

# **A Method to Analyze Thermal Comfort and Energy Consumption of Heating Systems for Electric Cars**

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## **Abstract**

In electric cars, heating the cabin is similar to that of combustion engine vehicles. This causes two problems. First, the need of energy for this system is high and thus reduces the range of the car. Second, research results show that other systems could improve the driver's thermal comfort. Therefore a method to analyze different systems is needed. In this study we show a method to analyze and evaluate different heating systems by help of a proband study. The main focus of this analyzing method is to determine the influence of different heating methods on the driver's thermal comfort. Additionally, the method provides results for the energy consumption of different heating systems. Compared to other methods, we established a method to evaluate those systems in an unsteady system in a real driving situation.

*Keywords: thermal comfort, component technologies, heating, analyzing methods, interior*

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## **1 Introduction**

The main challenge concerning electric cars is the short range compared to vehicles with combustion engines. Especially in winter, there is a high demand of energy for heating the cabin, which reduces the available energy for driving.

Therefore the focus of research is to reduce the energy needs of heating systems.

Actual heating systems are based on combustion vehicles and the comfort guidelines set for buildings [1]. Both are suboptimal for the application in electric cars. In combustion-engine driven vehicles there is enough waste heat to warm up the interior of the vehicle adequately. Thus there is no need to look for wise energy-saving heating systems for the manufacturer. Even comfort-optimizing systems such as seat or driving-wheel heating aren't configured for best energy use in combustion cars, as they are just additional systems and they do not influence the total energy demand significantly. Exactly this is the problem with electric cars. Every Watt, which is not used properly in an electric car, leads to less range in the end.

The application of comfort guidelines for buildings within cars has been discussed in expert groups for a long time. For sitting activities in buildings an ambient temperature of 21°C is considered as perfect. Indeed, the conditions for sitting activities in buildings can be seen as a steady state, but in contrast to this, driving a vehicle can't be seen in this way. Especially electric cars are normally used under unsteady conditions. The temperature in a vehicle's interior at the start varies intensely and depends on different factors. First of all, the surrounding temperature has a strong impact. Additionally, the solar radiation and the location of the parked car have a massive influence on the ambient temperature at the start and during the heating-up period.

So the vehicle is used in an transient interval for several minutes. This period of time influences the thermal comfort and sensation significantly [2], [3].

Additionally, the clothing of working people in buildings and the clothing of a car passenger vary intensely depending on different outside weather conditions like temperature and humidity. For this reason, the so far used guidelines for buildings can't be applied in vehicle technologies.

## 2 Methodology

Different studies discuss either alternative heating systems or the design rules based on buildings (e.g. [4], [5]). But the influence of those heating systems on the driver and his thermal comfort sensation in the unsteady car is a relevant point.

In [6] Kaynakli describes a study of thermal comfort during the heating period inside an automobile. This study combines theoretical and experimental methods to analyze thermal comfort. The aim is to validate the mathematical model with experimental data. The results show a good accordance. Nevertheless, this study analyzes just a parking situation. The sensitivity of temperature depends on various boundary conditions, e.g. passengers movement level or radiation. A realistic driving situation requires attention and actions of the driver and thus influences the sensitivity of temperature of a human body on physiological and psychological levels.

In this study, we discuss a method to analyze the influence of different heating systems, e.g. seat heating or underfloor heating, on the comfort of the driver. Therefore, we developed a climate test bench that includes a driving simulator. This test bench was used for different proband studies to develop the analyzing method.

### 2.1 System Description

Car heating methods can be clustered in different groups:

