Deliverable D2.3: Assessment of the SotA and fundamental concepts for thermal passenger comfort

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Lead Beneficiary	Fraunhofer
Deliverable Type	Report
Dissemination Level	Public
Due Date	30.04.2016 (Month 11)
Pages	27
Version	3.0[1]
Project Acronym	OPTEMUS
Project Title	Optimised Energy Management and Use
Project ID	653288
Project Coordinator	Virtual Vehicle Research Center (ViF) Alois Steiner (alois.steiner@v2c2.at)

European Commission | Horizon 2020 European Union funding for Research & Innovation

[1] First digit: 0 for draft, 1 for quality board approval, 2 for coordinator approval, 3 coordinator approved

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Version Log

Rev #	Date	Author	Description
0.1	04.04.2016	Damian Backes (ika)	Draft
1.0	11.04.2016	Damian Backes (ika)	For quality board approval
2.0	28.04.2016	Christoph Massonet (ika)	For coordinator approval
3.0	29.04.2016	Christoph Massonet (ika)	Coordinator approved

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Executive Summary

This deliverable assesses the state of the art both for HVAC systems as well as the measurement of the thermal environment and comfort assessment.

An overview is given over state of the art heating and cooling systems, both in production as well as in research. These systems are designed to increase comfort while also rising energy efficiency and hence reducing the impact of climatisation on the electric range.

In order to allow for a systematic development, objective means to measure thermal comfort are needed. Therefore, state of the art comfort indices and measurement equipment are presented as well.

(1) Introduction

The passengers' comfort in the vehicle cabin is becoming increasingly important due to several aspects. On the one hand, cabin climatisation has to become more efficient to minimize the reduction of the electric range. On the other hand, with the advancement of driving assistance systems, consumers are becoming more focused on the passenger cabin and the cabin comfort. Therefore, this deliverable will give an overview both for comfort assessment in the passenger cabin as well as possibilities to create thermal comfort while increasing energy efficiency.

For the comfort assessment, different indices describing the thermal environment will be presented and discussed concerning their ability to accurately assess state of the art and upcoming technologies for cabin thermal conditioning. Thereafter, a short overview of measurement equipment to determine these values is given.

Subsequently, state of the art climatisation technologies are presented. These include convective systems, such as electric heaters or heat pumps, but also contact and radiative heating and cooling. Different approaches and technologies for cabin heating and cooling are shown and discussed concerning their effect on passenger comfort and energy efficiency.

(2) Passenger Comfort

The passengers' comfort in the vehicle cabin is becoming increasingly important due to several aspects. Especially the development of energy efficient cabin heating and cooling systems calls for the objective assessment of thermal comfort, since energy efficiency has to be determined at same comfort levels.

Thermal Environment and Comfort Indices

As environmental conditions are very difficult to describe and the subjective sensation depends on many different parameters, comfort indices are needed to summarize the comfort assessment. These indices depend on physical parameters, such as the air temperature and velocity, the humidity and the irradiation, but also on individual parameters, such as the subject's metabolism or clothing. In order to effectively compare different conditions, these influences have to be combined to a single comfort index. Several approaches exist; the most important ones will be shortly discussed in the following paragraphs.

Air Temperature

For convective heating systems, which solely rely on the heated air ventilated through the passenger cabin, the mean cabin air temperature is often used to characterize the thermal environment. Figure 2-1 gives an overview for the target mean cabin air temperature related to the ambient air temperature. For homogeneous environments and standard clothing and activity, an air temperature of 22 °C is suggested. Due to higher losses through radiation, the target air temperature rises for lower ambient temperature.

