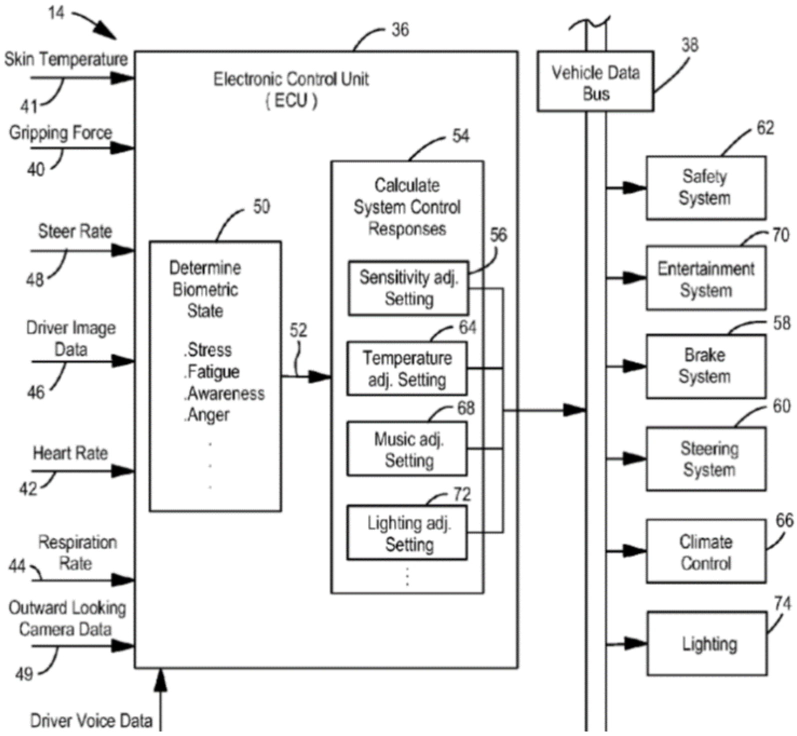

Figure 16: Block diagram of a global ECU comfort control system [52]

The only advanced concept of personal thermal comfort assessment ready-to-use in a vehicle is the "Active Wellness Seat 2.0" from Faurecia [53]. It combines sensors and functions detecting occupant's fatigue with new functions added to the seat:

- Heart beat and respiration rates;
- Body movement or fidgeting;
- Contact temperature and humidity;
- Blink, eye gaze and percentage of eye closure;
- Head tilt and facial expressions.

Figure 17: Active Wellness seat by Faurecia [53]

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Mainly engineered to countervail fatigue events through massage or other short-termed impulses, it can be used to give valuable inputs to any user-centric control functionality, since, with respect to autonomous driving, the seat will be the only fixed interface to passengers in future compartments of passenger cars.

Seat occupancy in general indicates the total number of passengers and is the baseline of distributed HVAC systems in order to save energy consumption on air-conditioning. For example, IR-heating techniques based on heated panels are commercially available as an accessory in Daimler's S class car and will be applied as well in the QUIET research project by ATT. Since the concept of local IR-heating by heated panels is published already often in the past it will be not discussed in detail here again.

Nevertheless, variable seat positions and location in a future vehicle compartment also requires new ventilation concepts. Realizing this need, the company Dr. Schneider Holding GmbH is working on different air-inlet concepts that provide direct as well as indirect air flows [54]. With the "satellite shower" as shown in Figure 18, the developers can deliver an air flow on-the-spot in a 330° turning angle or to spread the air flow over a huge area. This ventilation spot can appear on demand or sink into the dashboard when unused and change direction for windscreen defrost or passenger ventilation.

