Project Title:

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

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Publishable Executive Summary

QUIET aims at developing an improved and energy efficient electric vehicle with increased driving range under real world driving conditions. This was achieved by exploiting the synergies of a technology portfolio in the areas of user centric design with enhanced passenger comfort and safety, lightweight materials with enhanced thermal insulation properties and optimised vehicle energy management. In WP5 the results of the technology development work packages WP2, WP3 and WP4 merge together to create the QUIET demonstrator vehicle. JRC carried out the test of the demonstrator vehicle after the integration of all the innovative developed components in its Vehicle Emission Laboratories (VELA) in Ispra (Italy). The electric vehicle performance in terms of energy consumption, efficiency and driving range has been verified under different working conditions and driving cycles, as defined in QUIET project Task 1.1, together with the project partners. JRC contributed to the instrumentation of the vehicles with sensors and other equipment, in order to perform accurate and reliable measurements of advanced vehicle energy efficiency and consumption under different vehicle operating conditions. Other monitoring systems were installed by the project partners. JRC ensured also the proper installation of the vehicle on the roller-bench of the laboratory and the configuration of the testing cell to perform the tests. AIT, HRE, AVL/DE supported JRC during the testing of the vehicle on the test bed.

The results showed that the developed technologies integrated and qualified in a Honda B-segment electric vehicle validator enable a reduction in energy needed for heating and cooling the cabin of the electric vehicle under different driving conditions by approximately 12-14% compared to the Honda baseline 2017. Additionally, a weight reduction of about 28% of vehicle components (e.g. doors, glazing, seats, heating and air conditioning) was achieved resulting in a total 5% vehicle weight reduction. These efforts lead to approximately 26% driving range increase under cold (-10 °C) weather conditions and to approximately the same driving range in hot (+40 °C) weather conditions.

To evaluate the thermal comfort and the usability of the novel HVAC HMI prototype of the QUIET demonstrator, a final user study was conducted. Comparable to the perceived thermal comfort of the FIT EV after the usage of the HVAC system, also the QUIET demonstrator was perceived as “comfortable” and “acceptable” in both, the winter and summer conditions. Although the thermal comfort was not considered as discomfortable according to the ISO standard, users felt significantly colder in the QUIET demonstrator compared to the original FIT EV after the usage of the HVAC system in the winter condition. It can be concluded that the target temperature of HVAC heating strategy for the QUIET demonstrator needs to be increased slightly to fit the thermal comfort of the user even better. Regarding humidity and air flow no significant differences were found in the winter and summer condition for the QUIET demonstrator and the original FIT EV but the intensity of the air flow would need some slight improvements especially for the QUIET demonstrator as it was rated as “too breezy”. Overall, no significant difference was found regarding the overall thermal comfort preference for the QUIET demonstrator in comparison to the original FIT EV hence a slight increase of the target temperature in winter and slight decrease of the air flow intensity should be sufficient. The overall subjective usability based on the System Usability Scale (SUS) was rated as lower for the QUIET HVAC HMI compared to the FIT EV HMI but can still be regarded as “ok”. Although the usability issues negatively impact the usage of the QUIET HMI, it has potential to better support the user with an energy efficient usage of the HVAC system in comparison to the conventional HMI.

The broader public highlighting improvements on energy consumption, driving range, thermal comfort, user interfaces and the assessment of technology transfer from B to A, C and D-segment vehicles are also presented. AIT and ATT supported HRE during the test of the user-centric design and thermal comfort, while the technology transfer was carried out by HRE, AIT and UOZ.

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Abbreviations and Nomenclature

Table 1: List of Abbreviations and Nomenclature.

Symbol or Shortname	Description
AC	Alternating Current
BEV	Battery EV
CCT	Consecutive Cycle Test
EM	Electric Motor
EV	Electric Vehicle
HMI	Human-Machine Interface
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
MAC	Mobile Air-Conditioning
Ndis	Number of discomfort ratings
REESS	Rechargeable Electric Energy Storage System
SD	Semantic Differential
SOC	State of Charge
STP	Shorten Test Procedure
SUS	System Usability Scale
SUV	Sport Utility Vehicle
UBE	Usable Battery Energy
WLTC	World-wide harmonized Light vehicles Test Cycle
WP	Work Package

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1. Introduction

QUIET aims at developing an improved and energy efficient electric vehicle with increased driving range under real world driving conditions. This was achieved by exploiting the synergies of a technology portfolio in the areas of user centric design with enhanced passenger comfort and safety (Figure 1, AREA I), lightweight materials with enhanced thermal insulation properties (Figure 1, AREA II), and optimised vehicle energy management (Figure 1, AREA III). A novel refrigerant for cooling, combined with an energy-saving heat pump operation for heating, advanced thermal storages based on phase change materials, power films for infrared radiative heating, and materials for enhanced thermal insulation of the cabin were investigated to this purpose. Further focus was on lightweight glasses and composites for windows and closures, as well as light metal aluminium or magnesium seat components. Optimised energy management strategies, such as pre-conditioning and zonal cooling/heating the passenger cabin and user-centric designed cooling/heating modules further enhance the thermal performance of the vehicle. These strategies were implemented in a vehicle control unit enhanced by a novel Human-Machine Interface (HMI), which, beyond being intuitive and user friendly, also consider diverse users' needs, accounting for gender and ageing society aspects.

The developed technologies were integrated and qualified in a Honda B-segment electric vehicle validator enabling a reduction in energy needed for cooling and heating the cabin of an electric vehicle under different driving conditions.

In WP5 the results of the technology development work packages WP2, WP3 and WP4 merge together to create the QUIET demonstrator vehicle to be tested in its overall performance under different ambient temperatures. Moreover, an assessment of the thermal comfort and user-interfaces and of the impact of the developed solutions in the A, C and D-segment vehicles were also performed. The objective of the first task was to evaluate the thermal comfort and the usability of the novel heating, ventilation and air conditioning (HVAC) HMI prototype of the QUIET demonstrator. The objective of the second task was to deliver an assessment of the impact of the developed solution in the three areas (i.e. user-centric design of the e-vehicle, lightweight components with improved thermal performance, and integrated technologies for enhanced energy efficiency and comfort) in other vehicle segments. In particular downscaling towards A-segment and up-scaling towards C and D-segment was considered, thus covering beyond four-fifths of the circulating passenger vehicle fleet. The assessment is supported by virtual analyses of the systems and focuses on quantifying the impact on the specific energy consumption and driving range of the vehicle. AIT and UOZ supported HRE with virtual analyses. AIT and ATT supported HRE during the test of the user-centric design and thermal comfort.

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Figure 1: Expected reduction of energy consumption and weight in each of the three areas of the QUIET project.

2. Description of the deliverable

The scope of WP5 involves testing and demonstrating the enhancements that are developed in WP2, WP3 and WP4. The demonstrator vehicle was prepared for the integration by removing SotA components and systems, which were not required. Then, the developed innovations were integrated into the vehicle and their functionality was tested separately. Finally, the entire vehicle was tested, and measurement data were generated under realistic ambient and driving conditions. The aim of this deliverable 5.4 is to describe the achieved electric vehicle performance in terms of energy consumption, efficiency and driving range, user-centric design and thermal comfort under different working conditions and driving cycles as defined in Task 1.1. The assessment of the impact of the developed solutions in the A, C and D-segment vehicles are also part of the WP5 aims. The results of the vehicle testing allow to quantify and validate the achieved benefit regarding energy consumption and maximum driving range.

The report will provide a detailed description of the test campaign, the measurement equipment and methods used for monitoring the energy consumption, current flows and voltages in selected measurement points in the vehicle. The selected measuring points were located at the battery, at the electric motor and at the HVAC system, heater and A/C compressor, together with several temperature sensors and thermal comfort measurement devices. Additionally, the electric current from the grid during the recharges have been monitored to be able to reconstruct the efficiency cascade from the grid to the wheel during the several testing conditions with and without the use of the auxiliaries system in support to the performance optimisation.

3. Vehicle energy consumption and driving range

3.1. Experimental set-up

3.1.1 Test vehicle and laboratory

The QUIET project developed technologies were integrated in a HONDA B segment EV validator, which was tested in JRC Vehicle Emission Laboratories (VELA) in Ispra (Italy) [1] according to the test campaign defined in Task 1.1. JRC VeLA-8 facility is equipped with a 4x4 chassis dynamometer (independent roller benches)

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with a nominal power per axle of 300 kW that can achieve full road-simulation for speeds up to 260 km/h and accelerations up to ±10m/s2. This facility is designed to test passenger cars and light duty trucks, conventional fuel engine, full-electric and hybrid vehicles, at different ambient temperatures ranging from -30 ºC to +50 ºC. The inertia range varies from 250 up to 4,500 kg, while the wheelbase can be adapted from 1800 mm up to 4600 mm.VeLA-8 is equipped with an emission measurement system, with a driver aid system, to ensure consistent performance across all tests and with a data logger for real-time acquisition of signals from the measurement devices available, among which is a precision power analyser used for the electrical components during this test campaign. A precision vehicle-speed coupled blower allows reproducing on-road operative condition and vehicle cooling through relative air speed. VeLA 8 emissions measurement system is also customised to allow reliable hybrid vehicle testing during the phases when the combustion engine is switched off. A more detailed description of the facility can be found in [2], [3].

Figure 3 shows the demonstrator in JRC testing facility, while Figure 2 shows a schematic overview of the main installed new components. The tested vehicle is a 2013 year model with a total of 69733 kilometres before starting the tests. The vehicle's main characteristics are summarised in Table 2. The demonstrator is a 5-seat car, powered by a synchronous electric motor in front-wheel driving configuration. In normal driving mode, the electric motor (EM) is rated at 75 kW maximum power and 256 Nm maximum torque [4]. The vehicle is equipped with a 432-cells Lithium-Ion battery (Lithium titanium oxide anode), accounting for a 20 kWh nominal capacity and approximately 331 V nominal voltage [5]. The temperatures of the powertrain components are controlled by a water cooling system. The battery pack is not connected to this water cooling system but has an air cooling system. In normal operation, it relies on the natural air-flow around the battery modules. In the rare case that this is not sufficient, two battery fans are activated.

QUIET demonstrator was installed with a series of breakthrough technologies that enable lowering the energy consumption for heating and cooling the passenger cabin while reducing the weight of the entire EV validation platform:

- implementation of an air conditioning system based on the refrigerant R290 (propane), that has a significantly lower global warming potential compared to the standard refrigerant R134a, Figure 4;
- for heating the passenger cabin the air conditioning system works in heat pump operation combined with a phase change material (PCM) thermal storage system, Figure 5;
- infrared heating panels in the near field of the passengers enhance thermal comfort and reduce the energy consumption, Figure 5;
- the internal structures of the seats were redesigned and manufactured from lightweight materials like aluminium and magnesium while reducing the weight by 15 %, Figure 6;
- vehicle doors are manufactured by using a combination of glass or carbon fibre composite materials with a novel aluminium hybrid foam. The weight of the doors was reduced by 20 % while optimising the noise and vibration properties, Figure 6;
- closures were produced using carbon fibre and the original glazing (except the windshield) was modified to polycarbonate;
- development of a HMI which is specialised on EVs and which allows the user to interact with the user centric designed thermal and energy management, Figure 7.

The actual vehicle test mass was 1540 kg, including additional tools and monitoring equipment, of which 856.5 kg on the front axle and 683 kg on the rear axle. Despite the improvement in the weight of vehicle components (e.g. doors, windshields, seats, heating and air conditioning 28 % weight reduction) there is a total weight reduction of 5 % at vehicle level because of the extra components and monitoring systems installed on the vehicle.

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The compressor and heater system draw their electric power directly from the high voltage system of the car. The conventional AC system was modified to a heat pump system, operated with propane. The refrigerant cycle of the new system is very compact and operates with water-cooled components as condenser and evaporator. The water circuits are switchable to direct the heat flow to the point where it is needed for the respective operating point. For heating the waste heat from the condenser is used now. The existing HV heater was kept in the system for very low temperatures. The location of the corresponding air outlets inside the vehicle is shown in Figure 8 [6]. All the sub-systems are inter-connected by several power lines.

Table 2: Test vehicle characteristics

Architecture	BEV
Propulsion	Synchronous electric motor
Max. Power [kW]	75
Max. Torque [N·m]	256
Mass [kg]	1540
Battery	20 kWh – 432 Li-Ion cells 331 V (nominal voltage)

Figure 2: QUIET demonstrator tested at JRC Ispra VeLA 8 facility.

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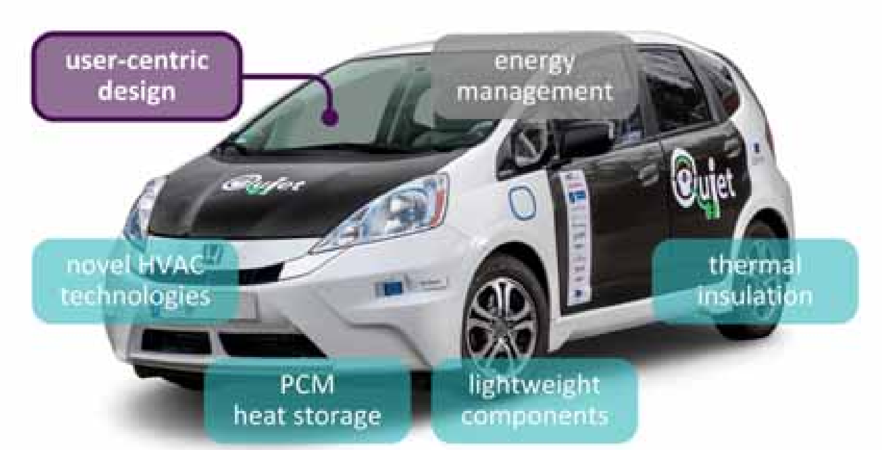

Figure 3: QUIET demonstrator with highlighted new installed components.

Figure 4: QUIET demonstrator air conditioning system based on the refrigerant R290 (propane), R290 compressor and safety valve.

Figure 5: QUIET demonstrator phase change material (PCM) thermal storage system and infrared heating panel.

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Figure 6: QUIET demonstrator lightweight seats, door crash beam with advanced pore morphology and lightweight composite doors.

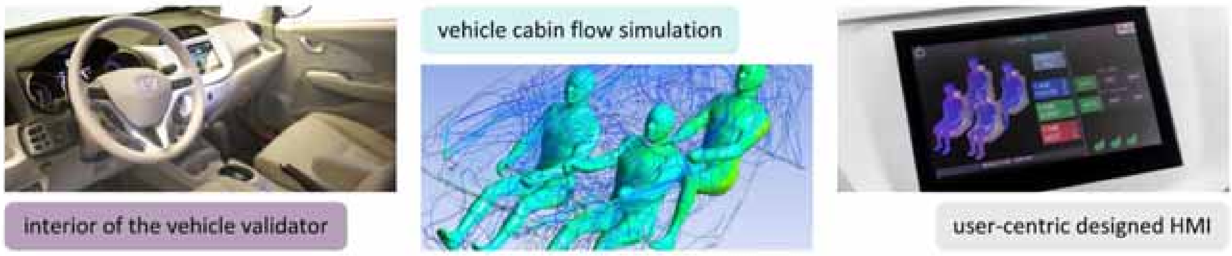

Figure 7: QUIET demonstrator new interior and user-centric designed HMI, based on vehicle cabin flow simulation.

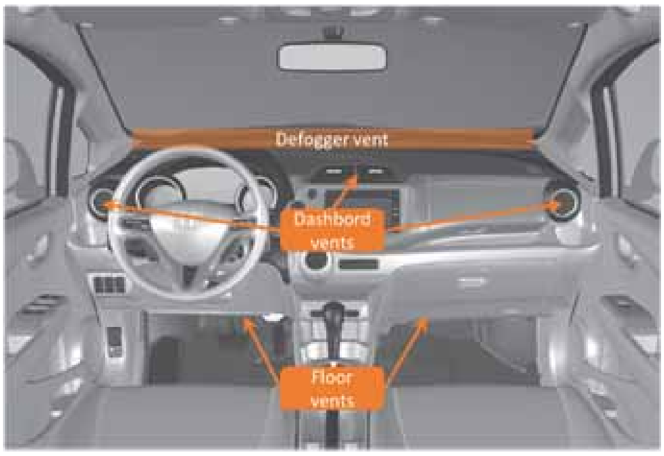

Figure 8: Air outlet locations [6].

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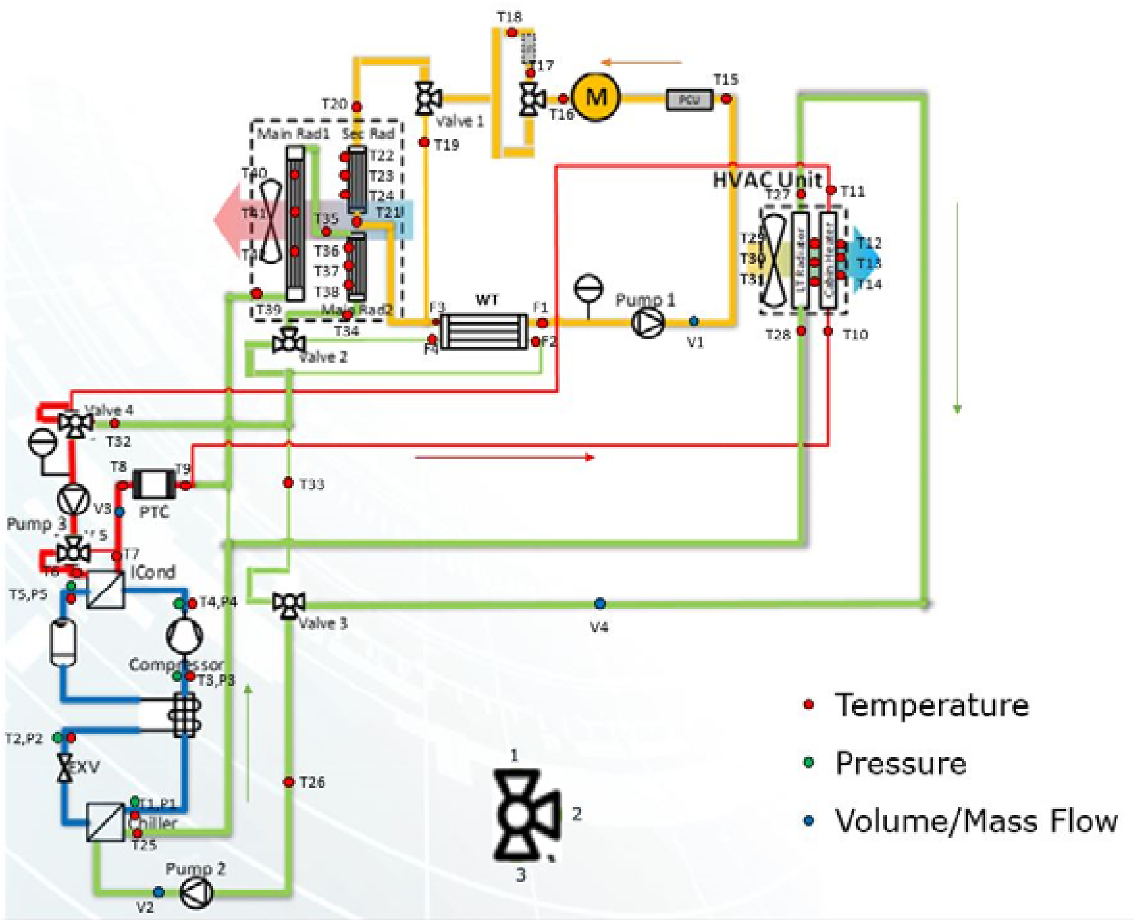

Figure 9: New HVAC system design.

3.1.2 Measurement Points

Grey circles in Figure 10 represent the measurement points on the vehicle used to monitor the energy flows. A detailed description of these measurement points is provided in Table 3. The measurement at the stage M_1 is acquired directly on the 6.6 kW AC recharging station, by monitoring the electric energy required to recharge the battery. The measurement at the stage M_2 is acquired both via the vehicle CANbus and via a current clamp directly mounted on the battery output power-line and voltage measurement from the CANbus. The measurement at the stage M_3 and M_4 is acquired only via CANbus, whereas the measurement at the stage M_6 is acquired both via the vehicle CANbus and via a current clamp and voltage measurement from the CANbus. The 12 V battery was also monitored via a current clamp and voltage measurement. Figure 11 illustrates the current probes installed on the HV battery, 12V battery and A/C compressor. The data can be either stored on the internal memory of the power analyser or acquired in real-time by the laboratory data logger.

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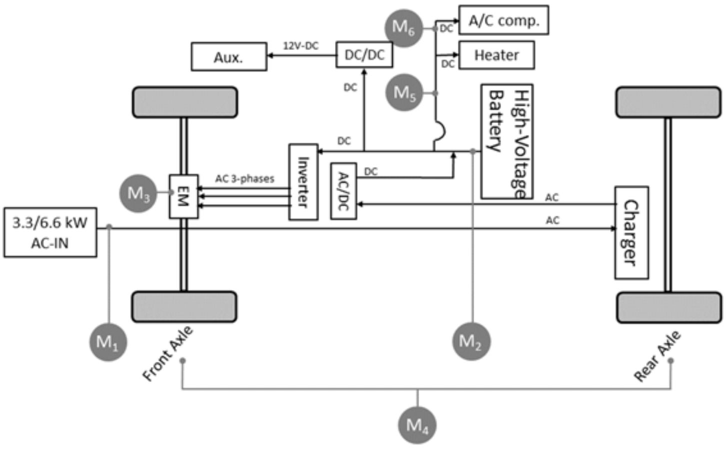

Figure 10: Schematic representation and measurement points (see Table 3).