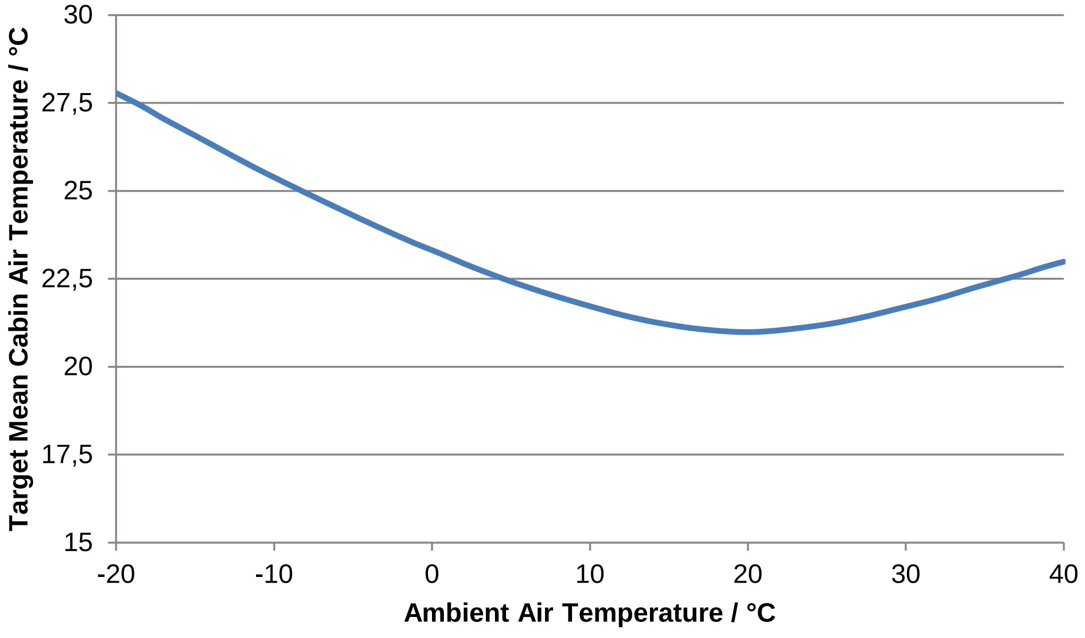

Figure 2-1: Mean Cabin Air Temperature depending on Ambient Air Temperature according to [B2]

For higher ambient temperatures it rises as well, since the insulation around the human body is reduced with lighter, e.g. summer, clothing.

Predicted Mean Vote

The most commonly used comfort index is the empirical predicted mean vote (PMV) by [B17] and standardized in [B4]. The PMV scales the subjective feeling to a range from -3 (too cold) to +3 (too hot) (cf. Table 2-1) and thus offers the possibility to rate a given condition on this scale. It was developed with the help of subjective ratings in proband studies, but can be calculated from objective measurement values by eq. 2-1.

$$PMV = \left(0{,}303 \cdot e^{-0{,}03 \cdot \dot{q}_{met}} + 0{,}028\right) \cdot \left(\dot{q}_{met} - \sum_{i=1}^{n} \dot{q}_i\right) \qquad \text{eq. 2-1}$$

In eq. 2-1, $\dot{q}_{met}$ describes the metabolic heat production in a human body, while $\dot{q}_i$ are the different heat flows between the body and the environment, as shown in Figure 2-2. These heat flows depend on a variety of additional parameters, such as clothing or the metabolic rate.

Table 2-1: Description of PMV indices

PMV index	Description
-3	cold
-2	cool
-1	slightly cool
0	neutral
+1	slightly warm
+2	warm
+3	hot

As can be seen by the description of the different indices, a PMV index of 0 describes a condition that is neither too hot nor too cold and is thus targeted for thermal comfort.

While widely accepted as a reference comfort index, also in the automotive industry, the PMV was developed with a different scope in mind. During the development, test participants were exposed to a uniform environment in stationary conditions as can be found inside buildings. While automotive passenger cabins do not comply with these conditions, the PMV has been adopted by different standards such as [B4]. In order to include these inhomogeneous environment parameters, a deviation from the original definition defines local PMVs for different body parts, which are then averaged for a global (whole body) PMV.

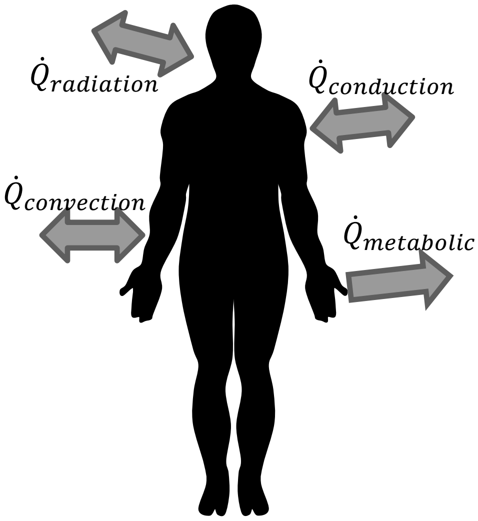

Figure 2-2: Heat flows between the human body and the environment

Predicted Percentage of Dissatisfied

The predicted percentage of dissatisfied (PPD) is closely related to the PMV and describes a portion of the population that is not satisfied with a given environment condition. For a given PMV the PPD can be calculated according to eq. 2-2 as a percentage.

$$PPD = 100 - 95 \cdot e^{\left(-\left(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2\right)\right)} \qquad \text{eq. 2-2}$$

As can be seen by the definition in eq. 2-2 and the resulting graph in Figure 2-3, the minimal PPD achievable is 5 so that 95 % of the population would rate this environmental condition as neutral and thus neither too warm nor too cold.

Globe Temperature

The globe temperature can be measured with a globe thermometer, which is standardized in [B3]. It is built as a temperature sensor inside a black hollow ball (globe). The temperature inside the globe depends on the convective heat transfer with the surrounding air and as well as radiation. It thus offers the advantage of combining these aspects in a single measurement value. On the other hand, globe thermometers show a slow reaction time to changing environment parameters and are thus limited in use considering transient measurements inside a passenger cabin.

Operative Temperature

The operative temperature is defined as the mean value of the air temperature and the average radiation temperature of the surrounding areas. This restricts its usage in a vehicle cabin due to inhomogeneous surface temperatures and the resulting need for intricate measurements to determine the average surface temperature. In addition to these disadvantages, the definition of the operative temperature does not allow for direct solar radiation.