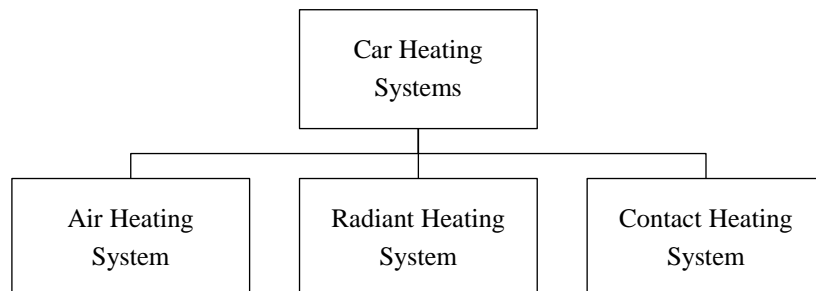


Figure 1- Different Heating Systems

Air heating systems are standard in passenger cars. In combustion engine cars the waste heat is used to warm the intake air. In electrical vehicles there is not enough waste heat for a direct heating of the intake air. Therefore two different methods are used. One method is the application of a PTC-Heater. This system converts electricity into heat and is used to warm the intake air. Unfortunately, a PTC-Heater needs a lot of electric energy to produce a comfortable warmth in the interior. Alternatively, it is possible to use heat pumps to heat the intake air. In the last years the potential of heat pumps is growing, still they aren't used area-wide. One reason is the decreasing performance in sub-zero surrounding temperatures.

Radiant heating systems are commonly known from buildings. They base on the principle that a heated surface exchanges heat with the surrounding environment by radiation. Normally, this principle is used in wall and floor heating systems. These aren't used in passenger cars so far, but they offer the opportunity to reduce the ambient air temperature in order to reduce the energy consumption.

Seat heating or driving wheel heating are examples for contact heating systems. In this systems the contact surfaces are heated to improve the comfort of passengers.

## 2.2 Experimental Setup

### 2.2.1 Test Bench



Figure 2: Test Bench - Interior View

For an optimal analysis of thermal comfort by the help of a proband study, a climate test bench was developed. Two containers build up the basic concept of the test bench. One is used as test ground and contains the test vehicle, the other container serves as control room. These containers are fixed together and connected by a passage. Figure 2 shows the interior of the test bench. Figure 3 gives an overview of the test bench and the control room.

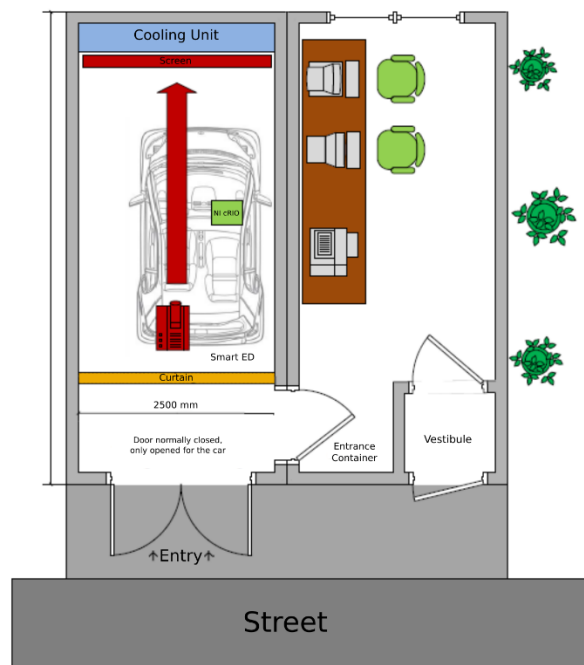


Figure 3: Test Bench [7]

The control room is used to monitor the test procedure as well as the interim and closing questionnaires (see 2.3). It can be entered via a porch and enables the test engineer to brief the proband outside the testing area.

The test ground is based on a cooling container and offers the possibility of a steady conditioning sub-zero degrees. The proband enters the test ground via a direct connecting door. A curtain prevents the test ground from intake air. During the test procedure the proband acts as a driver and is sitting in the car, which is placed in the middle of the test ground. To build up a realistic scenario, a driving simulation was developed and implemented. That allows for the driver having to cope with different scenarios during the survey. Hereby, the driver experiences a realistic ride while he is being interviewed.

For Technical Data see Table 1:

Table 1 - Technical Data of the Test Ground

Technical Data	
Temperature Range	-25°C up to +25°C
Inner Dimensions	5.48m * 2.28m * 2.25m
Max. Vehicle Dimension	3.80m * 2.00m * 1.65m

### 2.2.2 Test Vehicle

The test vehicle is equipped with temperature sensors as well as sensors to measure the air quality, like CO<sub>2</sub>-concentration and air humidity. These sensors stay the same during all tests. The location of the sensors was developed in [8]. As this experimental set-up showed good results, the sensors' positions were adopted.