Table 3: Measurement points summary (see Figure 10)

Measurement point label	Description
M_1	Energy from the grid to the high-voltage battery [Wh];
M_2	Current [A] and Voltage [V], from the high-voltage battery feeding the inverter, the low-voltage auxiliary systems and the heating and A/C systems; (acquired both by CANbus and current clamp measurement)
M_3	Rotational speed [rpm] and torque [N·m] of the electric motor; (acquired by CANbus)
M_4	Energy at the wheel [Wh]; (acquired by the dyno)
M_5	Current [A] and Voltage [V], from the high-voltage battery to the heater; (acquired by CANbus)
M_6	Current [A] and Voltage [V], from the high-voltage battery to the A/C compressor; (acquired both by CANbus and current clamp measurement)

Cabin thermal acquisition, according to the specifications described in the European MAC draft test procedure [7], has been also configured as shown in Figure 12 and synchronised to all the other laboratory data. Additional temperature sensors and thermal comfort measurement devices have been installed for monitoring the vehicle energy management system and the advance systems installed on the vehicle. The results from CAN current and CAN voltage measurements (Case 1) and AC/DC clamp for current and CAN voltage measurements (Case 2) will be presented in this report.

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Figure 11: HV battery, 12V battery and A/C compressor sensors

Figure 12: Cabin temperature sensors.

3.1.3 Test Driving Cycles

The distance specific energy consumption and the driving range estimates were derived performing laboratory tests in different environmental and driving conditions with and without the usage of the HVAC system of the vehicle. To create a starting point for the project, it was necessary to understand the baseline vehicle and its operating characteristics. The groundwork was laid using specifications of the base vehicle, which were extracted from HONDA documentations. Additionally, the behaviour of the vehicle and its systems was recorded during driving tests on a climatic controlled dynamometer test bench. The tests generated a set of data useful to calibrate the QUIET developed models in its several aspects of components optimisation and targeted efficiency and to evaluate the overall energy consumption performance of the demonstrator vehicle.
The test cycle for measuring the energy consumption of the QUIET demonstrator is based on the UN GTR15 regulation [8], [9]. For the purpose of this project, the following testing sequence was followed:

- soaking and charging overnight in climatic controlled area (at target testing conditions);
- testing on dynamometer, following the speed trace;
- repeating cycles until break-off criterion is reached (not able to follow speed trace for 4 seconds, due to power reduction);
- re-charging in climatic controlled area.

Three test cycles have been adopted in the test campaign and their phases are shown in Figure 13: the World-wide harmonized Light-duty Test Cycle (WLTC), the Mobile Air Conditioning (MAC) cycle and the World-

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wide harmonized Light-duty Shorten Test Procedure (WLTP STP) [7], [8] [6].The results of the WLTP and MAC tests will be reported.
The WLTC for Light Duty Vehicles (LDVs) [8], [9] was created to reflect real-world vehicle operation into a clearly defined cycle and it is a test cycle characterized by four phases: low speed (589 seconds and 3.09 km), medium speed (433 seconds and 4.76 km), high speed (455 seconds and 7.16 km) and extra-high speed (323 seconds and 8.25 km). These phases are designed to represent urban traffic, mixed conditions and highway conditions respectively. The Consecutive Cycle Test (CCT) where the WLTC cycle is repeatedly driven up to the complete charge depleting of the vehicle battery has been applied at +23°C, -10°C and +40°C without and with the HVAC system in operation to characterise the driving range and distance specific energy consumption of the vehicle in different ambient conditions. In order to determine the energy consumption of the HVAC system, the MAC cycle test procedure has been adopted [7]. This test prescribes a cycle made of three phases: the pre-conditioning phase (i.e. phase 1) plus two identical phases (i.e. phases 2 and 3), respectively with and without the HVAC system in operation. Phase 1 lasts for approximately 30 minutes at a constant speed of 90 km/h, while phases 2 and 3 last for approximately 16 minutes each, half driven at a constant speed of 50 km/h and half at 100 km/h. This test prescribes the minimum HVAC system mass flow rate (i.e. 230 kg/h), together with the monitoring of the cabin temperature in seven control points: four located on the dashboard and three behind the seats of the driver and the passenger (Figure 12). The test is carried out at the ambient temperature of +25 ºC, and the HVAC system of the vehicle must decrease the cabin temperature to a target value set below +15 ºC. The phase 1 is designed to stabilize the cabin temperature at this temperature, while phase 2 and phase 3 are designed to compare the energy consumption of the vehicle with and without the HVAC system in operation (cooling mode). During phase 2 the HVAC system must only maintain the cabin temperature around a steady-state value. A modified version of the MAC test procedure has been designed at -10 ºC, with the HVAC system in heating mode, with the phase 1 shortened to 15 minutes of driving plus 15 minutes of idling (keeping the HVAC system in operation) in order to have enough energy in the battery to complete the phases 2 and 3, as shown in Figure 13. The WLTP STP for pure electric vehicle driving range determination [8], [9] has also been applied to collect more data on the vehicle performance. The STP consists of two dynamic segments (DS1 and DS2 in Figure 13) combined with two constant speed segments (CSS_M and CSS_E in Figure 13). The dynamic segments DS1 and DS2 are used to calculate the energy consumption of the phase considered. The constant speed segments CSS_M and CSS_E are intended to reduce test duration by depleting the battery more rapidly than the CCT procedure. The test cycle is designed based on the vehicle characteristics.
Table 4 summaries the tests performed on the demonstrator vehicle. The vehicle is recharged after each driving range test using the 6.6 kW on-board AC charger. The recharging energy is recorded both at the mains and in the vehicle resulting in an average charging efficiency of approximately 92 % at +23 ºC and 91% at -10 ºC.

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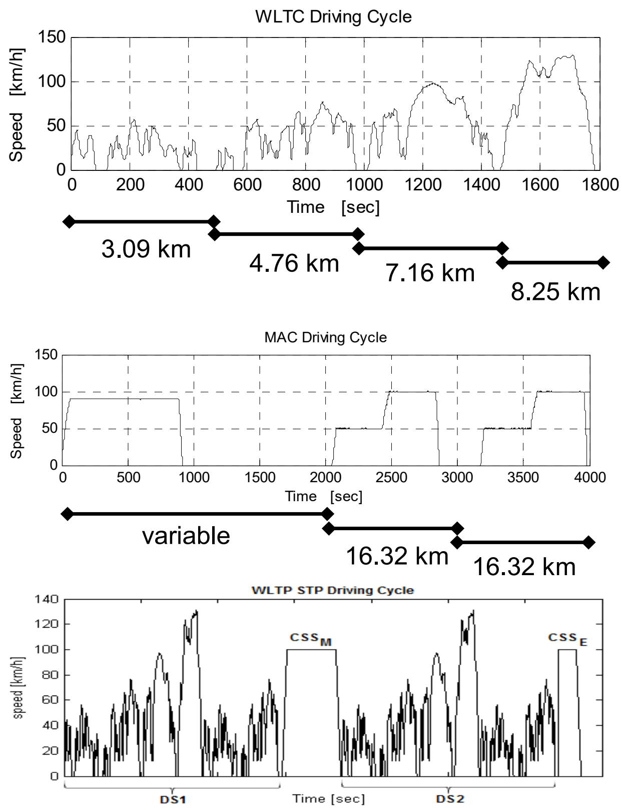

Figure 13: Driving cycles adopted: WLTC, MAC and WLTP STP [7], [8], [9].

Table 4: Laboratory and on-road driving tests

Cycle	Ambient Temperature	HVAC
WLTP CCT	23°C	off
WLTP CCT	-10°C	AUTO mode 2 seats occupied (heating)
WLTP CCT	40°C	AUTO mode 2 seats occupied (cooling)
WLTP STP	23°C	off
MAC	25°C	AUTO mode 2 seats occupied, 15°C enforced (cooling)
MAC	-10°C	AUTO mode 2 seats occupied, 22°C enforced (heating)

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3.2. Results and discussion

3.2.1 WLTP CCT energy consumption results

The WLTP CCT procedure [8], [9] has been applied to derive the distance specific energy consumption of the vehicle demonstrator in different ambient conditions with the HVAC system in operation. The WLTP test procedure has been developed to be carried out at +23 ºC. During this test campaign has been applied also at -10 ºC and +40 ºC to evaluate the impact of cold and warm temperatures on the energy consumption with the HVAC system in operation in support to the QUIET project objectives, but to also explore the limitations and strong aspects of the procedure when applied at different ambient temperature. The HVAC system was switched-on in heating or cooling mode immediately before the test (i.e. without performing the cabin temperature pre-conditioning).
In the WLTP [8], [9] the energy consumption is calculated applying a *K*-weighted according to the following equation (1):

$$EC_{DC,WLTC} = \sum_{j=1}^{n_{WLTC}} EC_{DC,WLTC,j} K_{WLTC,j} \quad (1)$$

where $EC_{DC,WLTC,j}$ is the electric energy consumption for the applicable WLTP test cycle *j* of the consecutive cycle Type 1 test procedure, in [Wh/km], calculated considering the electric energy change of all rechargeable electric energy storage systems (REESS) during the considered period *j*,

$$EC_{DC,WLTC,j} = \frac{\Delta E_{REESSj}}{dj} \quad (2)$$

$$\Delta E_{REESSj} = \sum_{i=1}^{n} \Delta E_{REESSj,i} \quad (3)$$

with *n* total number of REESS, and

$$\Delta E_{REESSj,i} = \frac{1}{3600} \int_{t_0}^{t_{end}} U(t)_{REESSji} I(t)_{REESSj,i} dt \quad (4)$$

with *U(t):* voltage of $REESS_i$ in period *j, I(t):* current $REESS_i$ during period *j*, t_0: initial time of period *j* and t_{end}: final time period *j*, *dj:* distance driven in the considered period *j* in [km] and n_{WLTC} the whole number of complete driven applicable WLTP test cycles. $K_{WLTC,j}$ is the weighting factor for the applicable WLTP test cycle *j*:

$$K_{WLTC,1} = \frac{\Delta E_{REESS,WLTC,1}}{UBE_{CCP}} \text{ and } K_{WLTC,j} = \frac{1 - K_{WLTC,1}}{n_{WLTC} - 1} \quad for\ j = 2 \ldots n_{WLTC} \quad (5)$$

where $\Delta E_{REESS,WLTC,1}$ is the electric energy change of all the REESSs during the first applicable WLTP test cycle of the consecutive cycle Type 1 test procedure in [Wh].
The distance specific energy consumption is reported for both K-weighted and not K-weighed for completeness in reporting the results.
The consumption values have been converted to an equivalent value expressed in litres of gasoline per 100 km (i.e. litres/100km, see values in parenthesis), by applying the conversion suggested by the Environmental Protection Agency (EPA, [10]) as per (6). The energy content of the gasoline fuel has been assumed equal to 8.90 kWh/litre (i.e. 115 kbtu/gallon),

$$Consumption \left[\frac{l}{100km}\right] = Consumption \left[\frac{Wh}{km}\right] . \frac{0.1123}{10} . \quad (6)$$

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3.2.1.1 Energy consumption at +23ºC

Table 5 provides the energy consumption results at +23 ºC calculated for each driving cycle of the CCT tests at the battery level (i.e. without considering the efficiency loss during the recharge) by the current and voltage at the battery outlet measured according to Case 1 and Case 2, explained above (i.e. M_2 according to Table 3). Both the whole combined energy consumption and the WLTP *K*-weighted value from the start of the test up to the break-off criteria are reported. The results given in Table 5 show that at +23 ºC and with the HVAC system switched-off the distance specific energy consumption of the demonstrator vehicle is slightly higher than the baseline vehicle one (i.e. 3.5%) and varies between approximately 136 and 130 Wh/km among the cycling, with higher energy consumption during the first cycle. Despite there is an improvement of the energy consumption of the electric motor, 106.8 Wh/km in the demonstrator versus 116-121 Wh/km in the baseline vehicle Figure 14, there is an increase of the total vehicle energy consumption due to the measurement system installed in the demonstrator. The energy consumption during the last driven cycle is almost the same in both vehicles.

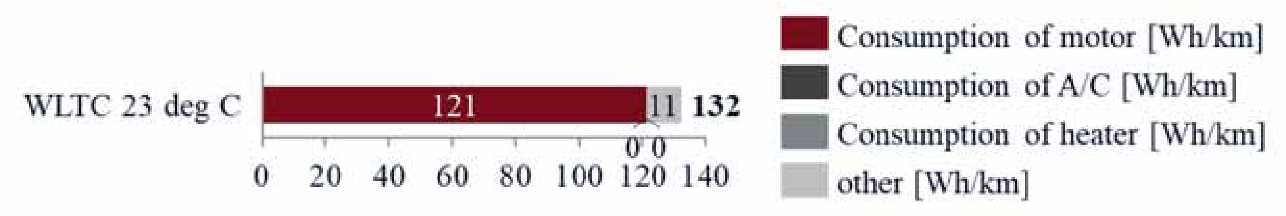

Figure 14: Distance specific energy consumption of the baseline vehicle components.

By converting the energy consumption results to the equivalent gasoline consumption, a consumption ranging from 1.5 to 1.53 l/100 km (combined data) is derived. These values will increase if the effect of the energy losses during the recharge (i.e. from the grid to the battery) is included.
The energy recuperation ratio is also calculated both at the battery and at the EM level. At the battery level it is calculated by dividing the battery energy inflow by the battery energy outflow measured by current and voltage (see measurement point M_2), while at the EM level it is calculated by dividing the electric motor recuperated energy by the electric motor driving energy (see measurement point M_3). These ratios provide a quick estimate of the impact of the energy recuperation on the total energy consumption for each cycle and test conditions. The ratio at the battery level is lower than that at the EM level, accounting for the energy losses between the battery and the EM (i.e. power lines and inverter) and it is slightly lower than in the baseline scenario (i.e. 22% against 24% at room ambient temperature). The differences between the two measurement modes (Case 1 and Case 2) is approximate 2-5% at 23 ºC.

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Table 5: Energy consumption results for the WLTP CCT at +23 ºC. Results for the two measurement cases (Case 1 - CAN current and CAN voltage measurements, Case 2 - AC/DC clamp for current and CAN voltage measurements)

		Demonstrator tests	
		Case 1	**Case 2**
		WLTC [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)
$T_{Amb.}$ = +23 ºC HVAC OFF	Cycle 1 combined	136.02 (1.53)	138.20 (1.55)
	Cycle 2 combined	131.02 (1.47)	137.91 (1.54)
	Cycle 3 combined	130.41 (1.46)	138.44 (1.55)
	Cycle 4 combined	132.80 (1.49)	139.74 (1.57)
	Cycle 5 combined	130.77 (1.47)	138.37 (1.55)
	Cycle 6 combined	/	/
	Total from start up to break off criteria combined	131.58 (1.48)	139.37 (1.57)
	Total from start up to break off criteria WLTP K-weighted values	133.13 (1.50)	138.54 (1.56)
	Rec. Ratio (Battery)	22.9%	22.9%

3.2.1.2 Energy consumption at -10ºC

The energy consumption of the demonstrator vehicle at -10°C with HVAC in operation was estimated combining the energy consumption of the HVAC system in operation at -7°C recorded during a static test consisting in warming up the cabin, lasting 3139 seconds, with the energy consumption of the demonstrator vehicle during a WLTP test without HVAC in operation at -10°C, lasting 3600 seconds, that is, two WLTC cycles, Figure 15 and Figure 16. The static power consumption of the measurement equipment, recorded during the test to be approximately 200W, was subtracted by the total power consumption of the vehicle. An ideal thermal transfer from chiller to Cabin Heat Exchanger was assumed.

The energy consumption of the HV battery, A/C compressor and heater has been extrapolated to 3600 seconds obtaining approximately 9757 Wh total energy consumed at the battery level while driving two WLTC at -10°C with HVAC in operation, approximately 207.6 Wh/km. Table 6 provides as comparison the energy consumption results at -10 ºC calculated for two driving cycles of the CCT tests without HVAC at the battery level by the current and voltage at the battery outlet measured according to Case 1 and Case 2. Both the whole combined energy consumption and the WLTP K-weighted value from the start of the test up to the break-off criteria are reported. The energy consumption ranges between 140 and 145 Wh/km.

At cold temperature and with HVAC system operating in heating mode the distance specific energy consumption of the baseline vehicle was approximately between 236 Wh/km to 240Wh/km. The HVAC system in heating mode has an impact that can be quantified in approximately 70-80% increase of the energy consumption in the baseline vehicle and of approximately of 52-60% in the demonstrator.

The energy consumption results are graphically shown in Figure 17, in function of the ambient temperature~~,~~ where it is visible the effect of different ambient conditions and auxiliaries load.

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The battery recuperation ratio is 18%, a lower value compared to the +23C test conditions. The differences between the two measurement modes (case 1 and 2) is approximately 2-3% at -10 ºC.

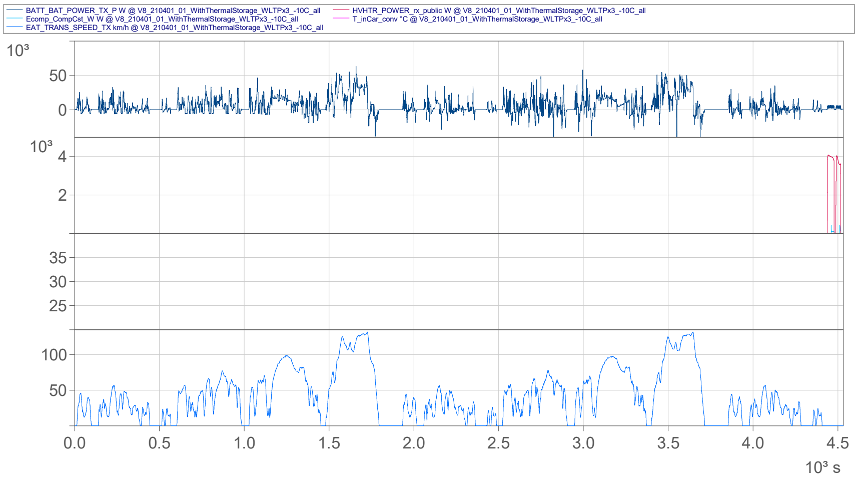

Figure 15: HV battery power during two WLTC at -10°C, without HVAC (3600 seconds).

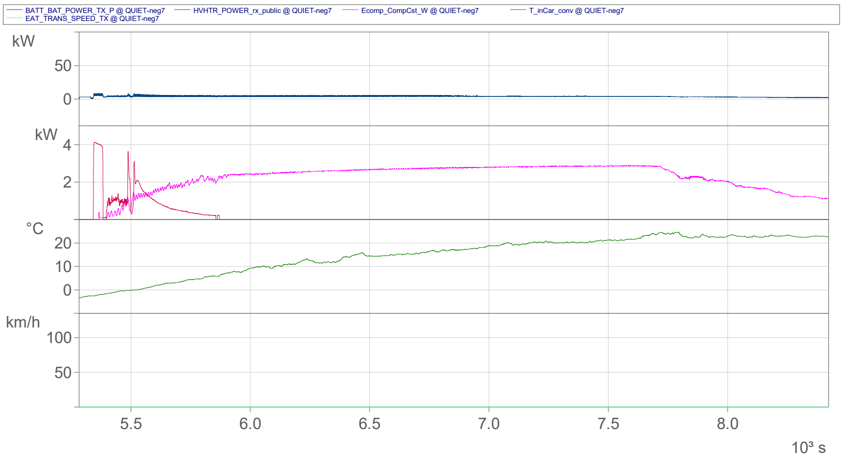

Figure 16: HV battery and HVAC power during a static heat up of the cabin at -7°C (3139 seconds).

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Table 6 Energy consumption results for the WLTP CCT tests at cold temperatures of the demonstrator vehicle. Results for the two measurement cases (Case 1 - CAN current and CAN voltage measurements, Case 2 - AC/DC clamp for current and CAN voltage measurements)

		Demonstrator vehicle tests	
		Case 1	**Case 2**
		WLTC [Wh/km] (l/100 km)	**WLTC** [Wh/km] (l/100 km)
$T_{Amb.}$ = -10 ºC HVAC OFF	Cycle 1 combined	159.42 (1.79)	163.36 (1.83)
	Cycle 2 combined	145.88 (1.64)	149.91 (1.68)
	Total from start up to break off criteria combined	140.79 (1.58)	144.70 (1.63)
	Total from start up to break off criteria WLTP K-weighted values	152.63 (1.71)	156.59 (1.76)
	Rec. Ratio (Battery)	18.15%	18.15%

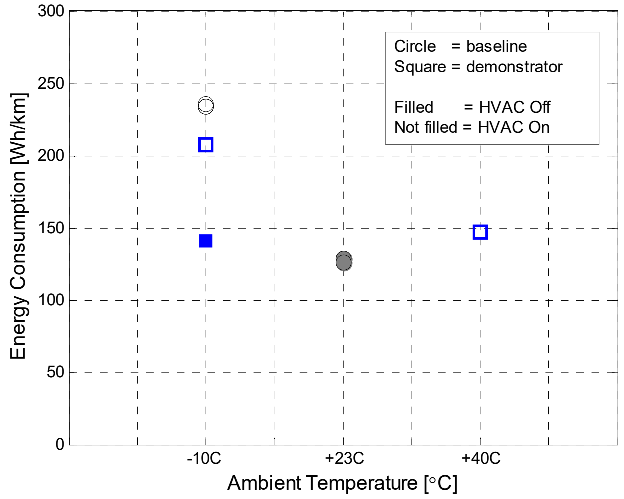

Figure 17: Energy consumption results of the baseline and demonstrator vehicle at different ambient temperatures from the WLTP CCT tests.