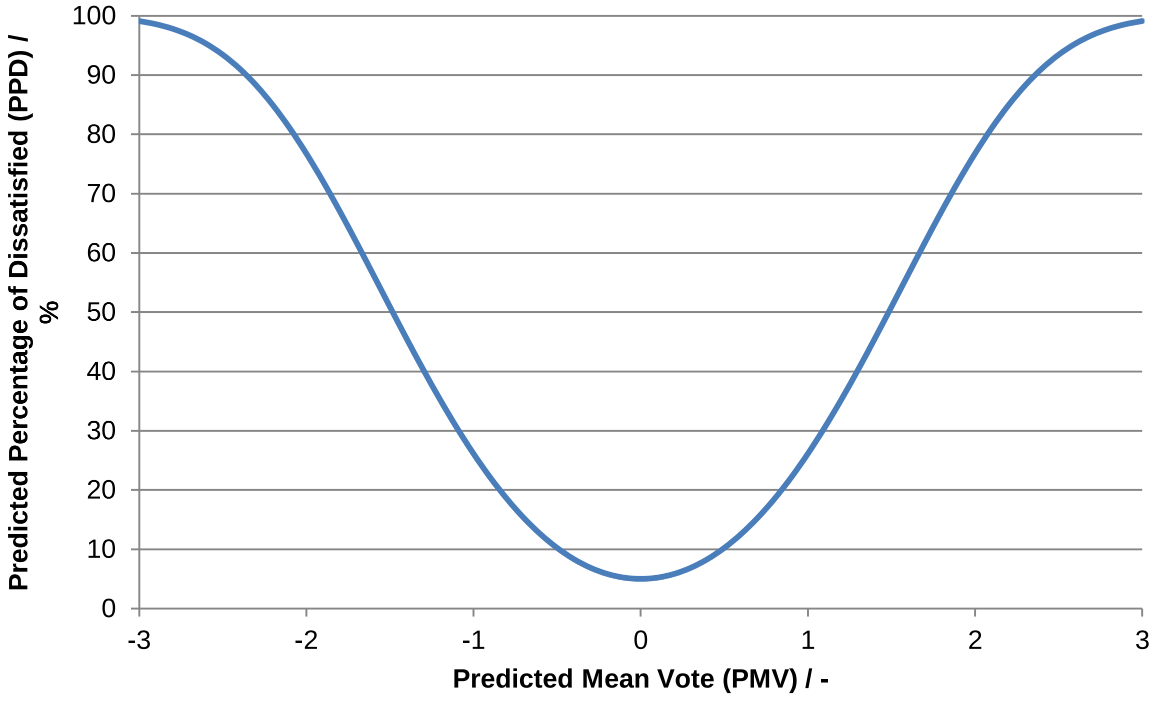

Figure 2-3: Predicted percentage of dissatisfied for given predicted mean votes

Equivalent Temperature

The equivalent temperature is described in [B1] and was developed for the description of the thermal environment in a passenger cabin. Therefore, relevant parameters such as air temperature and velocity as well as radiation are considered. The equivalent temperature describes a homogeneous temperature in a room without air movement, in which a human would lose the same amount of energy via convection and radiation, also known as the dry heat loss, as in the measured, inhomogeneous environment. In order to determine this temperature, the sensors, so called dry heat loss transducers, are heated and the resulting surface temperature is measured.

Comfort Measurement

All indices describing the thermal environment are based on one or several measurement values. Measurements can be conducted on different levels of approximation to the human body, ranging from basic sensor arrays (cf. Figure 2-4) to sweating thermal manikins.

A brief summary of different sensors and measurement systems to determine the thermal environment and thermal comfort is given in the following paragraphs.

Figure 2-4: Basic sensor system to determine thermal comfort consisting of 3 globe thermometers, 3 air temperature sensors and 3 air velocity sensors (ika)

Globe Thermometer

Globe thermometers are used to measure the globe temperature. They are standardized in [B3]. While most commercially available globe thermometers possess a diameter of 152 mm, the standard also allows for different diameters. In addition to the measurement of globe temperatures, globe thermometers can also be used to determine the radiative temperature, which can be used for the calculation of other indices, e.g. the PMV. In order to do so, the convective heat flow between the globe and the surrounding air has to be determined and thus the velocity and temperature of the air must be measured as well. The radiative temperature $\bar{t}_r$ can then be calculated using eq. 2-3 [B3]

$$\bar{t}_r = \left[\left(t_g + 273\right)^4 + 2{,}5 \cdot 10^8 \cdot {v_a}^{0{,}6} \cdot \left(t_g - t_a\right)\right]^{0{,}25} - 273 \qquad \text{eq. 2-3}$$

with the globe temperature t_g, the air temperature t_a and the air velocity v_a.

Dry Heat Loss Transducers

In order to measure the equivalent temperature, heated sensors must be used. These sensors can either be used as individual sensors (cf. Figure 2-5) or, more commonly used, in combination with a thermal manikin as shown in Figure 2-6, Figure 2-7 and Figure 2-10.