The energy consumption of the various heating systems is logged separately, depending on the used heating system. Figure 4 gives an overview of some temperature sensors in the car.

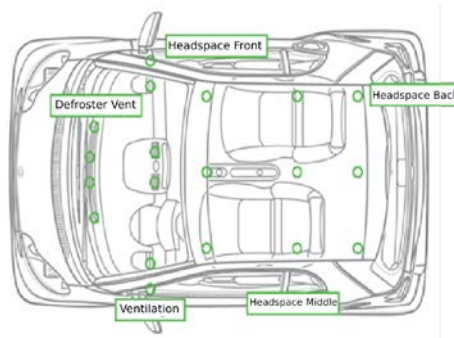


Figure 4 – Vehicle Top View [7]

### 2.2.3 Probands

The test persons were equipped with thermocouples and introduced in the test procedure. Depending on the experimental setup there were up to 21 probands interviewed, see Table 2.

Table 2 - probands

Experimental Setup	Number of probands	Age	Sex	Height	Weight
A 1	21	21 – 63 years	19 male 2 female	1.65 m – 1.98 m	62 kg – 120 kg
A 2	21	17 – 32 years	18 male 3 female	1.60 m – 1.92 m	51 kg – 130 kg
A 3-1	18	21 – 61 years	16 male	1.63 m – 1.95 m	60 kg – 102 kg

				2 female	
A 3-2	18	16 – 46 years	16 male 2 female	1.65 m – 1.93 m	60 kg – 95 kg

Figure 5 shows the location of the used thermocouples as described in [8].

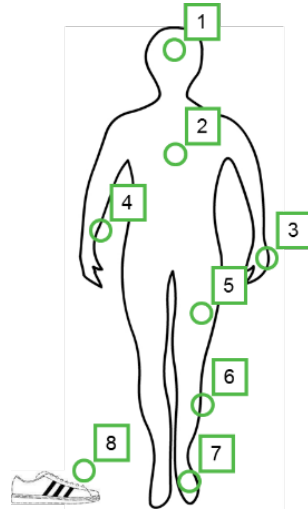


Figure 5- Thermocouples Location [7]

Each proband had to fill in a questionnaire. In addition to questions concerning thermal comfort and sensation, it contains questions about personal data (e.g. fitness, weight, etc.) as well as the clothing of the test person. The used questionnaire is similar to the one used in [8].

To evaluate the thermal sensitivity and thermal comfort, probands had to define their sensation with the help of the scale shown in Table 2 and Table 3.

Table 3 - Scale Thermal Sensitivity [8]

Extremely cold	Too cold	Cold	Slightly cold	Neutral	Slightly warm	Warm	Too warm	Extremely warm
-4	-3	-2	-1	0	1	2	3	4

Table 4- Scale Thermal Comfort [8]

Max. Discomfort	Very Unpleasant	Unpleasant	Slightly Unpleasant	Slightly Pleasant	Pleasant	Very Pleasant	Max. Comfort
-4	-3	-2	-1	1	2	3	4

### 2.3 Experimental Procedure

To analyze and evaluate different heating systems we developed an extensive testing method based on different tests in the foresaid test bench.

The previous research, such as [8], provided the substructure of this testing method. In four test phases we examined different heating systems and optimized the method.

Figure 8 shows a flow chart of the developed testing method.

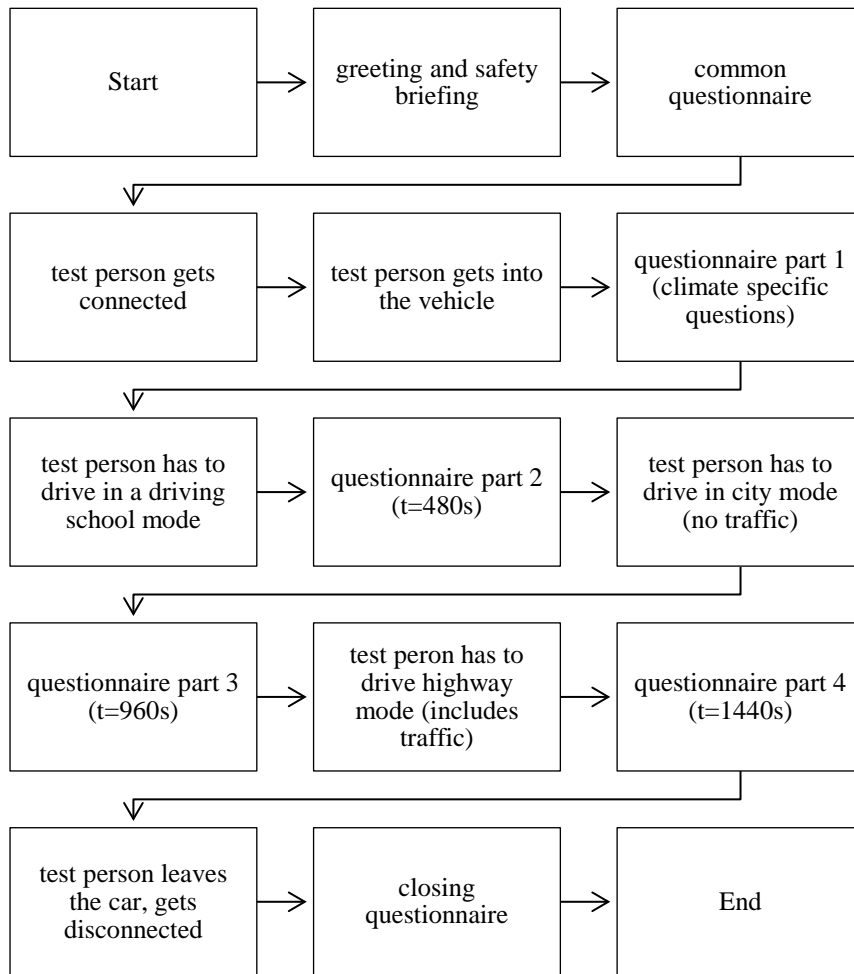


Figure 6: Flow Chart of the Proband Test Procedure

### 3 Results

In four different experiments we studied the following heating systems by the help of this analysis method. In all experiments we had the same boundary conditions, e.g. the surrounding temperature was set to  $-7^{\circ}\text{C}$ .

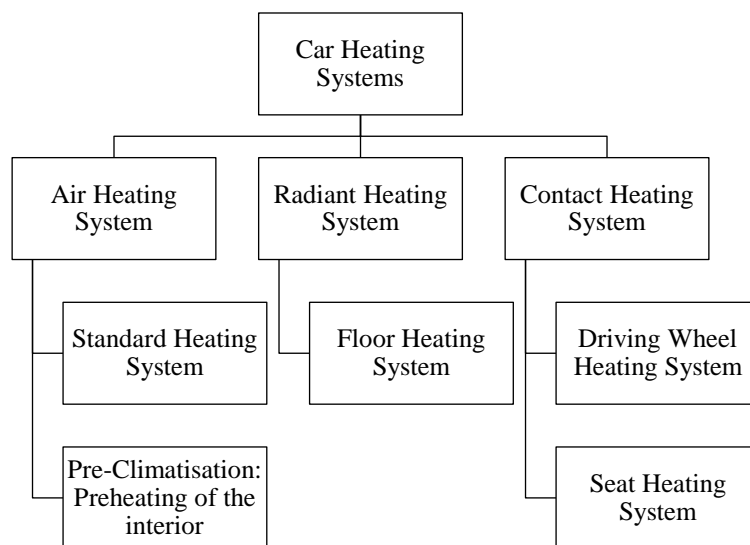


Figure 7 – Analyzed Heating Systems

The four different experimental setups were discussed in several expert rounds and are described in Table 4.

Table 5 - Experimental Setups

Name	Ambient Air Temp.	Ventilation Adjustment	Seat Heating	Driving Wheel Heating	Floor Heating	Comments
A1	22 °C	Front Window	Off	Off	Off	Similar to [8]
A2	18 °C	Feet	On (permanent)	On (permanent)	Off	
A3-1	18 °C	Feet	On (proband is allowed to switch of)	On (proband is allowed to switch of)	On	
A3-2	18°C (Preconditioning up to 5°C)	Feet	On (proband is allowed to switch of)	On (proband is allowed to switch of)	On	

Generally every additional system improved the driver’s thermal comfort and sensation. Furthermore, we were able to reduce the ambient temperature and still fulfilled the requirements of the probands or even exceeded them.