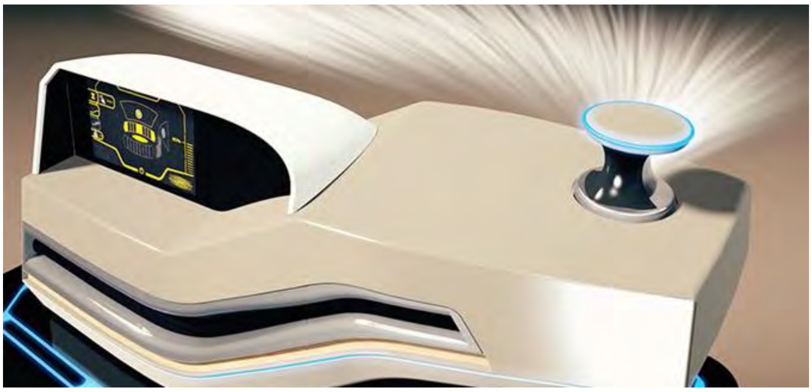

Figure 18: Satellite ventilation concept by Dr. Schneider Holding GmbH [54]

Moreover grille-free and hidden air vents, gap ventilation, flexible grille blades, new ventilation surfaces, cluster air vents, clean air vents and feel-good comfort air vents integrated into dashboards, pillars, seats, roof ceilings or new ventilation surfaces will become standard ventilation elements in smart air-conditioning concepts of the future. The influence of overhead "air showers" from the roof on the passenger comfort and different seat ventilation concepts is analyzed for example at Technical University in Munich [55] and first roof vents are already applied for product tests at different first tier suppliers.

Figure 19: Experimental setup of "cold air shower" [55]

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A different approach to assess passenger thermal sensation is offered by „Ingenieurgesellschaft Auto und Verkehr" (IAV) with their new operating HMI concept shown in Figure 20, asking for the passenger's thermal sensation and not for the target state of the HVAC system [56]. On a quartered circle diagram, the passenger can input his feelings from "too stuffy" to "too drafty", and from "too cold" to "too hot" for three regions of his body (head, torso, leg/feet). Even a personal HVAC setting can be achieved with this operating concept, the system is able to learn the preferences of each defined passenger.

Figure 20: Intuitive HVAC control concept and HMI from IAV [56]

All those innovations mentioned so far target the user-centered comfort of each passenger in a vehicle. Compared to conventional mobile HVAC systems, air-conditioning is needed to become complete different within the next decades to fulfill individual and local thermal comfort in a vehicle.

3. Thermal Comfort Targets in Vehicles

As mentioned before, the thermal environment in a car cabin is in the majority of cases highly inhomogeneous and transient with quick environmental changes. Therefore, the main target of thermal comfort development of car manufactures aims to reach the state of thermal neutrality with homogenous steady-state conditions as much as possible, irrespective of the environmental climatic conditions outside the vehicle. Nowadays each OEM uses different processes, test specifications and target values for their cars.

Furthermore, the state of neutral thermal condition is not fixed at all. In literature, there are different methods to determine thermal neutrality of standing naked humans, which depends on the number of measurement points at the body and the way they are weighted to a mean value. But these set point values do not apply anyway, because most of the times people are dressed and sitting in a car (and not standing).

However, to further information and orientation Table 7 shows the results of an experiment executed by Olsen and Fanger [57], where the resting subjects are seated, dressed in the so called KSU-uniform and exposed to thermoneutral conditions of $T_{air} = T_{wall}$ = 25.5 °C in a room with still air.

Table 7: Skin temperature distribution for resting man in comfort

body temperatures			experiment *)
rectal		[°C]	36.9 ± 0.3
mean skin		[°C]	33.5 ± 0.5
forehead skin		[°C]	34.2 ± 1.0
neck skin	posterior	[°C]	34.7 ± 0.8
thorax skin	anterior	[°C]	34.4 ± 0.6
	posterior		34.5 ± 0.9
arm skin	upper	[°C]	*33.5 ± 0.9*
	lower		*32.7 ± 0.8*
	average		33.1 ± 0.9
hand skin	back	[°C]	33.5 ± 1.0
abomen skin	anterior	[°C]	34.9 ± 1.0
	posterior		33.5 ± 0.8
leg skin (anterior)	upper	[°C]	*33.7 ± 0.8*
	lower		*32.6 ± 1.1*
	average		33.2 ± 1.0
leg skin (posterior)	upper	[°C]	*32.9 ± 0.9*
	lower		*32.2 ± 1.0*
	average		32.6 ± 1.0
foot skin	instep	[°C]	32.2 ± 2.0
evaporative weight loss		[g/m²h]	20.1 ± 6.9

*) mean values ± SD of 32 subjects

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Table 7 describes the neutral state of the adult test subjects. In Table 8 an overview of typical target values is given dealing with typical neutral conditions in a passenger compartment.