Figure 2-5: Dry heat loss transducer by LumaSense Tenchnologies

The sensors can also be arranged to represent a human body, as shown in Figure 2-6. While these sensors allow for measurements in defined areas, they are not able to determine asymmetries in the thermal environment, as often present in automotive interiors. In order to minimize these problems, different solutions, such as the DRESSMAN suit by Fraunhofer IBP, have been developed. The DRESSMAN, consists of an overall with several directional transducers attached to it, which can either be worn by a person or a thermal manikin (cf. Figure 2-7). It offers the possibility of objective measurements in real driving situations when worn by a test driver.

Thermal Manikins

A closer representation of the human body than individual sensors is given by thermal manikins. With sensors integrated into the manikin itself, additional factors, e.g. clothing, can be measured instead of approximated as in the examples above.

The thermal manikin Driver by PT Teknik was purpose-designed for the evaluation of passenger cabins. The heating wires are placed in the outer layer of the manikin with a spacing of 2.2 mm to ensure a uniform heat loss for each body part. The average surface temperature of each section is controlled individually while measured via the resistance of the nickel heating wire. Its functionality can be extended by modules, such as an artificial lung system for inhalation and exhalation (cf. Figure 2-8).

The thermal manikin Newton is available in a variety of different configurations. It features up to 35 independent thermal zones as well as dry or skin configurations. The anatomy can represent either a 50th percentile Western or Asian male. Similar to the PT Teknik manikin, surface temperature sensors and heating wires are integrated into the outer layer of the manikin and controlled individually.

Figure 2-6: Flatman by LumaSense Technologies consisting of MM0057 sensors

Figure 2-7: Dry heat loss transducer system DRESSMAN by Fraunhofer IBP

The PACO thermal manikin (see Figure 2-10) is based on Fanger's comfort model as described in [B4]. It features 16 combined comfort sensors and 8 separate temperature and humidity sensors. The comfort sensors are built as a combination of several sensors and measure the local temperature as well as the air speed and mean radiant temperature. The radiative temperature is measured similarly to the globe temperature above, but due to the positioning of the sensor allows the consideration of asymmetric thermal environments.

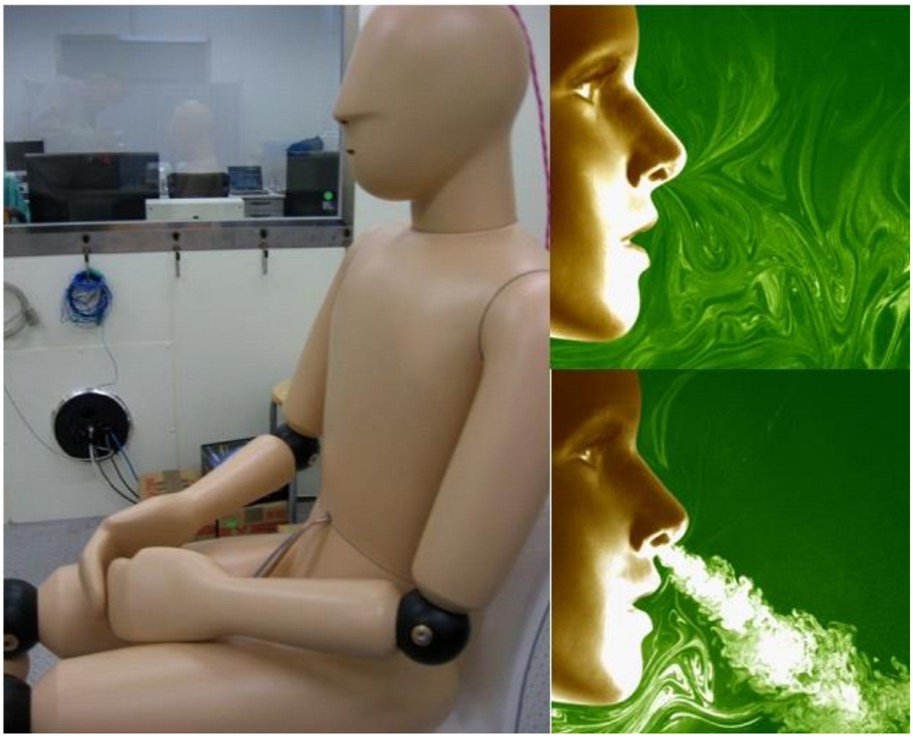

Figure 2-8: Thermal manikin "Driver" by PT Teknik (left) and lung module (right)

Figure 2-9: Newton thermal manikin by Thermetrics

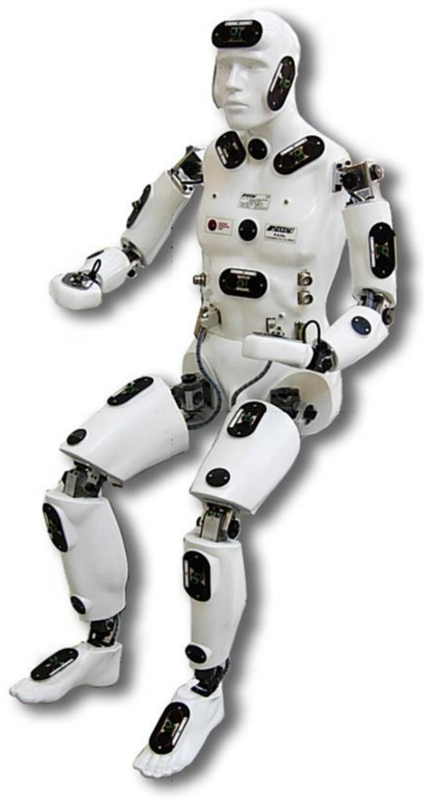

Figure 2-10: PACO thermal manikin

(3) Heating systems

As shown above, thermal comfort strongly depends on the thermal environment and thus especially on the air and radiant temperature. In order to create a comfortable thermal environment, the heat flow from or to the body has to be adjusted. This can be achieved with different methods which will be described briefly in the following paragraphs. Special focus will be put on radiative and panel heating systems, which are also developed in the course of the OPTEMUS project.