The results are exemplified with the help of the global thermal sensitivity and the global thermal comfort, shown in Figure 11 and Figure 12. Best results would show “0” in thermal sensitivity and “+4” in thermal comfort.

The comparison in Figure 11 shows, that overall the vehicle is seen as warm at the end of the test. Nevertheless, there are some differences between the setups. While setup A 3-2 (preconditioned car) shows the best results at the beginning of the test setup A2 provides the best outcome in the end.

Figure 12 shows, that each tested system improves the thermal comfort. But those results also show, that the tested systems are not satisfying in terms of maximum comfort. To analyze the differences between the setups and the reasons for those differences it is necessary to look at the different parts of the human body.

As this paper focuses on the analyzing method, a detailed analysis of the body parts would go too far and is therefore not of further interest.

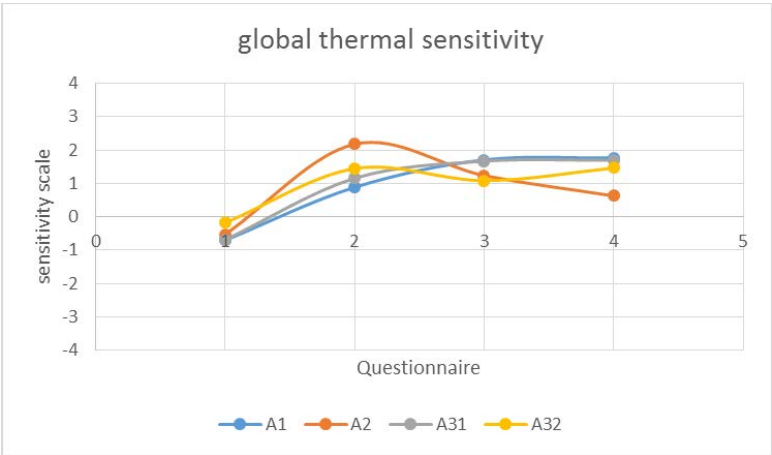


Figure 8 - Global Thermal Sensitivity for different experimental setups

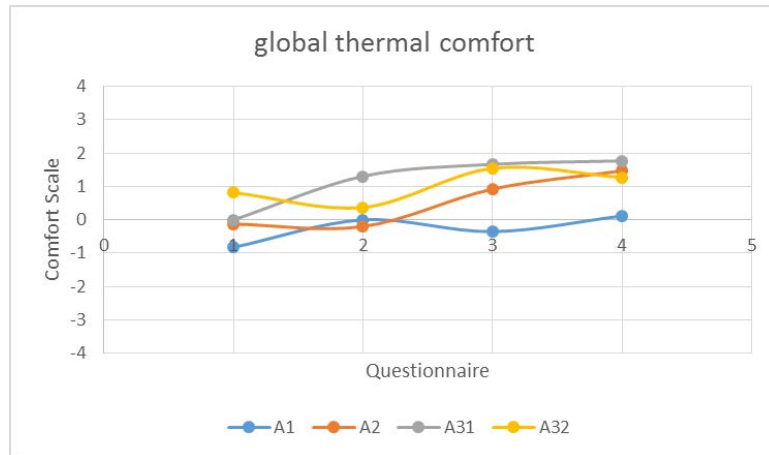


Figure 9- Global Thermal Comfort for different experimental setups

## 4 Conclusion

This paper illustrates a method to analyze thermal comfort and energy consumption of heating systems for electric cars. With the help of this method, different systems can be studied and compared to each other.

The method can be adopted on different cars and boundary conditions and enables the developer to optimize the heating system of the car.

The results show that there is a large potential for improvement in heating systems. They also indicate that there is a high potential to enhance passengers comfort and that none of the existing methods provides maximum comfort in cars.

Additionally, the method provides the possibility to analyze the influence of different heating systems on the energy consumption. This analysis is necessary for development of new heating systems. Even though passenger comfort is an important point in the development of new cars, no system will become serial if it is wasting too much energy.

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