3.2.1.3 Energy consumption at +40ºC

At the + 40 °C measurement there was a problem with the air recirculation mode. Normally, the requested rpm should decrease for a decreasing cabin temperature in recirculation mode, because it is easier to reach the target temperature after the LT-radiator. During the measurements instead no clear dependency between the compressor rpm and the cabin temperature was observed, thinking that probably there was an issue with the position of the recirculation flap. A plausibility check is carried out to investigate this assumption. Based on the heat flow of the water side, the air mass flow through the LT-radiator can be calculated by using the enthalpy difference on the air side. The enthalpy state of the air is determined by its pressure, temperature and

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humidity. It can be derived from a Mollier-h-x-diagram. For assuming recirculation mode the calculated air mass flow is unrealistic high. However, if fresh air mode is assumed, it seems to be too low. Hence from these analyses it can be derived that probably the position of the flap during the test was in between the two modes. If fresh air mode is taken into account for the measurement, the provided heat flow of the AC was far too high. With the same COP, the compressor consumption would be too high by the same factor. In reality, however, the COP increases as the heat flow decreases. Overall, this would lead to a significantly lower energy consumption by the AC-system. For 100% fresh air mode a theoretical benefit compared to the base line AC-system could be shown. Since this would only be theoretical and the exact position of the flap is not known, it is not possible to determine an accurate AC energy consumption from the measurement.
The QUIET system showed an AC consumption of 5.4 kWh while the baseline system showed an energy consumption of 1.4 kWh. Since a reduction factor of about 4.5 can be observed even in partial fresh air mode with less cooling requirement and a better COP, it is a valid assumption that AC consumption in the QUIET vehicle would decrease to 1.2 kWh.
From the tests results a total battery consumption of 18.440 kWh can be estimated for four WLTC. Subtracting the measurement system energy load of approximately 400Wh for the whole four WLTC cycles and applying the energy reduction factor to the AC measured energy consumption according to the above observation a distance specific energy consumption of approximately 147.3 Wh/km can be estimated.

3.2.2 MAC tests energy consumption results

Table 7 reports the distance specific energy consumption for the MAC test cycles, phases 1, 2 and 3 for the two measurement cases. The MAC test cabin temperature conditioning was performed according to [7], with the first phase of pre-conditioning. Only tests at 25 ºC were performed for the MAC cycle case. The ratio between the energy consumption from the phases 2 and 3 is reported, to highlight the influence of the HVAC system in operation on the energy consumption. Phase 1 (i.e. variable) is designed only to reach a steady-state cabin temperature. The results show that this impact is approximately between +14% and +18% of increase in the energy consumption in the cooling mode at +25 ºC ambient temperature. Table 7 reports the distance specific energy consumption also for the baseline vehicle tests, showing approximately a +12% increase in the energy consumption in the cooling mode at +25 ºC ambient temperature, whereas a +71% increase in heating mode. The energy consumption is higher in the demonstrator in respect to the baseline.
The second-by-second cabin temperatures measured during the MAC tests are reported in Figure 18 for the demonstrator. The cabin temperature measurement points reported are: left, mid and right probe positions (corresponding to driver's head, between the driver's and the passenger's seat and behind the passenger's head) and left, mid and right duct positions (corresponding to the left, mid and right outlet of the HVAC system located on the dashboard). According to the MAC specifications, the thermocouples located on the dashboard are four: left, mid-left, mid-right and right outlets of the HVAC system. For simplicity the mid duct temperature reported here is the average between the mid-left and mid-right duct measurements. The thermocouples in the cabin show that the temperature stabilizes approximately after 30 minutes in cooling mode in the demonstrator vehicle. Figure 19 illustrates the thermocouples readings at the simulated mannequin in the demonstrator vehicle, while Figure 20 thermal storage temperature readings.

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Table 7: Energy consumption results (MAC)

		Demonstrator vehicle				Baseline vehicle	
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
		MAC [Wh/km] (l/100 km)	MAC [Wh/km] (l/100 km)	MAC [Wh/km] (l/100 km)	MAC [Wh/km] (l/100 km)	MAC [Wh/km] (l/100 km)	MAC [Wh/km] (l/100 km)
$T_{Amb.}$ = +25 ºC	Phase 1 HVAC ON	175.8 (1.79)	168.6 (1.89)	172.7 (1.94)	171.3 (1.92)	143.3 (1.61)	117.1 (1.32)
	Phase 2 HVAC ON	155.1 (1.74)	148.8 (1.67)	153.6 (1.73)	152.9 (1.71)	140.9 (1.58)	107.6 (1.21)
	Phase 3 HVAC OFF	131.1 (1.47)	116.7 (1.31)	134.2 (1.51)	130.2 (1.46)	128.1 (1.44)	96.0 (1.08)
	Ratio	+18.3%	+27.5%	+14.4%	+17.4%	+10.0%	+12.1%
$T_{Amb.}$ = -10 ºC	Phase 1 HVAC ON	/	/	/	/	301.7 (3.39)	298.9 (3.36)
	Phase 2 HVAC ON	/	/	/	/	237.3 (2.66)	234.0 (2.63)
	Phase 3 HVAC OFF	/	/	/	/	146.7 (1.65)	136.9 (1.54)
	Ratio	/	/	/	/	+61.7%	+71.0%

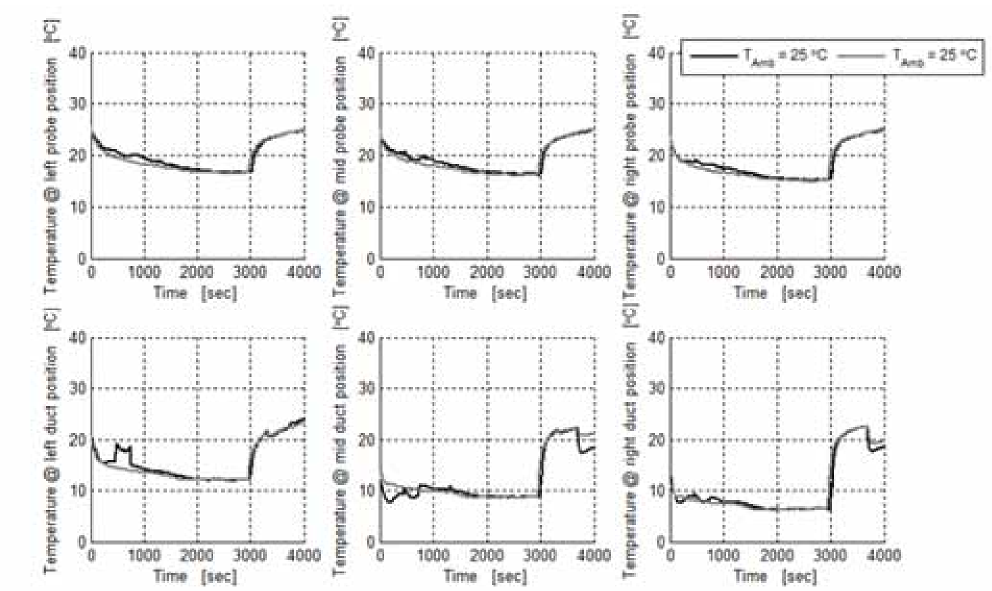

Figure 18: Thermocouples readings at the driver's head, between the driver's and the passenger's seat and behind the passenger's head (i.e. respectively left/mid/right probe positions) and at the left/mid/right duct outlets for the MAC driving cycle. Mid duct temperature is the average between the mid-left and mid-right duct measurements.

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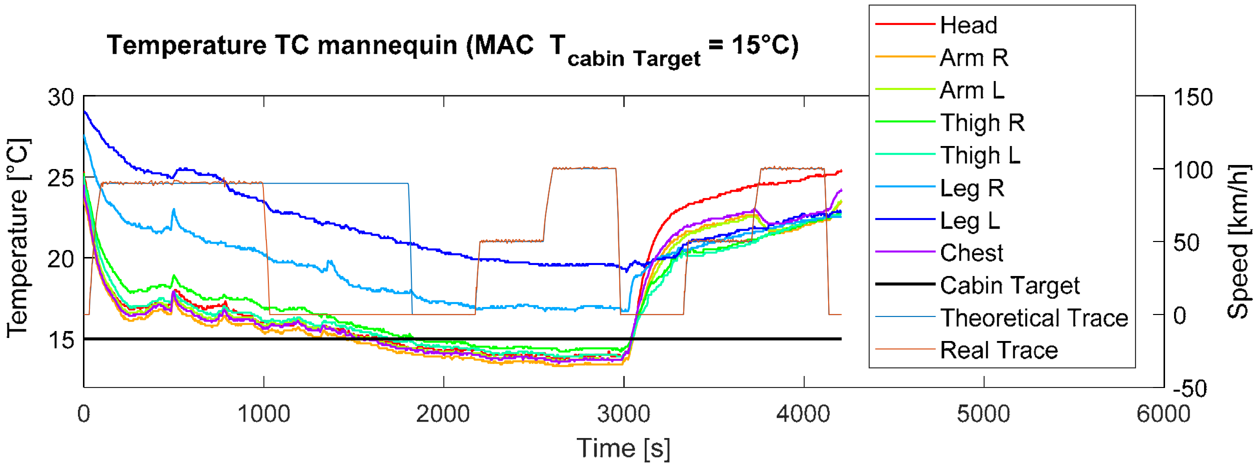

Figure 19: Thermocouples readings at the simulated mannequin in the demonstrator vehicle.

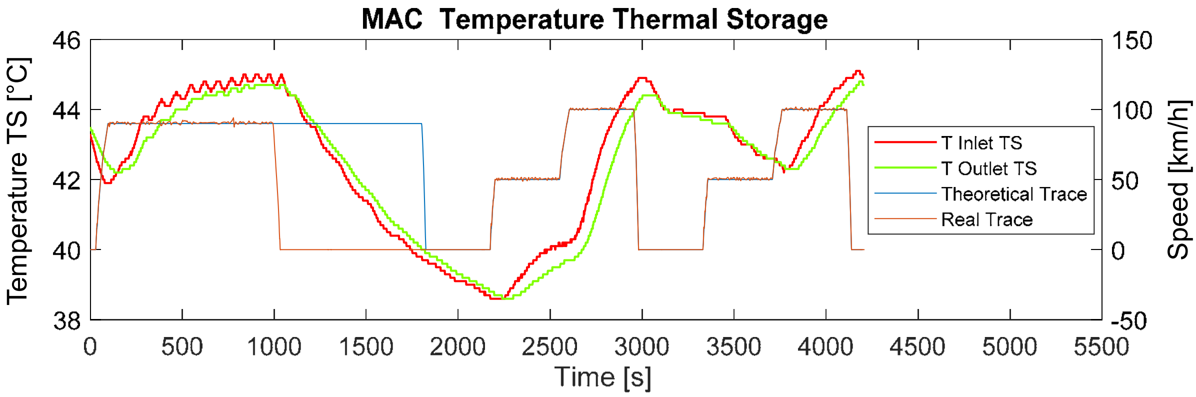

Figure 20: Thermal storage temperature readings during a MAC test at +25 ºC.

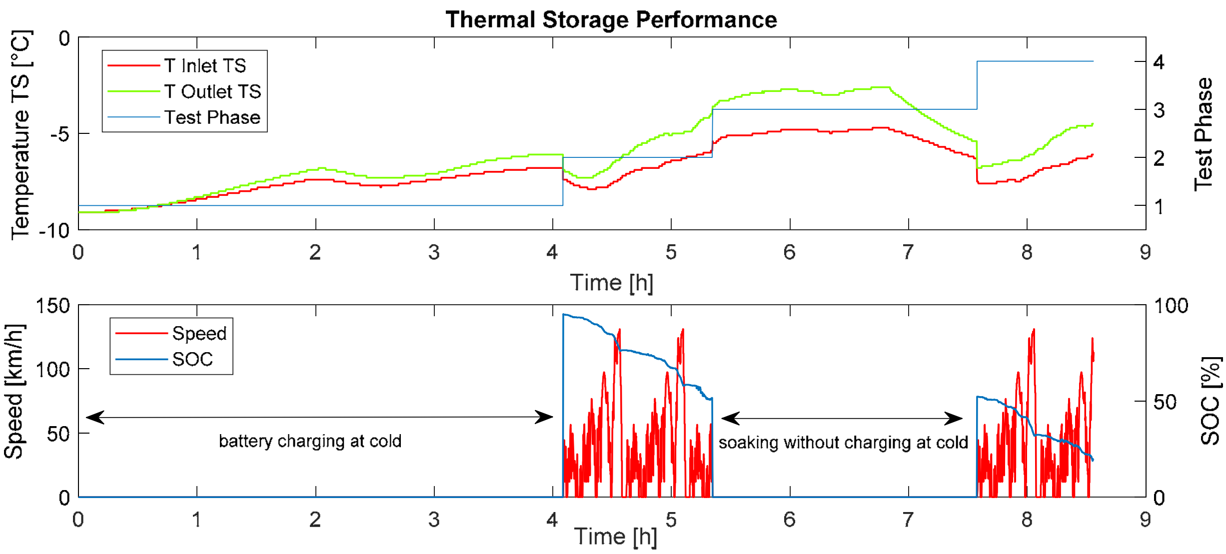

Figure 21: Thermal storage temperature readings during a sequence of CCT test at -10 ºC: recharge at cold, WLTC driving soon after the charge, soaking at cold without charging, WLTC driving at cold.

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3.2.4 Driving range results

According to the WLTP driving range test [8], [9], the type approval driving cycle has to be driven in sequence at a temperature of +23 ºC and with the auxiliary systems switched-off. The driving range is then determined by the cumulative distance driven up to when the break-off criterion is reached, that is, when the vehicle is not capable to follow the duty cycle anymore for four consecutive seconds or more. The accelerator control shall be deactivated, the vehicle coasted-down and parked within 60 seconds. The WLTP CCT pure electric range (PER) for a BEV is defined by:

$$PER_{WLTC} = \frac{UBE_{CCP}}{EC_{DC,WLTC}} \quad (7)$$

where UBE_{CCP} is the usable REESS energy determined from the beginning of the consecutive cycle Type1 test procedure until the break-off criterion,

$$UBE_{CCP} = \sum_{j=1}^{k} \Delta E_{REESS,j} \quad (8)$$

with $\Delta E_{REESS,j}$ the electric energy change of all the REESSs during phase j of the consecutive cycle Type 1 test procedure in [Wh] and $EC_{DC,WLTC}$ defined by (1).

Table 8 reports the driving range test results calculated with the WLTP CCT procedure. As reported above the WLTP procedures have been extended to cold and warm temperatures. The *K*-weighting coefficient might be differently defined. For this reason, the driving range reported in Table 8 for the -10 ºC and 40 ºC is primarily the distance driven up to the break-off criterion.

The results show a driving range of about 136 km at +23 ºC, shorter in respect to the vehicle demonstrator where it was about between 155 km and 156 km. This is principally due to the UBE recorded during the CCT test, lower than that of the baseline vehicle (i.e. 18103 Wh against 20164Wh of the baseline tests).

For what concern the -10 ºC case, the driving range for the demonstrator was derived as explained above, combining a static test of the HVAC at -7ºC with the two WTLC tests at -10 ºC. Knowing that the total UBE during the baseline vehicle tests at -10ºC was about 16.18 kWh, assuming a constant power consumption of the HVAC, it is possible to calculate how many kilometres can be driven in total at -10 ºC with the HVAC in operation. The total driven distance was derived to be 86.8 km [11], [12], [2].

For the baseline at -10 ºC and with HVAC system operating in heating mode the driving range was between 63 km and 68 km, depending on the battery temperature, approximately 59% shorter than the range at +23 ºC without HVAC system in operation. Comparing the two driving ranges at cold there is an improvement of 26% of the driving range of the demonstrator in respect to the baseline vehicle. This increase of the driving range is in line also to the simulated results presented in WP 1 / deliverable D1.2 / Task 5.6 and Task 8 (target = 25%, simulation results = 26.85%, measurements = 26%). Figure 22 shows a comparison of the driving range between the baseline vehicle and the demonstrator at cold temperature.

For what concern the +40 ºC case, the driving range for the demonstrator was derived based on the energy consumption estimated above and the total UBE available during the baseline vehicle tests at +40ºC. Assuming a constant power consumption of the HVAC in the remaining portion of the driving distance and an ideal thermal transfer from chiller to Cabin Heat Exchanger, a total driven distance driven between 137 and 140 km can be derived. Figure 23 shows a comparison of the driving range between the baseline vehicle and the demonstrator at warm temperature.

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Table 8: Driving range test results for both the WLTP CCT procedure at the different ambient temperatures

		Demonstrator test		Baseline tests					
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
		Driving Range [km]		Driving Range [km]		Driving Range [km]		Driving Range [km]	
$T_{Amb.}$ = +23 ºC HVAC OFF	WLTP CCT up to break-off K-weighted	136.08	136.44	154.43	154.10	154.74	124.10	149.24	148.90
	WLTP CCT up to break-off Not weighted	136.61		**156.50**		156.78		148.76	
$T_{Amb.}$ = -10 ºC HVAC ON	Estimated WLTP CCT up to break-off Not weighted	**86.8**		**68**		63.98		63.93	
$T_{Amb.}$ = +40 ºC HVAC ON	Estimated WLTP CCT up to break-off Not weighted	**137-140**		**137**		/		/	

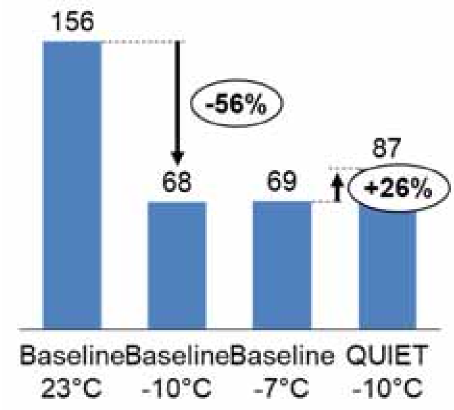

Figure 22: Driving range comparison baseline versus demonstrator vehicle at cold ambient temperature.

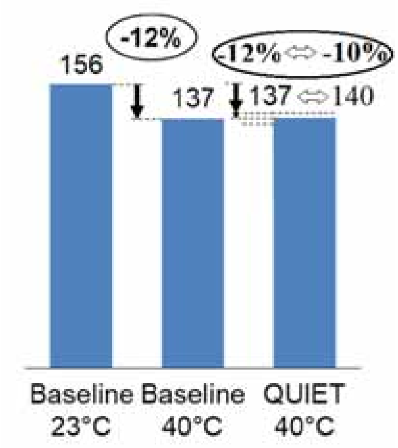

Figure 23: Driving range comparison baseline versus demonstrator vehicle at warm ambient temperature.

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4. User-centric and thermal comfort validation: final user evaluation

To evaluate the thermal comfort and the usability of the novel HVAC HMI prototype of the QUIET demonstrator, a final user study with N = 26 was conducted.

4.1 Experimental design

4.1.1 Objectives

The research objective of the final user study is to evaluate the thermal comfort and the HVAC HMI usability of the EV developed during the QUIET project.

4.1.2 Independent and dependent variables

For the evaluation, the novel EV and its HVAC HMI is compared to the baseline original EV (Honda FIT EV) and its HVAC HMI. Therefore, a repeated measurement with only one independent variable:

Car I – QUIET demonstrator and Honda FIT EV (Figure 24) is used in this final user study.

The final version of the QUIET HVAC HMI concept that was experienced in the final user study allows users to select single body parts on the cabin image on the left side of the display. After the selection of body parts, the user can indicate his/her current thermal feeling by selecting either the “I am cold” button to heat the cabin or the “I am hot” button to cool the cabin. Furthermore, users can stop the heating/cooling process to keep the current temperature by selecting “I am cosy”. To enable the selection of all passengers at the same time a “Select all” button is integrated next to the cabin image. When selecting one or multiple body parts the selection is visualized with a continuous white line around the respective body parts. After the operation of the “I am cold” or “I am hot” button, the previous selection is still available but visualized in dashed white lines. It is possible for the user to either use the previous selection or use the “I am cold” or “I am hot” buttons or start a new selection of body parts and the previous selection disappears.
Additional HVAC functions are located on the right side of the screen. Users can (de)activate inside air and front wind shield defrost. The users can switch between the Eco modes “Auto”, “Max” and “Off”. “Auto” regulates the Eco mode automatically and “Max” enables climatisation with the highest efficiency especially for low range use cases. Furthermore, the user can adjust the seat heating to be either regulated automatically by the HVAC system, or to be deactivated or activated permanently. In the upper left corner of the screen an “Off” button is located to switch off the HVAC system. At the bottom of the screen on the left side a progress bar visualizes the current state of the climatisation process, whereas on the right side the energy efficiency of the current climatisation process is visualized with up to 4 green leaves.
The dependent variables are listed in the Table 9.

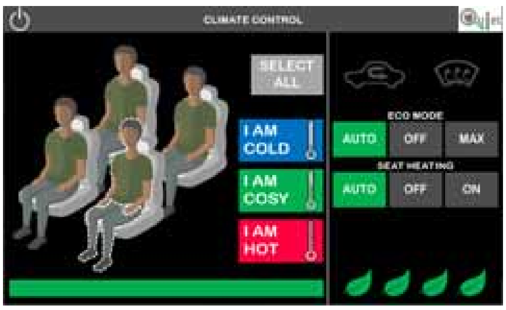

Figure 24: HVAC HMIs in QUIET demonstrator (left) and Honda FIT EV (right).