Convective Heating

The most common heating systems use convective heating, thus heating the air prior to entering the passenger cabin. This method of cabin heating can be used efficiently in vehicles with combustion engines, since waste heat is available over a wide range of use cases. With the implementation of electrified drive trains and the resulting high efficiency, the availability of waste heat at a directly usable temperature level has vastly vanished, so that additional heating has to be applied.

A large disadvantage of convective heating are slow heat up times resulting from high thermal capacities of the fluid system which is often used to transport energy between the heat source (combustion engine or electric heater) and the cabin heat exchanger.

In order to decrease the power demand for cabin heating, cabin air is recirculated rather than replaced with fresh air. Certain amounts of fresh air still need to be heated up from ambient temperature to avoid fogging, replace air losses and to ensure a proper CO_2 level.

Furthermore, the state of the art moves towards decentralized cabin heating and the usage of heat pump technologies. [B24] show temperature losses of up to 20 °C between the air outlet and the passenger. Therefore, air ducts close to the body are preferred. While decentralized heating results in smaller HVAC units, and thus allowing more control over the energy flows in each zone, heat pumps allow for the usage of anergy, such as low temperature waste heat or ambient air for cabin heating. Figure 3-1 shows such a system, with a main HVAC to provide global air heating and smaller systems integrated into each seat for local air conditioning [B7].

In addition to thermal comfort, proband studies, such as [B27], have shown that the ventilation system used to provide the necessary air flow through the passenger cabin causes considerable noise. This noise could be reduced with a load reduction of the convective heating system, e.g. by the noiseless heating systems described in the following.

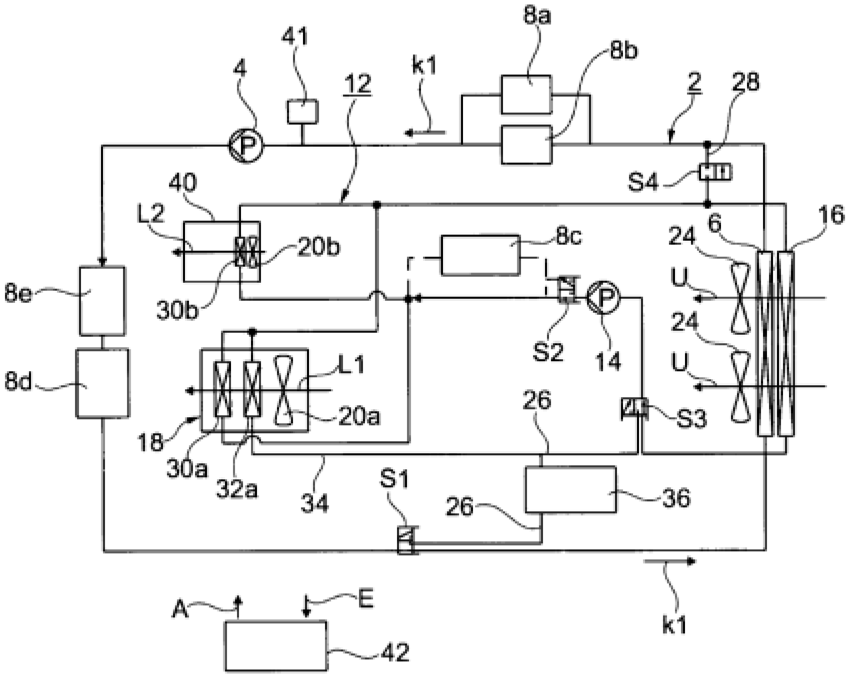

Figure 3-1: Heating system with main HVAC (18) and localized heating units (40) [B7]

Contact Heating

Contact heating systems are an energy efficient addition to convective heating systems while at the same time increasing comfort. These systems, such as seat heating or heated steering wheels, are already in series production. While available seat heaters use electric heating elements beneath the textile, [B8] describes a thread and thus textile elements, which can be heated directly. Furthermore, fluidic seat heating is investigated as well. The fluidic heating system (cf. Figure 3-2) offers the possibility of using waste heat from electric components at low temperatures, hence the electrical heating demand is reduced.