Table 8: Typical neutral conditions for thermal comfort in a compartment

THERMAL COMFORT		
Variable	**Dependency**	**Target**
Temperature	$f(x,y,z,t)$	Comfort Range (22 - 25 °C)
Ambient surface temp.	$f(x,y,z,t)$	$(T_{surf} - T_{air}) \leq 4K$
Humidity	$f(x,y,z,t)$	Comfort Range (30 – 70 %)
Air speed	$f(\bar{x},\bar{y},z,t)$	≤ 0.15 m/s
Air turbulence intensity	$f(\partial v / \partial t)$	< 20%, fluctuation > 2Hz
Activity rate	$f(Q/A,t)$	Work load (~ 0.8 - 1.2 met)
Clothing	$f(R_{cl}, R_{ecl}, f_{cl})$	Load case dependent

In general, a fixed and universal set point of thermoneutral conditions is hard to define, because the values are local and depend on the load case respective climate scenario, too. Therefore, the target values are expressed mostly in a range of comfort.

From chapter 2.1 it is known, that thermal comfort models translate the physical description of the body's thermal state into intuitive categories of cold, neutral or warm, comfortable or uncomfortable. Global models consider the complete thermal state, and local models hold for certain body parts, e.g. for the seat contact zone at the human back. In the following sub-chapters both will be considered.

3.1. Global or Overall Thermal Indices

According to Figure 3 global comfort models try to express the overall thermal comfort per passenger in a single value by using comfort index scales. Because many authors introduced their own scales, it is necessary to know the differences between these scales for the case of interpreting given thermal comfort index results. Following the most common indices are introduced shortly.

Bedford Scale

Bedford, investigated the comfort of persons engaged in very light industrial work (see [58]). A total set of 3085 observations were executed. Most of the observations were made on women and girls. Large differences in the comfort estimations were found. Large numbers of workers were asked about their feelings of thermal comfort, while the current climate was measured. The responses of the workers were classified with the following seven-point scale

Table 9: Seven-point Bedford scale

Much too warm	1
Too warm	2
Comfortably warm	3
Comfortable	4
Comfortably cool	5
Too cool	6
Much too cool	7

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ASHRAE and PMV Scale

"In studies made by Rohles et al., on 1600 college students, correlations between comfort level, temperature, humidity, sex, and length of exposure were presented. The thermal sensation scale developed for these studies is called the ASHRAE thermal sensation scale" (excerpt from [58]).

Table 10: Seven-point ASHRAE/PMV scale

Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

"PMV scale predicts the mean value of the votes of a large group of persons on the same psycho-physical thermal sensation scale as the ASHRAE 55. The theory is based on Fanger's heat balance of the human body. The human being is in thermal balance when the internal heat production in the body is equal to the loss of heat to the environment. In the PMV index the physiological response of the thermo-regulatory system has been related statistically to thermal sensation votes collected from more than 1,300 subjects. The index is derived for steady-state conditions, but can be applied with good approximation to minor variations of one or more of the variables, provided that time weighted averages of the variables during the previous 1-hour period are applied. It is recommended to use the PMV index only when main parameters are inside certain specified intervals." (excerpt from [59]).

Directly derived from PMV index (whereupon PMV values between -0.5 and +0.5 mark the comfort range), Fanger also introduced the PPD index, which calculates a prediction of the number of thermally dissatisfied people. Strictly speaking it is not an index, because PPD values are written in percent with a minimum of 5 % at neutral conditions and a maximum of 100 % at dissatisfaction level.

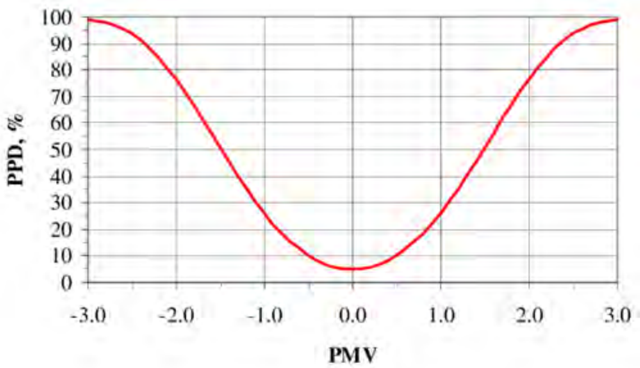

Figure 21: PPD as a function of PMV

Dynamic Thermal Sensation Index

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Another comfort model, which also uses a 7-step scale of ASHRAE and PMV is the DTS, which is based on a regression analysis of a large amount of experimental data and the physiological Fiala-model results [14]. The source data adopted by the model covered a large scope of air temperatures ranging from 13 °C to 48 °C and activity levels between 1 and 10. The DTS comfort model has been validated and widely applied after being developed. In opposite to the PMV this comfort model includes both, static and dynamic input signals.

Zhang's Comfort Indices

Zhang's comprehensive thermal sensation and comfort model [15] has been set up for a wide range of environments: uniform and non-uniform, transient and stable. The model was developed based on vast environmental test data representing steady and transient conditions. Zhang added two more steps at the end of the 7-point PMV scale by introducing the following 9-point scale for the thermal sensation:

Table 11: Nine-point scale of Zhang's thermal sensation

Very hot	+4
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3
Very Cold	-4

This scale is also defined and recommended in the ISO Standard DIN EN ISO 10551-01:2002.

Zhang's comfort model ranges from very uncomfortable = -4 to very comfortable = +4 (9-point scale).

DIN EN ISO Comfort Index

Finally, the thermal comfort scale of the ISO Standard DIN EN ISO 14505-2 should be mentioned. In contrast to Zhang and other indices mentioned above, this scale applies the interesting assumption to neglect the discomfort once dissatisfaction occurs and therefore only a 5-point scale was introduced as follows:

Table 12: Five-point ISO scale

Too warm, uncomfortable	5
Warm, but comfortable	4
Neutral, comfortable	3
Cold, but comfortable	2
Too cold, uncomfortable	1

In principle, the ISO comfort index can be represented also by a reduced Bedford scale (it needs getting used to the fact that the neutral state is not zero).

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Indices conclusion

Although the use of PMV is very limited due to the limited intervals of the input parameters, it is still the most common used index. In ISO Standard 7730 it is recommended to use the PMV index only if the six main parameters are inside the following ranges:

Table 13: Limits of PMV

Quantity	Range
Metabolic rate	58 – 232 W/m² [1 - 4 met]
Clothing value	0 to 0.310 (m²*°C)/W [0 to 2 clo]
Air temperature	10 to 30 °C
Mean radiant temperature	10 to 40 °C
Relative air velocity	0 to 1 m/s
Partial water vapor pressure	0 to 2700 Pa

Looking in detail to Table 13 one can see, that the PMV index is not applicable in highly dynamic heat-up or cool-down phases of vehicle air-conditioning. Thus, it is remarkable, that it is still used by the automotive industry to evaluate thermal comfort. For automotive comfort assessment other indices like DTS [14], ISO 14505-2 [23] or Zhang [15] should be applied. Table 14 sums up the advantages and disadvantages of each comfort model.

Table 14: Comparison of comfort models and indices

	Fanger (1970) PMV-Index	Fiala (1998) DTS-Index	Assessment of equiv. temperatures (EN ISO 14505-2)	Zhang (2003) Local comfort model
Input	•activity level •global boundary cond.: air- and wall temperature, air-velocity, humidity •clothing	•mean skin temperature •core temp.	local heat loss values	•locale skin temperatures •mean skin temperature •core temperature
Validity	stationary, global	dynamic global	stationary, local + global 6 assessment regions	dynamic, local + global 13 body parts
Remarks	not coupled with thermal manikin response	DTS similar to PMV	differing assessment for summer and winter clothing	model also provides max. thermal comfort value ⇒ applicable for optimization
Handicap	•not applicable for contact boundary conditions •model requires global cloth. definition (clo-value)	less validated for dynamic load cases	compared with Zhang: locale comfort predictions are quite undifferentiated	•very complex model •results sometime not transparent ("black box")
Output (Indices)	global therm. sensation on a 7-step-scale -3 .. cold -2 .. cool -1 .. slightly cool 0 .. neutral +1 .. slightly warm +2 .. warm +3 .. hot		local therm. sensation and comfort on a 5-step-scale 1 .. too cold (uncomfort.) 2 .. cold (but comfort.) 3 .. neutral (comfortable) 4 .. warm (but comfort.) 5 .. too warm (uncomfort.)	global and local therm. sensation on a 9-step-scale, from -4 (very cold) to +4 (very hot) thermal comfort on a 9-step-scale, from -4 (very uncomfortable) to +4 (very comfortable)

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Because people change their clothing with the weather and the season, ASHRAE Standard [11] specifies summer and winter comfort zones appropriate for clothing insulation levels of 0.5 and 0.9 clo, where 80 % of sedentary or slightly active persons find the environment thermally acceptable.

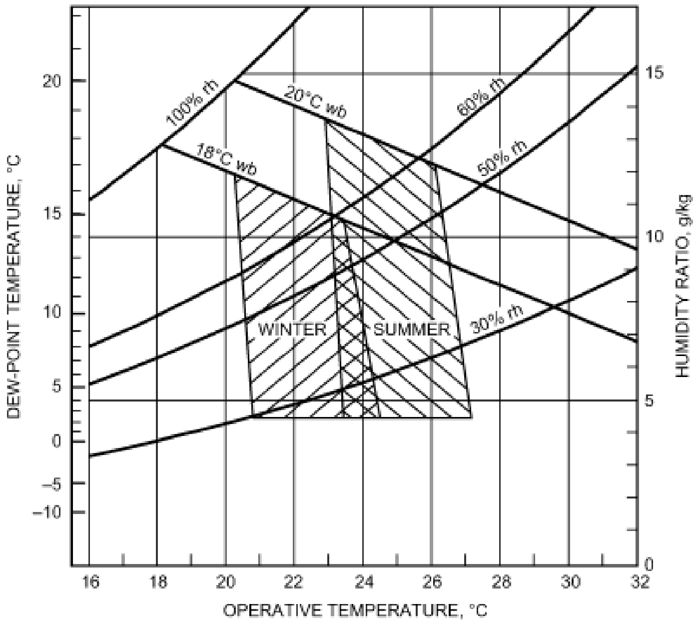

Figure 22: ASHRAE summer and winter comfort zones [11]
(Remark: wb = wet-bulb temperature, rh = relative humidity)

3.2. Local Thermal Indices

Global comfort indices as described in previous chapter 3.1 have a systematic disadvantage when local discomfort appears. That means for example if the subject has a warm head and cold feet, the global thermal comfort value might be neutral, because both effects cancel each other. For this reason, local comfort assessment is necessary, especially in an extremely inhomogeneous environment of a vehicle compartment.

The most common method to judge local comfort is the equivalent temperature (ET), which was already explained at the end of chapter 2.1. While ET is based on comparative experiments with thermal manikin and human subjects in the same conditions, it does not involve the use of the physical human body and thermo-physiological modelling. The subjects voted their thermal sensation using the mean thermal vote scale for each of the segments and for the whole body, while the manikin provided measured data of each segment and whole-body heat loss, which were transformed to ET values.

But the big advantage of ET is that it expresses the effects of combined thermal influences in a single figure, easy to interpret and explain. It is particularly useful for differential assessment of the climatic conditions. The basic assumption of this method is, that human beings are equally sensitive to different heat losses independent of the insulation of clothing worn and irrespective of the kind of combinations of heat losses. Today this seems to be true, at least for conditions close to thermal neutrality and within limited variations of the climatic factors.

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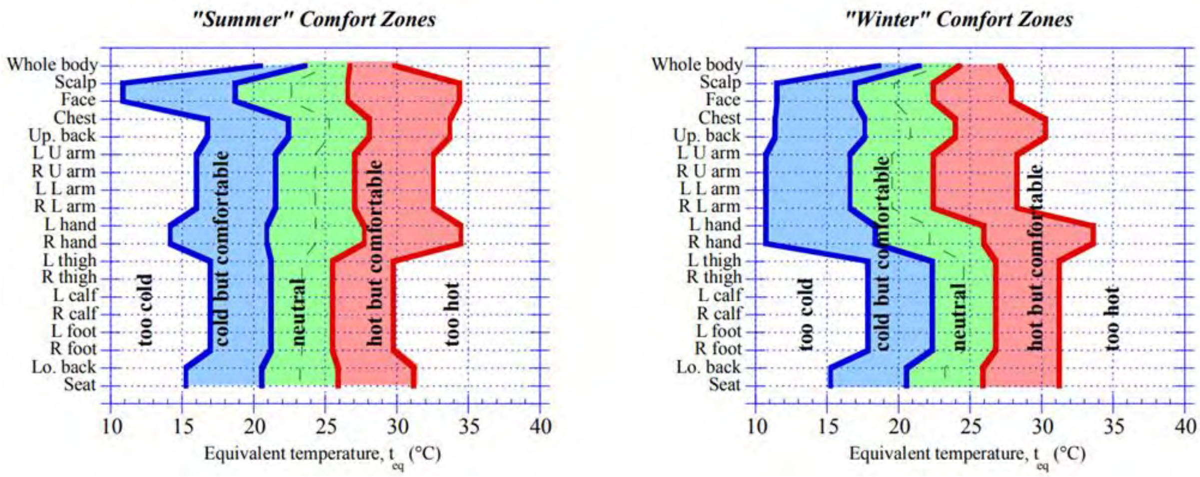
The ISO Standard DIN EN ISO 14505-2 [23] defines local thermal ETs and comfort indices of 16 body parts for the summer- and the winter case. Assuming that, the passengers are sitting in an air-conditioned environment and dressed in light summer clothing (0.6 clo) for the summer case and enhanced winter clothing ensemble (1.0 clo) for the winter case. Figure 23 illustrates the comfort tables for both cases.



(Abbreviations refer to L = left, R = right, U = upper)

Figure 23: Comfort zone diagrams for 16 segments of the body derived for the summer and winter case

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4. Conclusions

With the help of extensive literature research, the latest scientific findings of thermal comfort assessment are presented to the project partners in this document. Starting with the basics and a short overview of thermal sensation and thermal comfort developments from the past to the current state-of-the art, the user-centric needs and the use-case of the demonstrator vehicle Honda Fit EV were described, followed by trends how individual aspects like age, gender, fitness and ethnic or culture effect the thermal sensation. Finally, methods how to measure and gain optimized thermal comfort in a vehicle passenger compartment were presented. Due to the comprehensive scope of WP2.1, it was not possible to discuss each topic in detail and it is highly recommended to appropriate the given bibliography for further information.

However, comfort research is a wide field, thermal comfort only a small part out of it and satisfaction of individual comfort an almost unsolvable task, because too many personal factors are involved. Beside age, gender, fitness, ethnic and cultural aspects also anatomy, physique, physiology, internal metabolism, clothing, health, mood and psychology play an important role in individual comfort ratings. In a nutshell, thermal comfort is a highly subjective perception, hard to detect and even harder to satisfy for each individual user especially in such a heterogeneous and transient environment of a vehicle compartment.

For this reason, automotive industry should abandon the aim to create a general climate in which the highest possible percentage of a population is thermally comfortable. Instead of the “one-size-fits-all” approach everyone should have the possibility to adapt the systems to his single needs. The key to success are customized sensor concepts, intelligent controls, smart interior parts, easy human-machine-interfaces and distributed systems next to the passengers as outlined in chapter 2.3.3.

Nevertheless, the information of this document will give a guideline to the project partners how to judge their technological improvements and inventions with regards to thermal comfort. Together with the later performed user study of HRE and the upcoming thermal comfort simulations of ATT, the baseline of the actual thermal user comfort in the Honda Fit EV can be evaluated and compared to the final thermal comfort at the end of the project, after all QUIET measures are implemented. The provided thermal well-being should be at least equal or even better than the initial comfort level.

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9	**ECON**	eCon Engineering Kft.	Hungary
10	**RUB**	Rubitherm Technologies GmbH	Germany
11	**STS**	SeatTec Sitztechnik GmbH	Germany
12	**OBR**	Obrist Engineering GmbH	Austria
13	**JRC**	Joint Research Centre - European Commission	Italy