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Table 9: Description of dependent variables

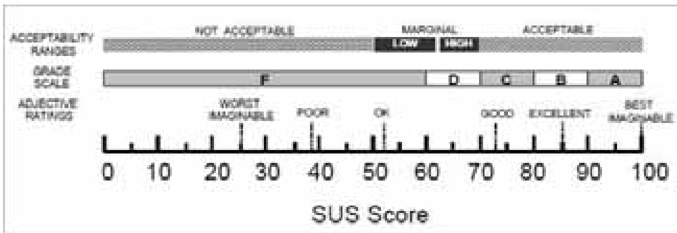
Purpose	Dependent variable	Description
Thermal comfort evaluation	Overall sensation	The thermal sensation is asked in the room environment, in the car before using the HVAC system, and after the HVAC usage. The participants are asked to describe their overall thermal sensation as well as for different body parts (Appendix B – Thermal comfort questionnaire).
	Preferred climate	In comparison to the perceived thermal sensation, participants are also asked about the preferred climate condition three times (Appendix B – Thermal comfort questionnaire).
	Humidity and air flow sensation	Participants are asked regarding their sensation about the humidity and air flow three times.
	Acceptance and satisfaction of the thermal condition	The acceptance and satisfaction regarding the current environment are asked three times with the answer possibilities yes/no (Appendix B – Thermal comfort questionnaire).
	Preferred car	The preference between both cars regarding the thermal comfort is asked. Participants can also choose no preference.
Usability	Task performance	The moderator rates the performance of the participants based on pre-defined criteria (Table 10).
	Task-based ease of use	The participants are asked to rate how easy it was to complete the task based on a 7-point Likert scale from 1-very difficult to 7-very easy.
	Task-based satisfaction	The participants are asked to rate how satisfied they were with completing the task based on a 7-point Likert scale from 1-very dissatisfied to 7-very satisfied.
	SUS (System Usability Scale)	10-item questionnaire to measure usability of the tested system. The outcome is an absolute value between 0-100. [13] 
	SD (Semantic Differential)	9 pairs of opposite words scaled from 1 to 5 (Appendix E – Semantic Differential (SD)) describing the tested system to measure the connotative meaning of the tested system. Participants are asked to describe the tested system with a suitable word and scale.
	Preferred HMI	The participants are asked to choose their preference of both HMIs regarding the usability. Participants can also choose no preference.

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Table 10: Description of task performance ratings

1	Correct solution, optimal operation path or alternative optimal operation path
2	Correct solution with unnecessary operation steps, or corrected mistake
3	Partly correct solution
4	Wrong solution, operation does not contribute to the solution or is even counterproductive

4.1.3 Participants

Due to COVID-19, it was only possible to recruit internal participants for the final user evaluation. All the N = 26 internal participants (20 male and 6 female) hold valid driving license. They are neither HVAC experts nor expert drivers, but experts in other automotive fields. Further detailed information regarding the participants is depicted in Figure 25 to Figure 29.

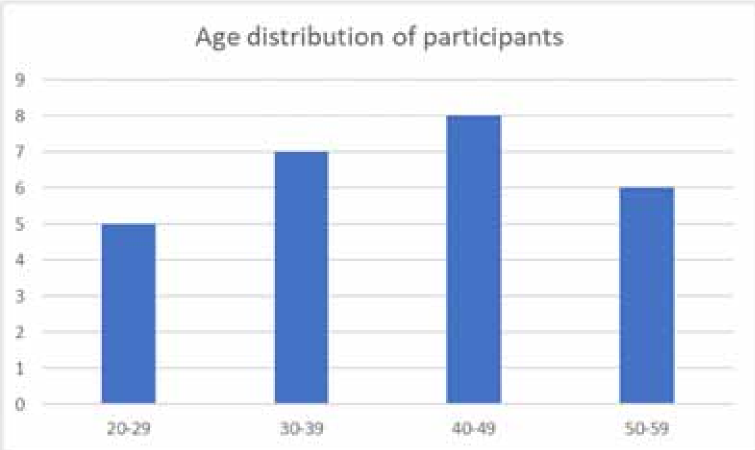

Figure 25: Age distribution of participants.

Figure 26: Driving mileage per year.

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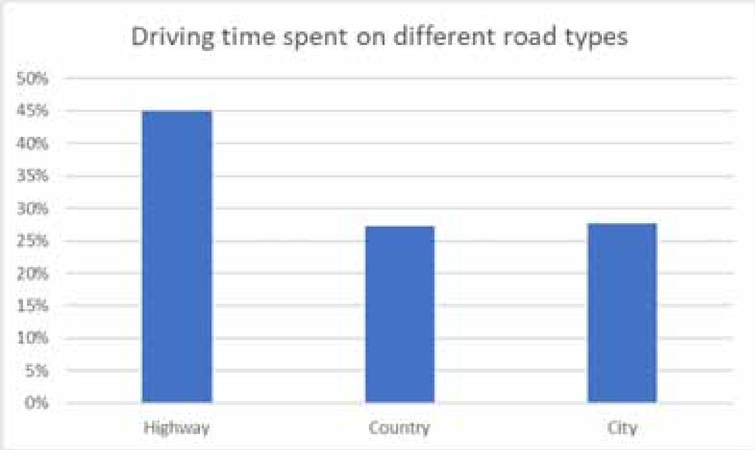

Figure 27: Driving time spent on different road types.

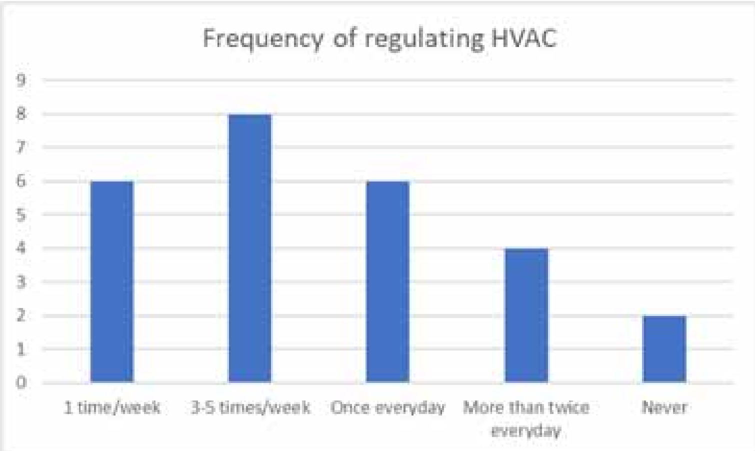

Figure 28: Frequency of regulating HVAC in own car.

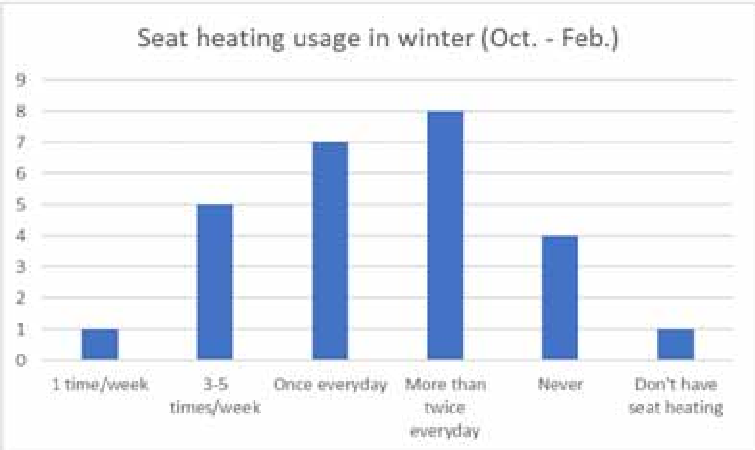

Figure 29: Seat heating usage in winter.

4.1.4 Procedure

To investigate the thermal comfort, a controlled thermal environment needs to be assured for the assessment, so that all participants have the same basis of assessment. Because constant climate conditions cannot be guaranteed in the outside environment over the complete test period and both winter and summer conditions

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have to be investigated, HRE decided to use the facility's chassis dyno climate chambers (Figure 30). Although this facility is not a full-size climatic wind tunnel, it is expected to be suitable for a direct comparison between the two test objects. However, the absolute thermal comfort ratings should be treated with reservation and cannot be seen universally valid results.

Figure 30: Chassis dyno in HRE.

As mentioned before, both winter (5°C, 80% relative humidity) and summer conditions (32°C, 40% relative humidity) should be considered. As the focus is not to compare the two weather conditions and to reduce the complexity of the experimental design as well as recruitment, part of the participants compared the two cars based on the winter condition and the other part based on the summer condition. All participants experienced two cars: the QUIET demonstrator and the baseline EV (Honda FIT EV). The order of the presented cars is balanced over all participants and tested climate conditions. This means that half of the participants started with the QUIET demonstrator and then experienced the baseline EV, the other half started with the baseline EV and then experienced the QUIET demonstrator. Each participant came to experience the 1st car (1st visit) and came again to experience the 2nd car (2nd visit). The length of each visit was 60 min., which means in total each participant spent 2 hours in the investigation.

To simulate a natural HVAC usage situation, a simple driving task was conducted by the participants on the chassis dyno. All participants conducted the HVAC HMI tasks (Table 11) while performing basic driving by trying to keep a constant speed of 40 km/h. While driving, the simulated road load from the chassis dyno was changed slightly. This required the participant to observe the car's speedometer constantly and to adjust the accelerator pedal position according to the changing boundary conditions. The selected HVAC tasks are common use cases while regulating the HVAC, which cover the areas of selecting an object, increasing/decreasing temperature, and regulating the Eco mode and seat heating. As the tasks fit the test story, the sequence of experiencing those tasks is not randomized.

Before the participants came to the test location, they were informed via email to read and sign the consent form, if they agree with the stated information. Furthermore, they received information and instructions about safety measures (e.g. wearing a face mask, keeping a safety distance of 2 m to other people, and regular disinfection of hands) that they need to follow during the study sessions. They were also informed to wear or to bring pre-defined types of clothing defined based on the [14] for winter and summer conditions to ensure a comparable baseline for the thermal comfort sensation for all participants. On the day of the interview, the participants have to bring the signed consent form and clothing.

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Table 11: Description of HVAC tasks for winter and summer conditions

Winter	Summer
Task 1 Please imagine you just entered the car after taking a walk outside. You are feeling cold and want to heat up as quickly as possible. Please set the climate control system to heat you up as quickly as possible.	Task 1 Please imagine you just get into your car after taking a walk outside. You are feeling warm and would like to be cooled as quickly as possible. Please set the climate control system to cool you down as quickly as possible.
Task 2 You have now set the climate settings to heat you up, but you still have cold feet. Please adjust the climate settings to heat up your feet.	Task 2 Imagine that you have been driving for a while now, but your upper body is still very hot, and you are sweating. Please set the climate control system to cool down your upper body.
Task 3 Imagine you have just picked up a friend who waiting for your arrival on the sidewalk. You are feeling comfortable now, but you can see that your friend on the passenger seat is feeling cold, so you want to adjust to climate control to heat him up.	Task 3 Imagine that you just picked up a friend. You are now comfortably cool, but you can see that your friend is still very warm. Please set the climate control system to cool down your friend a bit.
Task 4 After driving for a while both, you and your friend, are feeling a little bit too warm. This is why you want to adjust the climate settings to make you cool down a little bit.	Task 4 Imagine that you have been driving in the car with your friend for quite a while now. You two are feeling a little too cool. Please set the climate control system to warm you both up a bit.
Task 5 Imagine you and your friend are on your way back from your trip. The range of your electric vehicle is already low. You are feeling cold, so you want to adjust the climate settings to heat you up efficiently to not lose additional range.	Task 5 Imagine that you and your friend are now on the way back home from your trip. The range of your electric car is now relatively low. Since you are both warm, you would like to cool as efficiently as possible to save the range. Please set the climate control system to cool you and your friend down in the most efficient way.

Due to COVID-19, a special safety measurement was implemented to make sure that the participants could perform the test in a safe environment. The participant sat alone in the car performing the driving task and HVAC tasks. The moderator and the operator of the chassis dyno sat in different rooms. A video communication was available among three sides and a walky-talky was prepared as a backup solution. During the whole procedure the moderator and participant kept a safety distance of at least 2 m.

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As depicted in Figure 31, at the test location the moderator welcomed the participants. Afterwards the moderator introduced the participants to the procedure of the interview and the safety rules for the chassis dyno. If the participants were comfortable with the procedure, a short pre-questionnaire was filled out on a tablet to assess demographic data and information about driving behaviour (Appendix A – Demographic questionnaire). Next, the participants were asked to fill out the thermal comfort questionnaire (Appendix B – Thermal comfort questionnaire) on the tablet to assess the baseline in room environment. Then the participants were invited to get into the first test car. During the time in the car, the participants were asked to take off the masks, as the mask might have influenced the thermal sensation. After that, the participants filled out the thermal comfort questionnaire (Appendix B – Thermal comfort questionnaire) on the tablet to assess their baseline for the non-air-conditioned car environment and to provide their first impression of the HVAC HMI without operating it. Afterwards, the moderator instructed the participants about how to drive on the chassis dyno and the participants had 5 min. to get familiar with the task and the environment. As next, the participants were asked to start driving and keep a constant speed of 40 km/h. In the meanwhile, the evaluation tasks started, and the moderator read out the standardized task description. Participants could ask questions or start with the task. The same procedure was repeated for the other tasks. After each task completion, participants rated their subjective ease of use and satisfaction (Appendix C – Usability Questionnaire). After all tasks were completed, the participants were asked to answer the System Usability Scale (SUS) (Appendix D – System Usability Scale (SUS)) and fill out the thermal comfort questionnaire on the tablet (Appendix B – Thermal comfort questionnaire) again for evaluating the effectiveness of the HVAC system. These questionnaires were asked while the participants were not driving. The first visit ended with a short qualitative wrap-up (Appendix F – Final Questionnaire) about the overall impression of the HVAC HMI and the thermal comfort. The participant was kindly asked to leave the chassis dyno. During the time between two sessions, the car was ventilated and re-conditioned to the ambient summer/winter condition in the chassis dyno. Furthermore, the moderator disinfected all areas and equipment that were used and touched by the participant as well as his own equipment. The same procedure as the first visit was performed in the second car during the second visit. At the end, the participants were asked to compare both cars (Appendix F – Final Questionnaire).

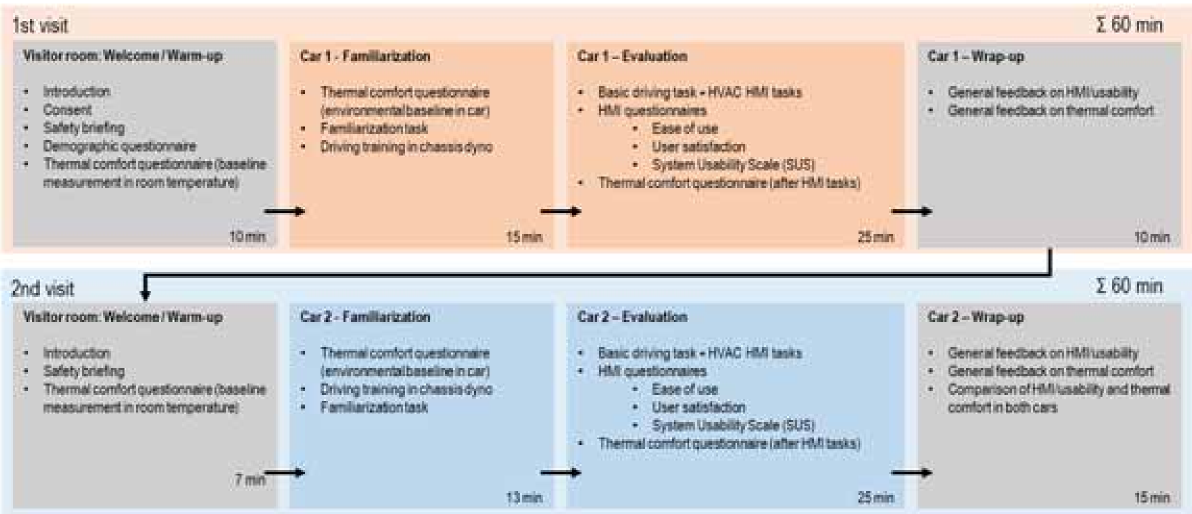

Figure 31: Test procedure of the final user study.

4.1.5 Data collection and analysis

N = 15 participants experienced two cars in the winter condition and N = 11 participants experienced them in the summer condition. The data used to evaluate the QUIET HVAC HMI were task performance (objective)

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and collected from questionnaires, which were subjective ratings from the participants. Part of the data was analysed by comparing to the criteria stated in [15]. The rest of the data was analysed using statistical analysis methods with the significance level 0.05. As the collected data do not fulfil the requirements for using parametric statistical analysis methods, non-parametric methods (Wilcoxon matched pairs signed-rank test, Chi-square test, Fisher's exact test, and McNemar test) were applied with R. Fisher's exact test instead of Chi-square test was applied for some datasets, because the requirement regarding the expected value could not be fulfilled. Due to the same reason, the effect size could not be calculated. Therefore, only the *p*-value is available for the results, which were analysed with Fisher's exact test.

4.2 Results

4.2.1 Thermal comfort

4.2.1.1 Overall sensation

According to [15], no discomfort was perceived regarding the thermal comfort in both cars after the usage of the HVAC system for both winter and summer conditions, as the median of the overall sensation ratings (Winter: $Mdn_{w\_after\_QUIET} = 0$, $Mdn_{w\_after\_FIT} = 0$; Summer: $Mdn_{s\_after\_QUIET} = 1$, $Mdn_{s\_after\_FIT} = 1$) and the number of discomfort ratings (Winter: $Ndis_{w\_after\_QUIET} = 0$, $Ndis_{w\_after\_FIT} = 0$; Summer: $Ndis_{s\_after\_QUIET} = 0$, $Ndis_{s\_after\_FIT} = 0$) are below the discomfort thresholds. The baseline condition in the car environment for winter before usage of HVAC system for both cars was considered as discomfortable ($Mdn_{w\_after\_QUIET} = -2$, $Mdn_{w\_after\_FIT} = -2$; $Ndis_{w\_after\_QUIET} = 2$, $Ndis_{w\_after\_FIT} = 3$). For the summer condition, the baseline condition in car environment only shows discomfort in the FIT EV due to higher median compared the threshold ($Mdn_{s\_after\_QUIET} = 1$, $Mdn_{s\_after\_FIT} = 2$; $Ndis_{s\_after\_QUIET} = 0$, $Ndis_{s\_after\_FIT} = 0$).
By applying the Wilcoxon matched pairs signed-rank test, the results of overall thermal sensation show a significant difference between the QUIET demonstrator and the FIT EV ($Z = 33$, $p < .05$, $r = 0.349$) for the winter condition after the HVAC usage. As shown in Figure 32, the perceived thermal comfort for the QUIET demonstrator is colder than the one for the FIT EV for the winter condition. The results also show significant difference before and after the HVAC usage in both cars ($Z_{QUIET} = 0$, $p < .001$, $r = 0.73$; $Z_{FIT} = 105$, $p < .001$, $r = 0.743$) for the winter condition. This means that both cars could significantly improve the thermal sensation after using the HVAC system. No significant difference is found for the summer condition (Figure 33).

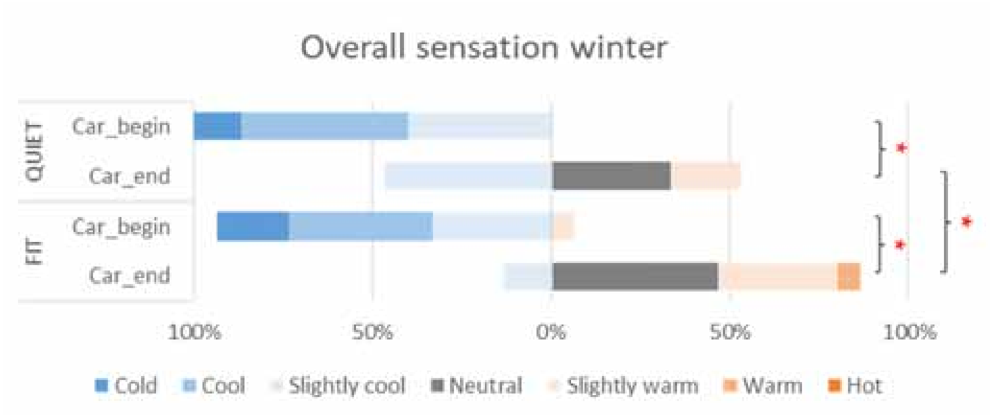

Figure 32: Comparison of overall thermal sensation for winter condition.

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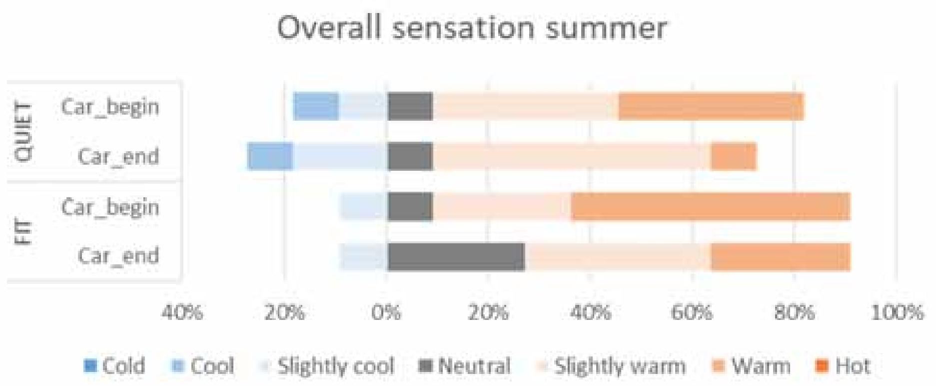

Figure 33: Comparison of overall thermal sensation for summer condition.

4.2.1.2 Preferred climate

To better understand the desired thermal condition of the participants, the preferred climate condition was asked. Same as for the overall thermal sensation, a Wilcoxon matched pairs signed-rank test was conducted to analyse the data. For the winter condition, significant differences ($Z_{QUIET} = 0$, $p < .05$, $r = 0.644$, $Z_{FIT} = 0$, $p < .05$, $r = 0.577$) between the preferred conditions before and after the usage of the HVAC were found in both cars respectively. It can be seen in Figure 34, that the preferred thermal condition before the HVAC usage is significantly warmer than the one after the HVAC usage for both cars. This means that the HVAC system could modulate the climate condition in the car to meet the participants' needs.

No significant results could be obtained for the summer condition (Figure 35). For both cars the participants would still prefer a cooler climate condition after the HVAC regulation.

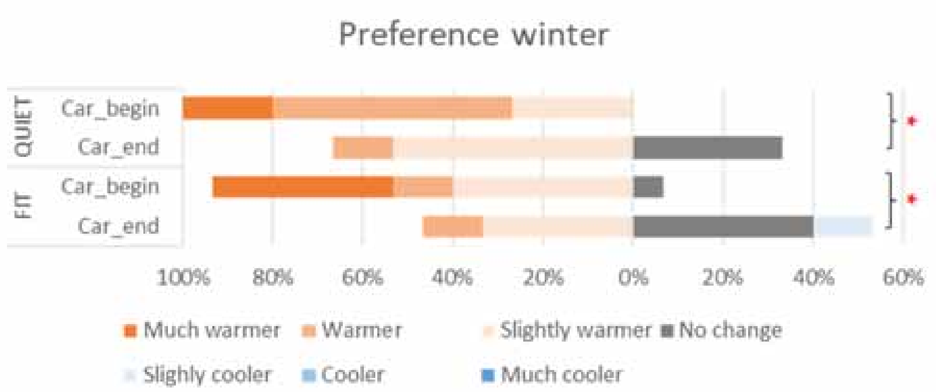

Figure 34: Comparison of preferred climate condition in both cars before and after HVAC usage for winter condition.

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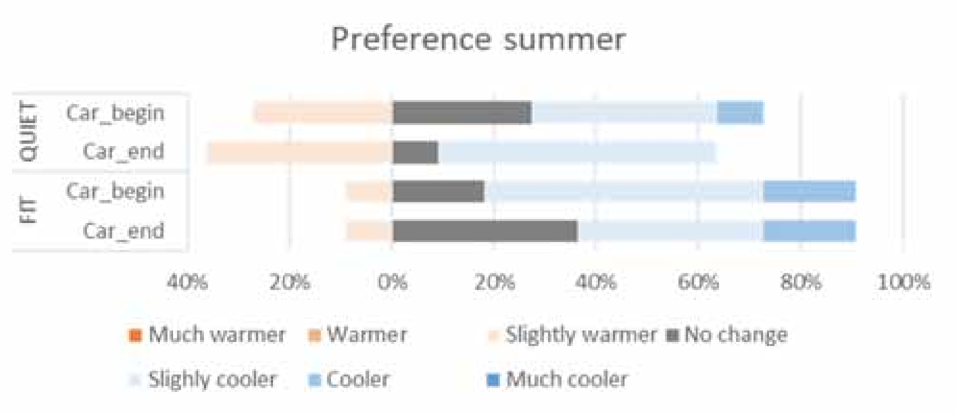

Figure 35: Comparison of preferred climate condition in both cars before and after HVAC usage for summer condition.

4.2.1.3 Humidity and air flow

The humidity and the air flow of the test environment before and after the usage of the HVAC system was evaluated by the participants. No significant differences were found in both winter and summer conditions. As shown in Figure 36, the perceived humidity and air flow in the winter condition were mostly rated as "just right". In the summer condition, the humidity was rated between "just right" and "too dry". The air flow was rated rather as "too breezy". A slight improvement in the air flow for the summer condition could be found in the FIT EV compared to the QUIET demonstrator.

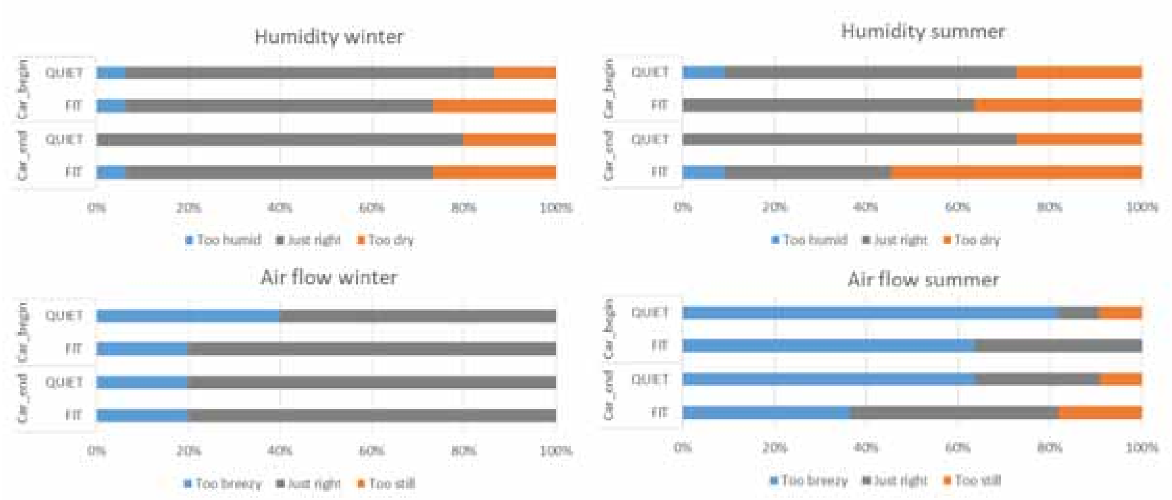

Figure 36: Comparison of perceived humidity and air flow in both cars before and after HVAC usage for winter and summer conditions.

4.2.1.4 Acceptance and satisfaction

The acceptance and satisfaction of the thermal condition were asked in the room environment, after arrival in the car, and after the HVAC usage in the car environment respectively. According to [15], the initial in-car environments in both cars were considered as not acceptable ($Ndis_{w\_car\_initial\_QUIET} = 12$, $Ndis_{w\_car\_initial\_FIT} = 9$) and participants were dissatisfied ($Ndis_{w\_car\_initial\_QUIET} = 11$, $Ndis_{w\_car\_initial\_FIT} = 6$) for the winter condition, which reflects the rated overall sensation. The environment after the HVAC regulation in both cars were rated

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as acceptable ($Ndis_{w\_car\_final\_QUIET}$ = 2, $Ndis_{w\_car\_final\_FIT}$ = 1) and the participants were satisfied ($Ndis_{w\_car\_final\_QUIET}$ = 4, $Ndis_{w\_car\_final\_FIT}$ = 1). For the summer condition, the initial in-car environments in both cars were rated as acceptable ($Ndis_{s\_car\_initial\_QUIET}$ = 1, $Ndis_{s\_car\_initial\_FIT}$ = 2) but the participants were not satisfied ($Ndis_{s\_car\_initial\_QUIET}$ = 5, $Ndis_{s\_car\_initial\_FIT}$ = 5). The environment after the HVAC regulation in the QUIET demonstrator was rated as acceptable ($Ndis_{s\_car\_final\_QUIET}$ = 1) but participants were not satisfied ($Ndis_{s\_car\_final\_QUIET}$ = 6). In comparison, the environment after the HVAC regulation in the FIT EV was rated as acceptable ($Ndis_{s\_car\_final\_FIT}$ = 1) and participants were satisfied ($Ndis_{s\_car\_final\_FIT}$ = 4).

The McNemar test was applied to analyse the data. As shown in Figure 37, both acceptance and satisfaction of the environment after the HVAC regulation in the QUIET demonstrator increased significantly in comparison to the environment before the HVAC usage for the winter condition (Acceptance: χ^2 (1, N = 15) = 8.1, $p < .005$, *Cohen's g* = 0.5; Satisfaction: χ^2 (1, N = 15) = 5.1429, $p < .05$, *Cohen's g* = 0.5). However, only the acceptance of the environment after the HVAC modulation in the FIT EV increased significantly in comparison to before for the winter condition (χ^2 (1, N = 15) = 6.125, $p < .05$, *Cohen's g* = 0.5), although the satisfaction rating for the environment before the HVAC regulation in both cars did not show any significant difference. The satisfaction with the FIT EV before and after the HVAC regulation did not show any significance. No significant differences (Figure 38) were found regarding acceptance and satisfaction for the summer condition, although some of the environments were rated as discomfortable [15].

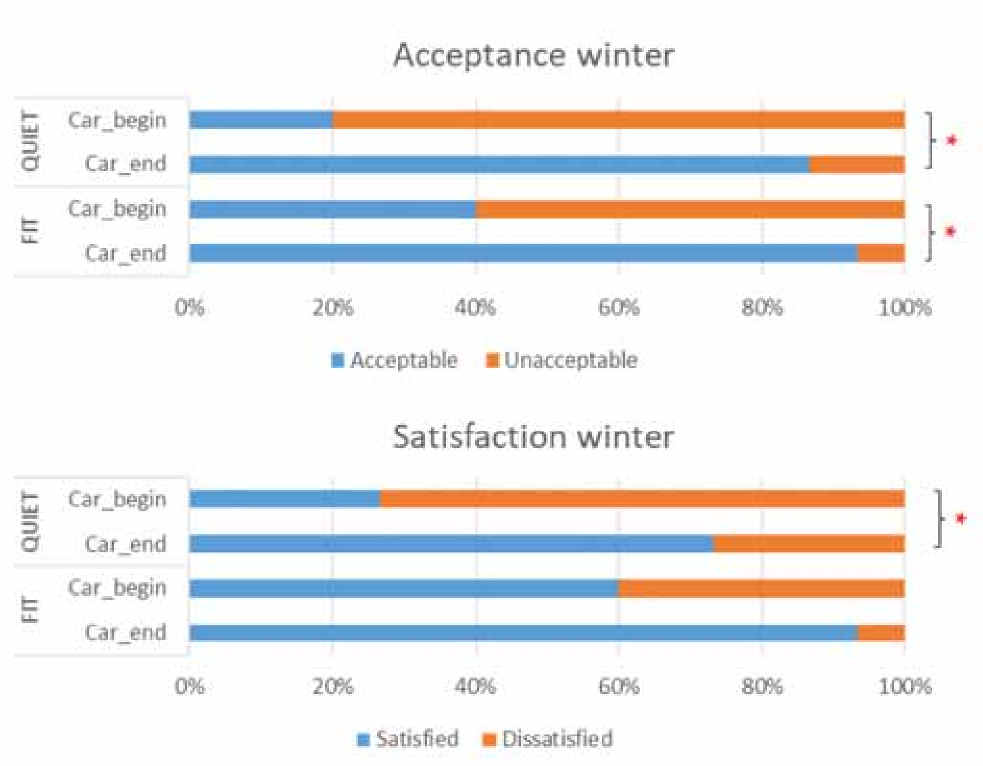

Figure 37: Comparison of acceptance and satisfaction of the thermal environment before and after HVAC regulation in both cars for winter condition.

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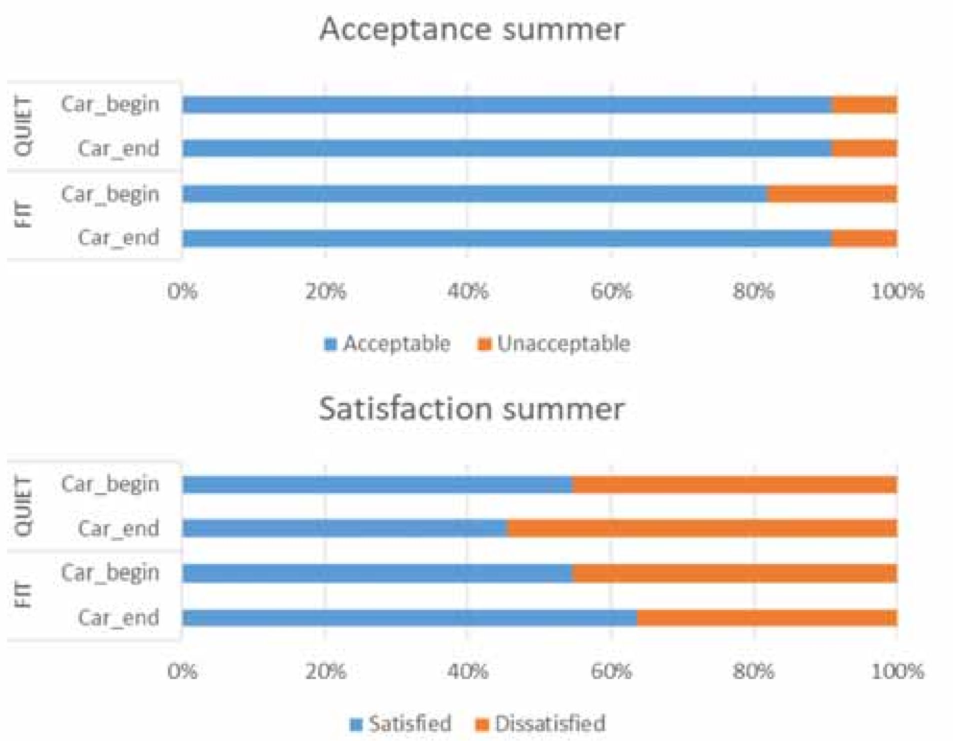

Figure 38: Comparison of acceptance and satisfaction of the thermal environment before and after HVAC regulation in both cars for summer condition.

4.2.1.5 Preference regarding thermal comfort

As shown in Figure 39, the FIT EV was slightly preferred regarding the thermal comfort for the winter condition, but no significance was found. For the summer condition, both the QUIET demonstrator and the FIT EV share the same preference.

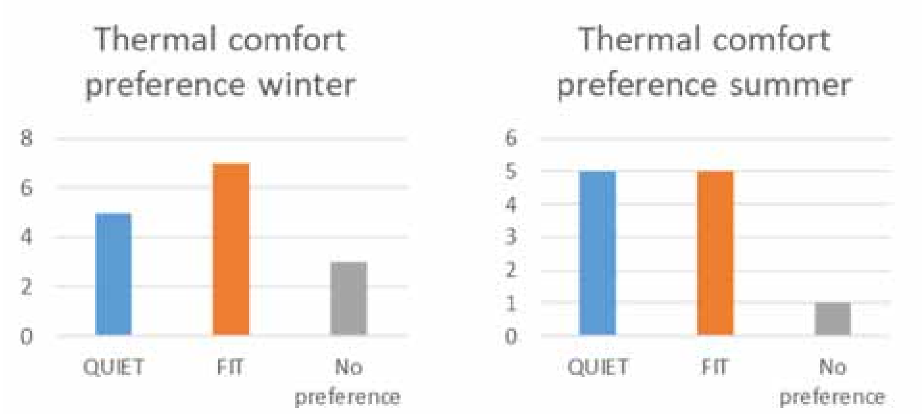

Figure 39: Users' preference regarding thermal comfort for both weather conditions.

4.2.2 Usability

The usability of both car HMIs was evaluated with both objective and subjective methods. At the end of the study, each participant was asked to choose the preferred HMI. These results are described in the following sections.

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4.2.2.1 System Usability Scale (SUS)

Wilcoxon matched pairs signed-rank test was conducted to compare the results. There is no significant difference found between the QUIET demonstrator HVAC HMI and the FIT EV HVAC HMI. However, different levels (excellent, good, OK) are defined in the score [16]. The overall trend (Figure 40 and Figure 41) shows higher scores for the FIT EV in both the winter condition lying in the "good" area and in the summer condition "OK" area, whereas the QUIET demonstrator received a lower rating lying in the "OK" area. In comparison to the SUS score (Figure 42) from the previous usability test, the results from the final user study are slightly lower but lying in the same area. The main reasons are summarized in section 4.3.1 Discussion.

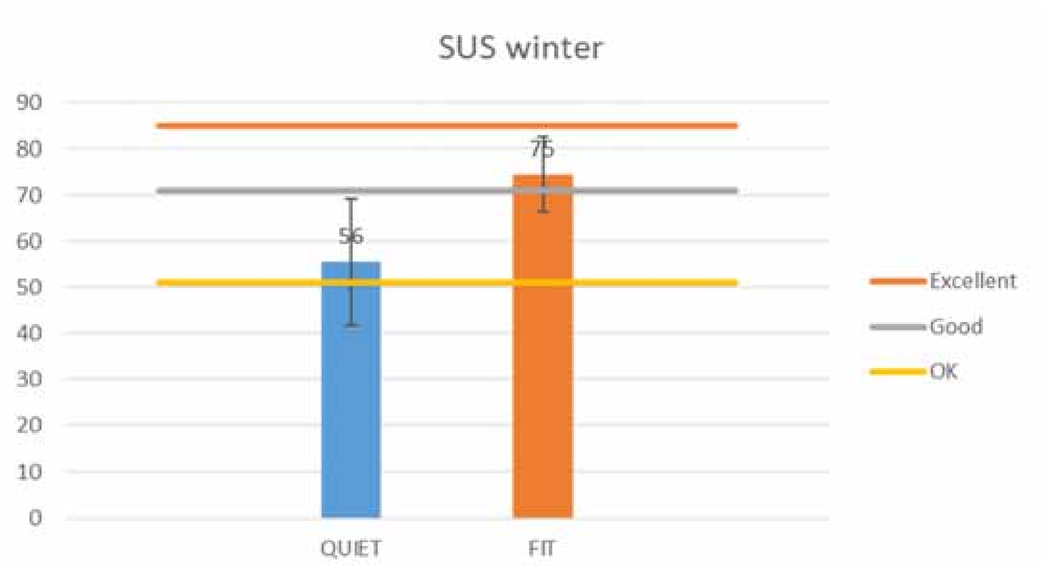

Figure 40: Comparison of SUS between QUIET demonstrator and FIT EV for winter condition.

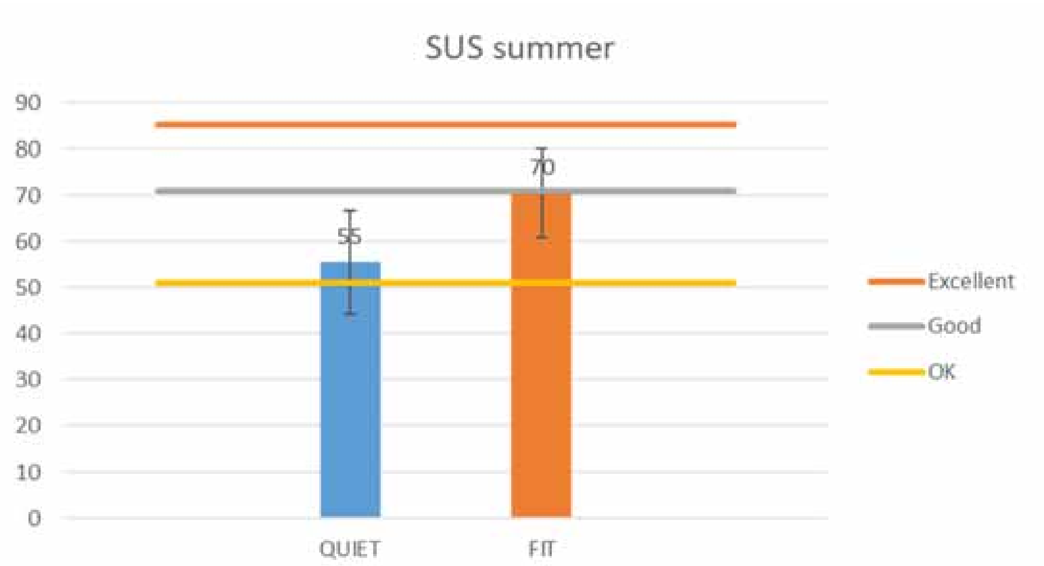

Figure 41: Comparison of SUS between QUIET demonstrator and FIT EV for summer condition.

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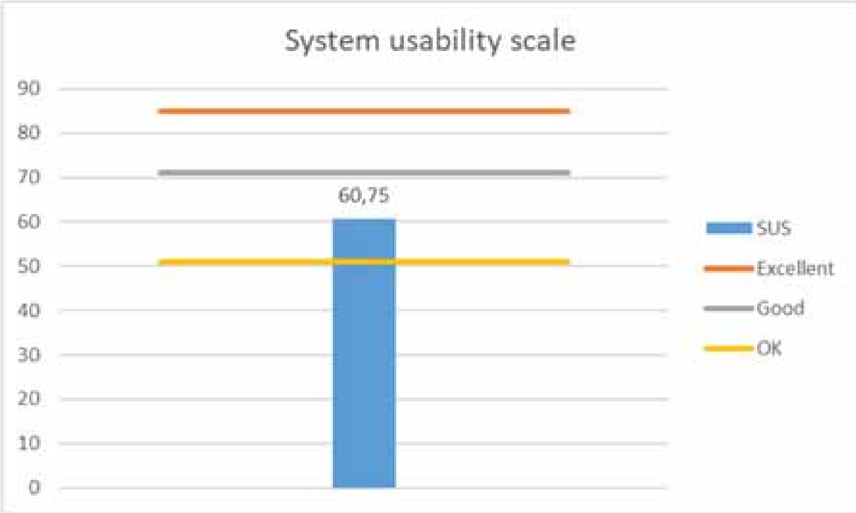

Figure 42: SUS score of QUIET demonstrator in previous usability test [16].

4.2.2.2 Semantic differential (SD)

A semantic differential was used to measure the connotative meaning of the tested HMIs. As shown in Figure 43 and Figure 44, both cars were rated as positive in both climate conditions. A Wilcoxon matched pairs signed-rank test was used to obtain statistical results. For the winter condition, the QUIET demonstrator was rated as significantly more "irritating" and less "likeable" than the FIT EV ($Z = 47.5$, $p < .05$, $r = 0.429$). For the summer condition, the QUIET demonstrator was rated significantly less "effective" ($Z = 0$, $p < .05$, $r = 0.593$) and more "difficult" ($Z = 0$, $p < .05$, $r = 0.424$) than the FIT EV.

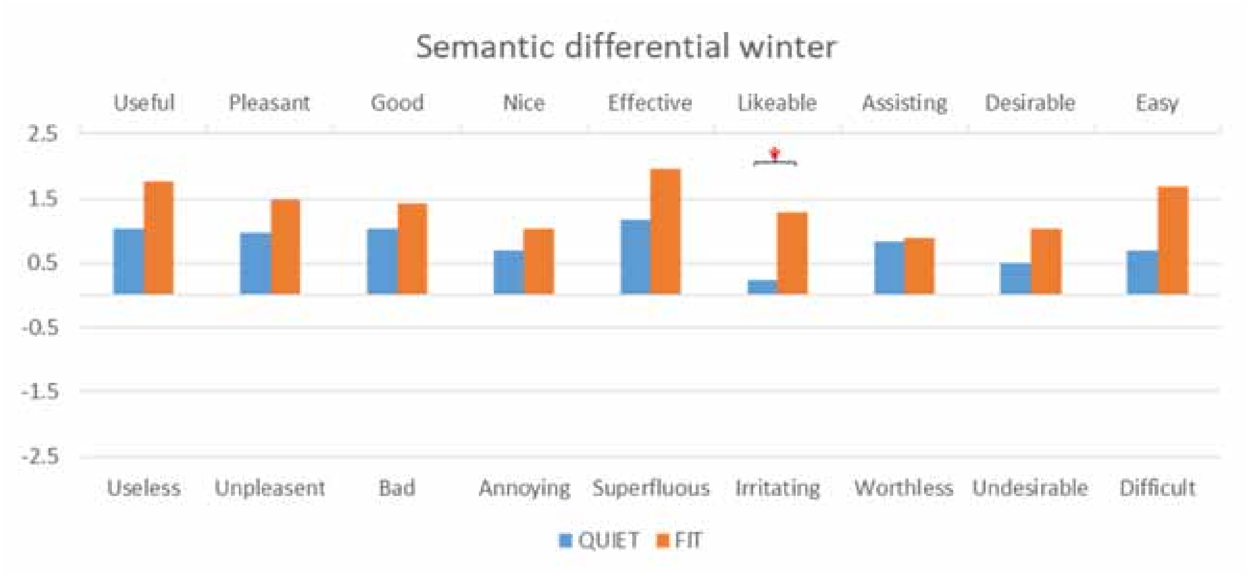

Figure 43: Comparison of SD between QUIET demonstrator and FIT EV for winter condition.

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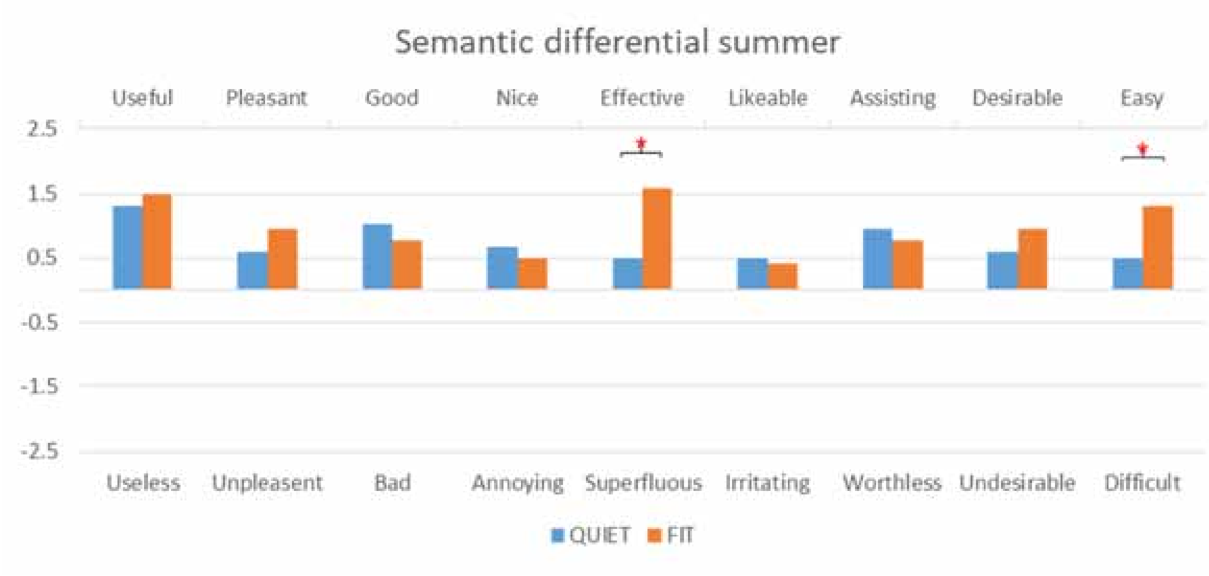

Figure 44: Comparison of SD between QUIET demonstrator and FIT EV for summer condition.

4.2.2.3 Preference regarding usability

As shown in Figure 45, the FIT EV was slightly preferred regarding the usability for the winter condition, but no significance was found. Similar to the winter condition, the preference did not show significance in regard to usability for the summer condition.

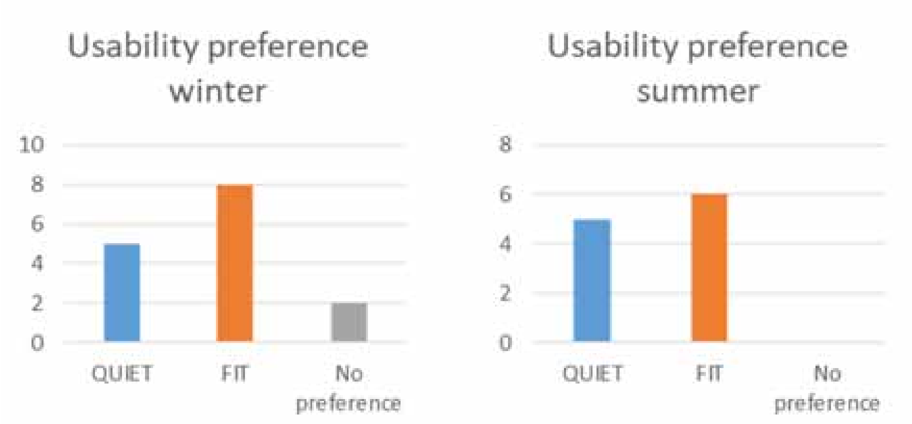

Figure 45: Users' preference regarding usability comfort for both weather conditions.

4.2.2.4 Task-based ratings and issues

To evaluate the QUIET demonstrator HVAC usability in comparison to the baseline (FIT EV HVAC) each participant had to solve 5 use cases in both cars, that were related to common thermal comfort issues in a summer or winter scenario e.g., the driver or passenger is feeling too warm or too cold respectively. Based on these 5 use cases, the participants had to operate the HVAC system accordingly in 5 tasks to adapt the climate inside the car. To support the plausibility of the use cases for the participants in a summer and winter scenario, the climate conditions in the test location were representative for a typical summer or winter day. Each of the participants either experienced the summer or the winter condition in both, the QUIET demonstrator and the FIT EV, in two separate sessions. The order of presentation was balanced over all participants to balance out

order effects. The metrics used to evaluate those tasks are listed in Table 9 (task performance, task-based ease of use, and task-based satisfaction).
In this section the task-based results for the winter and summer conditions are described for each of the 5 use cases per condition. Chi-square test or Fisher's exact test (requirements for Chi-square test were not fulfilled) was applied to analyse the data.

- Winter condition
  1. Task 1 – the driver is feeling too cold
     Although the task completion rate for the QUIET HMI was significantly better compared to the original FIT EV HMI (χ^2 (3, N = 11) = 20.118, $p < .001$, Cramer's V = 0.819), perceived ease of use and user satisfaction have a more positive tendency for the FIT EV HMI (Figure 46 and Figure 47). The main usability issue stated by the participants was the lack of feedback for the QUIET HMI. In many cases the visual change on the display after the system operation was not available long enough to be perceived by the participants. In addition, other indicators that would have helped to understand that the operation was effective like the change in climate (e.g., fan speed) or the change of the progress bar status was not obvious enough. This resulted in repeated activation of the "I am cold" button by the participants.

Figure 46: Task completion rating for task 1 in the winter condition for QUIET demonstrator and FIT EV.

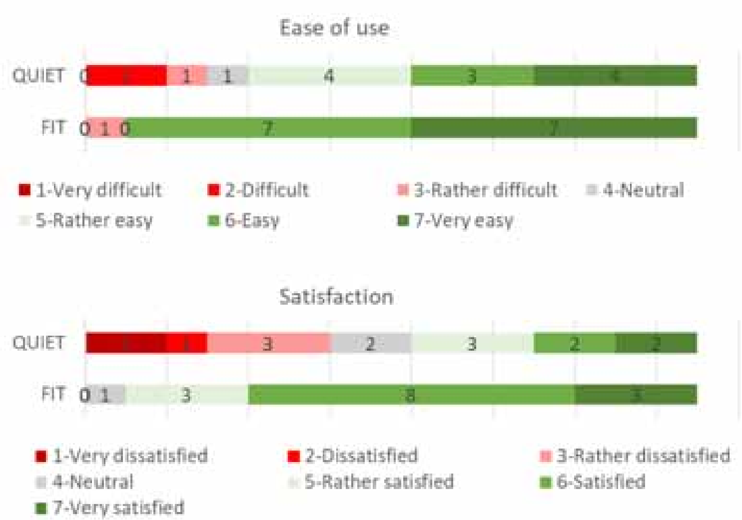

Figure 47: Ease of use and satisfaction user ratings for task 1 in the winter condition for the QUIET demonstrator and the FIT EV.

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2. Task 2 – the driver has cold feet

The average task completion rate to heat single body parts i.e., the lower body of the driver, was significantly better for the original FIT EV HMI compared to the QUIET HMI (χ^2 (3, N = 11) = 9.3158, p < .05, Cramer's V = 0.557). As shown in Figure 48, for the QUIET HMI there is a clear separation of half of the participants who did not have any problems and the other half of the participants who were not able to solve the task. This is also represented in the large number of participants who rated the ease of use and satisfaction of the HMI as low for this task, although overall no statistical significance was found for ease of use and satisfaction (Figure 49). The different task performance of the participants for this task is also reflected in the different qualitative user feedback. On the one hand some rated the HMI as maximally effective and on the other hand some participants were not sure in which order they had to press the buttons. Furthermore, opinions about the possibility to select single body parts differed among the participants. Some participants stated that they like the feature, but others rated it as unexpected and cumbersome. Like the previous use case, the participants struggled with the missing feedback. Furthermore, the difference between the dashed and continuous lines around the body parts was unclear for some participants.

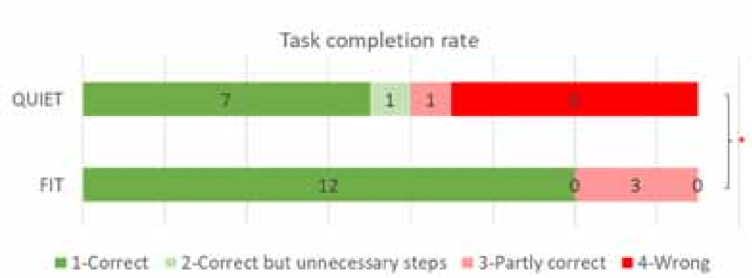

Figure 48: Task completion rating for task 2 in the winter condition for QUIET demonstrator and FIT EV.

Figure 49: Ease of use and satisfaction user ratings for task 2 in the winter condition for the QUIET demonstrator and the FIT EV.

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3. Task 3 – only the passenger is feeling too cold
   For the use case to heat the passenger the task completion rate for the QUIET HMI (Figure 50) was significantly lower than for the original FIT EV HMI (χ^2 (3, N = 11) = 8, $p < .05$, Cramer's V = 0.516). No significant difference was found for the ease of use and user satisfaction rating in this use case for the QUIET HMI and the original FIT EV HMI (Figure 51), but for user satisfaction in total N = 6 participants were dissatisfied with the QUIET HMI operation whereas no one was dissatisfied with the operation of the FIT EV HMI. The observed user issues were that in some cases a body part of the driver was still selected, and participants did not de-select it before selecting the passenger. Furthermore, the wording "I am" on the buttons was confusing for the participants when they wanted to adjust the temperature for the passenger. Still the main issue for the participants was the lack of feedback and in some cases counterintuitive feedback. Counterintuitive visual feedback occurred when the regulation logic of the HVAC system did not match with the operation logic of the participant (e.g., after selecting "I am cold", red body parts and blue waves were shown or although only the passenger was selected both, the driver and the passenger were visualized as blue bodies with red waves).

Figure 50: Task completion rating for task 3 in the winter condition for QUIET demonstrator and FIT EV.

Figure 51: Ease of use and satisfaction user ratings for task 3 in the winter condition for the QUIET demonstrator and the FIT EV.

4. Task 4 – the driver and the passenger are feeling too warm
   No significant differences for the task completion rate (Figure 52) as well as ease of use and user satisfaction (Figure 53) were found in task 4, where the participants had to lower the temperature for

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the driver and passenger. For the QUIET HMI only three out of 15 participants had usability issues during the operation. These occurred because the difference between the dashed and continuous line was unclear and difficult to discern while driving. In addition to the missing feedback that was mentioned in most of the tasks for the winter and summer conditions, participants did not understand the purpose of the progress bar, because the bar did not continuously increase like expected but jumped back and forth.

Figure 52: Task completion rating for task 4 in the winter condition for QUIET demonstrator and FIT EV.

Figure 53: Ease of use and satisfaction user ratings for task 4 in the winter condition for the QUIET demonstrator and the FIT EV.

5. Task 5 – heat efficiently with low range
For both, the QUIET HMI and the original FIT EV HMI the participants had difficulties to find a way to heat the car efficiently when the driving range is low. As shown in Figure 54, for the original FIT EV HMI the task completion rate is significantly lower compared to the QUIET HMI ((χ^2 (3, N = 11) = 8.75, p < .05, Cramer's V = 0.54). For the QUIET HMI 5 out of 15 people were able to solve the task without problems, whereas for the original FIT EV HMI only 1 participant did not encounter any issues. Although the task completion rate for the QUIET HMI is better than for the FIT EV HMI more participants rated the ease of use and user satisfaction negatively (Figure 55). Although the visualization of the energy efficiency of the current climatization process in form of the green leaves was initially understood by many participants only a few used it as an indicator for this task. Some participants misunderstood the ECO mode "Max" as less efficient (i.e., max power). Furthermore, the

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participants did not identify the seat heating as an energy efficient heating option and switched it off not trusting the "Auto" setting.

Figure 54: Task completion rating for task 5 in the winter condition for QUIET demonstrator and FIT EV.

Figure 55: Ease of use and satisfaction user ratings for task 5 in the winter condition for the QUIET demonstrator and the FIT EV.

- Summer condition
  1. Task 1 – the driver is feeling too warm
     The task completion rate for the QUIET HMI is significantly higher than the one for the FIT EV HMI ($p < .001$). For the FIT EV HMI no one was able to complete the task without problems (Figure 56). However, more participants rated the QUIET HMI as more difficult to use than the FIT EV HMI and less participants were satisfied with the QUIET HMI (Figure 57). The participants also mentioned the missing feedback as the main problem they encountered. They often selected "I am hot" repeatedly and even then, they were unsure if their operation was correct. Next to the usability issues, participants criticized the strong airflow and that an option to adjust the airflow was missing. Participants were irritated that the airflow did not stop immediately after they selected "I am cosy", because they would expect that the HVAC regulation stops.

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Figure 56: Task completion rating for task 1 in the summer condition for QUIET demonstrator and FIT EV.

Figure 57: Ease of use and satisfaction user ratings for task 1 in the summer condition for the QUIET demonstrator and the FIT EV.

2. Task 2 – the driver's upper body is feeling too warm
   No significant difference for the task completion rate was found for the QUIET HMI in comparison to the original FIT EV HMI in task 2 of the summer condition (Figure 58). As shown in Figure 59, the FIT EV HMI received significantly higher ratings for user satisfaction ($p < .05$). Similar to the winter condition, the participants commented on the missing feedback of the QUIET HMI. Furthermore, some participants were unsure in which order they have to the select the body parts and the "I am hot" button. The possibility to select single body parts was unexpected for some participants and the difference between the dashed and continuous lines around the body parts was unclear. Furthermore, the meaning of the term "regulating comfort" in the progress bar was unclear for some participants.

Figure 58: Task completion rating for task 2 in the summer condition for QUIET demonstrator and FIT EV.

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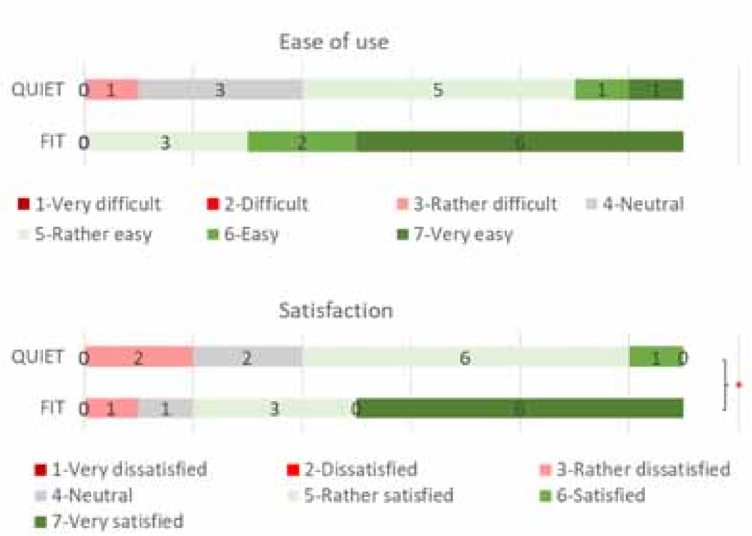

Figure 59: Ease of use and satisfaction user ratings for task 2 in the summer condition for the QUIET demonstrator and the FIT EV.

3. Task 3 – only the passenger is feeling too warm
   Similar results are found for the QUIET HMI in comparison to the FIT EV HMI for task 3 regarding task completion rate, ease of use, and satisfaction (Figure 60 and Figure 61). Issues for the QUIET HMI were, besides the missing feedback, that it is difficult to identify the driver in the image. Like task 3 of the winter condition, in some cases the driver was still selected and not de-selected before changing the temperature and the participants were irritated by the wording "I am hot" in this use case, because it refers only to the participant i.e., the driver and not the passenger. In addition, some participants criticized that the visualization of the waves did not correspond to the strength of the airflow. Furthermore, in some cases the cooling visualization was shown for the driver and the passenger although only the passenger was selected. Because the visualization was directly coupled with the regulation logic of the HVAC system, in some cases the visualization did not match with the operation of the participants. This led to additional operation steps of the participants because they falsely assumed that they did a wrong operation.

Figure 60: Task completion rating for task 3 in the summer condition for QUIET demonstrator and FIT EV.

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Figure 61: Ease of use and satisfaction user ratings for task 3 in the summer condition for the QUIET demonstrator and the FIT EV.

4. Task 4 – the driver and the passenger are feeling too cold
   Although the task completion rate (Figure 62) for the QUIET HMI is significantly higher than for the FIT EV HMI ($p < .005$), there is no difference regarding ease of use and satisfaction (Figure 63). Participants were even more satisfied with the FIT EV than the QUIET demonstrator. Like for the task 4 in the winter condition, the participants struggled to understand the difference between the dashed and continuous lines around the body parts. Again, the missing feedback was one of the main issues which was even emphasized because they did not notice and change in temperature as well. Some participants commented that they have the feeling that they can only select maximum heating or cooling, because no levels of "I am hot" or "I am cold" are available. Furthermore, the progress bar was not regarded as helpful, because it did not show the progress with a continuously increasing bar, but instead jumps back and forth.

Figure 62: Task completion rating for task 4 in the summer condition for QUIET demonstrator and FIT EV.

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Figure 63: Ease of use and satisfaction user ratings for task 4 in the summer condition for the QUIET demonstrator and the FIT EV.

5. Task 5 – cool efficiently with low range
   No significant differences for task completion rate, ease of use, and user satisfaction are found for the QUIET HMI in comparison to the FIT EV HMI in task 5 of the summer condition (Figure 64 and Figure 65). Overall, less participants used a wrong operation path in the QUIET HMI for energy efficient climatisation in comparison to the FIT EV. The same trend is visible for ease of use and user satisfaction where only for the FIT EV HMI negative ratings are available. Minor issues for the QUIET HMI involve the wording “Max” for the Eco mode. Some participants misinterpreted it as “full power” climatisation. In addition, some participants were still unsure if the body parts surrounded by a dashed line needed to be selected again for the next operation. Like in all previous tasks the missing feedback is mentioned as an issue for the QUIET HMI.

Figure 64: Task completion rating for task 5 in the summer condition for QUIET demonstrator and FIT EV.

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Figure 65: Ease of use and satisfaction user ratings for task 5 in the summer condition for the QUIET demonstrator and the FIT EV.

From the 10 tasks in the winter and summer conditions, task completion rates showed significant differences for 6 tasks. In 4 of these tasks the QUIET HMI received a better task completion rate in comparison to the original FIT EV HMI. Only in 2 tasks the FIT EV showed significantly better task completion rates.

In contrast to the task completion rate the perceived ease of use and user satisfaction show a higher number of negative ratings overall in comparison to the FIT EV. The following conclusions can be drawn from this observation:

- Although participants did not operate the conventional FIT EV HMI correctly in many cases, ease of use and user satisfaction are comparably high. This indicates that users are often not aware of their wrong HVAC operation with the conventional HMI that could lead to a less energy efficient usage.
- In contrast to the results of the FIT EV HMI, the QUIET HMI has significantly higher task completion rates in 4 of the 10 tasks, but still for these tasks the overall trend for ease of use and user satisfaction is lower than for the FIT EV HMI (except for the ease of use rating in task 4 – summer condition). We have observed usability issues for the QUIET HMI that apply to all tested use cases. These issues might have a negative influence on all ratings, especially the subjective ease of use and satisfaction ratings. These usability issues for the QUIET HMI are summarized in section 4.3.1.1 General usability issues.

4.3 Discussion and limitations

4.3.1 Discussion

4.3.1.1 General usability issues

Besides the task-based results of the usability evaluation there are global issues that apply for most of the operations with the QUIET HVAC HMI. These global issues are described in the following section. It can be assumed that these global issues have the largest impact on the study results.