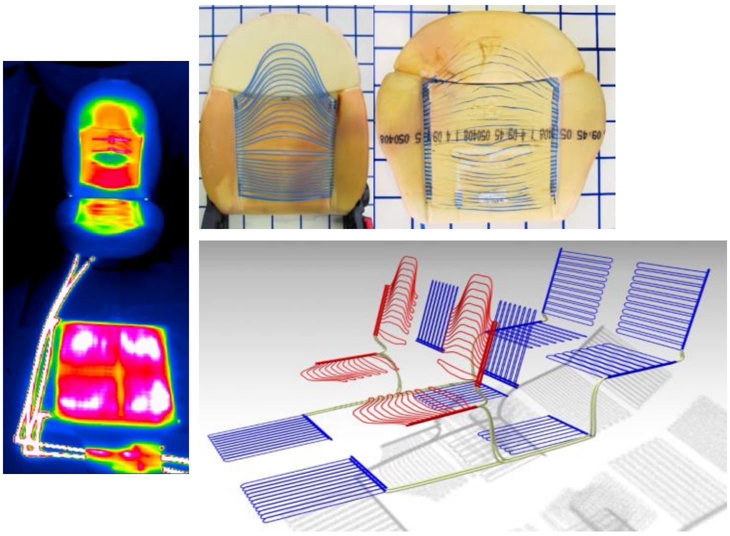

Figure 3-2: Fluidic seat heating, infrared photo (left), seat integration (top) and final design (red) vs. prototype (blue) (bottom) [B9]

Additionally, this system also provides the possibility for seat cooling, as proposed in [B28].

Contact heating is also considered for other surfaces in the automotive interior, such as the heated armrests in the S Class [B5] or by Yanfeng Automotive shown in Figure 3-3 [B29].

Figure 3-3: Heated armrest by Yanfeng Automotive

Radiation Heating

Considering different studies, such as [B27, B29], radiative heating allows for increased heating comfort combined with reduced heating power demand. As shown in [B32], different approaches for the integration of radiative heating into the passenger cabin exist.

Infrared Heating

Infrared heating systems use higher source temperatures than heating panels, as described in [B32]. Different patents exist for the integration of infrared heaters into the passenger cabin such as [B15] with the proposed integration into the A-pillar or into the seat [B33]. The main problem with infrared heaters is the high source temperatures, which lie well above safe surface temperatures for the human environment. These problems can be circumvented by transmitting elements between the radiation source and the passenger. Existing approaches include [B22] and [B23] (cf. Figure 3-4).

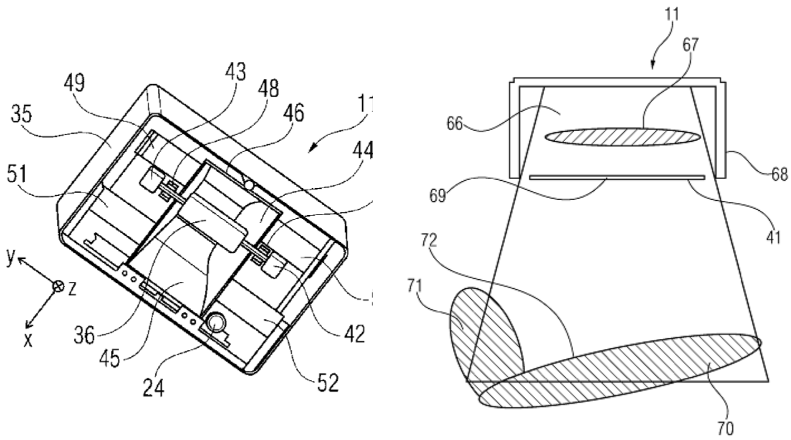

Figure 3-4: Infrared heater with transmissive element [B23]

Panel Heating

Panel heating systems avoid the high temperatures of infrared heaters, but create the need for larger areas to be heated. Meanwhile the heating panels are touchable due to the lower temperatures. Similar to contact heating, also fluidic heating panels are considered [B30]. The state of the art covers a wide range of areas with integrated heating panels as well as a variety of production processes for these panels.

For the production, surface elements are built directly as cover panels [B10] or as a sandwich panel. These include laminar heating elements attached to a panel as in [B14] or can build from an electroconductive film, which is placed on a support material, e.g. made from a foam plastic material [B13]. Other approaches include layer coatings, such as the electrical carbon nanotube-free coating layer for surface heating in [B11].

Heating panels can be integrated into almost all surfaces of a passenger cabin, e.g. floor panels, as described in [B12]. While underfloor heating can cover large areas in buildings, the floor surfaces in automobiles do not provide sufficient space for standalone heating panels in these areas.

Especially door panels are widely discussed, since vehicle doors offer rather large surfaces which are not yet occupied by other functions. [B16] proposes a decor element (cf. Figure 3-5), which can be heated, for a rear door, while the principle is also applicable for front doors.

A Heating element is integrated into a vehicle door to warm the side of a passenger. A reflective layer is integrated behind the heating element, while the cover towards the passenger cabin is made from a transmissive material [B26].

The approaches mentioned above can be combined to a complete heating system as in [B6, B31] (cf. Figure 3-7).

