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Market research and definition of procedure to comparison of comfort measuring systems for a vehicle cabin

Market research and definition of procedure to comparison of comfort measuring systems for a vehicle cabin

Forschungsstelle

Brno University of Technology

Faculty of Mechanical Engineering

Energy Institute/ Department of Thermodynamics and Environmental Engineering

Autoren

Jan Pokorný, Ph.D (pokorny.j@fme.vutbr.cz)
Jan Fišer, Ph.D (fiser@fme.vutbr.cz)

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Content

1 Introduction

The main aim and motivation of the project was to provide objective measurement tools for evaluation of thermal comfort provided by HVAC system (Heating, Ventilation and Air Conditioning) in vehicle cabin during WLTP/RDE tests. For the comparison of different type of cars brands and different equipped cabins it is very important to ensure that the level of thermal comfort is the same and results of energy consumption is objective and comparable. The output of the project is focused on the definition of the procedure to compare different thermal comfort measuring systems affordable at the market from the economic and scientific point of view.

HVAC system provides thermal comfort in vehicle cabins which is important condition for comfort a safe use of a vehicle. Thermal comfort is driven by parameters of cabin environment such as air temperature, mean radiant temperature and speed of air. HVAC system keep all these parameters in optimal ranges for humans but the control process cost some energy. In case of classical ICE (internal combustion engines) the energy for the heating was "just" reuse of waste energy from the combustion engine. In case of cooling the power consumption was up to 10 % of engine power and such load affected the driving range of the vehicle negligibly. Nowadays the power consumption of the auxiliary system as HVAC system are paid more attention because in an EV car there is no waste energy from combustion engine and the HVAC has to be powered from accumulators. Thermal management of EV (accumulator, HVAC) differs in winter and summer season substantially and the goal is to provide optimal operation temperature range for batteries and thermal comfort without inadequate reduction of driving range. From this reason the more focus is paid to efficiency of AC/HP systems (air conditioning/heat pump) and the overall power consumption of the HVAC, because these thermal management systems have significant impact on energy consumption, energy efficiency, range and emissions (emitted in power plants) of a vehicle.

The energy consumption and emissions is tested by WLTP/RDE procedure which was firstly introduced in 2017[1]. "*The new Real Driving Emissions (RDE) test measures the pollutants, such as NOx, emitted by cars while driven on the road and ensures that cars deliver low emissions over on-road conditions.*" [2]. The reason why the new types of the tests were introduced was finding that the emissions (NOx, etc.) and energy/fuel consumption measured by NEDC procedure not corresponds to emissions in the real traffic conditions. In 2021 the newest standard Euro 6d was applied included RDE tests. The next planned Euro 7 (after 2025) emission standard will push emissions limits down and only local emission free powertrain system such as plug-in hybrids and full electric vehicles (EV) will be able to meet requirements of the standard. But in BEVs the consumption of HVAC and thermal management system playing important role. In that times the objective tool for measurement of cabin thermal comfort level during RDE tests will be necessary.

[1] *https://en.wikipedia.org/wiki/European_emission_standards*
[2] *https://www.caremissionstestingfacts.eu/rde-real-driving-emissions-test/*

1.1 Objectives of the project and activities overview

We started this project with the assumption that HVAC system should be able to provide the same level of thermal comfort, not just to say all cars were setup to AUTO 22 [3], because the air temperature by itself not provides the complete picture of thermal comfort inside the cabin and each car manufacture can design the climate control systems differently. Thermal comfort is driven by parameters of cabin environment such as air temperature, mean radiant temperature and speed of air and effect of all parameters is integrated in one parameter called EHT (Equivalent homogenous temperature). The benefit to use EHT is that it integrates in one value more measurable factors important for thermal comfort evaluation. Therefore, this project is focused on the comparison of different thermal comfort measurement systems to find out if these systems provide

- similar and reliable results and to identify their strengths and weaknesses
- what difference is between the sensor-based systems and thermal manikin
- how their construction affects the manipulation in the cars
- different type of control modes to evaluate EHT: constant surface temperature (CST) vs. constant heat flux (CHF), etc.

For the laboratory testing we used the climatic chamber at Brno University of Technology (BUT)[4]. The research team at BUT has long experience with thermal manikin measurement (Newton) and thermal comfort research in general. The project started in 2020 in witch the first tests were performed. The project was prolonged to the 2021 due to the COVID-19 pandemic but in spied of that we performed additional advanced tests. In this year 2022 the final results of the project were presented and the final report was delivered to VDA-FAT organization.

The first three chapters of this report present the overview about the problematics of evaluation of thermal comfort in car cabins and present available thermal comfort measuring systems which are available on the market or in specialized laboratories. Chapter 4 defines the types of tests which were planned to perform. The exact setup of each test and their results are in Chapters 5 and 6. All these tests were carried out in the climatic chamber including the tests with the real cars. Chapter 7 and 8 brings highlighted results and observation how the different thermal comfort measuring system works.

The project was started by definition of objectives and activities:

Activity 1 – Market research for comfort measurement systems/ comfort measurement dummies:

- Market survey of comfort systems with focus on system using principle of Equivalent Homogenous Temperature (EHT) compatible with the ISO 14505-2.

[3] *AUTO 22 means automatic mode of the HVAC system to keep the „setpoint temperature 22 °C"*
[4] *https://eu.fme.vutbr.cz/about-us-dept-of-taee-laboratories-climate-chamber-2j*

- Market survey – EHT scientific systems (for research) and EHT compact devices (for standard testing) – considering their current availability and potential to be applied in different test facilities and laboratories
- Narrowed selection of perspective tools for EHT measurement - focus on the cost-effective solutions

***Activity 2 – Selection from systems available on the market**:*

- Specification of requirements to comfort system and preparation documents to procure devices for testing
- Communication with suppliers of comfort systems
- Final selection of devices used for test scenarios based on their availability and quality/price ratio
- Training for operation with selected systems

***Activity 3 – Development of test scenarios for a comparison of measuring systems**:*

- Design of experiment - definition of conditions for laboratory tests and tests with car
- Specification of sensor placement in laboratory tests and car cabin tests
- Preparation of all devices for the testing (Newton, procured EHT systems, test car, climate chamber)

***Activity 4 – Pilot testing of test scenarios for scenarios optimization and procedure troubleshooting**:*

- Performing pilot test with procured EHT system and thermal manikin Newton at climatic chamber in Brno
- Post-processing of the results

***Activity 5 – Final definitions of test scenarios, reporting 2020**:*

- Test scenarios update based on pilot tests results and final definition of test
- Project reporting and presentation to customer

1.2 Thermal comfort

Thermal comfort is defined as “the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE Standard 55).

At the project we focused on the evaluation of thermal comfort by the method of EHT and Comfort zones diagram. This method is designed for evaluation of thermal comfort in car cabins and it is part of the ISO 14505 “Ergonomics of the thermal environment — Evaluation of thermal environments in vehicles”.

The Equivalent Homogeneous Temperature (EHT) is one of the environmental indices (see Table 1.1) which integrates in one quantity more environmental factors of thermal comfort which were specified by Fanger, 1970. The effect of secondary factors as psychological state, stress, acclimatization and others are neglected to keep method robust and “simple”.

The primary factors of thermal comfort are these six:

Environmental factors of thermal comfort

- Air temperature T_{air} [°C]
- Mean radiant temperature MRT [°C]
- Air velocity (wind speed) w_{air} [m/s]
- Relative humidity RH [%]

Personal factors of thermal comfort

- Metabolic rate M [met]
- Thermal insulation of clothing R_{cl} [$m^2/(KW)$]

Table 1.1 Overview of environmental indices [5]

Healthy HEATING — Thermal Comfort Quality

environmental indices (resource: 2009 ashrae handbook – fundamentals, chpt 9, thermal comfort)					
temperature type	symbol	air	radiant	velocity	humidity
air or dry bulb (99.9% of all thermostats)	t_a or t_{db}	☺			
wet bulb globe (exposed to solar but t_a is shaded)	WBGT	☺	☺	☺	☺
equivalent or black globe	t_{eq} or t_g	☺	☺	☺	
mean radiant	MRT or t_{mr}		☺		
operative (abscissa on ASHRAE Std 55 psych chart)	t_o	☺	☺		
humid operative (defined at @100% rh and 0% rh)	t_{oh}	☺	☺		☺
effective (defined at @ 50%rh, assumed calm environment, skin wettedness & permeability index specified)	ET*	☺	☺		☺
standard effective (50% RH, <0.1 m/s air speed, and tr = ta, 1.0 met and a clothing level of 0.6 clo)	SET*	assumes $t_a = t_{mr}$		☺	☺

The EHT (or T_{eq}, t_{eq}) integrates effect of environmental factors as air temperature, air velocity, mean radiant temperature and also solar radiation, but not RH as can be seen in Table 1.1. It means that the EHT method is designed just for evaluation of the effect of the dry heat (sensible) loses. It does not include evaporative heat losses and it is not able to evaluate the effect of evaporation as thermophysiological models can do e.g. (Fiala, 1998).

However, the EHT by itself says nothing about the thermal comfort which can be expressed as Mean Thermal Vote (MTV) or Local Mean Vote (LMV). To evaluate thermal comfort based on EHT we need to compare these EHT values with so-called Comfort Zones Diagram (CZD), which reflects comfortable and acceptable range of EHT for specific body segments. These diagrams were obtained experimentally

[5] *From source: www.healthyheating.com/Thermal_Comfort_Working_Copy/Thermal-Environmental-Indices.htm)*

(Nilsson, 2004) for given group of people which was filling the questionnaires by their thermal votes. These tests were performed under specific conditions:

- It was assumed just the light sedentary activity of the people inside cabin which is approximately M=1 - 1.6 met (1 met = 58.2 [W/m^2])
- Test subjects had been dressed in clothing with the same thermal insulation.

These tests were performed for more types of clothing for which the thermal resistance of clothing was measured. In the ISO 14505-2 we can found diagram (CZD) for indoor summer (Rcl = 0.5 clo) and indoor winter clothing (Rcl = 1 clo), and they differ significantly on the local body parts (represented by segments on the thermal manikin).

After plotting the measured EHT into the CZD we can interpret the thermal comfort. Not just overall but also local one for each specific body parts. It depends just on the construction of thermal manikin and how many independently controlled segments it has. If the EHT for all considered body segments is in the neutral zone it means an optimal thermal comfort level. If some of the body parts is outside of neutral/warm/cold zone it means that on this specific body parts people would feel discomfort.

1.3 Equivalent homogenous temperature (ISO 14505-2)

To give a view in to the problematics of equivalent temperature we did brief literature review related to the equivalent temperature and its definition. In the Nilsson's PhD thesis (Nilsson, 2004) we found a comprehensive overview and historical background to this topic. If the reader is not familiar with the EHT procedure how it works or it is calculated, there can be found all relevant information and formulas. The next four paragraphs are directly cited from this source:

"Equivalent Homogeneous Temperature (EHT) (Wyon et al., 1989, Bohm et al., 1990). ***An alternative method*** *for the determination of "equal thermal environments" is the RST or* ***Resultant Surface Temperature*** *and the associated "equivalent temperature" (Mayer et al., 1993). A constant surface heat loss is assumed and the temperature of the surface segment (RST-value) that solves the heat balance equation, for inhomogeneous conditions is used as a measure of the climatic influence from the environment.*

Definition *of equivalent temperature today. The definition today (ASHRAE 62, 1989) reads "the equivalent temperature (teq) is the temperature of an imaginary enclosure with the mean radiant temperature equal to air temperature and still air in which* *__a person__* *has the same heat exchange by convection and radiation as in the actual conditions".*

The equivalent temperature is a recognized measure of the ***effects of non-evaporative heat loss from the human body*** *(Madsen et al., 1984, SAE J2234, 1993, Nilsson et al., 1999a). It is particularly useful whenever complex interactions of various heat fluxes are present. The equivalent temperature is derived from the operative temperature by the inclusion of the effect of air velocity on a heated body. The well-known operative temperature only considers the air temperature and the mean radiant temperature and is defined for the actual air velocity, whereas the equivalent temperature (teq) is defined for a standard low air velocity.*

One ***advantage of teq*** *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. However, the underlying hypothesis is that the teq value always represents the same "subjective" response irrespective of the kind of combinations of heat losses. Today this seems to be true, at least for conditions close to thermal neutrality (± 2 MTV) and within limited variations of the climatic factors (Bohm et al., 1990, Schwab et al., 1999) "*

For more details about RST method the VDA-FAT technical report written by Schwab et al., 1999 is very relevant source of information as it is the Nilsson's thesis (Nilsson, 2004) in case of EHT.

The next chapters are related directly to the activities specified in Chapter 1.1 which were planned for this project. In the following text can be found more technical and practical details about EHT method and there are presented also our experiences with the method.

2 Market research of EHT system

This chapter is related to **Activity 1** - Market research for comfort measurement systems/ comfort measurement dummies and **Activity 2** – Selection from systems available on the market.

As first step the literature and market survey about EHT system was done. There are two main groups of devices thermal manikin and local EHT probes/sensors. Mostly it can be found in-house systems (developed on universities or prototypes), but the commercial solution exists also. All systems operate somehow with the measurement of the heat flux from the surface, but there is one important feature that EHT sensors has to be actively heated.

2.1 Thermal manikins

Thermal manikins are useful but mostly very expensive devices with human body shape geometry which is split to various numbers of segments, that can be controlled separately. There exist the rigid types of manikins e.g. from copper which were firstly built in 40s for US army, but they are not suitable for the application of thermal comfort in the cars. The rigid types of manikin were developed for the defence and textile industry for testing of thermal insulation of clothing ensembles and this type of manikins are used in textile industry till today for outdoor clothing, protective clothing, etc.

However, for the purposes of testing thermal comfort in car cabins the segments should be connected by flexible joints. Some of the thermal manikins have the flexible joint or they are flexible itself see the Table 2.1 where are listed more or less advanced systems of the manikins which are possible to sit in the car. We have possibility to operate with Newton and PT-Teknik manikin. The information about other manikins are just reviewed from the technical documentation or from web pages promoting these systems. Except the Newton and PT-Teknik our research team had opportunity to see some in-house prototypes manikin during visiting other laboratories as was Sam manikin (EMPA, St. Gallen), Andy (Loughborough University), Karel (Brno Textile Institute) and Thor (Lund university). The first two manikins are too complex and too expensive to be used in automotive industry. Karel is rigid copper manikin, which was built for testing the sleeping backs and clothing thermal parameters. Thor is the prototype manikin form 80's which has been used by H. Nilsson and even its age it is still used in Lund University.

It can be concluded that on the market are just few commercial solutions of manikins ready to use in car cabins (Newton, PT Teknik[6]). More manikins are just rigid one for the testing of clothing ensembles which is suitable for textile industry not the automobile industry. For the automobile industry the EHT compact devices should be more suitable and affordable.

Thermal manikin Newton

Brno University of Technology (BUT) has bought thermal manikin Newton in 2011 with 34 independently controlled zones and allows to setup constant heat flux or constant

[6] *https://pt-teknik.dk/products/thermal-manikins*

temperature. Also, it is possible to use advanced control mode when surface temperature is controlled by thermophysiological model. For the purposes of this VDA-FAT project we used the standard control mode of manikin to evaluate EHT based on ISO 14505-2 (EHT+CZD method).

The Newton type manikin is produced by Thermetrics[7] and the company designed, developed and produced thermal manikins since 90's. It uses ThermDac software, which is well designed for laboratory tests and have all necessary function to do reports. Except this application the manikins generally are used for testing of the thermal insulation (ISO 15831, ISO 9920) of clothing and we used also our manikin for this type of work, including protective clothing for firefighters, medical staff, rescue staff etc. By this method is possible to estimate heat strain in the tested clothing and also effect on thermal comfort. The disadvantage is the price which was above 120 000 Euros per manikin few years ago. From this reason we tried to check the alternative solutions as the EHT sensors which we tested in our climate chamber.

PT Teknik manikin in cabin mock-up Practical usage of PT Teknik system:
For the short period of time we had possibility to install PT Teknik manikin in our car cabin mock-up inside the climate chamber see Figure 2.1. It has following features:

1) Flexible joints
2) Standard is 23 body zones
3) Price approx. 100 000 Euro

In comparison with Newton we found that both manikins are suitable for cars because have flexible joints, but the Newton seems to be more robust in daily use, especially form mechanical point view, but also the ThermDac software is more user friendly than the PT Teknik software.

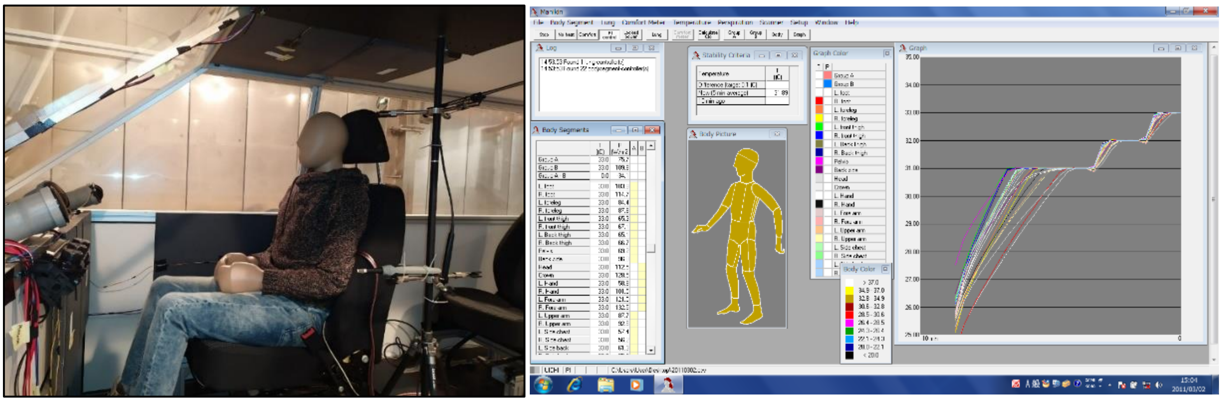
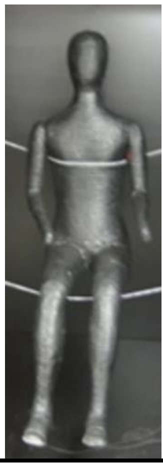


Figure 2.1 On the left: PT-Teknik manikin in cabin mock-up in BUT climatic chamber. On the right: PC app for this Manikin with visualization and see [5]

[7] *https://thermetrics.com*

Table 2.1 List of different type of manikins

Qinsun - Thomas ● 32 sweating zones moving ● weight 475 kg ● Control software ThermoTech Control analysis software http://www.qinsun-lab.com/428.html 	**ANDI Thermal Manikin** ● sweating model 35 zones, non-sweating 22 zones https://thermetrics.com/products/manikin/andi 	**Newton Manikin** ● up to 34 zones https://thermetrics.com/products/manikin/newton-thermal-manikin 	**Simon Manikin** ● simplified 13 zones thermal testing tool ● joints just shoulders and pelvis not sitting, for sleeping bags testing https://www.thermetrics.com/products/full-body-manikins/simon 
ADAM - Advanced Thermal Manikin ● the Advanced Automotive Manikin 120 sweating zones https://www.thermetrics.com/products/adam-advanced-thermal-manikin 	**Sherlock** ● Newton type manikin developed in Hohenstein institute https://www.hohenstein-academy.com/en/programm/seminar-detail/showteaser/webcast-thermophysiological-comfort-of-duvets 	**PT Teknik, Denmark** ● Flexible, Newton type manikin https://pt-teknik.dk/products/thermal-manikins/ 	**Low cost manikin DLR Gottingen** ● 1 zones https://www.dlr.de/as/en/desktopdefault.aspx/tabid-4702/7791_read-66988/ 

2.2 EHT compact devices (probes)

These compact devices are reliable for standard testing due to its lower price. The disadvantage is just local measurement of EHT which is directionally dependent in contrary of thermal manikin which integrates effects of heat transfer over human shaped body parts.

Comfortis

Comfortis is the commercial solution sold by Comlogo GmbH[8], which uses principle of RST (see chapter 1.2) and recalculation to the EHT. We have opportunity to borrow this system from the company, which is standardly using it for tests in climate chamber related to the heat load of cabin and measurement of comfort. Comfortis is set of 16 EHT probes which are using RST principle which can be placed on the passive (actively not heated) figurine. To keep some offset between the heated surface and actively heated EHT probe the each of these probes has associated adjacent air temperature probe, see Figure 2.2 (middle). All probes are connected to the power supply and data logger through the wires

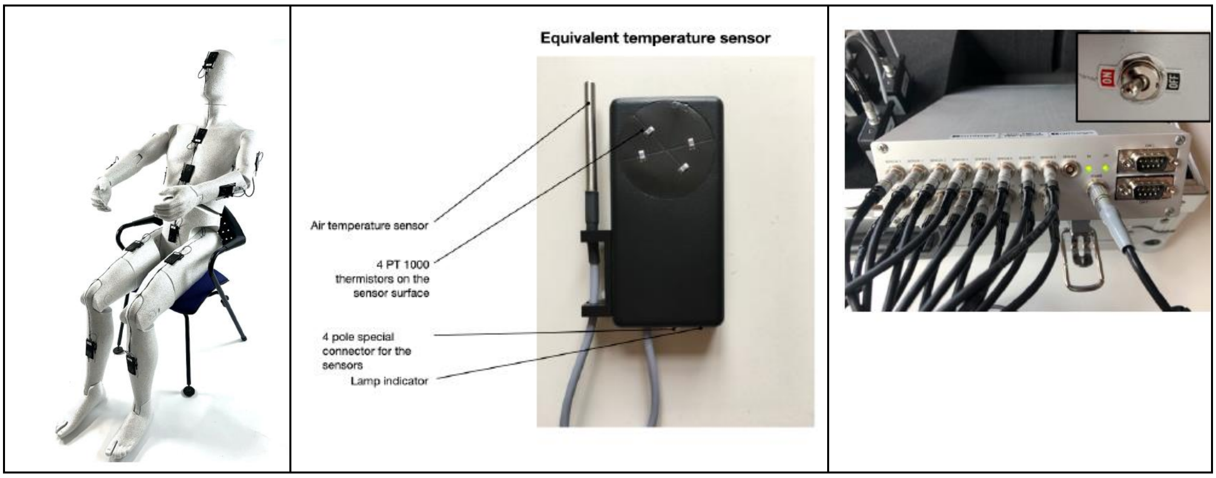


Figure 2.2 On the left: Polyuretane human body shape figurine with sensors. In the middle: Sensor in detail (black circle on the box) of equivalent temperature, using principle of RST which requires adjacent measurement of air temperature (metal cylinder), On the right: Data logger and power supply to the heated sensors. Source of figures - Comfortis Messystem - To measure the equivalent temperature.

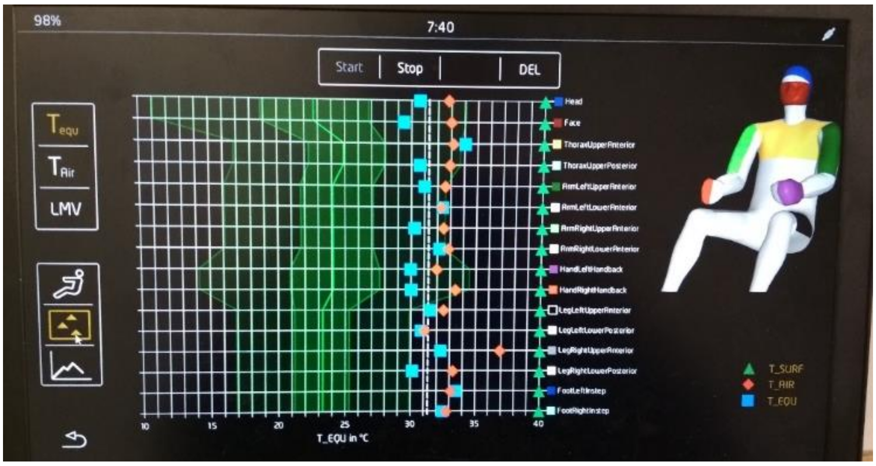


Figure 2.3 Comfortis visualization and logging SW.

[8] *https://comlogo.com/*

Dressman 3.2

Dressman is the dummy manikin equipped by the EHT probes, which can measure convective and radiative heat flows from that is possible to calculate EHT. It was developed at Fraunhofer institute IBP in Holzkirchen, see Figure 2.4. The first versions of this system of EHT probes comes from 1990. From the Fraunhofer IBP web page: *"The DressMAN 3.2 sensor system consists of between 16 and 60 sensors. These are either integrated into a wearable suit or attached with straps all over a manikin or a person's body. During the comfort measurement inside the vehicle, the DressMAN sensor imitates the heat balance of the human skin and measures the so-called equivalent temperature at 28 defined points, i.e. the warmth perceived, taking into account the air temperature, airflow, thermal radiation, humidity and solar radiation. These physically or "objectively" measured local equivalent temperatures are compared with the comfort diagram in the standard DIN EN ISO 14505-2, thus enabling thermal comfort to be evaluated in relation to the individual body parts. To make an in-depth scientific evaluation of the vehicle air conditioning system, the contact areas are also examined. Eight sensors placed on the back and underside of the thigh record the transfer of heat and moisture between the person and the seat"*. [9]

Figure 2.4 Dressman system introduction on the web page of Fraunhofer IBP[8]

BUT in-house EHT sensors

A compact sensor for measurement of EHT and associated android application was developed by BUT (Brno University of Technology) in 2017. The main feature is the low price and a compact design of sensor – just 20 x 20 x 10 mm (half volume of matchbox). The production costs were very low in comparison of standard heat flux meter, and it was produced approximately 20 pieces of sensor. Each sensor is connected thorough the communication link which provides also energy for heating. Small sensor not require such amount of energy as manikins, thus it is possible to

[9] *https://www.ibp.fraunhofer.de/en/business-units-and-products/product-developments/dressman.html*

power supply by 12 V and also this system is possible to connect to the car by OBD connection.

Below is the list of the main parameters.

- Sensor = all inside – heating, processor, electronic
- Digital processing inside = connected by RS485 digital bus, robust data transmission, EMC compatibility
- 3 modes – constant temperature, constant heat flux and Passive thermometer (air temperature)

In the Figure 2.5 is the scheme data process scheme in iHVAC system. For the evaluation of thermal comfort, it uses Comfort Zones Diagram as standard EHT comfort system and data are then possible to visualize in the android application. In the Figure 2.6 is depicted detail of sensor construction (boxed sensor, unboxed).

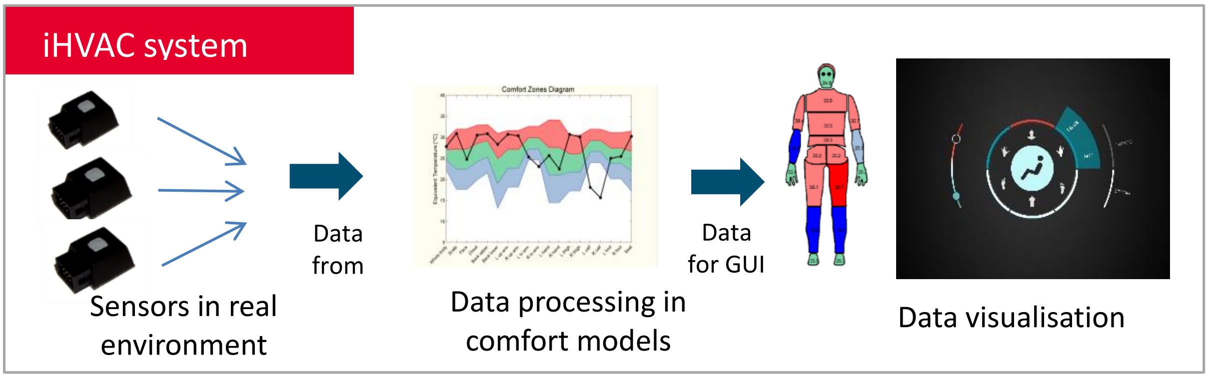


Figure 2.5 iHVAC system: sensor, used method ISO 14505-2 and visualization in the android application.

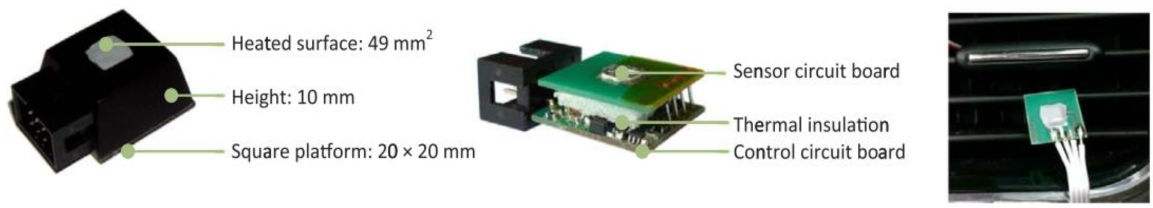


Figure 2.6 Detail of iHVAC sensor: box, integrated circuits and application of unboxed sensor to the car air vents.

The price of one iHVAC sensor is slightly below 100 euro and all these sensors were developed and built in cooperation with colleagues from Faculty of Electrical Engineering and Communication, BUT.

Sensors/flatman by Innova

Innova system includes rebranded solutions almost the same construction. The set of these EHT probes is possible to arrange in position corresponding to the driver position by some holders. This arrangement of probes to the measuring system is so called flatman and its disadvantage in contrary with the real manikin is the fact that it is influenced by the environment from the side where the human body is expected. From this point of view, the usage of dummy manikin (passive figurine) should be better option for evaluation of thermal comfort in car.

BUT own also this system of thermal comfort, but for the purposes of testing thermal comfort in cars we prefer thermal manikin solution.

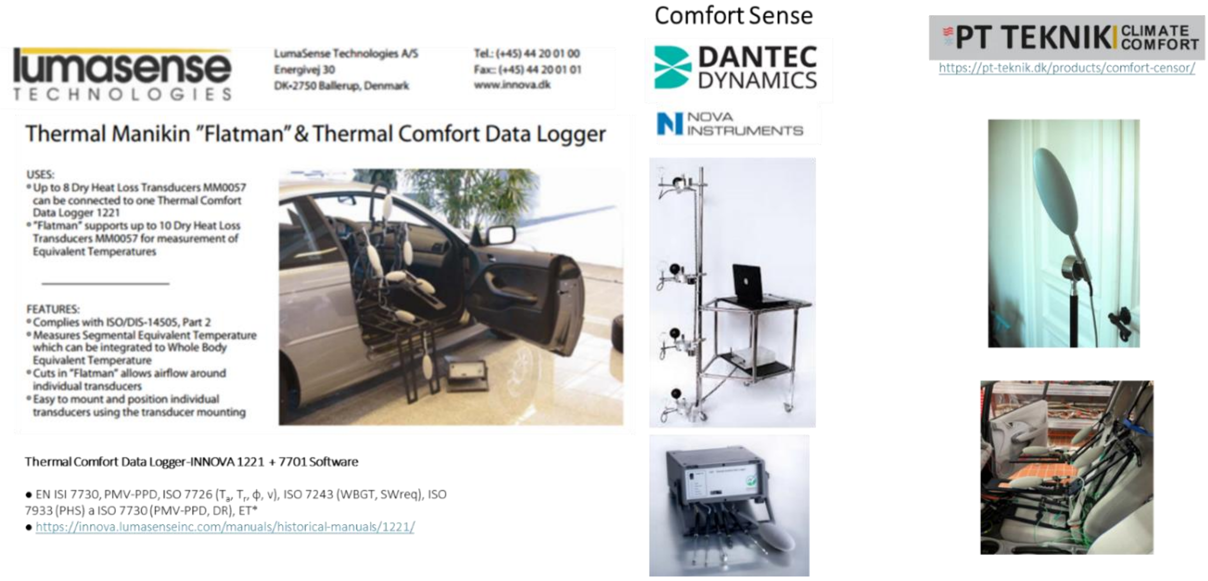


Figure 2.7 Detail of Innova Flatman system.

2.3 Final selection of the EHT systems to be tested

From all mentioned systems we have few systems directly in the laboratory at Brno University of Technology. We standardly use thermal manikin Newton, iHVAC and also, we have the system by Innova. To fulfil the project aims we added for the testing the Comfortis system and also for very short time we had possibility to have in our laboratory also the PT Teknik manikin.

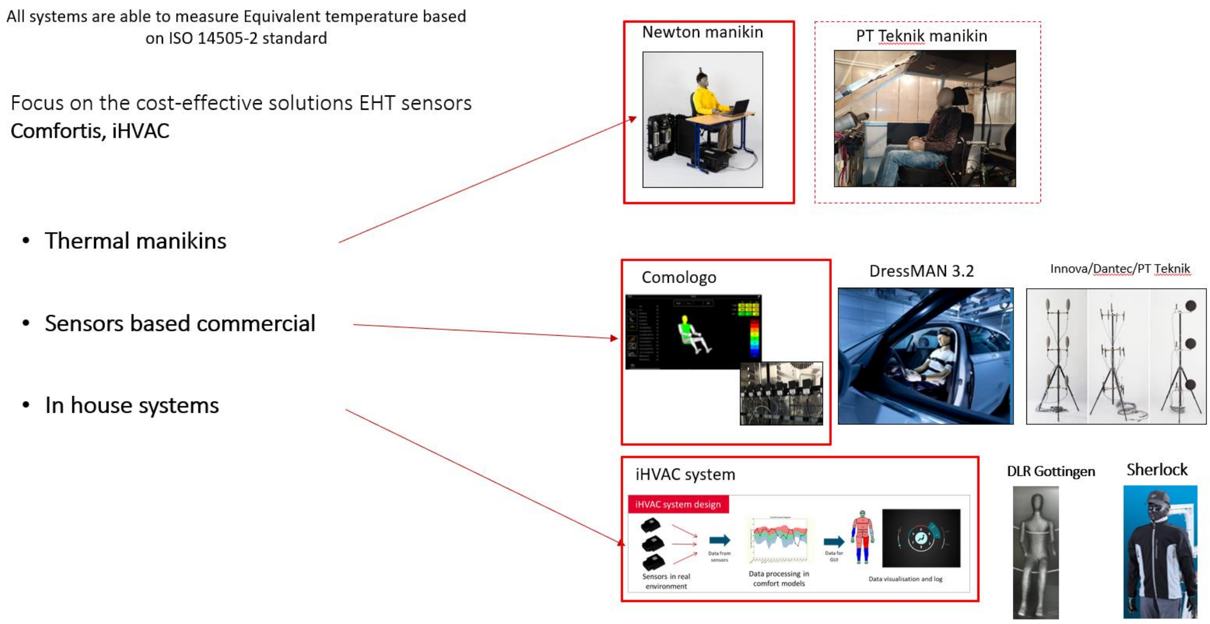


Figure 2.8 List of perspective tools for EHT measurement. In the red box are highlighted systems, which were used for solving practical part of the project.

The Comfortis system was borrowed for this project from the industrial partner. It was not possible to have Comfortis for all types of tests but we manage to borrow “him” for the fundamental tests and also the last test where we did test of real cars.

So, the final selection of thermal comfort measuring devices used in the frame of this project were following (see also Figure 2.8):

- **Newton** thermal manikin - measuring by its human body shaped surface
- **Comfortis** system – sensors were placed on the passive figurine (dummy)
- **iHVAC** system – sensors were placed on the same figurine as Comfortis

3 Methods

In the Introduction chapter was presented the equivalent temperature as one criteria of thermal comfort. Important part of ISO 14505-2 is the Comfort Zones Diagram, which give the final interpretation of the thermal comfort based on equivalent temperature. This diagram depends on the local thermal insulation at specific body parts. In the Chapter 2 we just reduced the number of comfort measurement system to be tested to number three.

These systems have different method how the final equivalent temperature value is measured. There are more methods (modes) how to measure equivalent temperature and they differ by the control of the sensor surface temperature:

1. **Constant surface temperature** (Newton, iHVAC) – measuring of heat flux from surface with constant surface temperature **(CST)** than calculation of the EHT.
2. **Constant heat flux** (Comfortis) – measuring of temperature of surface (**RST**) which is constantly heated by defined heat flux. The EHT is calculated from this RST value and the ambient temperature.
3. **Comfort balance -** it uses balancing of the surface temperature of the probe or manikin, which is not constant but it is adjusted by the expected human surface temperature.

For the evaluation thermal comfort, we used systems which uses EHT (Newton manikin, iHVAC) and also RST (Comfortis) see Figure 3.1. The first question which had to be answered is: **Are the EHT measured by CST and RST method really equivalent or not?** To better understand this issue the both methods constant surface temperature and constant heat flux are described in this chapter.

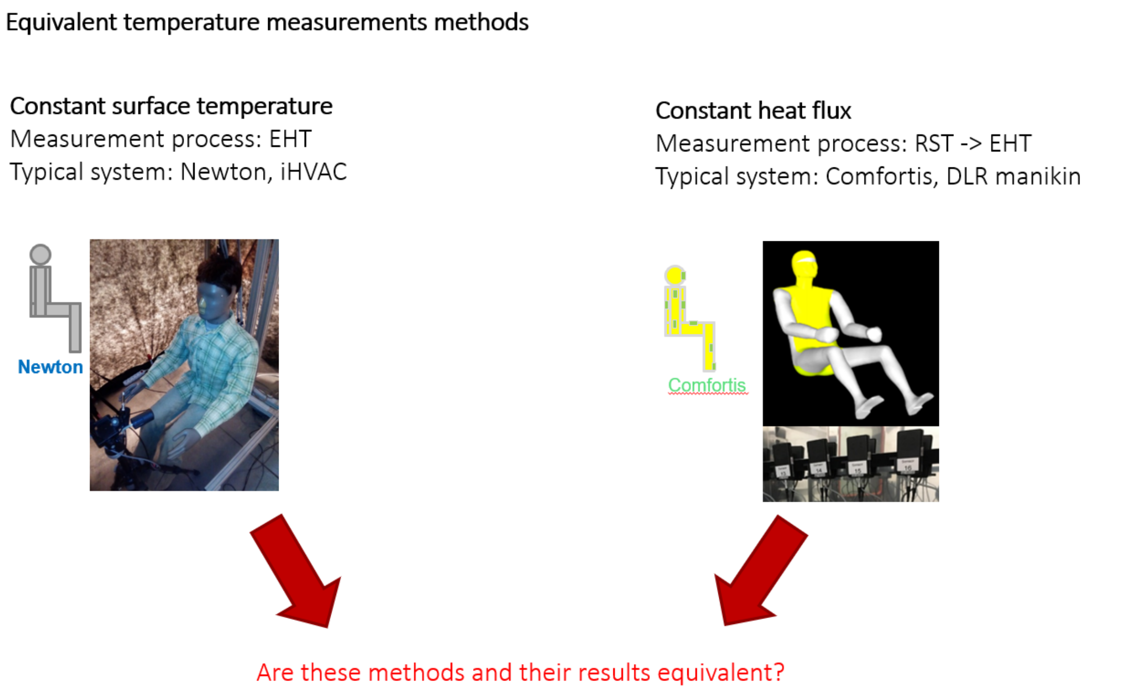
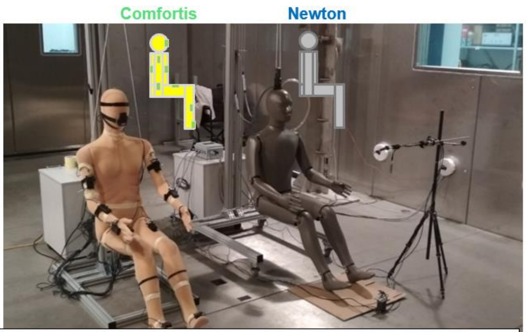


Figure 3.1 Mean thermal vote calculated from RST based on environmental conditions

The plan for evaluation of Comfortis and Newton systems

1) EHT calibration environment based on definition
2) Environment with constant wind speed
3) Transient conditions – changes of wind speed + air temp.



Arrangement for EHT validation of Comfortis and Newton measurement system

Comfortis – set of EHT sensor placed on dummy – Constant Heat Flux mode
Newton – thermal manikin measuring by whole surface – Constant Temperature mode

Figure 3.2 Arrangement of the first tests

3.1 CST - Constant surface temperature and evaluation of heat flux

The first method supposes that the mean surface temperature of the human is 34 °C. Actually, the real person has a different distribution of surface temperatures, especially in not neutral state where the distribution of surface temperatures is more complex due to the thermoregulation responses. But such situations are not typical for car cabins and it is acceptable to assume the state close to the neutral with one uniform surface temperature for whole surface of the body.

In case of thermal manikin Newton, it is possible to set up different surface temperatures to be more realistic and even it is possible to change it by using thermophysiological model or other type of models (e.g. empirical, etc.) The one problem is that between the adjacent segments with different temperatures could occur parasitic heat flows which will influenced the interaction of the manikin with the surrounding environment. The second problem is the time constant of the segment during their temperature changes. The increase of temperature is easy done by increasing electric power, but the cooling of the manikin is driven by heat exchange by convection+radiation and depend on surface-to-surrounding temperature difference.

The heated manikin on surface temperature 34 °C was used to obtain correlation with the human subjects (see Nilsson, 2004). Which means that for each body parts we know how much heat is comfortable to leave from the surface. This heat flux is than possible to recalculate based on clothing to the equivalent temperature, which define so called comfort zones diagram. Each zone is calculated for the specific range of LMV -3, -1.5, 0.5, +0.5, +1.5, +3. These values can be associated with percentage of dissatisfied people similarly as it is in ISO 7730.

The disadvantage of CST method is the fact that in environment warmer than 34 °C the thermal manikin measure zero heat flux which means equivalent temperature 34 °C. Thus, the CST method is not able to measure in hot environment far from the thermal comfort. In the opposite direction (i.e. in cold) it has the issue with the fact that thermal manikin is able to generate up to 500 W/m^2 which causes the CST method to be more sensitive to the cold and especially windy conditions than real human. Human can decrease surface temperature by vasoconstriction to reduce blood flow through the skin layer and in the extreme situation it can be up to 18 °C where is the threshold of the pain from cold. All these facts explain, why the EHT method is recommended to use from LMV= -2 to +2.

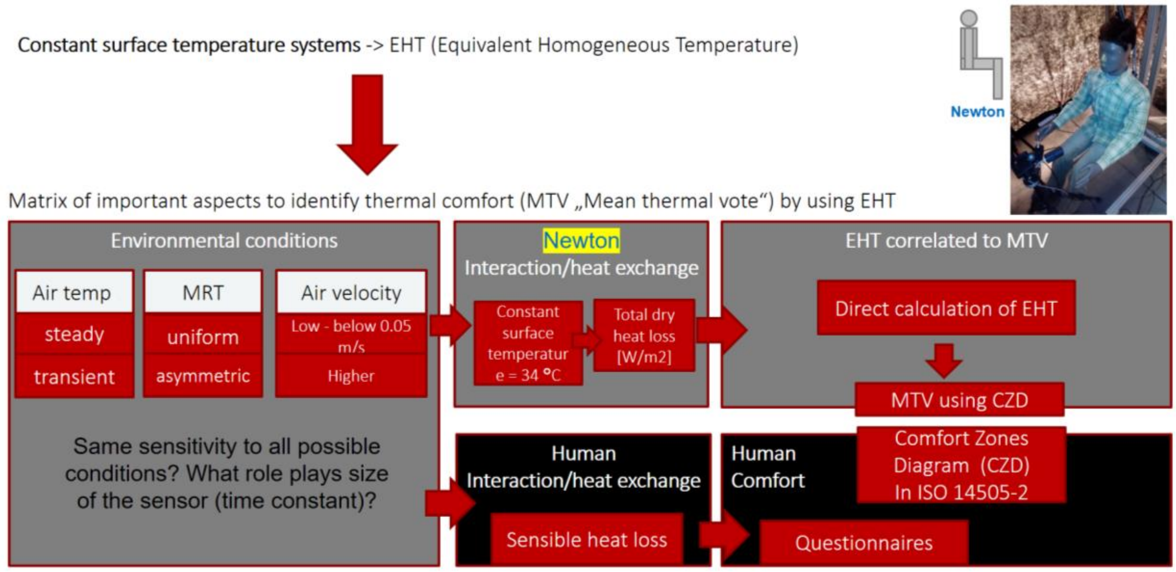


Figure 3.3 Mean thermal vote calculated from EHT by using CST mode (Newton, iHVAC)

3.2 RST - Constant heat flux and evaluation of resultant surface temperature

The second approach is to prescribed constant heat flux [W/m^2] to keep differences between the ambient air temperature and the heated surface, which is actually the resultant surface temperature. RST is than possible to recalculate by the calibration curve which is necessary to defined for all probes in the climatic chamber. The power consumption is given by the combining Stefan-Boltzmann law for radiation and Newton law for convection to keep the temperature difference at constant offset. For these purposes the adjacent air temperature probe is necessary to estimate the heat transfer coefficient by convection and to have the reference temperature of the ambient.

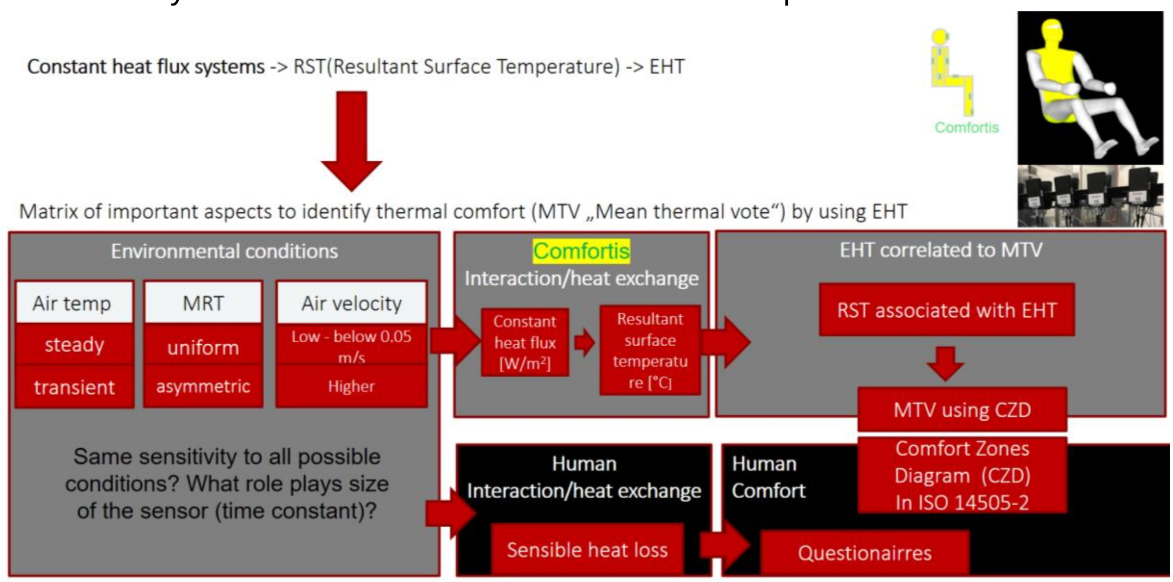


Figure 3.4 Mean thermal vote calculated from EHT based on RST (Comfortis)

The RST method requires the additional calibration curve and also it includes some internal calculation under some simplifying assumption about the radiation and convection heat transfer coefficients. On the other hand, this approach has advantage in the possibility to measure the heat transfer conditions warmer than surface temperature 34 °C, there is no problem in the cold conditions with not realistic heat production from manikin in comparison from human. But this method is suitable just for small sensor, because in warm and neutral conditions the surface temperature of the sensor can be 40 °C and more so this temperature is not suitable for manikin.

As partial conclusion of this problem it can be said that both methods CST and RST respect the physical laws of heat transfer, but the idea behind is slightly different and each method is suitable for different applications. CST is good for conditions close to the neutral, RST is suitable also for extreme cold and warm conditions.

3.3 Human subject test and questionnaires

The fundamental research in the field of thermal comfort and equivalent temperature is still open issue, especially the issue of perception of equivalent temperature by human and definition of Comfort Zones Diagram. From this reason the human subject studies by using questionnaires can help to identify weaknesses of each approach mentioned above. This experimental method is the most representative, but also most expensive, because to have some relevant results it requires to have at least eight test persons or more. The ISO 7730 model was established based on the measurement with more than 1000 people. The ISO 14505-2 EHT model it was just derived for 20-30 people. In the past we did some comparative study also on the pool of 20 test subject and we found the method valid with just small adjustment on the scalp and face segments. In this mentioned study however, we not tested the effect of different wind speeds. The effect of windspeed was arising issue in this project and we tried to experimentally investigate how the human really feel the effect of the wind and what indicates RST and EHT methods. However, it was possible to performed just pilot study with 3 volunteers, due-to COVID19 restrictions (see chapter 6.1.2).

3.4 Sensitivity to the air temp., radiant temp., solar radiation and windspeed

The main assumption of the methodology is the human thermal sensation is in correlation with heat losses from the human body. The method is not able to evaluate the evaporation and respiration heat losses which can be neglected in low metabolic rates as are typical for seating in the car 70 - 90 W/m^2 see ISO 14505-2. Other forms of heat losses are assumed to be equivalent and they are summed into one value of heat losses, which is in correlation with human thermal votes. In the (Zhang, 2003) was proved that even the local thermal comfort can be affected by local thermal sensation of other body parts, which means that heat stress one-part can be compensated on another part in some range of temperatures not far from the neutral.

During the first tests, which are presented in the Chapter 5 we found that the sensitivity to the ambient environment differs for the CST and the RST method, especially the convection heat transfer and the windspeed higher than 1 m/s. In FAT report (Schwab, 1993) was mentioned also the third option so-called comfort balance mode which combines both principles. Instead of constant surface temperature the surface temperature is in some way affected by the heat fluxes to keep “temperature comfort level close to neutral, to reduce the extra-heating power to not exceed the realistic heat production of human which can leads to overestimation of cold sensation. This was documented in the test T4 - T7 see next chapters.

The comfort balance method is one of the directions which can be investigated more deeply in future to avoid disadvantages of CST and RST. Also, the idea of more realistic surface temperature on the manikin and usage thermophysiological models can be the way how to improve the thermal comfort evaluation. But one should keep in the mind the main advantages of EHT and Comfort zones diagram (ISO 14505-2) that it expresses the effects of combined thermal heat load on the human as a single figure, which is easy to interpret and explain and also the results are possible to reproduce.

4 Design of tests

This chapter is related to the **Activity 3** “Development of test scenarios for a comparison of measuring systems”, especially to “Design of experiment – definition of conditions for laboratory tests and tests with car”.

When we had all system in out laboratory we defined different type of tests of different complexity to be able distinguish between the effect of the changing temperate or changing wind speed. Thanks to the fact that our scientific team has at its disposal a climate chamber for cars we were able to design the fundamental tests but also the realistic tests with real car cabin. Before the own measurement we proposed the plan to perform 4 types of tests:

Case 1 – Quasi static conditions – uniform environment

- validation of measurement Teq (see tests T1, T3)

Case 2 – Quasi static conditions – forced convection

- systems comparison (see tests T4, T6, T7)

Case 3 – Transient temperature changes in chamber

- controlled temperature –systems comparison (see tests T2)

Case 4 – Transient changes in car cabin or mock-up, HVAC ON

- validation of simulated conditions (see tests T5, T8)

We followed this schedule during whole solution of this project, and related to this we performed 8 different testsT1-T8 (T1-T5 pilot tests, T6-T8 advanced tests). The specification of sensor placement in laboratory tests and car cabin tests preparation of all devices for the testing is described later directly with the achieved results of the measurement see Chapters 5 and 6

4.1 Tests in climate chamber – Quasi static conditions

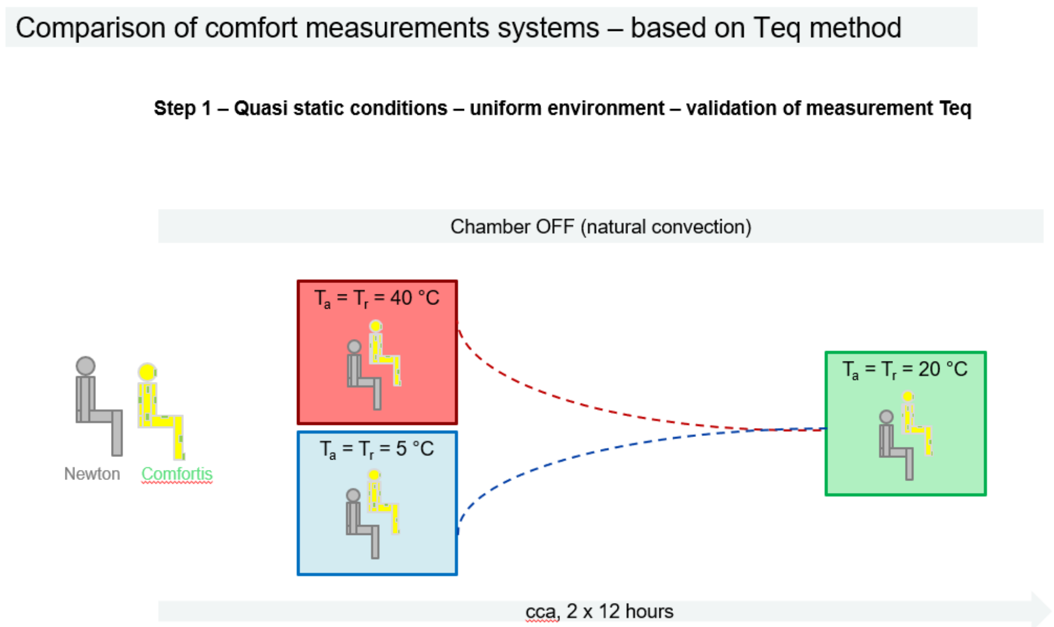


Figure 4.1 Example of test design with static conditions – slow change of temperature with constant no-wind conditions.

We planned to start with the simplest case 1 (see Figure 4.1) just to compare the EHT systems in slowly changing environment without any action (closely related to the calibration conditions. The reason was that each of this EHT systems requires before its usage the calibration of the probes, so we tried to imitate this calibration process.