- Global usability issues
    1. Lack of feedback: The lack of visual feedback due to a very short or even counterintuitive visualizations was the most severe usability issue in this user study and had a negative influence

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on the usability in most use cases. A short visualization was e.g., when the coloured red or blue body and the respective blue or red waves were shown for just a few seconds. This was the case when the HVAC system had already reached the target temperature and no adaption of the HVAC system was necessary according to the HVAC strategy. A counterintuitive visualization was e.g., when a red body and blue waves were shown on the display after the participant selected the option "I am cold". This case appeared especially at later stages of the study sessions when the HVAC system had already exceeded the target temperature and had to adapt the climatisation again in the opposite direction as initiated by the participant. In these cases, the visualisation was opposite to the operation of the participant and caused confusion and wrong operation of the HVAC system. Because of the not perceivable or counterintuitive visual feedback participants repeated the button press as they assumed that their operation was not successful. The progress bar that could have served as an additional visual feedback did not support the user to understand that the operation was successful mostly because it was not recognised by most of the participants. A solution for this feedback issue would be to decouple the animation from the heating/cooling logic to give sufficient feedback to the users. In addition, a haptic or auditory feedback after a button press could help users to understand that the operation was successful. Although the QUIET HMI has been tested in a pre-study, the above-mentioned issues only occurred in the final user evaluation, because it was the first time that the HMI was tested when coupled to the underlying HVAC heating and cooling logic. During the pre-test a click-dummy was used and the system reaction to the participant's button press of "I am cold" or "I am hot" was always a pre-defined and simulated short heating or cooling visualization respectively. In these cases, the visualization always matched the user's expectations.

2. Selection of body parts: Most participants initially understood that they had to select the body parts of the passengers first before defining their state with the "I am cold" or "I am hot" buttons. However, some participants regarded it as cumbersome that they had to select the upper and lower body separately. They would have preferred to select the entire passenger by default and then de-select the body parts if needed. In a few cases the participants did not understand that they were able to select several body parts before defining their state. Thus, they selected the state for each body part separately. Besides this small issue, which requires more clicks to select single body parts, the participants appreciated the possibility to make thermal adaptions for the upper and lower body separately. The previously mentioned option to select whole bodies first and then having the possibility to de-select single body parts if necessary has also been discussed as an option after the pre-test [16]. This option was not implemented as it was expected that other usability issues would have evolved from this solution besides an increased complexity of the system. Another minor issue that was related to the selection of body parts is the location and colour of the "Select all" button. Some participants realized late in the progress of the session, that they could have used the "Select all" button for previous use cases. This was the case because the button is not located close enough to the cabin image on the left side, but close to the "I am…" buttons in the middle of the screen. Other participants did not use the "Select all" button, as they regarded it as greyed-out or they falsely assumed that it would unnecessarily heat the rear seats as well.

3. Global settings: For the global settings on the right side of the screen, only minor issues were observed. Most of the participants were able to understand the functionality of the Eco mode correctly. However, a few participants criticized the label "Max" in this context, because they

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associated it with “maximum power” instead of “maximum eco mode”. Next to the Eco mode, for the seat heating a minor usability issue was revealed. When they were asked to heat efficiently with a low driving range, some participants did not trust the seat heating mode “Auto” and instead switched the seat heating off. This was due to a wrong user expectation, that the seat heating would consume too much energy. The 4 leaves in the lower right position of the screen could have served as a good indicator in this use case. Although most of the participants correctly interpreted it as the energy-saving-state (1-4 leaves), only a few used it to adapt their operations accordingly. For one participant it was observed for the task 5 in the winter condition that the seat heating mode was corrected from “Off” to “Auto” after perceiving the decrease in number of displayed leaves

- Assessment of the initial user understanding and mental model
  Next to the task-based evaluation of the QUIET HVAC system, qualitative user feedback was obtained before and after the 5 user cases were presented to the participants.
  The first impression of the HVAC HMI was assessed before the participants started with the operation of the system. It depicts the initial understanding and mental model of the participants without having any experience with the system. In general, participants mentioned most of the elements on the display when asked to describe the QUIET HVAC HMI. Furthermore, their initial understanding of the functionality was correct for most of the participants. Initially, some participants had difficulties to correctly understand the “Select all” button, because it looks inactive due to the grey colour. Furthermore, participants falsely assumed that the button is connected to the “I am …” buttons because of their positioning close to each other.
  Although all participants initially mentioned the leaf icons, a few participants misinterpreted them as an indicator of the air flow intensity. In contrast to the other elements on the screen, the status bar was the element that was mentioned only by a few participants and it can be concluded that it is not as perceivable as the other elements on the display.
  Furthermore, most participants correctly assumed that they have to select the body parts first, before selecting the “I am …” buttons. Although the logic of the “I am …” buttons, denoting the current thermal status of the user is different compared to the conventional logic of denoting the thermal target status, i.e., the target temperature, most participants understood the new logic. During the first use case a few participants selected the wrong option but were able to correct it quickly.

4.3.1.2 Why no difference of thermal comfort found in summer?

As described in section 4.2.1.1 Overall sensation, no differences in thermal comfort were found in the summer condition at the beginning and at the end of the session. According to the thermal comfort analysis [15], also the initial climatic conditions in the soaked, non-air-conditioned car was regarded as acceptable. Regarding the fact that the study was conducted in winter it can be assumed that for the participants the general sensation regarding warm temperatures was not as sensible as for cold temperatures hence there could have been a higher tolerance for temporal warm conditions comparing to temporal cold conditions. Furthermore, the target temperature of the summer condition was 30°C which is a less significant temperature difference to the room temperature in the preparation area (22°C) compared to the winter condition (5°C).

4.3.2 Limitations

There are some unintentional factors that have an influence on the study results that have to be mentioned and known when reading the results. These factors are described in the following section.

4.3.2.1 Limited sample size and representativeness of the sample

Due to the current COVID-19 pandemic, the recruiting possibilities of participants was limited. Instead of being able to access a pool of external participants, only internal participants i.e., employees of Honda R&D Europe (Deutschland) GmbH and the Honda Research Institute GmbH were recruited for the final user study. Although, expert test drivers and HVAC as well as HMI specialists were excluded from the study, the sample is not fully representative because most of the participants are experts in the automotive field. Furthermore, due to the limited availability of the employees at the test site and because of extensive home office work as well as issues with the QUIET demonstrator functionality during the study conduction only N = 26 valid datasets (each consisting of two test sessions) were obtained. This limits the statistical power of the results because possible effects are harder to detect.

4.3.2.2 QUIET demonstrator hardware

Due to a malfunction of the IR heating panel in the door at the driver side at the end of the field phase, only 12 out of 15 participants in the winter condition were able to experience the IR heating system. For the other 3 participants the IR heat panels needed to be turned off.

4.3.2.3 Interaction of the QUIET demonstrator HMI and the heating/cooling logic

As already explained in section *4.2.2.4 Task-based ratings and issues* and section *4.3.1.1 General usability issues* there was no visual, haptic or auditory button feedback for the "I am…" buttons on the QUIET HMI due to the prototype. Users often were confused about the missing feedback and assumed that they made a wrong operation. In addition to the direct button feedback missing, the indirect feedback of the HMI visualizing the started heating or cooling process was often missing or sometimes counterintuitive due to the implemented HVAC strategy. Whenever the temperature in the cabin had already reached the target value or even exceeded it, the visualization on the HMI display was not visible or even opposite to the user input respectively. This resulted in a mismatch between the participant's expectations towards the HVAC heating/cooling logic after making an operation and the actual/visualized HVAC strategy. This mismatch limited the user understanding and building of clear mental model of the system' logic and hence influenced the results of the final user evaluation.

5. Assessment of the impact of the developed solutions in the A, C and D-segment vehicles

5.1. HVAC system investigation by cabin scale-up

This investigation analyses the possible impact of the QUIET approach applied to vehicles of different vehicle segments. As baseline, we defined the vehicle from the QUIET project, the B-segment Honda Fit EV ("FitEV").

For the investigation of the impact to other vehicle segments, 4 different target segments were chosen:

- B-SUV segment:
- C segment:
- D segment:
- D-SUV segment:

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Each of these segments represents a popular BEV model, which is currently on sale in Europe. The technical parameters of these underlying vehicle models were used to conduct a numerical parameter study. Foundation of this study are the existing simulation models, which were previously created in the QUIET project.

5.2 Model description and assumptions

For this study, the relevant parts of the developed Fit EV vehicle model are scaled to the respective vehicle segments. This scale-up analysis includes the entire vehicle model for calculating the propulsion power during three consecutive Worldwide Harmonized Light Vehicles Test Cycle (WLTC) cycles – with a total duration of 5400 s – as well as the thermal cabin model for calculating the required thermal power to condition the cabin at a specific temperature.

For the up-scaled thermal cabin a generic model is used. It is assumed that the aspect ratio of each of the analysed vehicles is approximately the same. Taking advantage of this assumption, the outer surface, which represents the thermal interface to the ambient, will be scaled with the respective cabin volume. This means for a scale factor x:

$$V_1 = V_2 \cdot x \rightarrow A_1 = A_2 \cdot \sqrt[3]{x^2} \quad (9)$$

with V_1 and A_1 being the cabin volume and thermal surface area of the reference vehicle (FitEV) and with V_2 and A_2 being the cabin volume and thermal surface area of another vehicle. Indeed, the thermal losses of the respective passenger cabin increase with increased thermal surface area.

For simplicity reasons, and to ensure a fair evaluation between the different options, the thermal model includes only the scaled passenger cabin with heating power as an input. The HVAC system including control strategy will be neglected in this study. Instead, heat-up and cool-down trends, which have been derived from FitEV measurements, will be used. In a post-processing step the measurement data have been filtered to achieve a smooth transient behaviour between start temperature and steady state temperature. The model calculates the required thermal power that needs to be supplied from the HVAC system to follow that curve. This ensures that each of the different models follows the same cabin temperature trend while the required power demand for keeping that temperature can be calculated.

Figure 66 shows the adapted entire vehicle model that was used for this study. The model consists of the physical vehicle model to consider the required power demand of the propulsion system during the WLTC cycles and, additionally, a simplified thermal cabin model for calculating the required thermal power demand to follow the desired cabin temperature trend.

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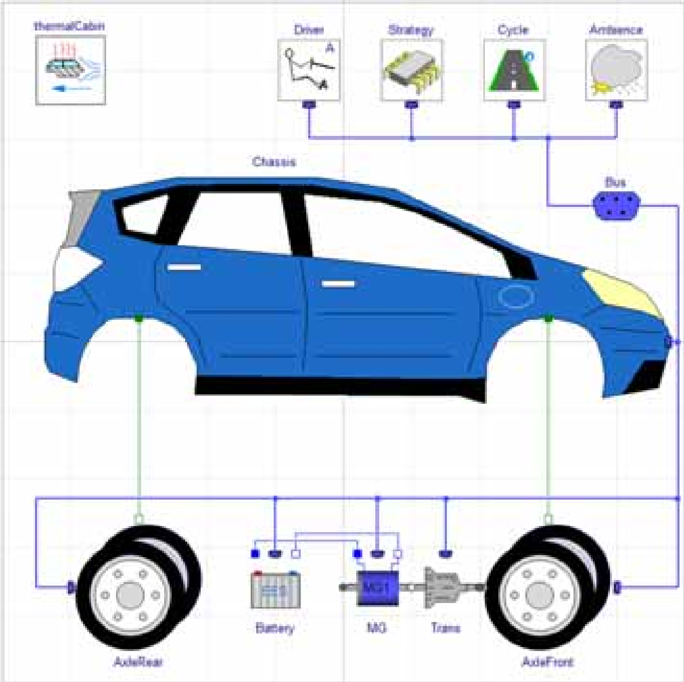

Figure 66: Total vehicle model including thermal cabin model implemented in Dymola/Modelica.

5.3 Setting the study scenarios

In this study, the abovementioned total vehicle model including the thermal cabin model is applied in different setups. The analysis includes the different vehicle segments at varying ambient conditions. The main model parameters, which are varied dependent on the simulated vehicle are listed in Table 12. These data are derived from public sources. Thereby, mass is the total vehicle mass; f_0, f_1 and f_2 are the polynomial coefficients of the drive resistance (constant, linear and cubic, respectively). Both parameter sets were sourced from the Environmental Protection Agency (EPA) of the United States of America [17]. C_w is the drag coefficient; A_{Front} is the frontal area used for calculating the drag [18]; and V_{Cabin} is the considered cabin volume. This cabin volumes were estimated, based on the official interior dimensions of these vehicles. The calculation was conducted according to the Unites States 'Code of Federal Regulations' 49 CFR § 523.2, Section "Passenger-carrying volume" [19]. The underlying dimension were taken from the individual vehicle specifications.
In addition to the vehicle type also the ambient temperature is varied. The distinct ambient temperatures which are considered in the variation study are the heat-pump mode -10 °C, -5 °C, 0 °C, 5 °C, 10 °C and 15 °C and the cooling mode 25 °C, 30 °C, 35 °C and 40 °C. All possible combinations have been evaluated using the implemented simulation model. In all cases, the target cabin air temperature is set to 22 °C.

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Table 12: Model parameters of the different vehicles

parameter	unit	vehicle Fit EV (B)	B-SUV	C	D	D-SUV
mass	kg	1644	1700	1520	1757	2585
f_0	N	84.78	110.58	115.16	160.18	159
f_1	N/kph	1.12	-0.55	0.95	-0.36	1.07
f_2	N/kph²	0.03	0.04	0.03	0.03	0.03
c_W	-	0.33	0.33	0.29	0.23	0.28
A_{Front}	m²	2.16	2.37	2.3	2.22	2.65
V_{Cabin}	m³	2.53	2.66	2.61	2.75	2.92

5.2 Results and discussion

Figure 67 shows the worst-case scenario for cooling mode, i.e. cooling down the cabin at an ambient temperature of 40 °C. The results show that each of the vehicles can follow the exact same trend of the cabin temperature to ensure fair evaluation between the different options.

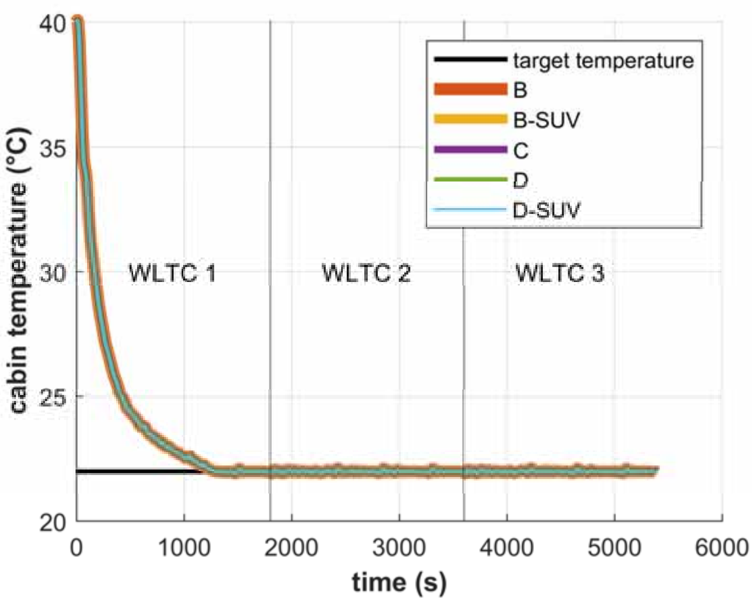

Figure 67: Cool-down scenario at 40 °C ambient temperature.

Figure 68 also shows a worst-case scenario but for heating mode, i.e. heating up the cabin at an ambient temperature of -10 °C. Also, in this case the results show that all vehicles can follow the desired cabin temperature trend. This will be the basis for the further evaluations.

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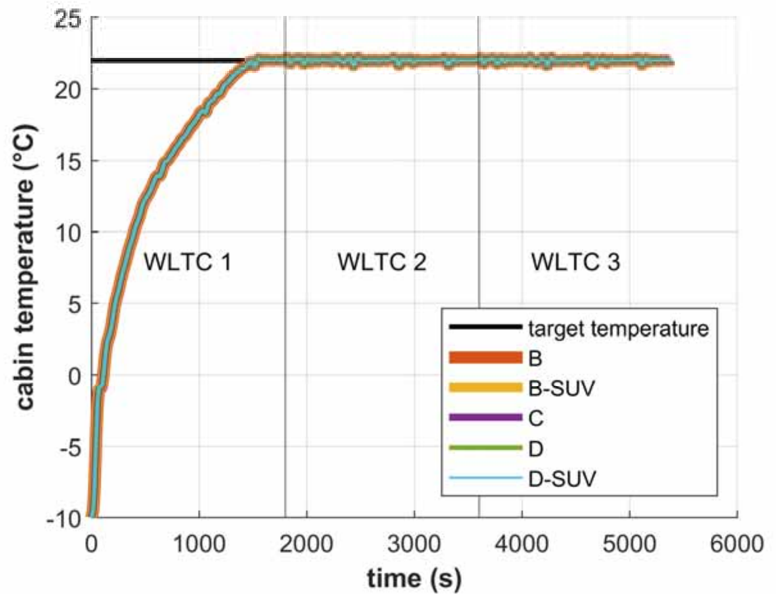

Figure 68: Heat-up scenario at -10 °C ambient temperature.

In the next step, the share of the mean thermal power of the HVAC system compared to the mean propulsion power during the last one of the three WLTCs is analysed. The third WLTC was chosen because there the cabin temperature has already reached its target value (cp. Figure 67 and Figure 68). This, in turn, means that the cabin temperature is already at steady state and the required thermal power is only the power needed to maintain the steady state temperature. This allows for the analysis whether it would make more sense for a specific vehicle to put the focus for optimizations rather on the HVAC system or on the propulsion system. For this part of the analysis only positive values of the propulsion power has been used. In case of negative power of the propulsion system (i.e. recuperation during braking) the power has been set to 0 W before calculating the mean propulsion power. This allows for fair comparison to the required mean thermal power. The proposed share can be calculated based on the following equation:

$$\frac{mean\ thermal\ power\ [W]}{mean\ (positive)\ propulsion\ power\ [W]} * 100\ \% \qquad (10)$$

Figure 69 depicts the results of this evaluation in a surface plot. The evaluation has been performed for each of the ambient temperatures and for each of the vehicles, respectively. The results show a clear linear trend along the ambient temperature within each vehicle segment. Additionally, the B, C and D segments all have approximately the same share of mean thermal power to mean propulsion power, while the B-SUV has a slightly lower share and the D-SUV has a significantly lower share. This raises the assumption that the QUIET measures would have almost the same impact on the B-SUV, C and D segments like on the B segment, while the impact on the D-SUV would be lower.

Table 13 presents the same results as Figure 69, but in a more readable tabular form. The results, again, prove that the D-SUV segment has a lower share of mean thermal power to mean propulsion power than the other vehicles in all ambient conditions. Indeed, the gap between the different vehicle segments is greatest for extreme ambient conditions, such as -10 °C and 40 °C.

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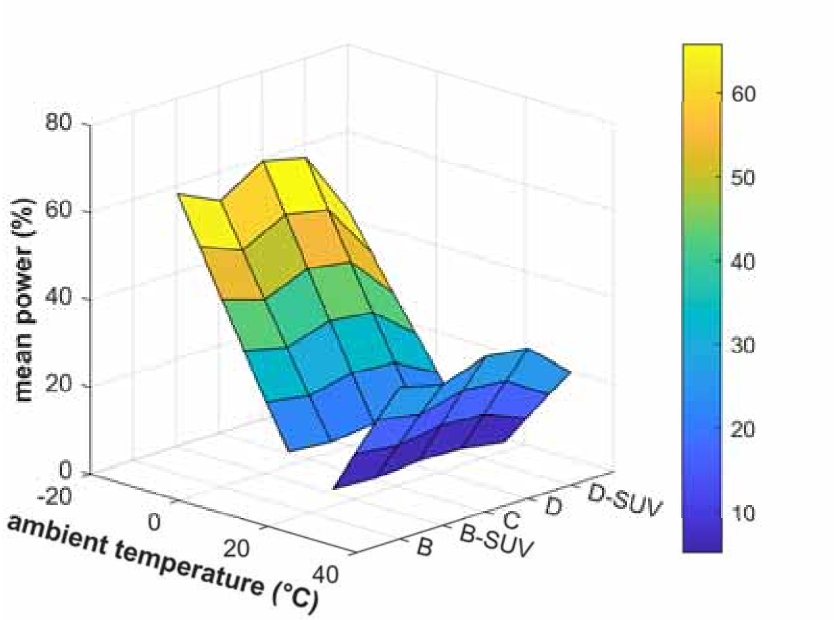

Figure 69: Share of mean thermal power of HVAC system compared to mean propulsion power during last WLTC.

Table 13: Share (%) of mean thermal power of HVAC system compared to mean propulsion power during last WLTC

		ambient temperature (°C)									
		-10	-5	0	5	10	15	25	30	35	40
segment	B	64.3	53.6	43.0	32.7	22.5	12.5	7.0	16.5	25.9	34.9
	B-SUV	59.6	49.7	39.9	30.3	20.9	11.6	6.5	15.3	24.0	32.4
	C	65.7	54.7	44.0	33.4	23.0	12.8	7.2	16.9	26.5	35.7
	D	63.4	52.8	42.4	32.2	22.2	12.3	6.9	16.3	25.5	34.4
	D-SUV	47.8	39.9	32.0	24.3	16.8	9.3	5.2	12.3	19.3	26.0

Another significant aspect of this study is the total energy consumption. Therefore, the share of thermal energy of the HVAC system to the propulsion energy during all three consecutive WLTCs (total distance of approximately 70 km) is analysed. This means that the total amount of energy includes the initial heat-up or cool-down phase of the passenger cabin as well as keeping the cabin temperature at the required value for the rest of the simulation. In this part of the analysis, the recuperation power is considered for calculating the total propulsion energy. This means that recuperation during braking reduces the total propulsion energy. The share of energy is calculated based on the following equation:

$$\frac{total\ thermal\ energy\ [Wh]}{total\ propulsion\ energy\ [Wh]} * 100\ \% \qquad (11)$$

Figure 70 shows the share of total energy at different ambient temperatures during all three WLTC cycles. Indeed, the trends of the different vehicles look similar to the previously described share of power. However, as the investigation of the total energy includes also recuperation phases, which reduce the total propulsion energy, as well as the initial phase where the cabin temperature is not yet at steady state, the numbers are different. Again, the share of energy of the C and D segment can be compared to the values of the B segment. Only the values of the B-SUV and D-SUV are lower than for the other vehicles, whereas the values for the

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D-SUV have the lowest values. This supports the previous conclusion that the QUIET measures could have a similar impact for the B-SUV, C and D segments as for the B segment, where the impact on the B-SUV is the lowest, and the impact for the D-SUV is expected to be even lower than for the B-SUV.

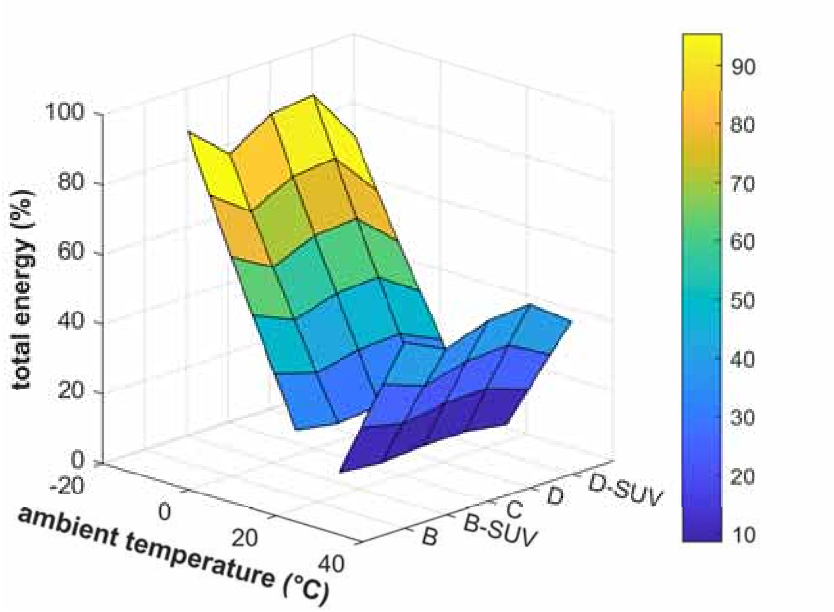

Figure 70: Share of thermal energy of HVAC system compared to propulsion energy during 3 consecutive WLTCs.

The results from the surface plot shown in Figure 70 are listed as numeric values in Table 14. The table highlights even more the similarity of the results for the B, C and D segments. The calculated share for the B-SUV is slightly lower and the lowest share of all vehicle segments has been found for the D-SUV.

Table 14: Share (%) of thermal energy of HVAC system compared to propulsion energy during 3 consecutive WLTCs

		ambient temperature (°C)									
		-10	-5	0	5	10	15	25	30	35	40
segment	B	95.3	78.8	63.1	48.0	33.2	18.8	10.5	25.1	39.6	53.4
	B-SUV	85.0	70.3	56.2	42.8	29.6	16.8	9.4	22.4	35.3	47.6
	C	92.5	76.5	61.2	46.6	32.2	18.2	10.2	24.4	38.4	51.8
	D	94.1	77.9	62.3	47.5	32.8	18.6	10.4	24.8	39.1	52.8
	D-SUV	78.1	64.6	51.7	39.4	27.3	15.4	8.6	20.6	32.5	43.8

The analysis is leading towards a conflict between the technical and the economic aspects. When purely looking at the technical findings in the aforementioned paragraphs, it emerges that the energy efficiency of the HVAC system is more relevant for smaller cars with a relatively low driving resistance. This is resulting in a lower energy consumption from the drivetrain, leading to a higher relative importance of the HVAC. For larger cars, especially SUV, this balance is shifted. Due to the higher energy demand needed for overcoming the driving resistances, the drivetrain is responsible for a higher portion of the overall vehicle energy demand. Therefore, the energy consumption from the HVAC has a lower relevance.
This becomes even more prominent, when the use case of smaller passenger cars is considered. Small cars (as the B-segment baseline of the QUIET project) are often used as city cars for short distance journeys. As can be seen from Figure 2 and Figure 3, the HVAC has the task to initially heat up or cool down the cabin from

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ambient conditions. During short distance trips, the HVAC systems will not leave this phase, causing it to operate under high load for the entire trip.
Apart from the technical perspective, it is also necessary to consider the economic feasibility. When looking at the economic situation, one can see that the technical conclusions can clash with the target sales prices of these vehicles. On the one hand, SUV and higher segment cars are usually selling for high prices, which usually allows to include more costly technologies into those vehicles. On the other hand, small cars are usually sold for lower prices, which also reduces the possibility to integrate costly technologies into those vehicles.
This leads to the situation that it is economically very challenging to apply advanced HVAC solutions for vehicles, where improved HVAC efficiencies would be most beneficial.
For smaller vehicles, low-cost systems, which can reduce energy consumption at the beginning of a trip would be most beneficial. In general, complex systems might be easier to accommodate in larger and higher cost vehicles.

6. Conclusions

QUIET aimed at developing an improved and energy efficient electric vehicle with increased driving range under real world driving conditions. This was achieved by exploiting the synergies of a technology portfolio in the areas of user centric design with enhanced passenger comfort and safety, lightweight materials with enhanced thermal insulation properties and optimised vehicle energy management. The accuracy of the results obtained for the energy consumption and driving ranges during all the tests were assured by using the customised data logger system that allows to accurately and reliably measure parameters at several locations within the vehicles without interfering with the operation of the components.
Figure 71 illustrates the final comparison of the driving range of the baseline and the QUIET demonstrator at the different ambient temperatures. At +23 ºC and with the HVAC system switched-off, distance specific energy consumption results between approximately 130 and 136 Wh/km. This corresponds to a driving range of 136 km.
At warm temperature and with HVAC system in operation in cooling mode the distance specific energy consumption is approximately 147.3 Wh/km, resulting in a driving range between 137 and 140km km, showing an improvement of the driving range at warm of 1-2 %. At cold temperature and with HVAC system operating in heating mode the distance specific energy consumption is approximately 207.6Wh/km, resulting in a driving range of 86km, showing that with the installation of the innovative components and technologies an improvement of the driving range at cold of 26% was achieved.

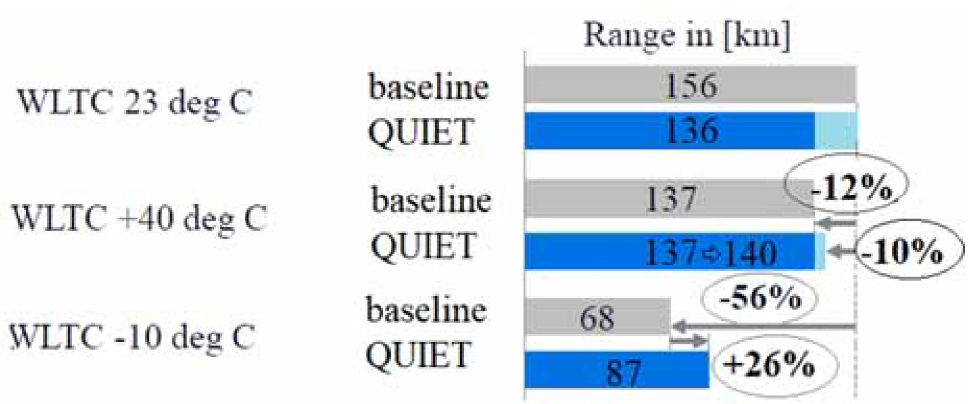

Figure 71: Driving range of the baseline and demonstrator vehicle at different ambient temperature.

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To evaluate the thermal comfort and the usability of the novel HVAC HMI prototype of the QUIET demonstrator, a final user study was conducted. Comparable to the perceived thermal comfort of the FIT EV after the usage of the HVAC system, also the QUIET demonstrator was perceived as "comfortable" and "acceptable" in both, the winter and summer conditions. Although the thermal comfort was not considered as discomfortable according to the ISO standard [15], users felt significantly colder in the QUIET demonstrator compared to the original FIT EV after the usage of the HVAC system in the winter condition. It can be concluded that the target temperature of HVAC heating strategy for the QUIET demonstrator needs to be increased slightly to fit the thermal comfort of the user even better. Regarding humidity and air flow no significant differences were found in the winter and summer condition for the QUIET demonstrator and the original FIT EV but the intensity of the air flow would need some slight improvements especially for the QUIET demonstrator as it was rated as "too breezy". Overall, no significant difference was found regarding the overall thermal comfort preference for the QUIET demonstrator in comparison to the original FIT EV hence a slight increase of the target temperature in winter and slight decrease of the air flow intensity should be sufficient.

The overall subjective usability based on the System Usability Scale (SUS) was rated as lower for the QUIET HVAC HMI compared to the FIT EV HMI but can still be regarded as "ok". In contrast to the SUS score, the QUIET HMI received better results for the objective task completion rates in comparison to the original FIT EV HMI, but also here subjective user ratings like ease of use and user satisfaction showed a higher number of negative scores for the QUIET HMI. This negative subjective experience is strongly influenced by the usability issues that were apparent in all the tested use cases, i.e., the lack of feedback after the selection of "I am hot" or "I am cold" and the mismatch between the user operation and the resulting visualisation of the heating/cooling process on the display. These issues seem to have a stronger negative influence on the subjective experience than on the actual task completion rate but an improved interaction of the HMI and the HVAC strategy to match the users' expectations has high potential to improve the overall user experience including and better usability.

From the FIT EV findings we can conclude that users are often not aware of their wrong HVAC operation with conventional HVAC HMIs. Although many false operations were observed during the study and the task completion rate was significantly lower for the FIT EV, subjective user ratings were more positive than for the QUIET HMI. Especially if energy efficient usage of the HVAC system is necessary, users struggle to find a suitable HVAC setting with the conventional HMI of the FIT EV.

Although the above-mentioned usability issues negatively impact the usage of the QUIET HMI, it significantly outperforms the FIT EV HMI regarding task performance in 4 out of 10 tasks and hence has potential to better support the user with an energy efficient usage of the HVAC system in comparison to the conventional HMI.

From the assessment of the impact of the developed solutions in the A, C and D-segment vehicles, it emerges that the energy efficiency of the HVAC system is more relevant for smaller cars with a relatively low driving resistance. This is resulting in a lower energy consumption from the drivetrain, leading to a higher relative importance of the HVAC. For larger cars, especially SUV, due to the higher energy demand needed for overcoming the driving resistances, the drivetrain is responsible for a higher portion of the overall vehicle energy demand. Therefore, the energy consumption from the HVAC has a lower relevance. This becomes even more prominent, when the use case of smaller passenger cars is considered. During short distance trips, the HVAC systems will not leave the initial heating up or cooling down the cabin phase, causing it to operate under high load for the entire trip. When looking at the economic situation, SUV and higher segment cars are usually selling for high prices, which usually allows to include more costly technologies into those vehicles. On the other hand, small cars are usually sold for lower prices, which also reduces the possibility to integrate costly technologies into those vehicles. This leads to the situation, which it is economically very challenging

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to apply advanced HVAC solutions for vehicles, where improved HVAC efficiencies would be most beneficial.

For smaller vehicles, low-cost systems, which can reduce energy consumption at the beginning of a trip would be most beneficial. In general, complex systems might be easier to accommodate in larger and higher cost vehicles.

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8. Acknowledgment

European Union's Horizon 2020 research and innovation programme

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Project Partners:

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Participant No	Participant short name	Participant organisation name	Country
1 Coordinator	**AIT**	AIT Austrian Institute of Technology GmbH	Austria
2	**HRE**	Honda R&D Europe (Deutschland) GmbH	Germany
3	**AVL**	AVL List GmbH	Austria
4	**QPD**	AVL Thermal and HVAC GmbH	Germany
5	**VEN**	VENTREX Automotive GmbH	Austria
6	**UOZ**	University of Zagreb	Croatia
7	**IFAM**	Fraunhofer Institute for Manufacturing Technologies and Advanced Materials IFAM	Germany
8	**ATT**	ATT advanced thermal technologies GmbH	Austria
9	**ECON**	eCon Engineering Kft.	Hungary
10	**RUB**	Rubitherm Technologies GmbH	Germany
11	**STS**	SeatTec Sitztechnik GmbH	Germany
12	**OBR**	Obrist Engineering GmbH	Austria
13	**JRC**	Joint Research Centre - European Commission	Italy

Appendix A – Demographic questionnaire

1. Gender
   - ☐ Male
   - ☐ Female
2. How old are you? ___________________
3. Are you right hander or left hander?
   - ☐ Right
   - ☐ Left
4. What car do you drive? When was it built?

___________________________ , _____________

5. Kilometres per year:
   - ☐ 0 – 4.999 km
   - ☐ 5.000 – 9.999 km
   - ☐ 10.000 – 20.000 km
   - ☐ more than 20.000 km
6. How much of your driving time (in %) do you regularly spend on…

   The autobahn ____________

   Country roads ____________

   Inside a city ____________
7. How often do you regulate the climate
   - ☐ Never
   - ☐ 1 time/week
   - ☐ 3-5 times/week
   - ☐ Once everyday
   - ☐ More than twice everyday
8. How often do you use seat heating in wintertime (Oct. – Feb.)
   - ☐ Never
   - ☐ 1 time/week
   - ☐ 3-5 times/week
   - ☐ Once everyday
   - ☐ More than twice everyday

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Appendix B – Thermal comfort questionnaire

Part 1: Baseline for room environment

1. What was your main (physical) activity level during last hour? (Check the ones that are appropriate including the amount of time you have spent.)

☐ **Reclining: _________ min**	☐ **Light activity: _________ min**
☐ **Seated: _________ min**	☐ **Medium activity: _________ min**
☐ **Standing relaxed: _________ min**	☐ **High activity: _________ min**

2. What is your typical level of thermal sensation?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

3. Please indicate how you would describe your current feeling.

Active	☐	☐	☐	☐	☐	☐	☐	**Passive**
Healthy	☐	☐	☐	☐	☐	☐	☐	**Sick**
Relaxed	☐	☐	☐	☐	☐	☐	☐	**Tense**
Awake	☐	☐	☐	☐	☐	☐	☐	**Tired**
Pleasant	☐	☐	☐	☐	☐	☐	☐	**Unpleasant**
Restful	☐	☐	☐	☐	☐	☐	☐	**Stressful**
Comfortable	☐	☐	☐	☐	☐	☐	☐	**Uncomfortable**
Powerful	☐	☐	☐	☐	☐	☐	☐	**Weak**

4. Please rate on these scales how you feel now

	Overall	Head	Trunk		Arms	Upper legs		Lower legs		Feet
			Front	Rear		Front	Rear	Front	Rear	
+3 Hot										
+2 Warm										
+1 Slightly warm										
0 Neutral										
-1 Slightly cool										
-2 Cool										
-3 Cold										

	Overall	Head	Trunk		Arms	Upper legs		Lower legs		Feet
			Front	Rear		Front	Rear	Front	Rear	

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3 Very uncomfortable										
2 Uncomfortable										
1 Slightly uncomfortable										
0 Not uncomfortable										

5. How do you feel at this moment in terms of humidity?

Too dry	Just right	Too humid
☐	☐	☐

6. How do you feel about the air flow at this moment?

Too still	Just right	Too breezy
☐	☐	☐

7. Please rate on the scale how you would like to be now.

Much warmer	Warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler
☐	☐	☐	☐	☐	☐	☐

8. Please indicate how acceptable you find this thermal environment now.

Acceptable	Unacceptable
☐	☐

9. Please indicate how satisfied you are with this thermal environment now.

Satisfied	Dissatisfied
☐	☐

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Part 2: Baseline for car environment

1. Please rate on these scales how you feel now

	Overall	Head	Trunk		Arms	Upper legs		Lower legs		Feet
			Front	Rear		Front	Rear	Front	Rear	
+3 Hot										
+2 Warm										
+1 Slightly warm										
0 Neutral										
-1 Slightly cool										
-2 Cool										
-3 Cold										

	Overall	Head	Trunk		Arms	Upper legs		Lower legs		Feet
			Front	Rear		Front	Rear	Front	Rear	
3 Very uncomfortable										
2 Uncomfortable										
1 Slightly uncomfortable										
0 Not uncomfortable										

2. How do you feel at this moment in terms of humidity?

Too dry	Just right	Too humid
☐	☐	☐

3. How do you feel about the air flow at this moment?

Too still	Just right	Too breezy
☐	☐	☐

4. Please rate on the scale how you would like to be now.

Much warmer	Warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler
☐	☐	☐	☐	☐	☐	☐

5. Please indicate how acceptable you find this thermal environment now.

Acceptable	Unacceptable
☐	☐

6. Please indicate how satisfied you are with this thermal environment now.

Satisfied	Dissatisfied
☐	☐

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7. If you are dissatisfied with the climate here, which of the following points contributes to your dissatisfaction?

☐ **Humidity too high**	☐ **Heat from surfaces**
☐ **Humidity too low**	☐ **Drafts from windows**
☐ **Air movement too high**	☐ **Drafts from vents**
☐ **Air movement too low**	☐ **Heating/cooling does not respond quickly enough**
☐ **Incoming sun/radiation**	
☐ **Other:** (Please describe any other issue related to being too hot or too cold here.)	

8. Are there any additional comments about the current thermal environment?

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Part 3: Comparison for car environment

1. Please rate on these scales how you feel now

	Overall	Head	Trunk		Arms	Upper legs		Lower legs		Feet
			Front	Rear		Front	Rear	Front	Rear	
+3 Hot										
+2 Warm										
+1 Slightly warm										
0 Neutral										
-1 Slightly cool										
-2 Cool										
-3 Cold										

	Overall	Head	Trunk		Arms	Upper legs		Lower legs		Feet
			Front	Rear		Front	Rear	Front	Rear	
3 Very uncomfortable										
2 Uncomfortable										
1 Slightly uncomfortable										
0 Not uncomfortable										

2. How do you feel at this moment in terms of humidity?

Too dry	Just right	Too humid
☐	☐	☐

3. How do you feel about the air flow at this moment?

Too still	Just right	Too breezy
☐	☐	☐

4. Please rate on the scale how you would like to be now.

Much warmer	Warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler
☐	☐	☐	☐	☐	☐	☐

5. Please indicate how acceptable you find this thermal environment now.

Acceptable	Unacceptable
☐	☐

6. Please indicate how satisfied you are with this thermal environment now.

Satisfied	Dissatisfied
☐	☐

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7. If you are dissatisfied with the climate here, which of the following points contributes to your dissatisfaction?

☐ **Humidity too high**	☐ **Heat from surfaces**
☐ **Humidity too low**	☐ **Drafts from windows**
☐ **Air movement too high**	☐ **Drafts from vents**
☐ **Air movement too low**	☐ **Heating/cooling does not respond quickly enough**
☐ **Incoming sun/radiation**	
☐ **Other:** (Please describe any other issue related to being too hot or too cold here.)	

8. Are there any additional comments about the current thermal environment?

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Appendix C – Usability Questionnaire

1. How easy was the operation for you?

Very difficult 1	Difficult 2	Slightly difficult 3	Neutral 4	Slightly easy 5	Easy 6	Very easy 7

2. How satisfied were you with the operation?

Very dissatisfied 1	Dissatisfied 2	Slightly dissatisfied 3	Neutral 4	Slightly satisfied 5	Satisfied 6	Very satisfied 7

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Appendix D – System Usability Scale (SUS)

1. I think that I would like to use this system frequently.

Strongly disagree 1	2	3	4	Strongly agree 5

2. I found the system unnecessarily complex.

Strongly disagree 1	2	3	4	Strongly agree 5

3. I thought the system was easy to use.

Strongly disagree 1	2	3	4	Strongly agree 5

4. I think that I would need the support of a technical person to be able to use this system.

Strongly disagree 1	2	3	4	Strongly agree 5

5. I found the various functions in this system were well integrated.

Strongly disagree 1	2	3	4	Strongly agree 5

6. I thought there was too much inconsistency in this system.

Strongly disagree 1	2	3	4	Strongly agree 5

7. I would imagine that most people would learn to use this system very quickly.

Strongly disagree 1	2	3	4	Strongly agree 5

8. I found the system very cumbersome to use.

Strongly disagree 1	2	3	4	Strongly agree 5

9. I felt very confident using the system.

Strongly disagree 1	2	3	4	Strongly agree 5

10. I needed to learn a lot of things before I could get going with this system.

Strongly disagree 1	2	3	4	Strongly agree 5

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Appendix E – Semantic Differential (SD)

Please rate the system based on the following description.

Use less	1	2	3	4	5	Useful
Unpleasant	1	2	3	4	5	Pleasant
Bad	1	2	3	4	5	Good
Annoying	1	2	3	4	5	Nice
Superfluous	1	2	3	4	5	Effective
Irritating	1	2	3	4	5	Likeable
Worthless	1	2	3	4	5	Assisting
Undesirable	1	2	3	4	5	Desirable
Difficult	1	2	3	4	5	Easy

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Appendix F – Final Questionnaire

1. What is your overall impression of the car´s Human Machine Interface?

2. Overall, what do you like about this car´s Human Machine Interface?

3. Overall, what didn't you like about this car´s Human Machine Interface?

4. What is your overall impression of the climate control efficacy?

5. For 2^{nd} car (visit): Which Human Machine Interface of these two tested cars do you prefer? Why?

6. For 2^{nd} car (visit): Which thermal sensation in these two tested cars do you find more comfortable? Why?

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