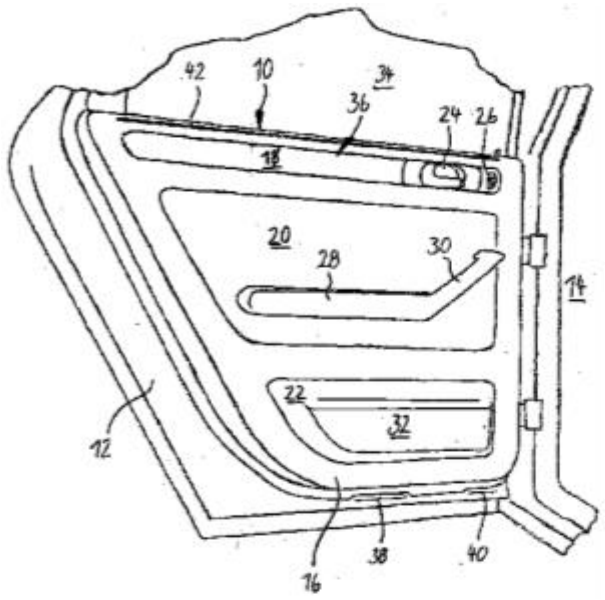

Figure 3-5: Decor heating element in door (18) [B16]

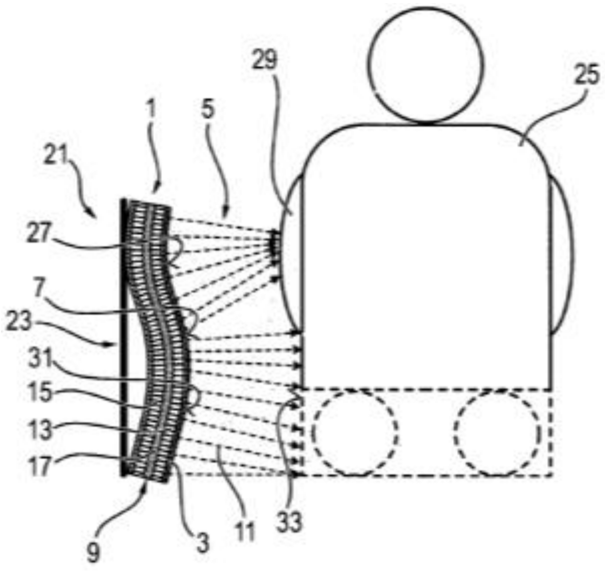

Figure 3-6: Heating element for a vehicle door, with a reflective layer to reduce heat losses [B26]

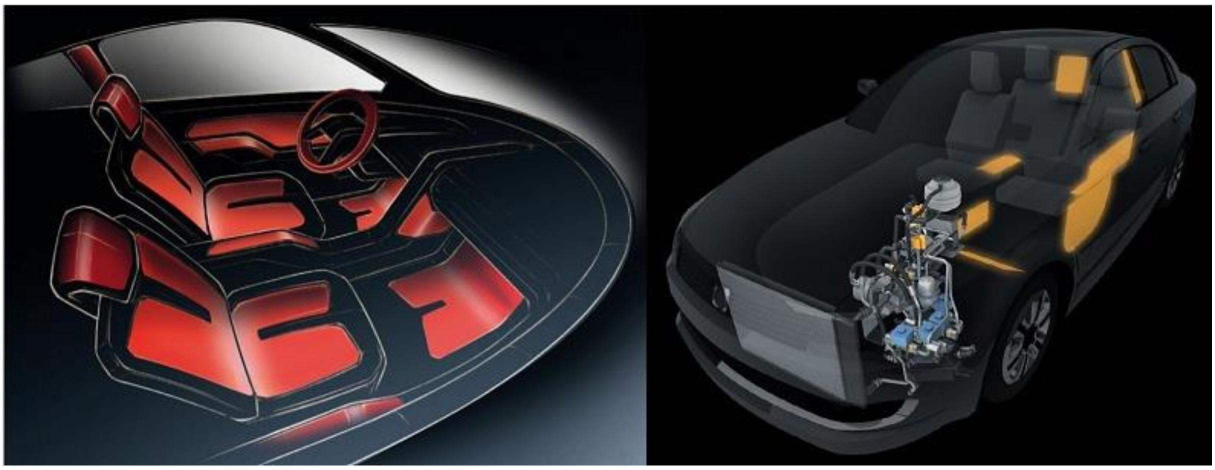

Figure 3-7: Cockpit with heating panels on different contact and close-to-body surfaces (left [B31], right [B6])

(4) Cooling Systems

The comfort models described above are also applicable for vehicle cooling, since the same principles apply regarding the energy balance around the human body. Therefore, a decrease in radiative or conductive application of energy will allow for higher temperatures of the surrounding air resulting in the passenger comfort. The state of the art in mass production relies solely on convective energy transfer, resulting in high peak demands of cooling power, of up to 10 kW [B24], in order to cool down interior surfaces.

Therefore, the same principles and approaches as for heating systems exist for cooling systems as well. In addition to these concepts, especially heat up prevention is discussed.

Heat Up Prevention

In order to reduce the initial cooling power needed for the cabin cool down, many approaches have been developed. Mainly, these include the reflection of solar radiation, the exchange of the cabin air in order to prevent air heat up as well as passive and active surface cooling (cf. Figure 4-1).