The case 2 (see Figure 4.2) was just adding of forced convention without any change, which imitated calibration of the probes for the wind, later in the text just „Wind tests" by using the stand fans

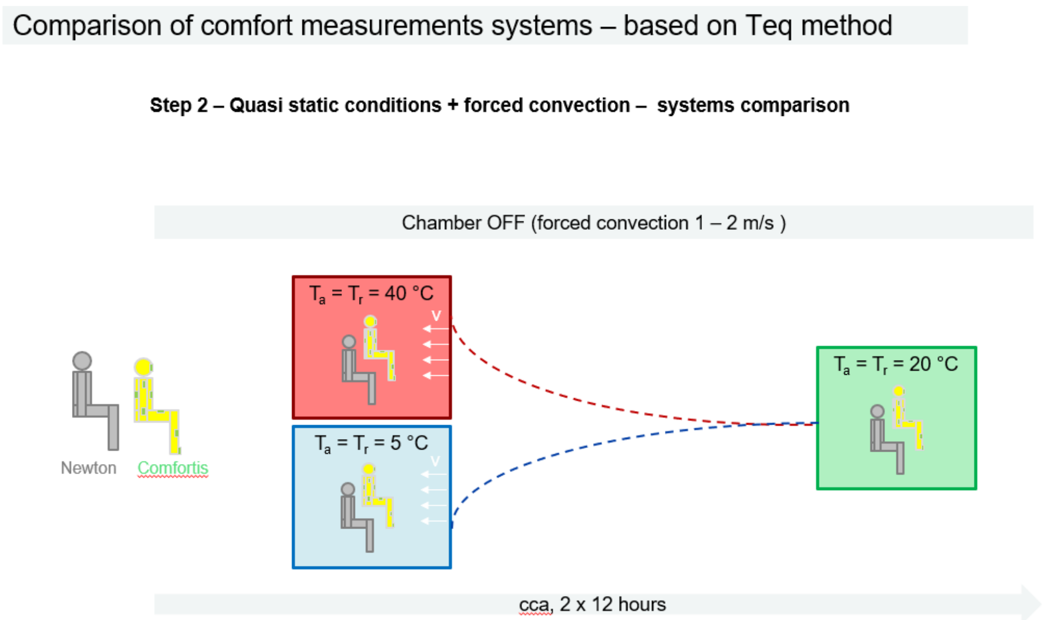


Figure 4.2 Example of test design with static conditions – slow change of temperature with constant windspeed

Both cases not required the active control of climate chamber and it was sufficient just at the beginning prepare chamber for temperature +5 °C, and +40 °C and to monitor temperature and wind speeds in climate chamber. Because the climate chamber is well isolated the change from +40 or 5 °C to 20 °C was quite slow. It took 12 hours. The reason why we use these starting points (cold/hot) was to reveal if it is any difference between the EHT systems how they react on the slow temperature decrease and slow temperature increase.

4.2 Tests in climate chamber – Transient temperature changes

Because the perception of the thermal comfort can be different based on the changing ambient conditions, the case 3 (see Figure 4.3) was designed for the evaluation of EHT systems how react to the transient changes of environment. These tests were shorter but required active control of climate chamber in the real time. In the schemes are suggested some specific values of temperatures but during the real testing we adjusted these scenarios based on the real behaviour of the tested EHT system to cover interesting operating conditions where the system can differ.

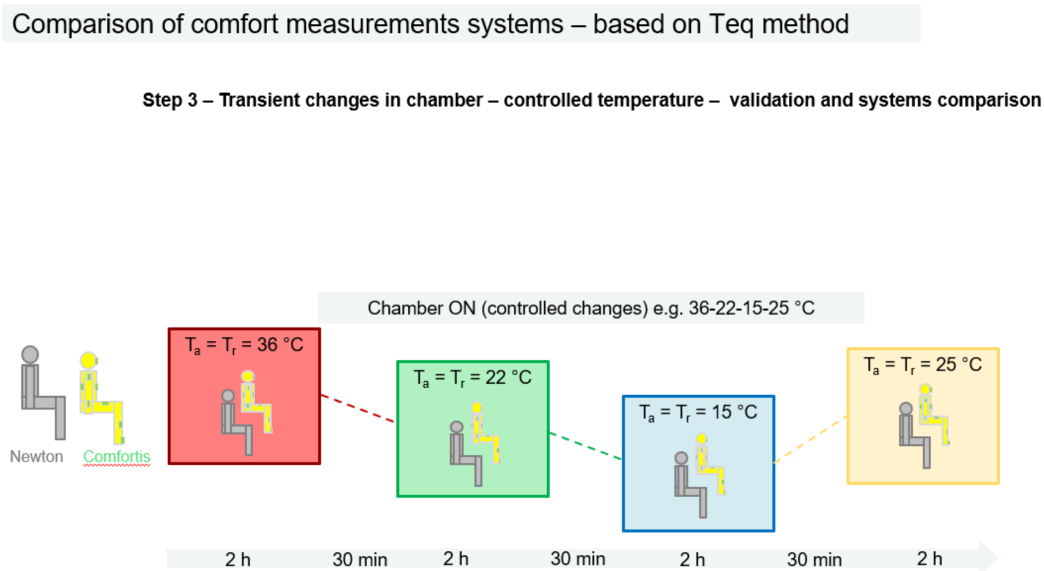


Figure 4.3 Example of test design with transient conditions

4.3 Tests in cabin mock-up

The last case 4 (see Figure 4.4) was tested in cabin mock-up and car cabin to imitate the realistic environment, which car cabin can provide. These tests required actively controlled ambient environment in the climate chamber (cold/hot) and also the cabin space had to be air-conditioned to provide thermal comfort. In the tests we suggested to apply setup HVAC AUTO 22 °C to provide acceptable level of thermal comfort.

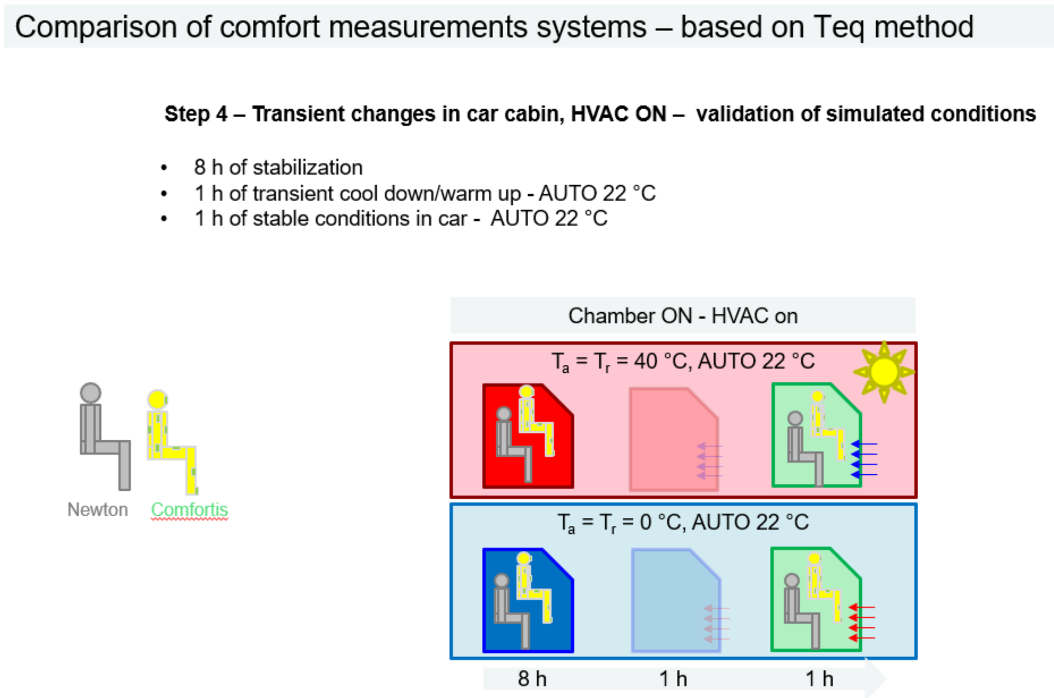


Figure 4.4 Example of test design in cabin or cabin mock-up.

5 Results of pilot testing

Related to the **Activity 4** - Pilot testing of test scenarios for scenarios optimization and procedure troubleshooting:

- Performing pilot test with procured EHT system and thermal manikin Newton at climatic chamber in Brno
- Post-processing of the results

At beginning the attention was paid to comparison of the thermal manikin Newton and Comfortis. As was already written these devices both evaluate equivalent temperature but in different way (CST vs. RST). The issue was to identify if they can provide the same value of EHT and interpretate the thermal comfort for the same environment similarly. We investigated different temperature and wind conditions, see the Figure 5.1. where overview and snapshots from the firsts test T1-T5 performed in 2020 are shown. Each of this test is described in following and they can be split into two categories “no wind” tests and “wind” tests.

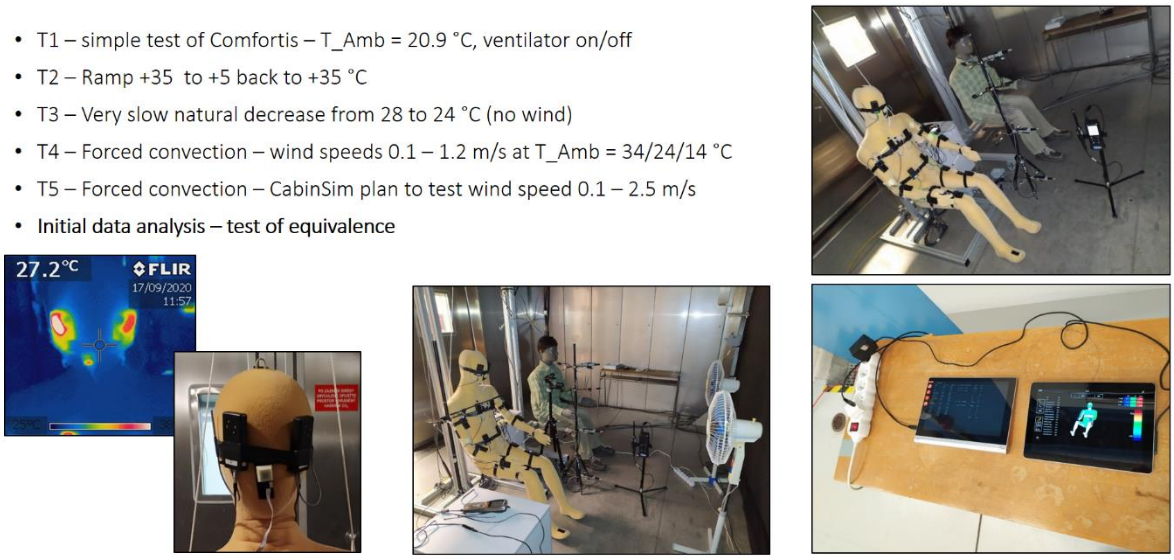


Figure 5.1 Pilot testing T1-T5 (wind and no wind tests). Overview and snapshots.

5.1 Steady and transient temperature tests – no wind

In this type of scenarios, we investigated how differs EHT value provided by Newton and Comfortis in situation where the temperature is stabilized or it is slowly changing. We eliminated effect of windspeed, thus only natural convection casing thermal plume around the manikin was present.

5.1.1 T1 – Simple test of Comfortis – T_Amb = 20.9 °C, ventilator on/off

We started with the simplest case - calibration of air temperature probes in uniform environment 21 °C (climate chamber with stable conditions, no forced convection). We were focusing just on the air temperature of the both systems to be sure that they are well calibrated. For this purpose, we used our calibrated temperature probe and measurement system TESO 480. We also tested the reaction of these air temperature probes to the constant wind.

During the setup of Comfortis system, we took care to not place air temperature sensors of Comfortis system to the plume caused by heated surfaces of Comfortis EHT sensors. Additionally, we placed in front of the Newton manikin and Comfortis calibrated certificated temperature probe connected to the logger Testo 480 and external probes belonging to Newton manikin (see Figure 5.2).

The results on the Figure 5.2 (upper chart) shows, there was offset 0.4 - 1 K against the calibrated thermometer Testo 480. In case of the Newton external temp. probes was the difference up top 0.1 °C (chart on the right). It means that air temperatures measured by the Newton external probes match our certified calibrated probes very well.

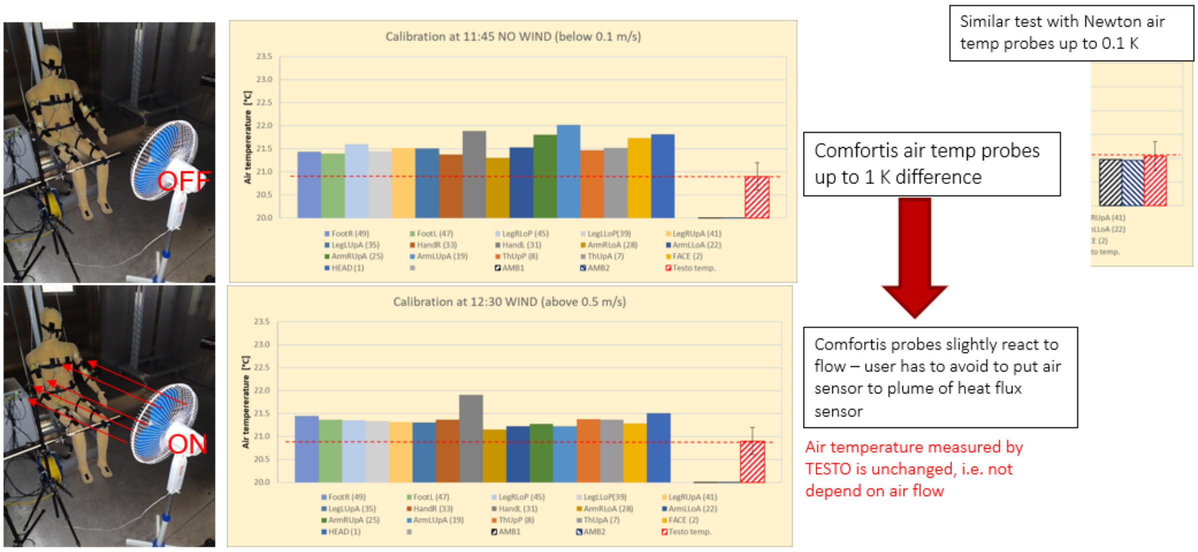


Figure 5.2 Verification of the air temperature probes of Comfortis system.

The temperature probes of Comfortis system slightly react to the air flow (see Figure 5.2 bottom chart), which can be caused by the neighbouring heated EHT sensors. We found some differences between the situation when the Comfortis EHT sensors were placed vertically or horizontally. Later we found based on the documentation that it is not bug but the feature of the system.

<u>Summary</u>: Supported air temperature probes of both systems measured with acceptable accuracy. Placement of the EHT sensor (Comfortis) requires more attention to avoid some errors due to the measured values are directionally dependent. In contrary thermal manikins are measuring by whole surface.

5.1.2 T2 – Ramp +35 to +5 back to +35 °C

The next step was to investigate transient temperature changes in wide range of temperatures from +5 °C to +35 °C. The change of temperature was controlled by climate chamber to keep temperature slope 6 °C/h for cooling and 12 °C/h for heating.

Goal was to compare all systems (Newton, Comfortis and iHVAC) in no wind conditions and the time schedule of experiment was following:

- 4:00 - Climate chamber 35 °C
- 8:15 - Ramp 6 °C/h from 35 to 5 °C
- 14:15 - Reached 8 °C then 30 min steady
- 14:45 - Ramp 12 °C/h back to 35 °C
- 17:45 - End of the test – Reached 28.5 °C

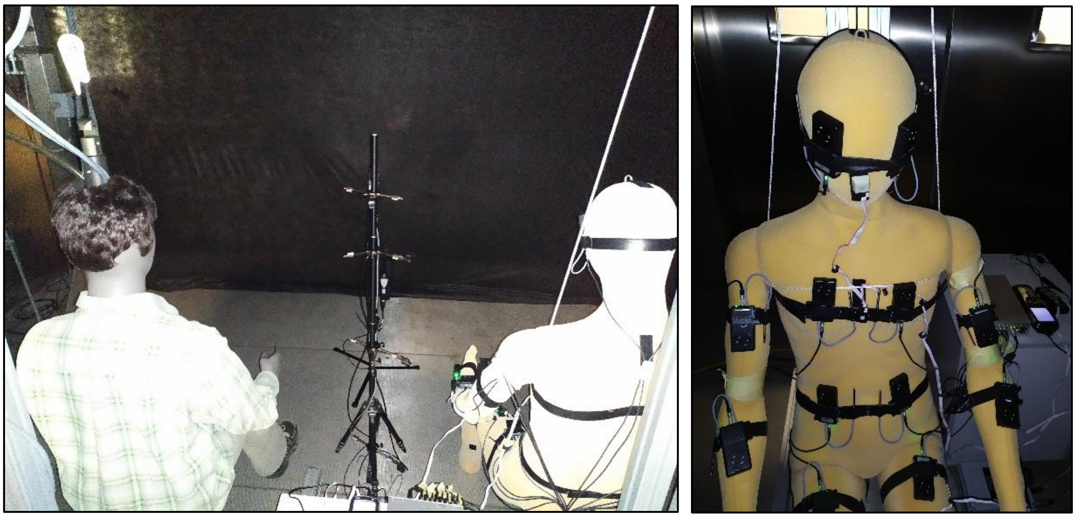


Figure 5.3 Photo documentation. (Left) Comfortis and Newton in front of blanket. (Right) Detail on Comfortis with iHVAC sensors

In the Figure 5.3 is possible to see the installation of the experiment in the climatic chamber. To reduce the airflow around the manikins during the period when the chamber was running (it produces small wind approx. 1-3 m/s), the black blanket nonwoven material was applied to reduce wind speed close to 0.1 m/s.

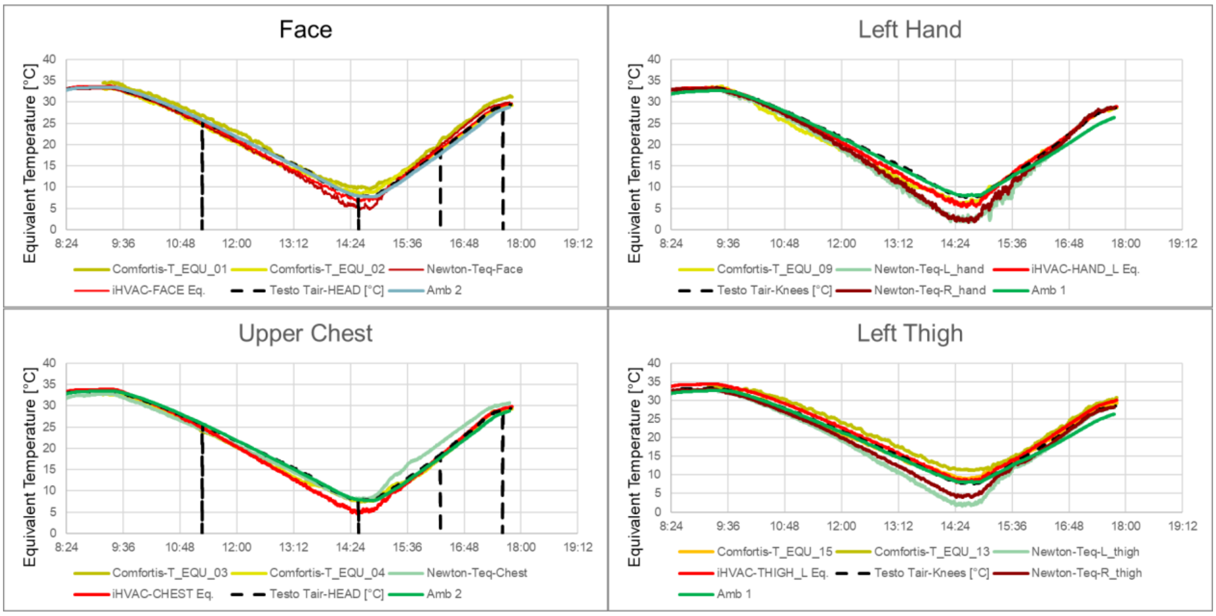


Figure 5.4 Comparison of equivalent temperatures for Comfortis, iHVAC and Newton system + air temperatures measured by Testo and Newton. For (Face, Left Hand, Upper Chest, Left Thigh).

The disadvantage of the usage of this blanket was that it caused temperature delay in the space behind the blanket compared to temperatures in front of it where the climate chamber vents delivering air-conditioned air are placed. From this reason at the end of the test it was not reached Tamb = 34 °C as was planned but only 28.5 °C see Figure 5.4. On the same figure can be seen that that above 10 °C the sensor behaves quite the same for all body segments, but below 10 °C start to be little different for some parts.

Summary: In no wind conditions systems behaves similarly except the temperature lower than 10 °C.

5.1.3 T3 – Very slow natural decrease from 28 to 24 °C (no wind)

The aim of the experiment was to compare systems in no wind conditions and to calibrate the Newton manikin for given clothing. Time schedule of experiment was:

- 16.9. 17:47 Climate chamber OFF at 28 °C
- 17.9. 11:50 Climate chamber OFF at 24 °C

The manikins were in the same positions as in previous test case T2. The IR (infra-red) photos reveals the heat dissipation from Comfortis (local sensors) and Newton (heated surface).

Comfortis uses constant heat flux – e.g. It still keeps difference between ambient air and heated surface

- Wider operating range especially at higher temperatures 60 °C no problem

Newton uses constant temperature mode setup for 34 °C surface

- Lower surface temperatures are necessary for manikins due their large surface area, in low temperatures easily can be reached 500 W/m^2 limit for heating manikin.
- To avoid this is possible to dress manikin in clothing as human did. This has no effect on the principle of EHT and help reduce the heat losses. Disadvantage is still in the surface temperature limit of 34 °C, so in hot environment manikin does not measure.
- This can be acceptable because the usage of EHT is focus mainly on thermal comfort range and in hot environment sweating occurs, which the comfort zones diagram doesn't take into account.
- operating range to 34 °C

On the Figure 5.5. are thermal images of the Comfortis and Newton. The actively heated surfaces are visible in infrared; these surfaces allow to evaluate EHT. Comfortis has discrete set of heated sensor and manikin Newton uses one surface temperature for the whole surface. However, his surface is covered by real clothing which explain why the IR images shows different temperatures (because they are related to the clothing layer). Only Face segment where is no clothing had temperature close to 33.2 °C which is closed to 34 °C. Actually, in the log it was 34 °C, because Newton measure by its own the surface temperature for all segments. Also, it should be noted that thermal imaging is not accurate contact measurement.

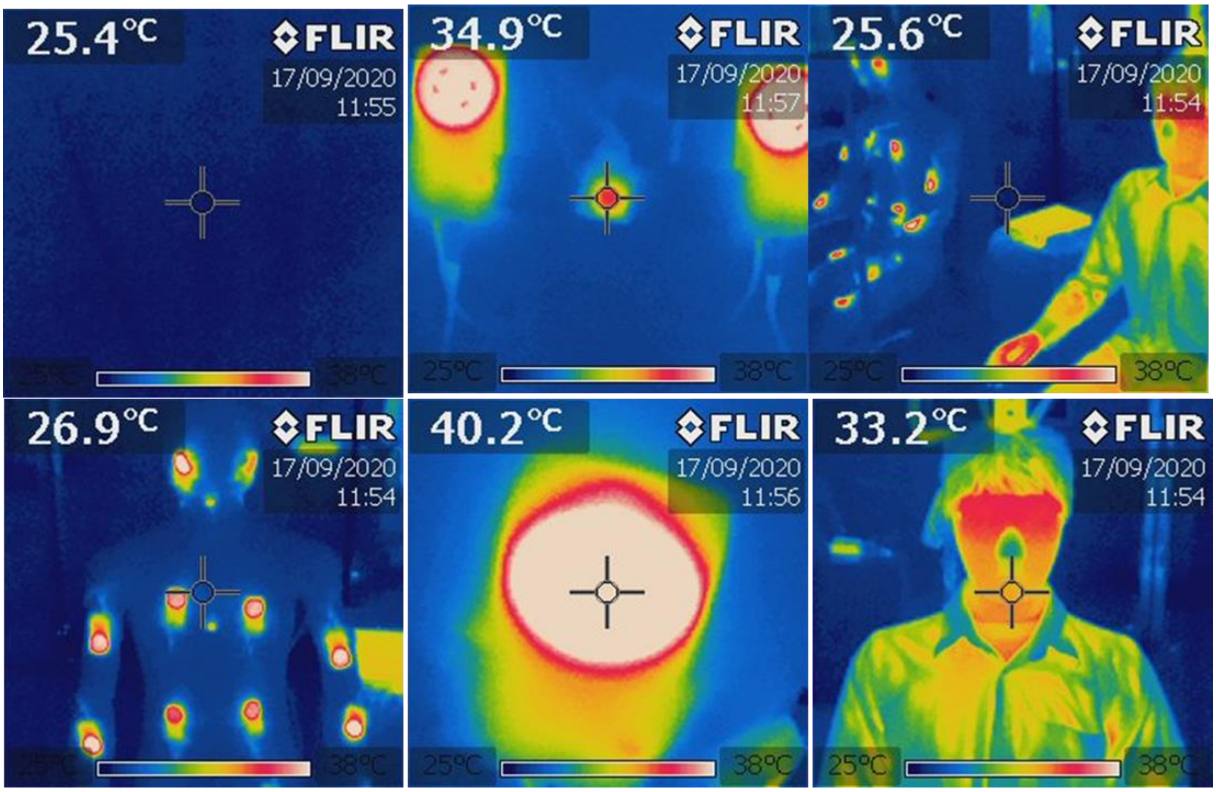


Figure 5.5 Comparison of heated surfaces of Comfortis probe and Newton manikin by IR camera.

Summary: The systems operate in different modes which influence the heat transfer phenomena near the probe, see infra-red photos above.

5.2 Wind level tests

The sensitivity of the second parameter (wind speed) was investigated in the following tests. In these tests were added forced convection to create non-uniform environment and we were interested how it will change the parameter the evaluation of thermal comfort for all considered systems. We carried out experiments for different combination of temperature and wind speeds.

5.2.1 T4 – Forced convection – wind speeds 0.1–1.2 m/s at T_Amb = 34/24/14 °C

The aim of the experiment was to compare systems in wind/no wind conditions for warm/neutral/cold environment. Time schedule of experiment was:

- 8:00 Climate chamber 34 °C
- 10:20 Climate chamber 24 °C
- 12:40 Climate chamber 14 °C
- 15:00 End of the test

Altogether it was measured 12 combinations of environmental conditions – 4 (wind) x 3 (temp). For each temperature we considered no wind, wind lvl 1/2/3 conditions. For each wind level was time period of 30 minutes for stabilization and 10 min for logging. To provide objective comparison of the different EHT systems must be secured the “same” ambient conditions for both, especially in the case of the wind tests we need to generate the very similar velocity field in front of Newton manikin and Comfortis. From this reason we setup stand fans as same as it was possible and during the experiments we continuously measured air velocities in front of each system.

On the Figure 5.7 there are all air mean velocities measured in the head level for all of 12 tests at Comfortis and Newton place. From this result can be seen that the AVG windspeed was in tolerance of 1 SD for both systems, still small differences were present even two identical fans were used. It means statistically that these two air flows should have the same effect.

So, we had ideal conditions in the climate chamber to evaluate differences between the both comfort systems. The difference between the measured values could be only caused just by different control mode or construction.

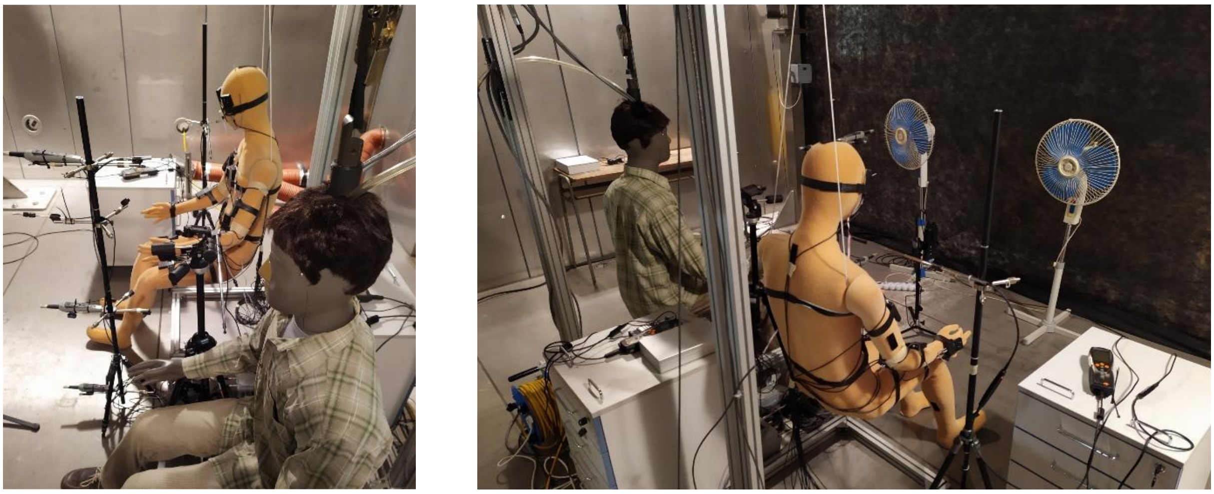
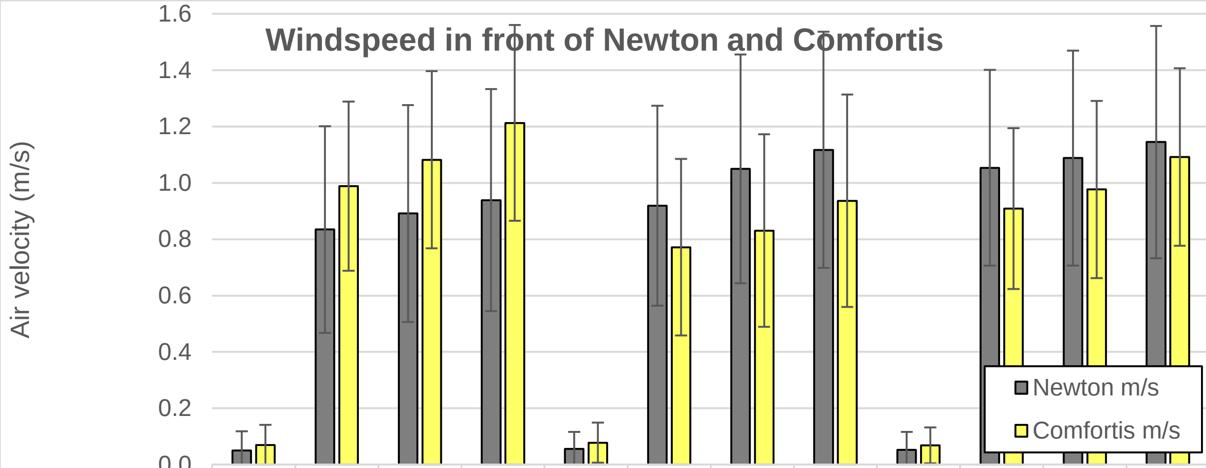


Figure 5.6 Photo documentation of the experiment.

In the Figure 5.8 can be seen the time chart for the Face with all 12 combinations of temperature and wind speed.

- 1st step – 34 °C wind lvl 1/2/3
- Temperature stabilization and no wind
- 2nd step – 24 °C wind lvl 1/2/3
- Temperature stabilization and no wind
- 3rd step – 14 °C wind lvl 1/2/3

From the results can be seen that the systems behave differently. Especially the Newton manikin was very sensitive to the low temperatures and higher wind speeds in comparison with other system Comfortis and iHVAC.



	No wind 34 °C	Wind lvl 1 34°C	Wind lvl 2 34°C	Wind lvl 3 34°C	No wind 24 °C	Wind lvl 1 24°C	Wind lvl 2 24°C	Wind lvl 3 24°C	No wind 14 °C	Wind lvl 1 14°C	Wind lvl 2 14°C	Wind lvl 3 14°C
Newton m/s	0.05	0.83	0.89	0.94	0.06	0.92	1.05	1.12	0.05	1.05	1.09	1.15
Comfortis m/s	0.07	0.99	1.08	1.21	0.08	0.77	0.83	0.94	0.07	0.91	0.98	1.09

Figure 5.7 Verification of the symmetry in the climate chamber in front of manikin Newton and Comfortis to check if the conditions are the same for both and thus results of EHT is comparable.

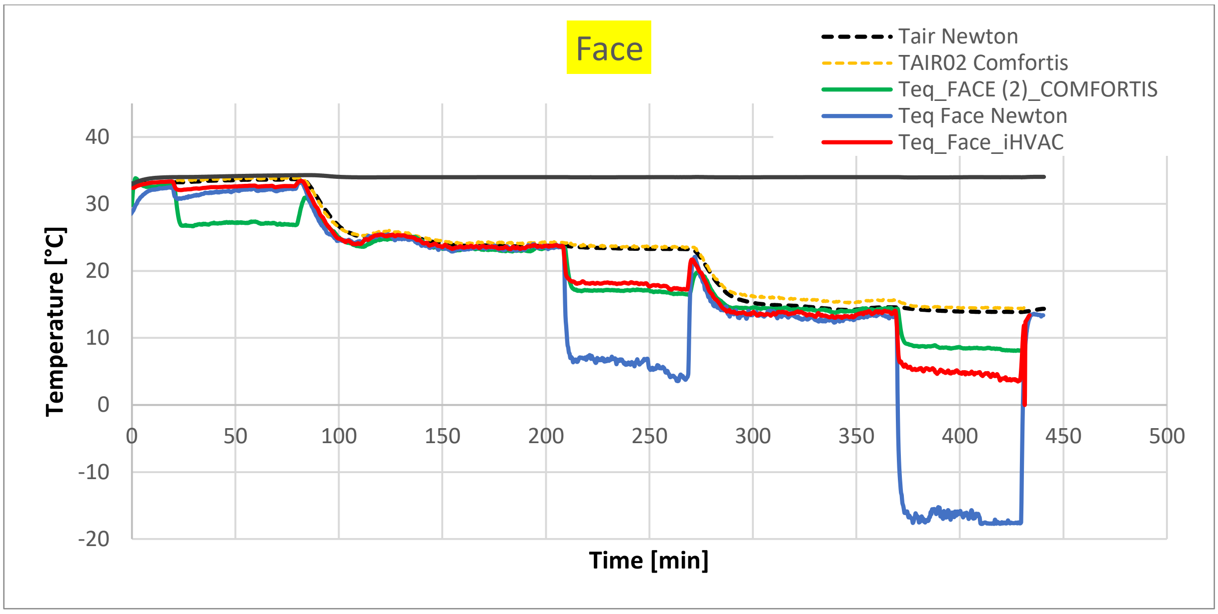


Figure 5.8 Results of wind test, which reveals different sensitivity to combination of wind speed and air temperatures.

<u>Summary</u>: In the wind conditions there exist different behaviour for constant temperature (CST) and constant heat flux mode with RST to decide which approach for EHT is more accurate → test of equivalence e.g. 1 m/s at 25 °C implies EHT=20 °C

5.2.2 T5 – Forced convection – CabinSim plan to test wind speed 0.1 – 2.5 m/s

The last fundamental test was to investigate for the same temperature inside the cabin mock-up the effect of different ventilation rates with added switch-on/off of the ventilation air heating. We tested flow rates form 30 m^3/h to 200 m^3/h through the vents in the dashboard of the cabin mock-up. We were focused on the evaluation of thermal comfort for the Face segment. The experimental setup is on the Figure 5.9. There is plot with comparison of the averaged velocity near the Face of Comfortis (co-driver) and Newton (driver). This plot proves the symmetry of air flow inside the cabin mock-up to have same effect on the Newton and Comfortis near their Faces. However, during the evaluation, see Figure 5.10 we found big differences between both systems when the wind speed became higher than 1 m/s.

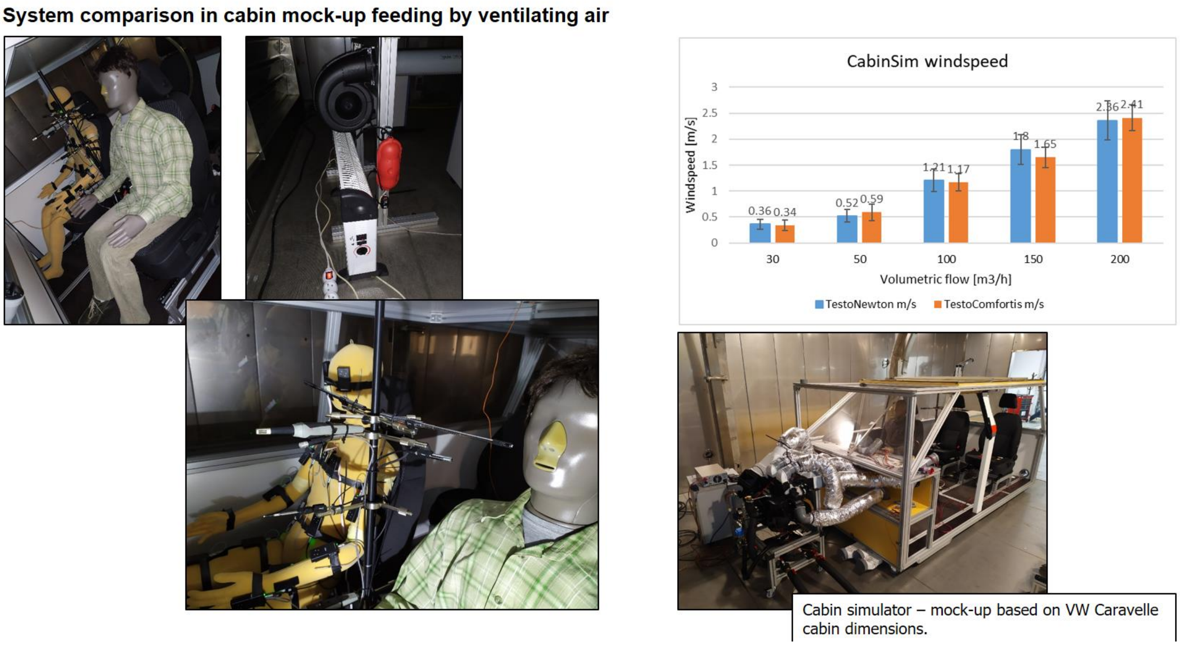


Figure 5.9 Test in car cabin mock-up with photos and the chart proving that the wind speed at co-driver and driver seat was the same.

At the first moment we were firstly confused from these results and we were not albe to consider which comfort system is showing right results and why they differ a lot for higher wind speed. To answer the question "What is wrong?" we needed post-processed all data measured till this moment from tests T1-T5. Based on these collected data it was possible to analyse and to carry out so-call test of equivalence to verified that EHT definition works well in case of Newton and Comfortis. We also revisited what was exactly written in Nilsson PhD thesis

> "*An **alternative method** for the determination of "equal thermal environments" is the RST or Resultant Surface Temperature and the associated "equivalent temperature" (Mayer et al., 1993).*

After the experiment T5 it was clear that **alternative method** does not mean implicitly to be **equivalent method** in meaning of obtained results. From the Figure 5.10 can be seen that manikin Newton with using of constant surface temperature seems to be too sensitive to higher windspeeds. We found that the power for heating the Newton manikin segment exceeds the expected production of real human by 3-4 times. This unrealistic high heat production we found is problematic when the EHT temperature is evaluated. It leads to equivalent temperature below 0 °C just due to the wind.

Summary: It was proved that Comfortis and Newton evaluated differently higher windspeed than approx. 1 m/s. It was not error of the EHT systems, but the feature of the usage CST with constant surface temperature mode vs RST with constant heat flux mode.

Figure 5.10 Results of the experiment

5.3 Test of Equivalence and interpretation of EHT

Based on the results from the wind tests especially T4, T5 we were additional data post-processing for all measured test T1-T5 to prove test of equivalence for thermal manikin Newton and Comfortis system, see Figure 5.11.

The idea is simple. For each system we collected already data about EHT for uniform steady environment (on the left side of the figure) and also for non-uniform (on the right side of the figure). We checked a set of data to find the same heat flux for non-uniform environment (wind) and then to find the same value of heat flux in the data about non-uniform environment (no wind). If this value in non-uniform environment give us a value of EHT, the value should correspond to the temperature of uniform environment. Surprisingly both systems proved this test of equivalence. So, the systems differing in the heat flux values in non-uniform environment (with wind), but the data were in both systems consistent with non-uniform data (heat flux and air temperature). Based on this it was not possible to answer the question which system is wrong. From this reason we added some advanced tests with the human subject the partly answer the question. The reason why we needed to the the human subjects test and also more considred about the treal human heat losses was the defntion of EHT. In the defiontion is not wrttien

*…in which a **sensor/manikin** has the same heat exchange…,*

but in the defiontion is wrttien

*…in which a **person** has the same heat exchange…*

see Figure 5.12, where is writeen whole defiintion)

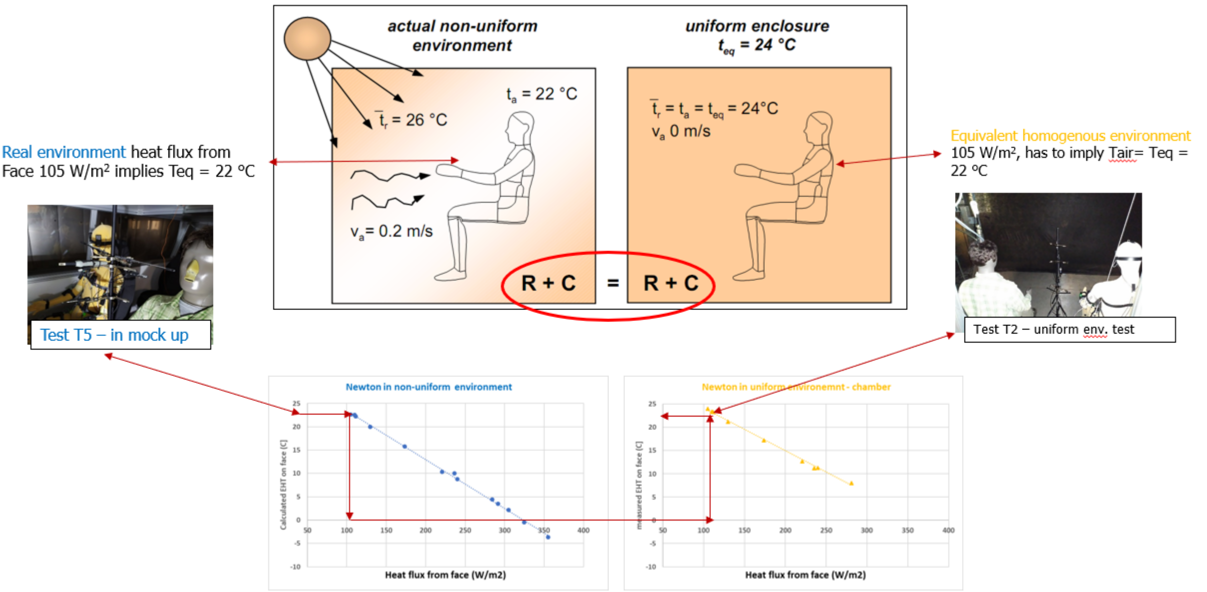


Figure 5.11 Test of equivalence proved that Comfortis and newton provides EHT temperature which corresponds to the same dry heat losses as in real no-uniform environment

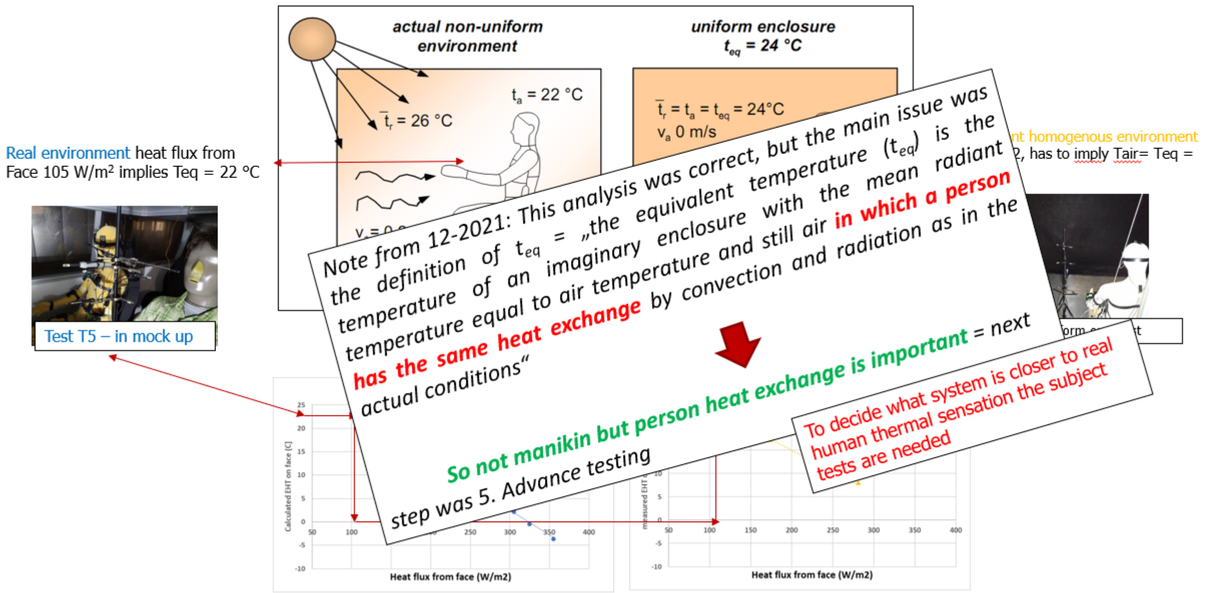


Figure 5.12 Revision of exact definition of EHT to explained why even the both systems fulfil test of equivalence give different results.

By the revision of exact definition of EHT we found that test of equivalence is necessary condition but not sufficient. Because the EHT systems should provide realistic heat fluxes close to the real person not just manikin or other EHT system. Which means that to decide which systems is right we need to perform human subject tests for given conditions. This was the conclusion of the pivot testing. We manage to operate different EHT systems and evaluate results, but for from the methodology was necessary to reveal which solution is more suitable for car cabin applications. Also, from this reason we designed advanced tests to more deeply investigate raised issues during work on the project.

6 Results of advanced testing

*Related to the **Activity 5** - Final definitions of test scenarios:*

- Test scenarios update based on pilot tests results and final definition of test

From the first pilot tests T1-T5 we found the different sensitivity to air flow especially higher than 1 m/s. From this reason we performed additional tests T6-T8 which focus on more practical aspects of using the EHT method. The goals of the advanced test are stated below.

Goal: 1. To check the effect of wind speed on Teq

- T6 – wind speed vs. different Teq system

Goal: 2. To evaluate effect of wind speed on thermal sensation on real human

- T7 – pilot human subjects test

Goal: 3. To test the different Teq system in real cabin under realistic conditions (Winter, Summer)

- T8 – car cabin tests AUTO 22 and same thermal comfort level

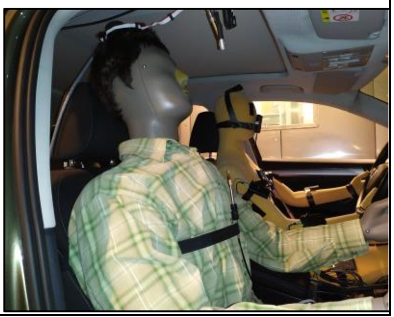
T6 – wind speed tests	**T7** – pilot human subjects tests	**T8** – pilot car tests AUTO 22 °C
		

Figure 6.1 Photo documentation for the test T6-T8

6.1 Advanced wind level tests

We added additional wind test T6 and T7 where we also investigated the thermal votes of test persons. For both tests we have not Comfortis system available. We focused mainly on the evaluation of the manikin Newton and iHVAC how they react to the wind.

6.1.1 T6 – wind speed vs. different Teq system

We investigated effect of different wind speeds from almost 0, 0.65, 1.0, 1.2, 1.65, 1.85 to 2.48 m/s. At ambient temperature of air T_Amb = 22 °C. The iHVAC system and thermal manikin Newton were used. On the Figure 6.2. can be seen the experimental setup in the climate chamber and on the Figure 6.3 are results for Newton manikin and iHVAC sensors. The Newton manikin was again the most sensitive to the wind as was in the test T5, but we also found differences between boxed and unboxed sensors of iHVAC, which we actually were expecting. The sensor 44 was boxed and the values could be comparable to the what we could expected from the Comfortis systems.

Unboxed iHVAC even it was all running on the constant surface temperature mode and theses sensor were a little bit closer to the newton manikin.

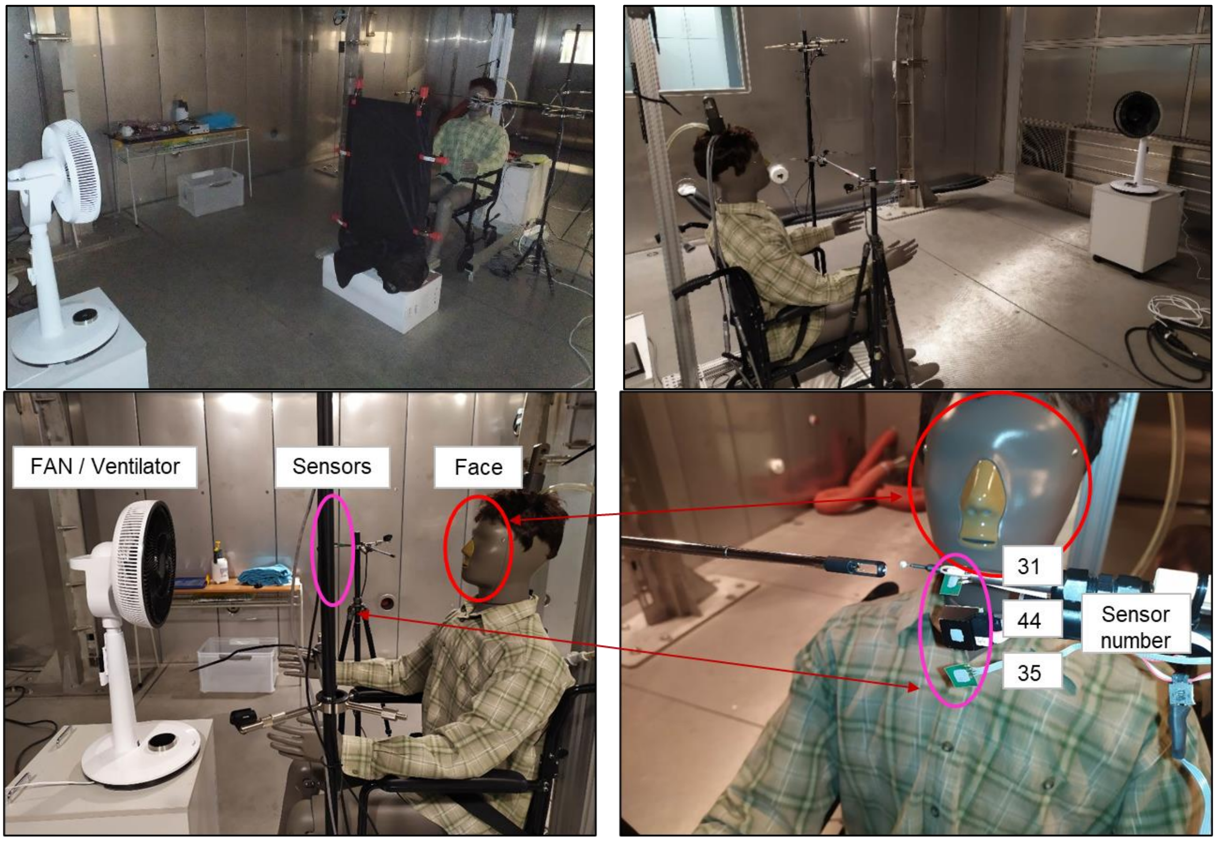


Figure 6.2 Wind level tests, Photo documentation of the experiment (a) setup to stabilized air flow near the manikin by using black blanket reducing air speed to the minimal value. (b) The setup for adjustment standard velocities. (c) Setup for to obtain maximum wind speed, with the probe placement. (d) Placement probes in detail.

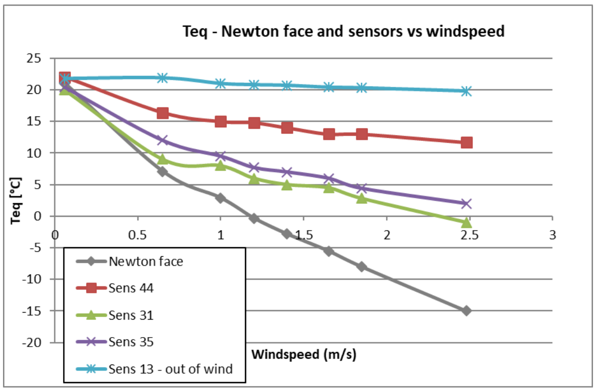


Figure 6.3 Sensitivity of iHVAC probes a thermal manikin Newton to the wind speed.

Based on these results we stated the hypothesis that with higher heat fluxes generated by the sensor which are above the human production limit the EHT start to be unrealistic and not correspond to the human thermal votes as it was in case when the heat fluxes are limited to some maximal level of heating. As was said thermal manikin Newton allow to produced 500 W/m2 which is almost 5x higher that can be expected in situation of the sitting person.

Summary: The results show the same discrepancies between systems as in test T5. We established basic hypothesis, which we were trying to verify in test T7 with human subjects.

6.1.2 T7 – pilot human subjects test

We repeated the test T6 with the small group of people (3 man) to identify, which system reaction to the wind is more realistic in comparison with human face. In the Figure 6.4 is the photo documentation of the experiment with thermal manikin and real human. In the same figure (plots on the left) are also relation between heat flux and MTV and Teq for manikin and human.

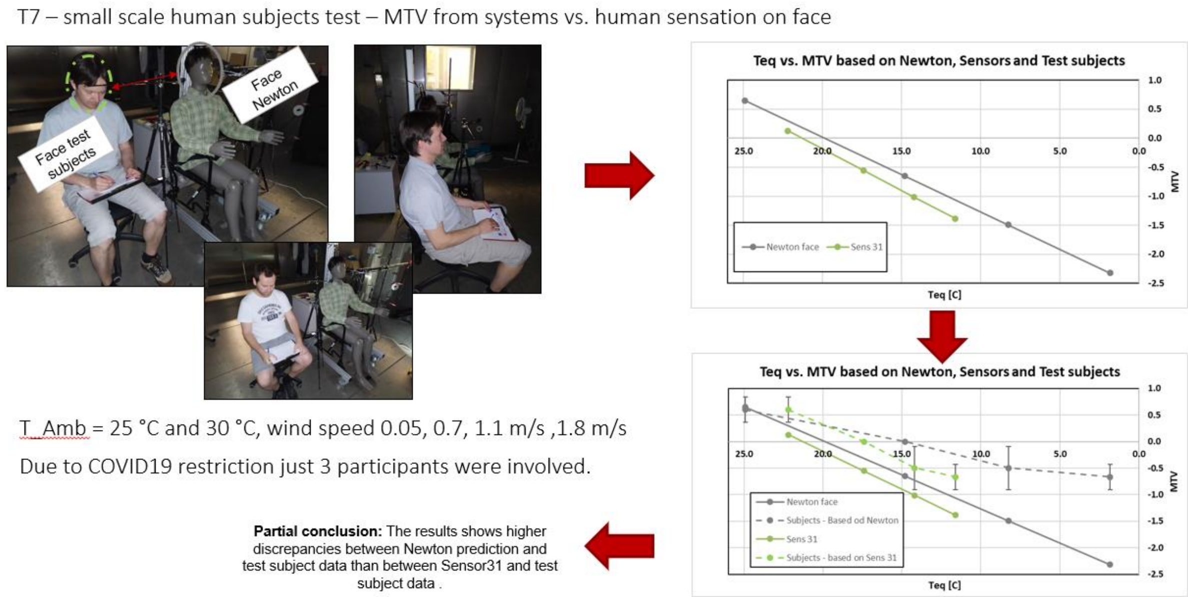


Figure 6.4 Photo documentation for the test T7 with the plot of MTV (human) versus MTV based on Teq from Newton and iHVAC on Face.

The Figure 6.5 presents dependency of the wind speed on the final Teq and MTV with added thermal votes form test subject (red squares).

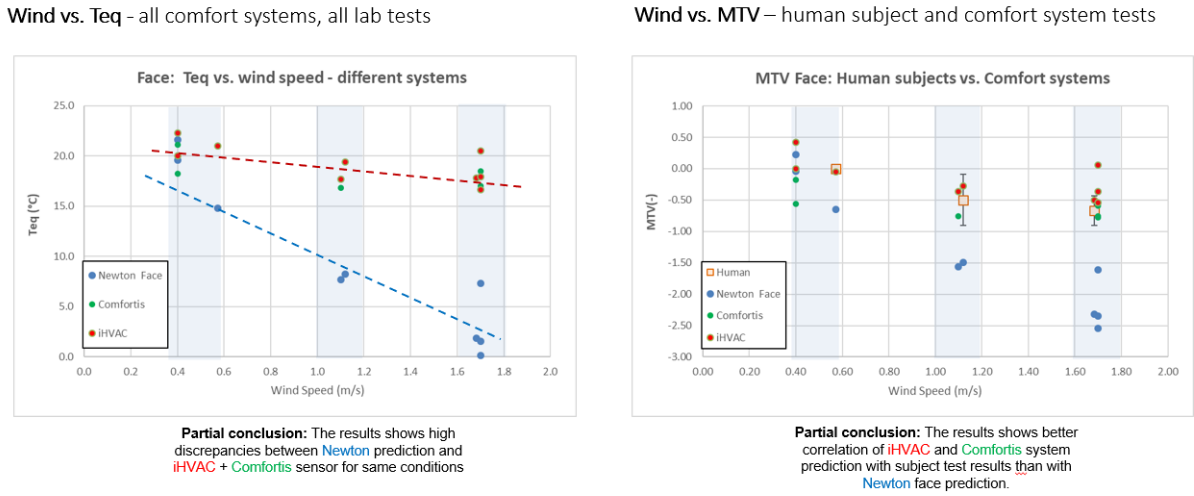


Figure 6.5 T7-all results with human subject tests compared with iHVAC, Comfortis and Newton.

From the plot on the right where the human subject data are plotted can be concluded that in windy conditions the Comfortis and iHVAC have better agreement with human subjects than thermal manikin Newton. To confirm the hypothesis stated in the previous test T6 we needed to evaluate the heat fluxes from all comfort systems to check their value against standard human heat load for sitting person 100-180 W (approx. 1-1.6 met).

By combing the winter and summer tests together we obtained very important plot on Figure 6.6. It can be seen that here is no problem in environment with temperatures above 20 °C, but below this temperate the thermal sensation starts to be different for Newton (the grey line) and human (the green dashed line). When Newton measured heat flux below 100 W/m^2 the MTV of Newton and test person was quite the same between 0 – 0.5 on the sensation/comfort scale. If we look in the plot to the left, it can be see that below 10 °C is the "Newton prediction" (grey line) too far from the reality (green dashed line). When the Newton had 300 W/m^2 it predicts MTV=-2.2 instead of real human -0.7.We revealed the behaviour of sensors/manikin and real human how they react to the wind. It can be seen that comfort systems fit the human subjects in warm condition well, but in cold conditions the manikin the Newton is too sensitive to the cold.

Based on this result we propose to use comfort balancing mode as the criteria for manikin surface temperature to fulfil the definition of EHT in the cold and wind. The Newton manikin reacts to the wind too much sensitively, because the thermal manikin Newton keeps 34 °C with the higher heat flux than in case of real human.

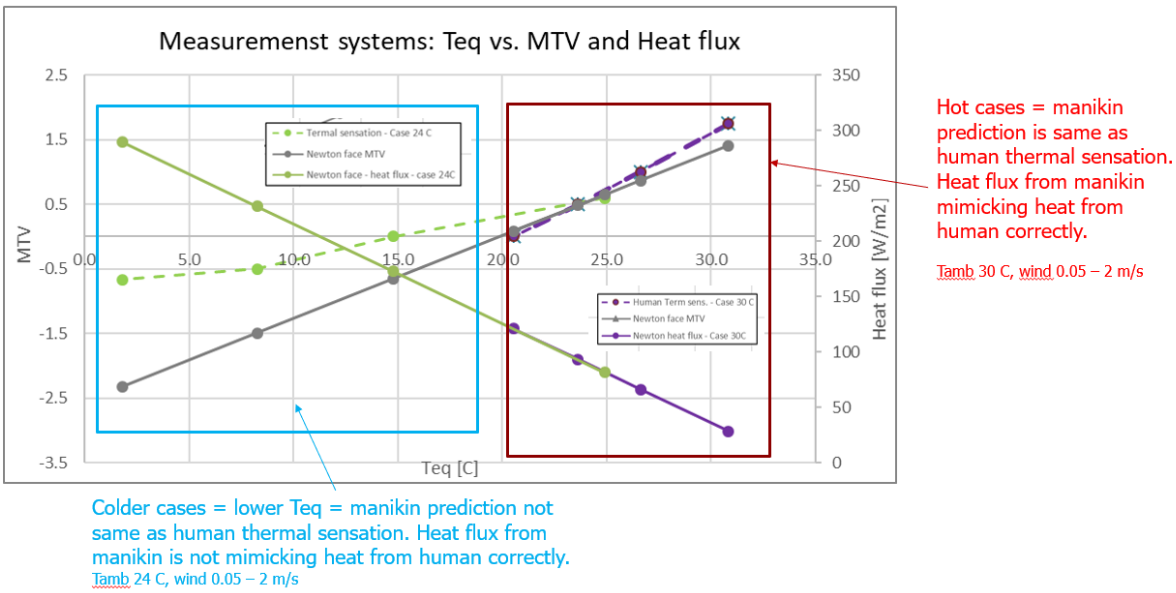


Figure 6.6 T7-all results for Winter and Summer conditions with comfort system and human subjects.

<u>Summary</u>: Thermal manikin Newton has tendency to overestimate effect of the wind in cold environment, because it is able to heat much more than real person. From this reason we recommend for such type of condition give some maximum heat production limit, this approach is actually close to the comfort balancing mode which is also option

to use. The disadvantage is that this mode can be setup differently, there is no standard way how to do that.

6.2 Tests with real cars in climate chamber

Based on the all of test T1-T7 we found some strength and weaknesses of different EHT system or system using RST in laboratory conditions. The last step was to prove the method how it will work in the real cabin. It does not mean that we performed real driving tests, but we did the measurement with car in our climate chamber. We were limited by the fact that car engines had to be in idling mode, but in the case of EV this is not such big issue as it can be in case of cars with ICE. For this final test we had again available all comfort systems: Comfortis system, Newton and iHVAC. Newton manikin and some additional temperature, RH and air velocity sensors. Moreover, we were connected to the CAN unit of each car to follow some temperatures at inlets, and other parameters related to the thermal management of vehicles/batteries in case of EV/PHEV (as power or fuel consumption etc.)

6.2.1 T8 – car cabin tests AUTO 22 and same thermal comfort level

The aim of these tests was to identify: “What are the differences between evaluation of thermal comfort by different EHT systems in real cabins of different cars?” As the benchmark test we used in each car automatic mode for the HVAC system with standard settings „AUTO 22“. The conditions for the tests were following: Own measurement procedure took 1 hour; manikins and probes were at driver/co-driver seat. We investigated two seasonal conditions: winter and summer.

In **Winter** test cases **(-5 °C, 0 W/m^2)** it was necessary pre-cooling of 8 hours. So, each car started with the interior protocoled to temperature of – 5°C. and during one hour the cabin was stabilized on some thermal comfort level. At the end of the stabilization we evaluate a thermal comfort for Comfortis and Newton.

In **Summer** test cases **(+30 °C, 800 W/m^2, RH 50%)** the pre-heating was 5 hours without Solar lamps. The lamps were switch on just at the start of the procedure so we did not simulate the situation when the car is parking long-time on the sun. The reason was the fact that manikin Newton controlled by surface temperature mode has no possibility to cool down actively, which means that the system would be overheating and will not operate form the beginning of the test, because it is not possible to evaluate temperatures till the manikin is not cooled down by ambient environment. In contrary the Comfortis using RST is avoiding these problems because it keeps and offset on the surface temperature. The disadvantage is that the surface temperature can be 40-50 °C which is unrealistic in case of human. This can be acceptable just in case of small sensor but nor for the whole manikin.

The HVAC was powered by electricity from batteries in case of EV/PHEV. In case of ICE the HVAC was powered by engine, which was always just idling due the BUT climate chamber construction not allows the operate engine under the load.

Important setup: outlets/vents always set to centre - centre. The definition of the climatic conditions as temperature were done in agreement with RDE test specification minimum -5 °C to maximum +30 °C. RDE for mild conditions is defined from 0 °C till + 30 °C for altitude up to 700 m asl and max. temp. range is from -7 °C till +35 °C for altitude up to 1300 m asl.

Figure 6.7 Photo documentation all results for Winter and Summer conditions with comfort system and human subjects.

We investigated altogether four different cars: three form Škoda brand with claasical ICE, Plug-in and BEV and one Hyundai EV, see Figure 6.8. Each car was prepared for the test to have full charged batteries. In case of ICE we had to pay attention to exhaust gas which always need to be push out from the chamber. In case of PHEV this "fresh air system" was setup just for sure, because we tried to operate this vehicle in electric mode also as much as possible.

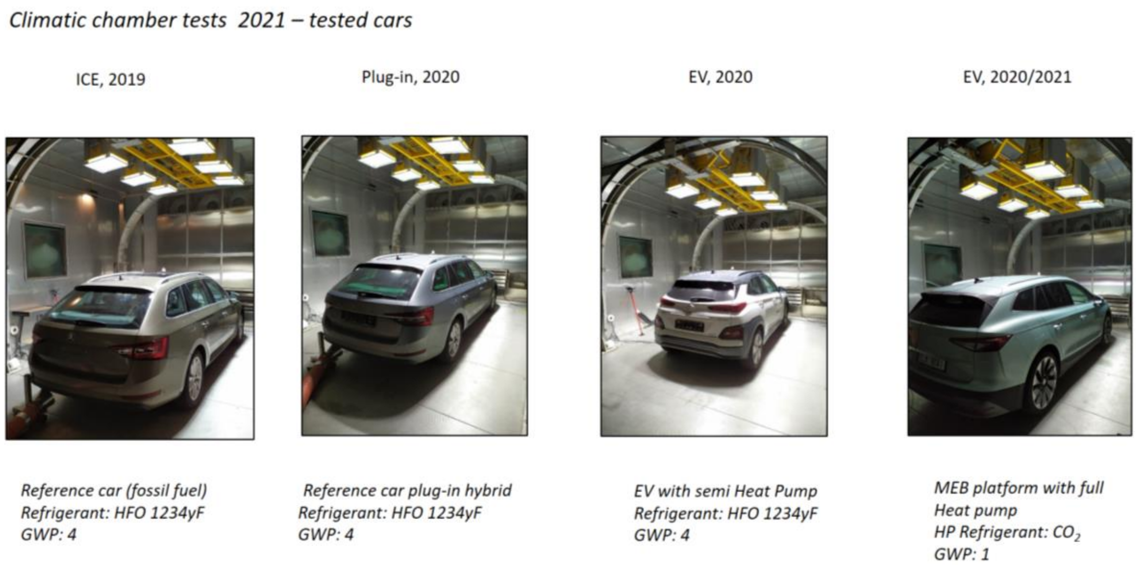
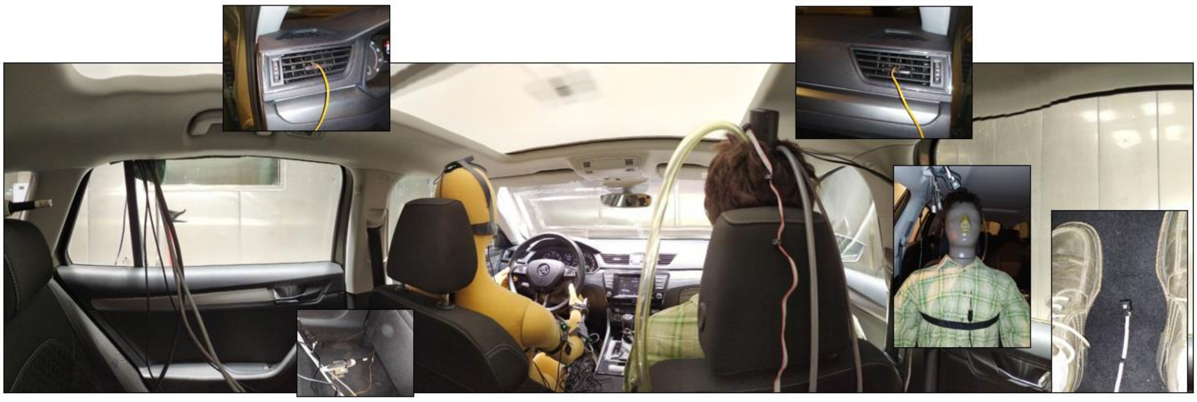


Figure 6.8 Photo documentation of the cars used for the testing

In the Figure 6.9 can be seen the experimental setup by panoramic view to the interior and in the Figure 6.10. are images from the end of experiment when we always each car photo documented by using infra-red camera Flir-i7. It can be nicely seeing the hot dashboard and even hotter the glass roof, which in sunny weather really can increase the thermal load going into the cabin and also can affect negatively the thermal comfort.



Teq measurement: *Newton (VUT), Comfortis (Škoda) a sensor iHVAC (VUT)*
HVAC: *air temp. measured in right and left outlet of dashboard*
Cabin space: *sensors Newton (2 x t, RH, w_a), sensors Comfortis (16 x t), and system Testo on the rear seat and driver seat (2 x t+RH, w_a)*
Surface temperatures: *IR camera Flir i7*
Data about energy consumption: *Škoda – reading OBD, Hyundai – display monitoring + OBD*

Figure 6.9 Photo documentation of experimental setup inside car cabin

Figure 6.10 IR photo documentation during experiments to identify surfaces radiant temperature.

<u>Summary</u>: we investigated the real car cabin environments for summer and winter season and compare the indoor microclimate in car cabin by using thermal manikin temperature, RH and windspeed probes. Also, the IR camera was used as indicator of heat transfer

6.3 Final methodology (demonstrated on test T8)

On the collected set of data form T8 we would like to demonstrate how the evaluation of thermal comfort looks like practically.

6.3.1 Comfort zones diagrams (Winter/Summer)

In this subchapter there are all results measured by thermal manikin Newton and evaluated thermal comfort by Comfort Zones Diagram and EHT similarly to the ISO 14505-2. On the Figure 6.11, there are results from winter season conditions for all cars and one additional scenario AUTO 24°C in case of Hyundai EV. In the Figure 6.12 there are results from the summer season conditions also with additional scenario with setup Hyundai EV to ATUO 24 °C.

Due to the limited capacity in the climate chamber the summer and winter test were performed in row, which is reason why for the summer test case the same clothing as in winter were used (shirt with T-shirt, trousers and boots, see Figure 6.11). The changing of the clothing on the manikin requires manipulation outside the car which means that experimental setup would be necessary to repeat twice instead of just on installation for one car. Typically, in summer clothing the AUTO 22 °C can be to low temperature avoiding to cold sensation when the shorts and short sleeves T-shirt with sandals is used.

It means that for summer conditions the thermal votes were higher because of the manikin had warmer clothing than is typical for summer season. In case of iHVAC and Comfortis this is possible setup just as some value. In case of thermal manikin, the clothing is part of the measurement and had to be changed physically, which requires to put manikin out of car, change clothes and sit him back.

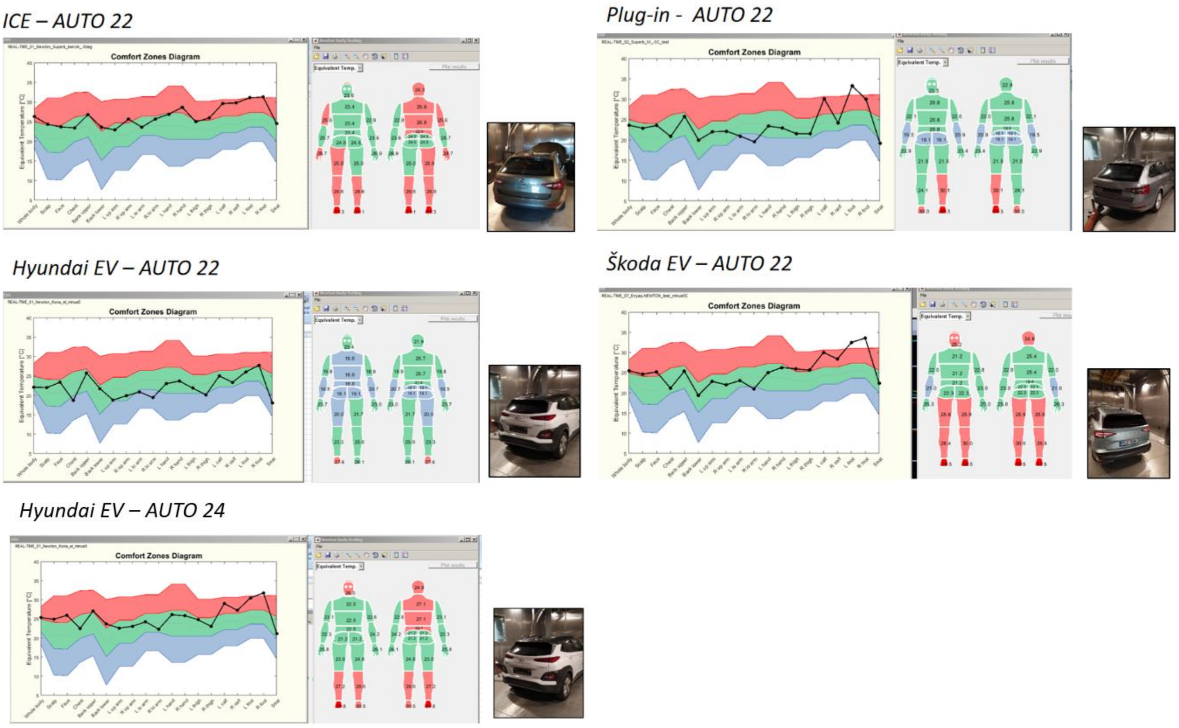


Figure 6.11 Comfort zones diagram and EHT (black curve and values visualized on the figurine) for Winter conditions

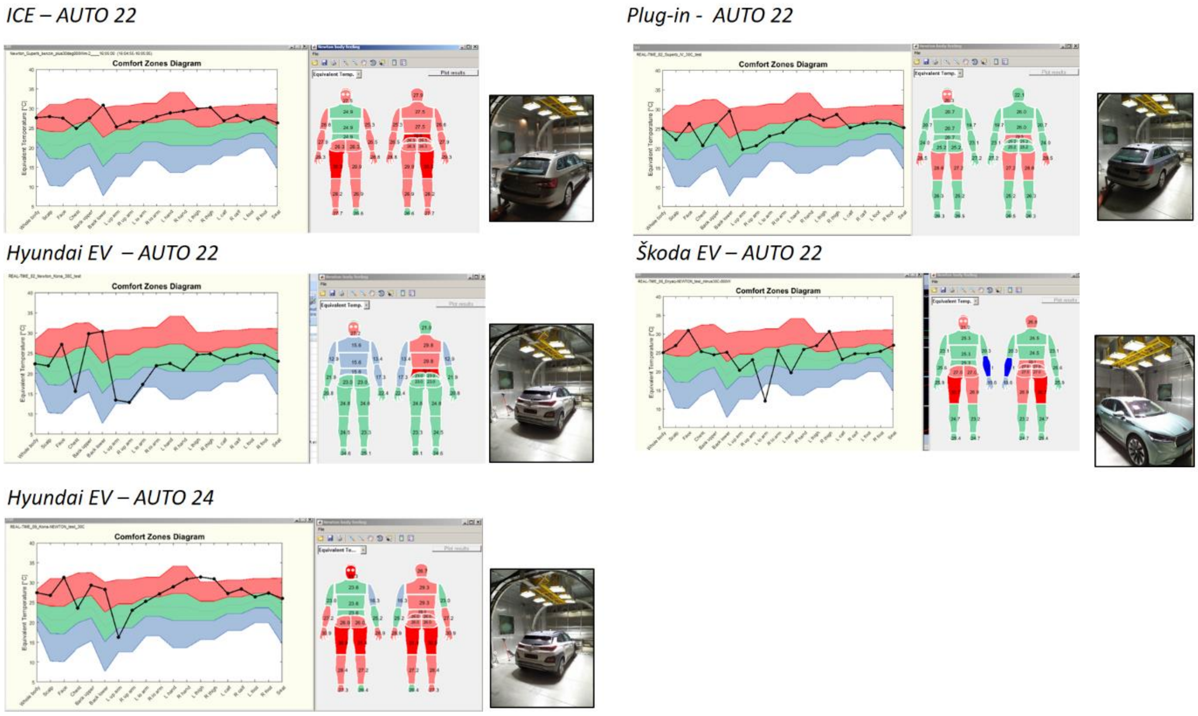


Figure 6.12 Comfort zones diagram and EHT (black curve and values visualized on the figurine) for Summer conditions

6.3.2 Final comparison of different comfort systems and cars

Based on the methodology presented in previous chapters we compared four types of cars with different powertrain systems, see Figure 6.8: 1) Škoda with ICE, PHEV and full EV powertrain, and Hyundai full EV. In the Figure 6.13 are all compared all investigated EHT system for all cars during winter/summer season. All cars had setup AUTO 22°C, just in case of Hyundai EV was evaluated also setup for AUTO 24 °C. From the results can be seen that Comfortis and Newton system in Summer/Winter season give the similar results after the stabilization at the end in the Face segment. We evaluated the Face segment due to it has significant influence on the overall comfort in the car. The air velocities are up 0.43 m/s which is still in the range when the different between the methods is no significant also thanks to the quite neutral temperatures.

The next plots on Figure 6.14 express the dependency of Teq on air temperature. In uniform environment should be Teq and Tamb the same (see identity line in the plot). In the winter the Teq is below the “identity line” which means that the Teq is reduced by radiation from cooler surfaces of windows. In the Summer Teq is influenced by slightly higher airflow, but there can be see larger differences between the system how it reacts to the solar radiation. The reason is that the probes are very dependent on the orientation and the solar radiation caused asymmetric heat load. In contrary the thermal manikin uses for the evaluation of Teq the whole its surface which means that integrates asymmetric load and reacts in better way to the solar radiation.

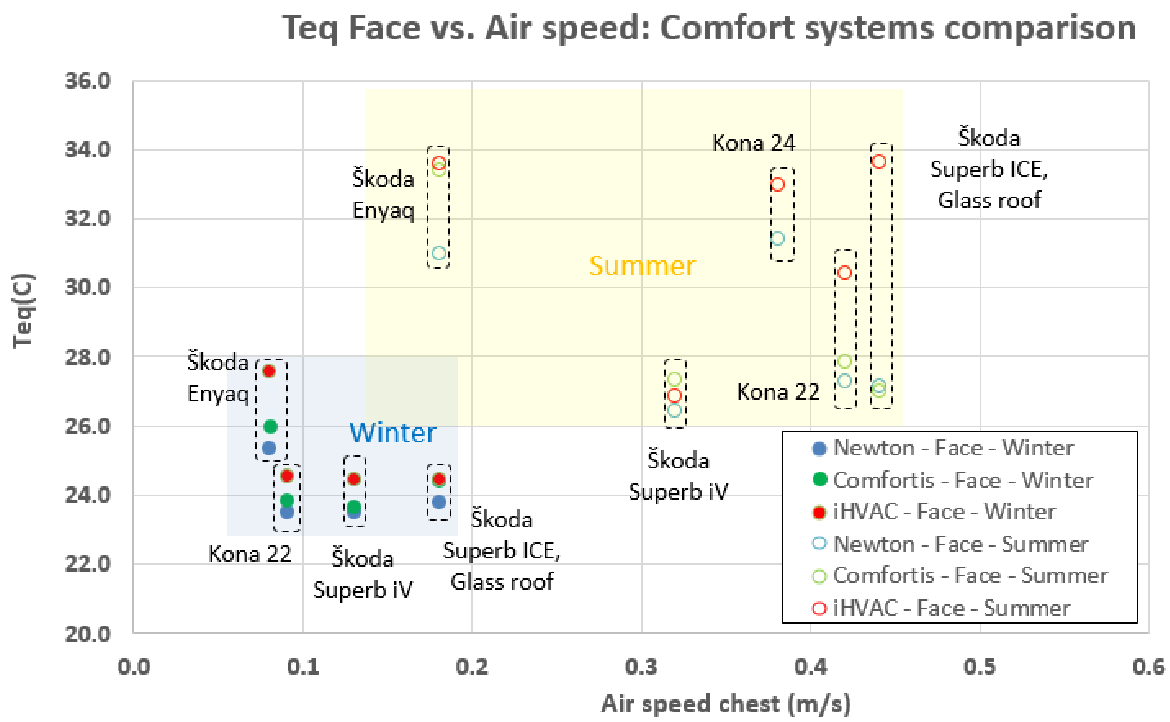
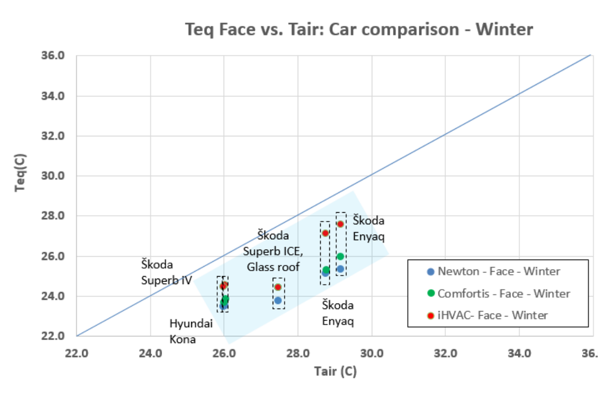
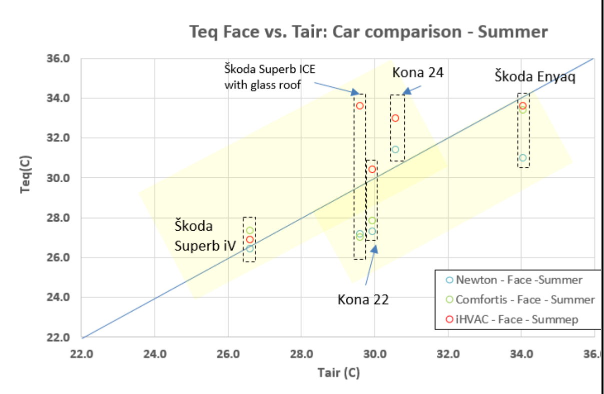


Figure 6.13 Equivalent temperature as function of wind speed for different types of sensors and cars





Partial conclusion: In winter cases Teq is lower than Tair in all measured cabins. Probably effect of "cold radiation" from windows. Results from all systems is very similar (max. discrepancy 2 °C in Enyaq)	Partial conclusion: In summer cases Teq and Tair are spread around temperature identity line. No clear correlation was observed. Systems reported different results (see Superb ICE)

Figure 6.14 Equivalent temperature as function of air temperature for different types of sensors and cars. The line denotes points where the equivalent temperature is the same as air temperature.

All test cases from Figure 6.14 are plotted in 3D graph in Figure 6.15, where the 3rd axis is the air velocity w [m/s].

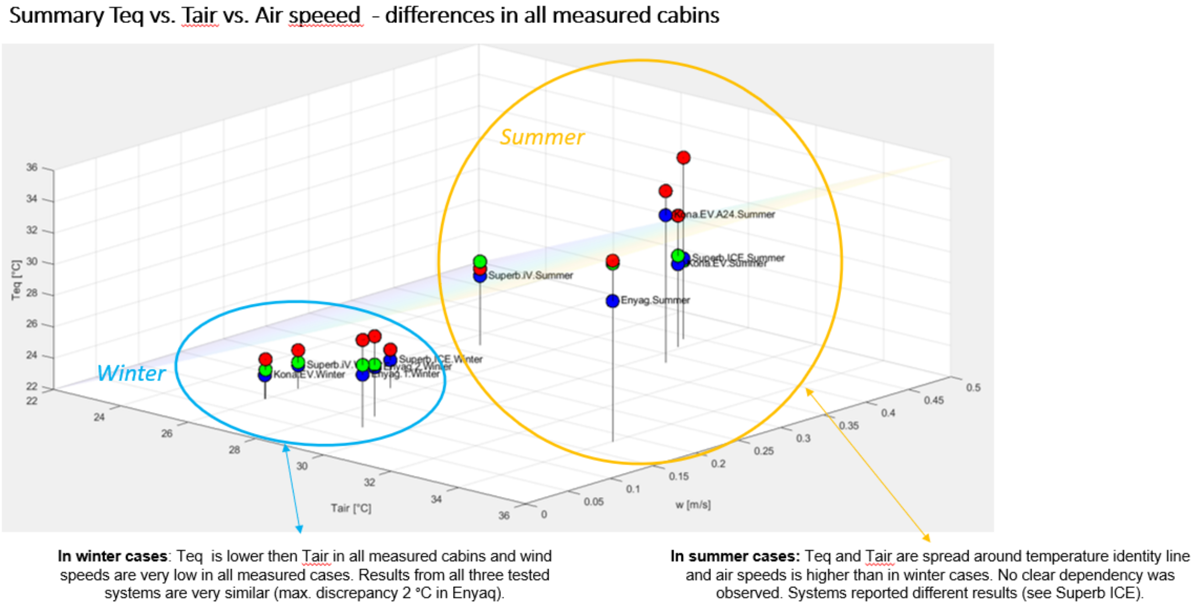


Figure 6.15 3D plot combining both previous figures together, the coloured plane is again the set of points where the equivalent temperature is the same as air temperature.

Based on this plot can be the difference between the seasons cars and used comfort system.

It can be concluded that in the test case investigated in T8 on the setup of car for some comfort level the differences between the systems are not so dramatically as in laboratory tests because the air velocity inside the cabin around the manikin is much lower than 1 m/s except some transient states at beginning where the car is pre-cooled. These comfort systems provide additional information which it is not possible obtain by just measuring of the temperature.

7 Discussion

We tried to fulfil all planned activity and added some practical information about the real evaluation of thermal comfort in real cars. In the next lines are checked all important points to be met with some additional information.

7.1 Summary

- The first pilot tests were evaluated in 2020, due to the Covid simulation the project was finished in 2021 and reported in 2022.
- RST with constant heat flux and CST with constant surface temperature were investigated and results of EHT were compared.
- The system Comfortis (RST) x Newton (CST) x iHVAC (CST) were used for pilot testing.
- Advanced testing was done in 2021 to fulfill the 2nd part of the project:
  A) to compare thermal sensation: method of equivalent temperature vs. human subject votes;
  B) to test the methodology on the real car cabins including one care with fossil fuels engines, two cars with full EV and PHEV.

Issues and questions arise during first half of the project were:

- Issue: Theoretically should be possible recalculate MTV from iHVAC to Newton manikin (there is different Rair on face).

  ✔ Yes, it is.
- In the cabin mock-up testing with Newton manikin on driver and also co-driver seat is necessary to avoid effect of asymmetry of environment in the mock-up. To verify this the air velocity w_{air}, air temperature T_{air} and equivalent temperature will be monitored.

  ✔Tested in real cabins Comfortis as driver, Newton/iHVAC as co-driver
- Test with volunteers will be better a random order of flow rates, to ensure that test person will not know actual flow rate

  ✔Yes, we performed test in this way to avoid the human expectations which can strongly influence the final thermal comfort vote. Also, human feel differences more step-wise (ASHRAE 7-point to 9-point scale is sufficient) than the probes which provide continuous information.
- Minimalist variant is a test just with people to obtain regression (T_{air}, w_{air} vs thermal sensation/comfort). ,

  ✔We did this regression

and vision for the ongoing research not just applied but even fundamental.

- If the project will last longer, would be possible to analyse more deeply database from the project, especially for the Face segemnt, which is more exposed to the car environment (not dressed, close to the vents).

  ✔ At the moment we just evaluated Face for summer and winter situations in real cabin, the typical air flow around Face differs

8 Conclusion

Based on this experimental investigation of thermal comfort systems we proposed the testing procedure how it can be possible to evaluate effect of HVAC on the overall power consumption of EV which is important with respect to the driving range of these EVs. We tested more comfort measurement systems to compare them in laboratory basic test cases and also more advanced tests as was the testing of real cars with different powertrain systems.

8.1 Main observation and conclusion from the project

1) The thermal comfort systems Comfortis, Newton, iHVAC are similarly sensitive to the change of air temperature.
2) In combination with the wind speed, the manikin Newton differs from thermal sensation of test subject, mainly for higher velocities than 0.6 m/s. This is caused by the fact that Manikin setup in CST mode produces unrealistic heating power to keep set surface temperature 34 °C. This heat flux is not related to the situation on the real human, where the surface of the skin dropped due to vasoconstriction and heat flux is not raising so steep. To avoid this we suggested „comfort balance mode“ to regulate temperature of the manikin to be more realistic and similar to temperature of human skin.
3) Small sensor in cold environment has not this issue because they don’t produce such much heating power.
4) This was confirmed by human subject tests, that manikin Newton overestimated cold sensation in such conditions
5) Based on the real tests in car cabin we found that most of the issues mentioned above are not problem in car cabin environment – mild temperature close to the neutral, lower velocities (measured on the chest) 0.1 m/s (winter), 0.4 m/s (summer)
6) The benefit of Teq is not just effect of windspeed but also by radiation (winter cases).
7) The human body shape of manikin and its placement on the car seat eliminate possible problems is probably more accurate than the local probes. Local probes are very sensitive to „specific placement“, and it is more possibilities to misinterpreted objective situation, mainly in RDE tests.
8) We found significant differences between the cars from different brands when the HVAC was set to AUTO 22 case.

8.2 Issues related to the project

1) Real placement of the probes in car in RDE test.
2) Definition of the proper clothing, at the moment in 14505-2 are just diagrams (CZD) for winter and summer clothing.
3) Apply different HVAC automatic control: AUTO 22 °C for winter, AUTO 24 °C for summer?

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List of Figures

List of Tables

Abbreviations

AC/HP	Air Conditioner/Heat Pump
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
AVG	Average
BUT	Brno University of Technology
CAN	Controller Area Network
CHF	Constant Heat Flux
CST	Constant Surface Temperature
CZD	Comfort Zones Diagram
DIN EN ISO	Deutsches Institut fur Normung; Europaische Norm; International Standardization Organization
EHT	Equivalent Homogenous Temperature (synonymous to equivalent temperature which can be noted as teq or Teq)
EMC	Electromagnetic Compatibility
EMPA	Eidgenössische Materialprüfungs und Forschungsanstalt (Swiss Federal Laboratories for Materials Science and Technology)
ET*	Effective Temperature
EV	Electric Vehicles
HVAC	Heating, Ventilation, Air-conditioning
ICE	Internal Combustion Engine
iHVAC	Innovative Sensor for HVAC
IR	Infra-red
LMV	Local Mean Vote
M	Metabolic Rate
MTV	Mean Thermal Vote
MRT	Mean Radiant Temperature
NEDC	New European Driving Cycle
OBD	On-board Diagnostics
PHEV	Plug-in Hybrid Electric Vehicle
RDE	Real Drive Emission
RH	Relative Humidity
RST	Resultant Surface Temperature
SAE	Society of Automotive Engineers
SD	Standard deviations
SET*	Standard Effective Temperature
WBGT	Wet Bulb Globe Temperature
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
VDA-FAT	Verband der Automobilindustrie - Forschungsvereinigung Automobiltechnik

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Verband der Automobilindustrie e.V. (VDA)
Behrenstraße 35, 10117 Berlin
www.vda.de
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Forschungsvereinigung Automobiltechnik e.V. (FAT)
Behrenstraße 35, 10117 Berlin
www.vda.de/fat

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