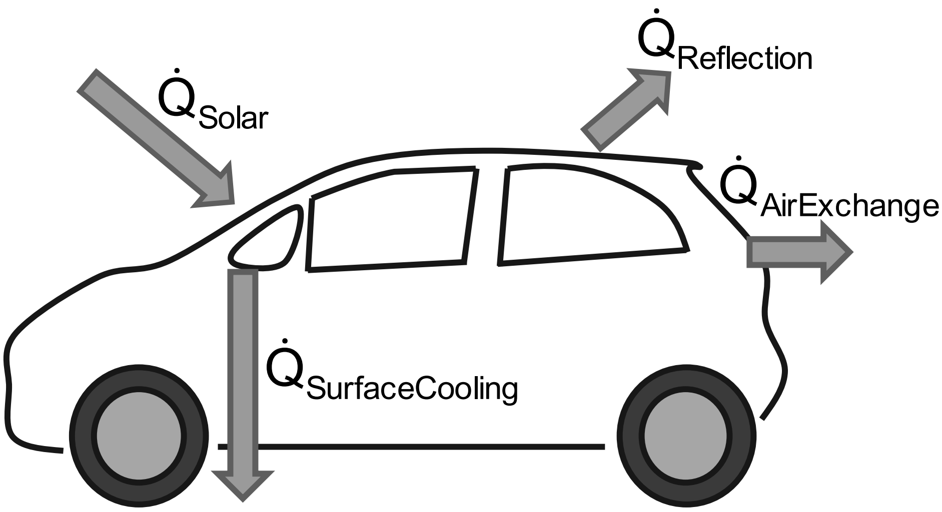

Figure 4-1: Principal possibilities to reduce cabin heat up

The reflection of solar energy can be increased by the usage of special glasses, either with low transmission coefficients for certain wavelengths or with different transmission properties for driving and parking [B19]. Other approaches include solar driven fans in order to remove hot air from the passenger cabin [B18] or passive heat pipe systems in order to cool down exposed interior surfaces [B21]. [B19] also describes the influence of the color of the vehicle and the interior components. The difference between the same vehicle completely in white and black was measured to be as high as 27 °C on the hottest parts.

Contact Cooling

Simple seat cooling approaches include ventilated seats such as [B20], reducing heat accumulation in the seat. Especially fluidic or thermoelectric seat heating systems also offer the possibility for seat cooling. [B25] conducted proband tests on the influence of cooled seats on the acceptable air temperature. The experimental setup can be seen in Figure 4-2.

Figure 4-2: Experimental setup for heated and cooled seat in [B25]

Probands were asked to rate the thermal environment on the PMV scale, as well as its acceptability. The results show that the steady state was reached faster than with an air conditioning system only. Additionally, the acceptability for higher air temperatures increased with the help of a cooled seat. Overall, with the implemented control algorithm, an increase of 2.3 °C in cabin air temperature was found to provide the same thermal comfort than the standard neutral assessment without cooled seat.

Panel Cooling

In addition to the passive panel cooling system in [B21], also active panel cooling systems have been developed. Especially thermoelectric elements which can be used to heat and cool surfaces offer great potential considering energy efficiency. [B34] describe such an heating system, similar to [B7], combining heated and cooled seats with thermoelectric panels.

(5) Conclusions

In this deliverable, different methods to assess the thermal environment including the associated measuring equipment are shown. Furthermore, different means and technologies to create thermal comfort during the heating and the cooling period are discussed.

While the measurement of the cabin air temperature is sufficient for the comparison of convective heating systems, it is inadequate for either comfort assessments as well as the comparison of heating systems which include contact or radiative heating components. While not developed for the purpose of the assessment of inhomogeneous environments, the PMV is widely accepted as a comfort index. With modifications, such as the consideration of local comfort, it can be used to assess automotive passenger cabins despite their large inhomogeneity. The PPD as a function of the PMV gives a useful indication about the acceptance of a thermal environment. On the other hand, information is lost during the calculation of PPD indices, so that it should not be used exclusively for comfort assessments.

Considering thermal comfort during the heating period, different approaches on cabin heating have been presented. Combined convective and contact heating systems represent the state of the art in series production, but show considerable disadvantages concerning thermal comfort and energy efficiency in electrified vehicles such as the Fiat 500e. While heat pump technologies offer the possibility of decreased power consumption, they still show comparatively slow heat up times due to high thermal capacities. These problems can be faced with radiative heating systems, such as presented above. While radiative heating systems alone will not be sufficient as can be seen in [B27, B29], they offer high potential for upcoming heating systems. Thus a combination of all heating concepts, convective, conductive and radiative, as in [B6], show promising results. These combined concepts do not only increase efficiency and thermal comfort, but provide advantages regarding the cabin acoustics, as well.

The same principle is valid for cabin cooling at high ambient temperatures and solar radiation. Approaches like a cooled seat as in [B25] allow higher cabin air temperatures at constant comfort ratings. Additionally, systems reducing cabin heat up, as in [B21], or the OPTEMUS smart cover panel, show considerable advantages over the state of the art.

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Abbreviations and Definitions

PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied