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

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Publishable Executive Summary

For the implementation of the QUIET demonstrator car, a suitable control strategy for the novel HVAC strategy has been created. This development control strategy was conducted within the project QUIET and was described in D2.2. At the end of D2.2 an initial formulation of this operation strategy was demonstrated in a simulation environment. This enables the initial assessment of the resulting behaviour of the main components of the novel HVAC system. These cases were used for the first-level assessment in this deliverable. Overall, it could be confirmed that high efficiency gains can be expected from the new HVAC implementation in comparison to conventional HVAC systems. At the same time, some secondary issues appeared. These should be addressed and re-evaluated before implementing the final operation strategy in the demonstrator vehicle.

Additionally, to the operation strategy, a thorough assessment of the novel Human Machine Interface (HMI) was performed. The results of a small, internal user study was analysed and summarized. In general, the novel HMI scored 'OK' in the presented form. From the interview, several improvement items were identified and documented. For the majority of these items, only little implementation effort would be required. The HMI system can therefore be easily updated, before the HMI is finally implemented into the demonstrator vehicle. This process has already been started.

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Abbreviations and Nomenclature

Table 1: List of Abbreviations and Nomenclature.

Symbol or Shortname	Description
AC	Air Conditioning
AER	All Electric Range
COP	Coefficient of Performance
EV	Electric Vehicle
HMI	Human Machine Interface
HVAC	Heating, Ventilation & Air Conditioning
PMV	Predicted Mean Vote
SUS	System Usability Scale
WP	Work Package

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1. Introduction

QUIET aims at developing an improved and energy efficient electric vehicle (EV) with increased driving range under real-world driving conditions. This is 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 developed technologies will be integrated and qualified in a Honda B-segment electric vehicle validator. Among these, a novel refrigerant for cooling, combined with an energy-saving heat pump operation for heating, advanced thermal storages based on phase change materials, powerfilms for infrared radiative heating and materials for enhanced thermal insulation of the cabin will be investigated. Further focus is put on lightweight glazing for windows, as well as light metals like aluminium or magnesium for seat components. Optimized energy management strategies, such as pre-conditioning and zonal cooling/heating of the passenger cabin as well as user-centric designed cooling/heating modules will further enhance the thermal performance of the vehicle. WP3 involves developing new lightweight vehicle components with improved thermal performance in order to reduce the entire vehicle weight and to guarantee improved passenger-compartment insulation. For the windshield, different technologies and structures based on innovative approaches will be investigated. Further, vehicle components like lightweight doors will be developed and realised by combining novel materials for enhanced thermal insulation with lightweight composites. Additionally, lightweight materials such as aluminium or magnesium will be used for realising seat-structure components for optimising the weight of the reference vehicle. All developed lightweight components (windshield, doors and seats) with improved thermal performance will be ready for integration into the reference vehicle at the end of WP3.

1.1. Description of the deliverable – Goal

Goal of this deliverable is the assessment of the technical solutions, which were developed in WP2. The evaluation will be conducted along the task structure of WP2. The assessed items include the multi-physical model itself, the derived optimised operation strategy and finally the novel Human machine Interface (HMI) for the HVAC system.

This desk-based first-level assessment shall provide valuable feedback to the involved project partners before the integration of the solutions into the demonstrator vehicle is being carried out. In case of major issues, countermeasures can still easily be implemented before the finalisation of the demonstrator build-up.

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2. Assessment of multi-physical vehicle model

During T2.2, a comprehensive vehicle model was developed by QUIET project partners. It describes the demonstrator car platform itself, as well as the novel HVAC system. This chapter shall give an overview on the capabilities of these models.

2.1. Model of demonstrator platform

For the QUIET demonstrator car, the Honda Fit EV baseline car will be used as platform. In order to assess and optimise the novel HVAC solutions of QUIET, a high level of detail for the involved carry-over systems is needed. Therefore, the model of D1.2 was significantly enhanced during T2.2. The enhancements successfully added detail to the original model which was shown in D1.2. A strong emphasis was put on modelling the different thermal phenomena. A big emphasis was put on improving the heat transfer from the cabin to the ambient environment.

Unfortunately, some simplifications needed to be made. As not the entire automotive development toolchain could be applied during this collaborative research project, some effects needed to be neglected or simplified. This includes air leakage of the cabin and thermal losses of the car body surfaces. Although not measured directly, both effects were present in the baseline measurements. When calibrating the model according to these baseline tests, the neglected effects are therefore considered indirectly.

2.2. Model of novel HVAC

Additional to modelling the carry-over components, a model of the novel HVAC was needed. A comprehensive model was set up, reflecting each component individually. As each component could be measured separately on a test bench, the prediction quality of the HVAC model should exceed the accuracy of the vehicle and cabin model.

In order to reflect the actual perceived passenger comfort, the idea was to incorporate a thermal comfort model in the simulation. It was decided to use the established Predicted Mean Vote (PMV) index. Besides air temperature, this index shall reflect air speed and radiation effects when calculating the thermal comfort index.

However, for computational optimisation it is desirable to reduce the complexity of the involved models. The prediction of realistic air speeds at each body section of the occupant requires complex simulations and mapping. To reduce the mathematical complexity of the model, a simple assumption was made for the air speeds in relation to the blower air mass flow. This assumption needs to be carefully checked during the evaluation of the completed demonstrator vehicle.

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3. Assessment of energy management strategy

During T2.3, UOZ used the developed model framework to derive an optimal operation strategy for the new vehicle thermal systems. The new operation strategy shall combine the opposing goals of achieving high energy efficiency and high user comfort at the same time.

As described in Chapter 2.2, the HVAC model should have the highest accuracy of all implemented models. Therefore, it is reasonable to start the optimisation with strong focus on this part of the system. The optimisation procedure was focussing on delivering a certain heating or cooling power while maintaining a high Coefficient of Performance (COP). The resulting parameters for the HVAC control were later used in a combined model. As a result, the behaviour of the HVAC system in combination of the surrounding vehicle and the effects on cabin conditions could be predicted at a very early stage. This analysis is very valuable in understanding the user perception of the chosen control strategy.

3.1. Selection of evaluation scenarios

As seen in D4.1, the novel HVAC system is capable of six main operation modes. These modes cover the complete operation range of an automobile HVAC system. For QUIET, the task is to demonstrate an improved All Electric Range (AER) for two severe benchmark scenarios. These scenarios were defined in the project proposal as follows:

- Heating at -10 °C ambient temperature
- Cooling at +40 °C ambient temperature

For the heating case, the HVAC operation is dominated by pure heating, with nearly no available excess heat from the powertrain. For the cooling case at +40 °C, the HVAC system is operating entirely in AC cooling mode.

Therefore, these cooling and heating conditions were the starting point of the control strategy optimisation tasks. At the same time, these two modes are the most fundamental operation scenarios for HVAC operation. It is therefore efficient to start any optimisation work with these cases to grasp the general behaviour and the sensitivities of the system.

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3.2. Assessment of management strategy

As discussed before, the operation strategy was mainly investigated for the severe baseline tests.
The overall performance of the system can be described with just a few parameters. To characterise the system efficiency, COP is the most suitable value. It is described by dividing the instant heating or cooling power output by the required electrical input power.

On the other hand, the experience for the cabin occupant is dominated by the cabin temperature, radiation effects and the overall airflow in the cabin. All of these parameters are considered in the PMV thermal comfort index. As this index is the target function of the optimisation loop, these factors are well considered. For the creation of the HVAC and cabin model, several assumptions and simplifications were necessary for the implementation of the PMV index. Therefore, this assessment of the operation strategy shall focus on directly measurable operation parameters. For the customer, cabin air inlet temperature and blower fan speed can be directly experienced. Additionally, the required time to reach comfortable cabin conditions are relevant for the customer.

In conclusion, the following assessment of the current state of the operation strategy focusses on the following parameters:

- Time to reach target temperature
- Air inlet temperature
- Blower fan speed
- COP

3.2.1.Balancing Comfort and COP

As seen in D2.2, two opposing cost functions were considered during control strategy optimisation. On the one hand a high COP shall be achieved, while on the other hand user comfort, represented by the PMV index, shall be kept in the comfortable range. It is easy to see from Chapter 3.7 of D2.2, that the trade-off between both targets is especially prominent under cabin conditions, which are close to the desired target value. For this case, a careful adjustment of the parameters to get a well-balanced solution has to be made.

When looking at the situation before a comfortable temperature range is achieved, the optimisation solutions for each cost function differ just slightly. As a consequence, the "Max COP" option can be chosen, without any major negative impact on the comfort level of the vehicle occupants.

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3.2.2. Cooling scenario

Time to reach target temperature

In cooling mode, the model predicts a cool-down time below 400 seconds. This performance is roughly in line with the baseline performance.

Air inlet temperature

The inlet temperature responds to the required cooling demand. For the presented operation strategy, relatively high air inlet temperatures are preferred. This behaviour is beneficial in terms of efficiency, but at the same time it can be critical regarding hygiene. In conventional HVAC systems, air humidity tends to condensate on the surface of the evaporator. This is especially the case on warm summer days with high humidity. Under these conditions with high cooling demand, the evaporator of these conventional systems is operating at temperatures below 5 °C. At the same time, these low temperatures are inhibiting the development of bacteria etc.. As the presented operating strategy is now targeting higher evaporator temperatures, the risk of creating a culture medium for germs and bacteria is higher.

Cabin blower speed

To provide sufficient cooling power while maintaining these high cabin inlet temperatures, the control strategy needs to apply high cabin blower speeds. During the initial cool-down phase, this is in line with the behaviour of most conventional automobile AC systems. When the cabin temperature is getting close to its target value and the cooling demand is reduced, those systems start to reduce blower speeds. This is not the case for the presented strategy. Here, the blower speed remains high, whereas higher cabin inlet temperatures are allowed. This is again beneficial for the COP of the AC system operation. The main drawbacks of such a behaviour are the relatively high noise level of the blower and the high air speeds near the occupant.
This can cause a reduced comfort level for vehicle occupants, although the general thermal comfort demands (PMV index and air temperature) are fulfilled.
This effect is amplified by the design of current HVAC system of the baseline car. Such systems, especially in cost conscious vehicles, are not designed to be especially quiet or free of draught at high blower speeds.

COP

The key factor to judge the efficiency of the chosen operation strategy is the COP. In 2011, the German Environment Agency (Umweltbundesamt, UBA) published a study on the efficiency of an automotive HVAC systems using R134a or CO_2 as refrigerant [2]. In the course of this study, COP was studied under different boundary conditions using a conventional automotive HVAC system. The developed Scenario 3 of this study resembles closely the stationary conditions of QUIET's benchmark case. For this Scenario 3, the UBA measured a COP of 1.5. According to the simulations of D2.2, the newly designed HVAC of QUIET is predicted to achieve a COP of nearly 2 under even more severe conditions. This indicates the very high potential of the novel system to reduce the electric energy consumption for cabin cooling.

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3.2.3. Heating scenario without IR heating

Time to reach target temperature

In heating mode, the model predicts a heat-up time below 400 seconds. This performance is equivalent to the above-mentioned cool-down time. This is a big improvement compared to the baseline performance.

Air inlet temperature

In general, the inlet temperature responds to the required heating demand. However, the air temperature is quickly settling at the lower optimisation threshold of the cabin inlet temperature. Still, this lower threshold is significantly lower than the inlet temperatures of conventional HVAC systems under these conditions.

Cabin blower speed

As the cabin inlet temperature is set to the lower optimisation threshold, the blower speed needs to be reduced in order to adjust the heating output. As the predicted heating demand drops with time, the blower speed is reduced to less than half of the maximum value. This is eliminating the issue of high noise levels, which was highlighted in Chapter 3.2.1.

COP

The usage of R290 as a refrigerant allows the full operation of the heat pump even at the benchmark test conditions (-10 °C). Mobile heat pump systems using conventional refrigerants like R1234yf suffer from significant loss of power. Additionally, to the heat pump, electric heaters need to run in parallel. The additional power consumption of these heaters deteriorates the system's COP drastically.

Großmann [3] even states, that heat pumps using the conventional refrigerant R1234yf are not suitable for operation below -5 °C ambient temperature.

In contrast, for the newly developed HVAC system COP values above 2 are predicted under stationary conditions at -10 °C. This gain in COP provides a very high benefit for the heating efficiency under cold winter conditions.

3.2.4. Heating scenario with IR heating

Effect on Comfort

In this initial implementation, the IR heating was used to boost the thermal comfort. This means, that the IR heaters are operating in parallel to the unmodified heating operation strategy. The time to achieve an acceptable thermal comfort level was reduced drastically. However, the baseline performance was over-achieved even without IR heating.

Effect on COP

As the IR heating was running in parallel to the HVAC, the overall COP was slightly reduced. This was caused by the additional electric power consumption of the IR panels itself. However, the reduction of COP was only very small compared to the gained comfort level. Furthermore, this drawback only occurred during the initial heat-up phase.

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3.3. Recommendations for final implementation

In order to optimise the performance of the final demonstrator, a few items shall be considered before defining the final operation strategy.

Due to the high COP of the system, high heating and cooling outputs can be achieved by the system. In order to hit the right balance between efficiency and comfort, it is necessary to not over-achieve the heat-up and cool-down duration of the baseline car. A high efficiency potential lies in the appropriate selection of heating and cooling demand. Especially in case of heating with IR panels, a high efficiency potential should be accessible by further reducing heating power output and/or cabin target temperature.

Choosing appropriate scenarios for the tuning of the HVAC control software needs to be done carefully. Of course, the selected optimisation cases at -10 °C and +40 °C need to be considered when tuning the HVAC system, as these conditions were outlined in the project proposal. As these boundaries were set for the system design, it can be expected that the novel HVAC can provide enough cooling and heating capacity for all conditions.
For the actual customer, less severe cases could be more relevant. Extreme cases occur just a few times per year, whereas mildly hot and cold conditions are experienced more often by a wider range of users. On the other hand, the constraints of a funded project do not allow a fully tuned and tested HVAC operation map. To counteract this dilemma, it will be necessary to select a low number of scenarios for defining the operation strategy. These additional operation points should be in line with the later user evaluation in WP5.

As described above, the desire of achieving a high COP is resulting in relatively high blower speeds. The implied noise levels should be checked before finalising the operation strategy. A potential countermeasure would be to reduce the maximum allowed blower speed in situations with low power demand.

In the current optimisation work, the HVAC system was running permanently in fresh air mode. This is a realistic behaviour for the heating case. However, this behaviour is not reasonable under summer conditions. Under such conditions, conventional HVAC systems actively switch into recirculation mode to save energy and to speed up the cooling process. More advanced HVAC systems are even capable to select intermediate settings with a partial air recirculation. Unfortunately, this will not be possible with the given vehicle baseline. However, an intermitted switching between fresh air mode and recirculation mode should be considered.

In total, D2.2 demonstrated, that it is possible to derive an operation strategy with an attractive trade-off between comfort and efficiency. With the elaborated parameters for the simulation runs, it will be possible to re-run the optimisations using the final boundary conditions of the new HVAC system. These boundaries shall be carefully reviewed and confirmed by all involved project partners which provide the various components for the new vehicle systems and HRE as provider of the baseline platform.

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4. Assessment of HMI

4.1. Development process

In order to enhance the efficiency of the development process, a direct collaboration between AIT and HRE was established. In regular phone and web meetings, AIT shared their recent results in the development of the novel HVAC HMI. HRE provided instant feedback from their own experience in developing and evaluating automotive HMI solutions. This direct collaboration along the development process allowed AIT to refine their concepts continuously in order to achieve the desired performance. The continuous exchange allowed HRE to guide the development at AIT, in order to reach a result, which is suitable for the use a passenger car.
Looking back at the execution of T2.4, the work on the HMI proved to be very efficient. During this continuous exchange, many new ideas arose and were implemented subsequently. With a reasonable amount of work load, the maturity of the novel HMI concept improved at a steady pace.

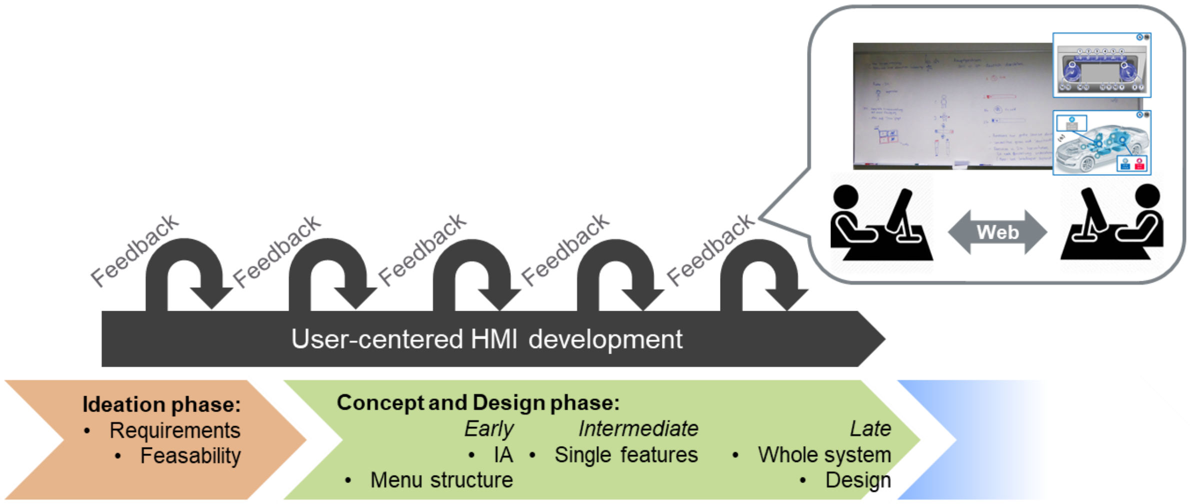

Figure 1: HMI development concept

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4.2. Expert evaluation

An expert evaluation using a small sample size was conducted to assess the first impression of the HVAC HMI prototype. The goal of the expert evaluation was to test the concept and the basic usability of the HVAC HMI prototype. Use cases were not included in this study, therefore the operation flow was not evaluated. The collected feedback was indented to be reflected into the first HMI draft before going to the next evaluation step.

4.2.1.HMI concept

In comparison to conventional HVAC HMIs the new concept is based on a user-centric design approach. Getting away from a temperature-based regulation, the new concept allows users to operate the system based on their current thermal comfort impression. Instead of providing multiple operation possibilities like A/C, Auto, Sync, temperature, ventilation intensity and direction, which lead to multiple possibilities to use and also to accidentally misuse the system, the new concept provides a limited amount of operating options in order to reduce complexity and increase usability. Especially in the context of electric mobility the HVAC HMI should support the user to operate the HVAC system in the most energy efficient way, helping to avoid over-regulation.

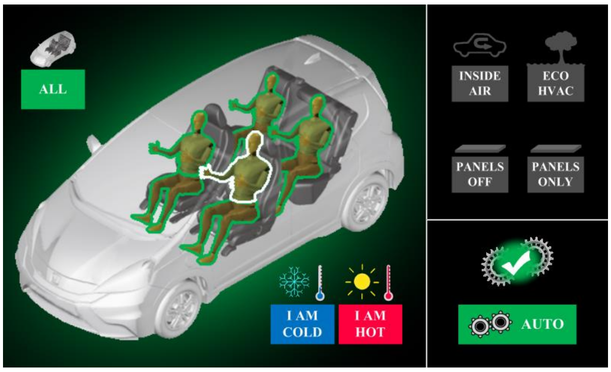

Figure 2: HMI visualization when HVAC is levelled off

The first version of the HMI concept that was reviewed in the expert evaluation allows users to select single body parts on the 3D image of the FIT EV and then either heat the cabin with the "I am cold" button or cool the cabin with the "I am hot" button. To enable the selection of all 4 passengers at the same time an "All" button is integrated in the upper left corner allowing to manipulate the climate for the whole cabin.
Additional functions that do not directly influence single body parts are located in the upper right area of the screen. By activating the "Inside air" button users can switch to recirculation of air within the cabin. "Eco HVAC" can be used in order to heat or cool in the most energy efficient way, especially when the range of the EV is low. Infrared heating panels can be turned off ("Panels off") or used as only heating source ("Panels only"). If none of the two buttons is selected panels are activated or deactivated based on auto regulation.

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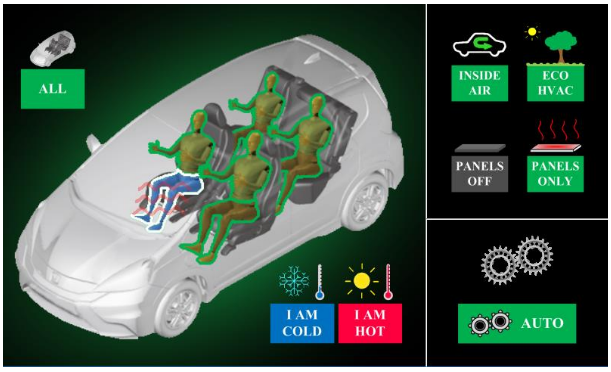

Figure 3: Heating of passenger's lower body with infrared heat panels, active air circulation and Eco mode

In a heating scenario, after the user selected the body part and "I am cold", the heating process is visualized as blue body parts with red waves that fade over time. To communicate to the user that the system is regulating the cogwheels rotate in the lower right part of the screen.

When the adjusted thermal comfort conditions target is reached, the blue colour of the body part returns to its original colour and the red waves vanish. Furthermore, the cogwheels stop rotating and a green check mark appears indicating that the regulation process is finished.

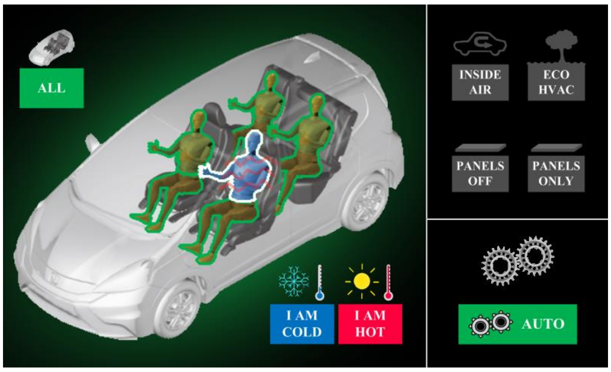

Figure 4: Heating of driver's upper body

In a cooling scenario the same process is shown as in the heating scenario, except the selected body parts are coloured in red and blue waves indicate the cooling process.

In both heating and cooling conditions, the background colour of the displayed vehicle changes from green over yellow to red depending on how energy consuming the current climate regulation is. E.g. if only one body part is selected less energy is needed to adapt the climate, hence the background colour is green (Figure 4). If all passengers are selected via the "All" button for cooling more energy is needed, which is indicated as a red background colour (Figure 5).

The "I am hot" and "I am cold" buttons allow repeated selection up to three times in a row, so the user can indicate how large the perceived gap is between his current thermal impression and the desired climate.

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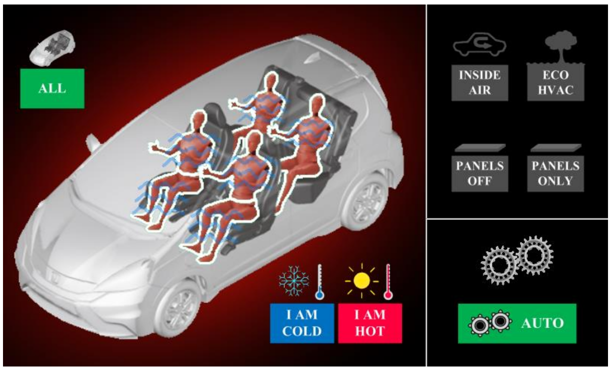

Figure 5: Cooling of the whole cabin

With the Auto button located in the lower right corner of the screen users can switch to the manual mode (Figure 6).

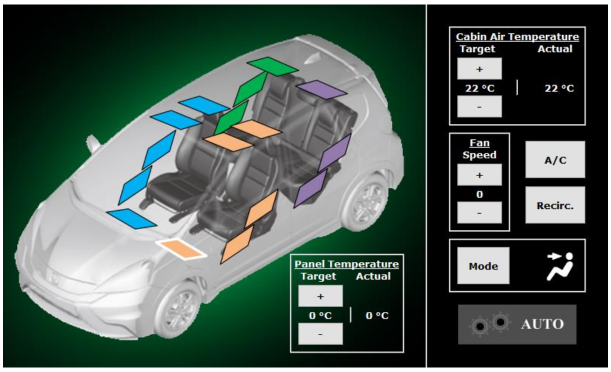

Figure 6: HMI visualization of the manual mode

4.2.2. Method

The evaluation was conducted at HRE with N = 3 internal HMI experts and included the basic assessment and evaluation of the usability as well as user experience from an expert point of view. Due to the small sample size, the evaluation was not use case based and did not include quantifiable ratings. Instead, experts evaluated the concept qualitatively without guiding. Each evaluation session had a length of 30 min.

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4.2.3.Expert feedback summary

In the following list the usability concerns are collected that were encountered by the HMI experts:

1. “All” button: If users select the “All” button by accident there is no easy way to go back to the initial selection. This might increase the number of steps as well as the visual, mental and haptic workload of the users
2. Whole body selection: A more frequent use case will be to select a whole body instead of only the upper or lower part separately. In the current implementation many operation steps are needed to heat or cool a whole body or multiple parts
3. Panels: Panels might not be understood, because users might not know what the functionality of the panels is and where they are located. The spatial separation of the buttons from the image on the left side might make it even harder to understand
4. Cogwheel to show heating/cooling in process: Users might not understand what the rotating cogwheel means
5. Eco HVAC button: The term “HVAC” is too technical for users, most of them will not understand the meaning
6. Eco mode: Users might not understand the advantages of the Eco mode if the benefit (e.g. extended range) is not communicated to the user
7. Auto and manual mode:
    a. For the “Auto” button, the cogwheels are not needed and might even lead to a misinterpretation that the “Auto” button and the cogwheels to visualize HVAC regulation might be related
    b. Users might not understand the functionality of the “Auto” button. When selecting the “Auto” button users will go to the manual mode, which is not directly communicated to the user
8. Defrost: A defrost button is missing in the Auto mode
9. Colour of passengers: The initial colouring of the mannequins might be too prominent to perceive colour changes when changing the climate settings (red or blue colouring). Furthermore, the green framing of not selected body parts might lead to misuse, because green could be interpreted as active

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4.2.4.Improvement proposals

Based on the usability concerns stated by the experts, the following improvement proposals were suggested:

1. Cogwheel to show heating/cooling in process: Use titles like “heating” or “cooling” to show that the rotating cogwheels indicated that the heating/cooling process is regulating
2. Whole body selection:
   a) An option to go back to the user’s initial selection would be necessary. This could be achieved by going back to either default selection of the upper body of the driver or to the last-user-mode when selecting the “All” button again
   b) Allow control of multiple body parts simultaneously by enabling the selection of more than one body part for one climate setting
3. Panels: Replace the word panels with another term (e.g. Thermal radiation, Radiant heating, Infrared heating, IR heating, Direct heating) so that users can better understand the underlying functionality of the infrared heating panels
4. Eco HVAC button: Delete the technical wording HVAC, as “Eco” or “Eco Mode” would be sufficient for users to understand the functionality
5. Eco mode: Make the benefit of the Eco button transparent to the use by e.g. showing how much range is gained. A gamification approach could also be used so that the user is rewarded when using the eco mode by visualizing it in an appealing way (e.g. show plants growing or flowers flying by)
6. Auto and manual mode: Delete the cogwheels in the Auto button and rename “Auto” to “Manual” to show to the user that it leads to the manual mode. In the manual mode the button then has to be renamed to “Auto” again
7. Defrost: Add a defrost button to the Auto mode
8. Colour of passengers: Change the background colour of the passengers to a more neutral (grey) tone and also change the framing of not selected body parts to grey

4.2.5.Refinements in first HMI prototype for initial user evaluation

The first draft of the HVAC HMI concept was modified by AIT based on the improvement proposals from HRE. The refinements and reasons are shown below:

1. Cogwheel to show heating/cooling in process: “Regulating comfort” text is added to the cogwheels to make it easier to understand for users that the HVAC is regulating. To use “heating”/”cooling” is not feasible as parallel heating and cooling is possible

2. Whole body selection:
   a) When clicking on “Select all” button, all bodies are selected. When clicking on “Select all” again, the previous selection of body parts is shown
   b) Multiple body parts can be selected before changing the climate setting. An additional “Select none” button is integrated to allow fast de-selection of all body parts

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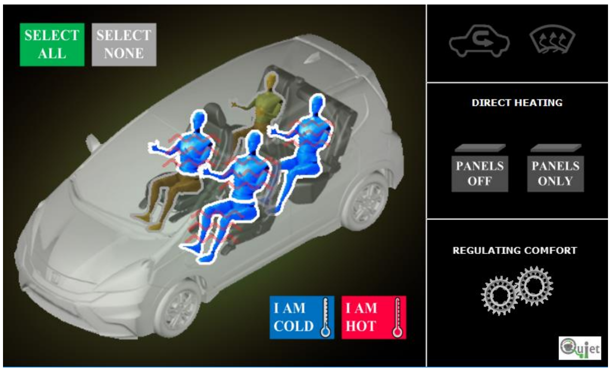
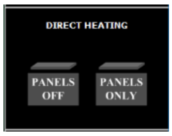


Figure 7: Multiple selection of body parts



3. Panels: The heading "Direct heating" is added to the panels to make the user understand the underlying radiant heating functionality
4. Eco HVAC button: This button is deleted as there is no need for such a function. The novel HVAC system will run as default on an optimised operation strategy (see D2.2)

5. Auto and manual mode: The button to switch between auto mode and manual mode is hidden behind a QUIET project logo, as the manual mode will not be part of the HMI concept tested in the final user evaluation

6. Defrost: A defrost button is added, which replaces the Eco mode button. Furthermore, the title "Inside air" is deleted as the icon is known and does not need further explanation
7. Colour of passengers: The opacity of the red and blue colouring is increased and the framing of body parts that are not selected changes from green to grey

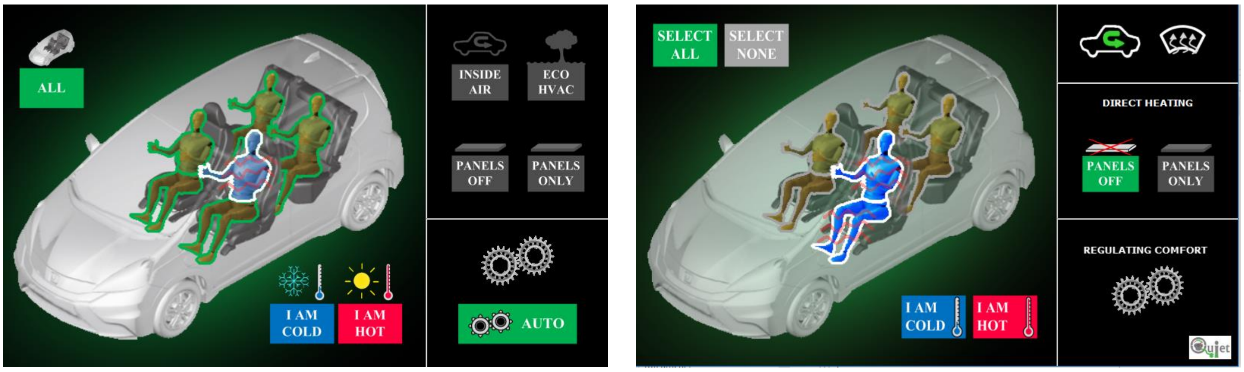


Figure 8: Change visualization between first and second version

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4.3. Initial user evaluation

The initial usability evaluation was conducted with the refined HVAC HMI prototype. After collecting the feedback of HMI experts, the opinion of non-experts was of interest.
Usability findings for some basic HVAC use cases were collected, giving additional input about concept acceptance as well as usability and user experience to the initial expert evaluation.

4.3.1. Method

The initial usability evaluation was conducted at HRE with N = 10 internal participants (no HVAC experts, but experts in the field of advanced driver assistance systems and EV mobility). Task performance as well as subjective ease of use and user satisfaction of different use cases were assessed in winter and summer scenarios. Each individual interview session had a length of 30 min.

6 use cases including 4 for winter and 2 for summer were used for the evaluation:

1. Winter: The user enters the vehicle. The vehicle and the user are cold. When the engine is started, the HVAC starts to regulate automatically. The user does not need to do anything as the climate is already adapting
2. Winter: After 10 min of driving the vehicle is getting warmer but the driver still has cold feet. The user wants to heat only the lower body
3. Winter: The driver picks up a passenger, who is feeling cold. The user wants to heat the passenger area only
4. Winter: The range of the EV is low, but the vehicle and the user are cold. The user wants to heat in the most efficient way
5. Summer: The user enters vehicle. The vehicle and the user are hot. When the engine is started, the HVAC starts to regulate automatically. The user wants to understand what the HVAC is doing based on the visualizations on the HMI
6. Summer: The vehicle has cooled down and the user feels chilly. A passenger enters who is feeling hot. The user wants his area to be warmer and the passenger area to be cooler

Whenever it was possible the participants had the option to compare the usability of the new concept with the FIT EV HVAC HMI. For this comparison purpose the HMI prototype was installed on a "Windows Surface" device that was attached to the vents of a FIT EV.

Figure 9: Experimental setup for the initial usability evaluation

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To assess the task performance as well as subjective user evaluations about ease of use and task satisfaction in a standardized way, 3 rating scales were used in addition to qualitative user feedback.

1. Task performance rating: Expert rating (filled out by the moderator) about the performance of participants as an objective metric

Not solved	Major problems	Minor problems	Hesitation	No problems
Participant was not able to solve the task.	Participant was able to solve the task but took a wrong path and did not directly correct mistakes.	Participant was able to solve the task but did not use the direct path. Nevertheless, mistakes were recognized and corrected instantly.	Participant was able to solve the task without mistakes, but showed obvious hesitation.	Participant is able to solve the task without any mistakes or hesitations and used the direct path.

Figure 10: Task performance rating evaluation scale

2. Subject Rating (ease of use and satisfaction): Rating about how participants perceive the interaction with the system on different dimensions

1 Very difficult/ Very unsatisfied	**2** Difficult/ Unsatisfied	**3** Rather difficult/ Rather unsatisfied	**4** Neither nor	**5** Rather easy/ Rather satisfied	**6** Easy/ Satisfied	**7** Very easy/ Very satisfied
❍	❍	❍	❍	❍	❍	❍

Figure 11: 7-point Likert scale of subjective user ratings

3. System Usability Scale (SUS): 10-item questionnaire to measure usability of the tested system. Outcome is an absolute value between 0-100.

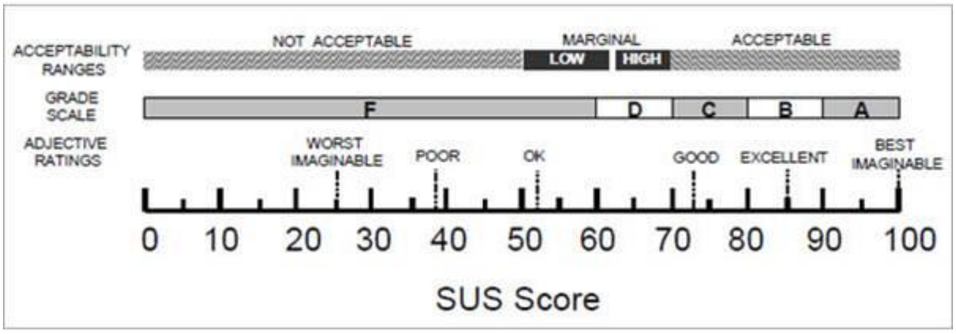

Figure 12: Acceptability, grade and adjective ratings of SUS scores [1]

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4.3.2. Use case evaluation

The following chapter contains the usability findings per use case including the results of the performance and user ratings. The screenshots of the prototype visualize the optimal setting users should achieve for each use case.

The evaluation started with a first contact exploration of the HMI to understand which parts are understandable to the users and which are not.

1. First contact impression:

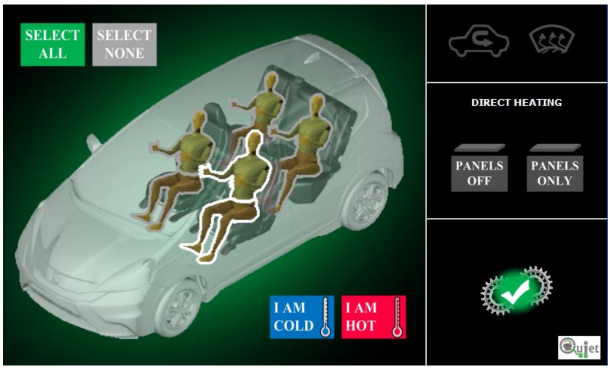

Figure 13: HMI screen used to assess the initial user impression

Users were often surprised by the new concept and needed some time to process the information.
The left side of the screen was mostly understood, although some users were unsure what to expect when selecting “I am hot/cold”.
Most problems in understanding occurred on the right side, where panels were completely unclear for most users.
Furthermore, the cogwheels were often misinterpreted as additional settings.

Figure 14: Performance rating of users' first contact understanding

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2. Winter scenario – Automatic heating after starting the engine:

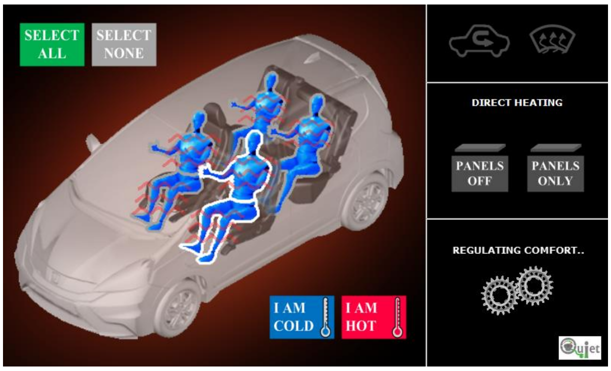

Figure 15: HMI visualization of whole cabin heating

Users were able to understand the basic concept of the HMI based on the visuals on the display. Users understood that the climate was regulating and that the driver was selected.

Nevertheless, some items like background colouring, panels and use of regulating comfort were unclear.

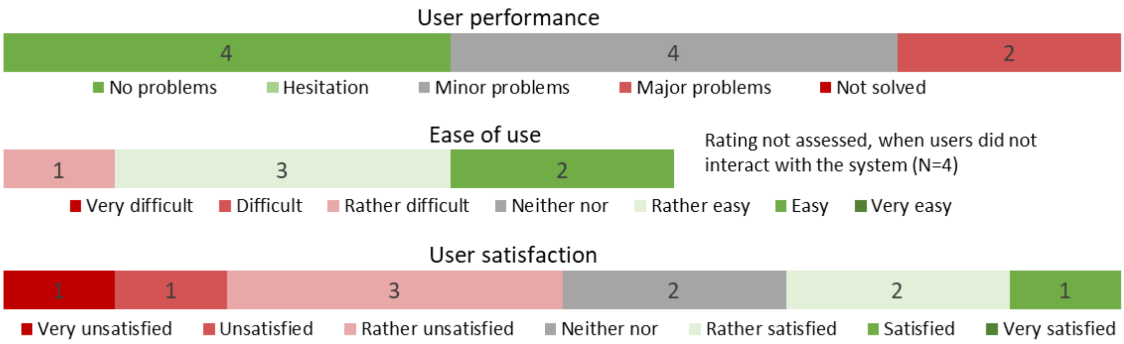

Figure 16: Performance and subjective user rating for use case 1

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3. Winter scenario – Driver has cold feet:

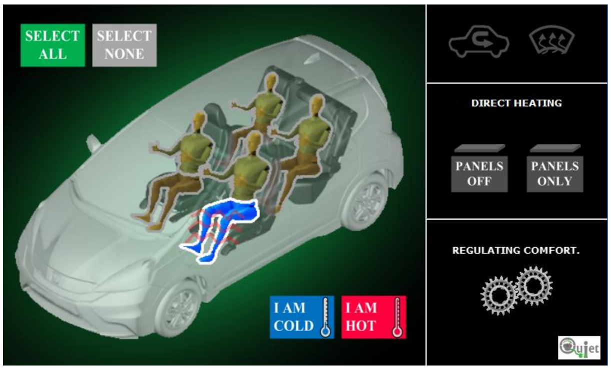

Figure 17: HMI visualization of heating the driver's lower body

Most users quickly understood how to operate the system. Ease of use was rather good, but users would have liked to have a more efficient way to make a selection of body (parts) without the necessity to deselect. For some users the new concept was challenging at first, because they were searching for conventional controls to direct the vents to their feet (e.g. mode button).

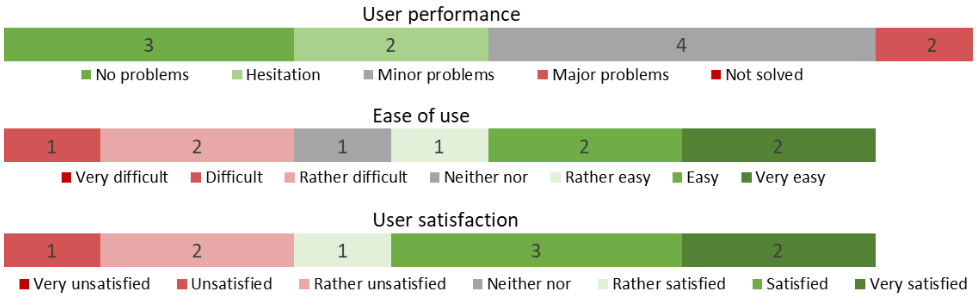

Figure 18: Performance and subjective user rating for use case 2

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4. Winter scenario – Passenger is feeling cold:

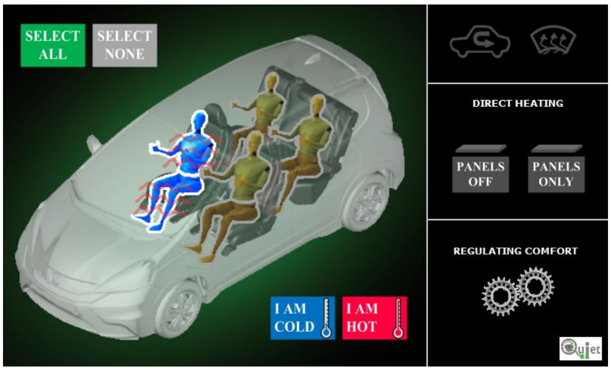

Figure 19: HMI visualization of passenger side heating

Most users were able to solve the task. Again most issues occurred because users had to deselect body parts from past settings. Users either did not recognize their mistake or they had the impression that the operation was not efficient due to unnecessary steps.

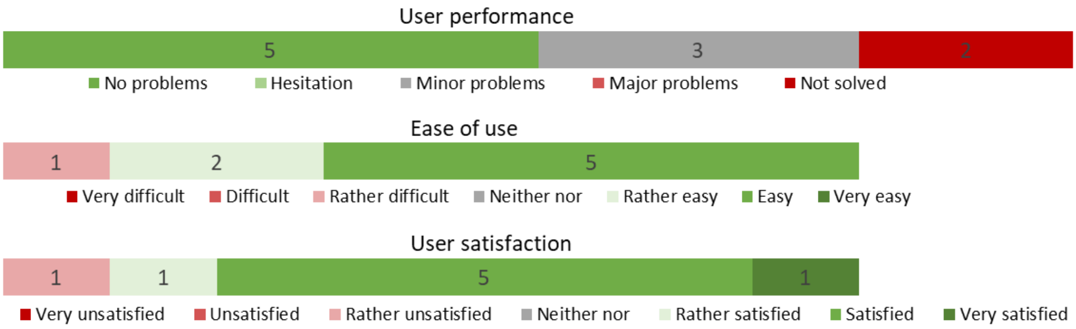

Figure 20: Performance and subjective user rating for use case 3

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5. Winter scenario – Heating with low range:

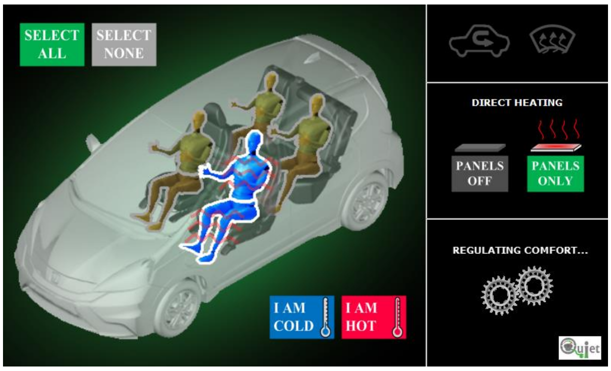

Figure 21: HMI visualization of heating the driver's whole body with infrared heating panels only

Many users had feasible ideas how to heat efficiently (e.g. turn HVAC off except seat heating). Unfortunately they did not see a possibility to set a comparable setting in the new HMI. Even with the title “Direct heating” the panels were not understood. In most cases users didn’t try them out at all. The few users who used panels had difficulties to operate them because the interaction with the left side of the screen (3D image with passengers and “I am cold” button) was unclear.

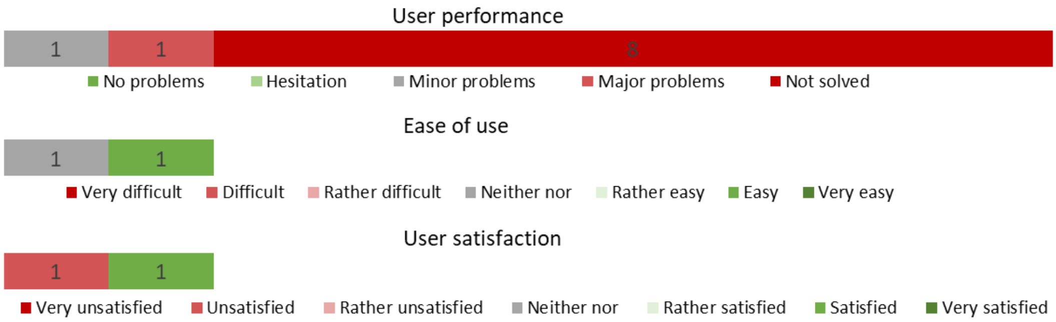

Figure 22: Performance and subjective user rating for use case 4

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6. Summer scenario – Automatic cooling after start of engine:

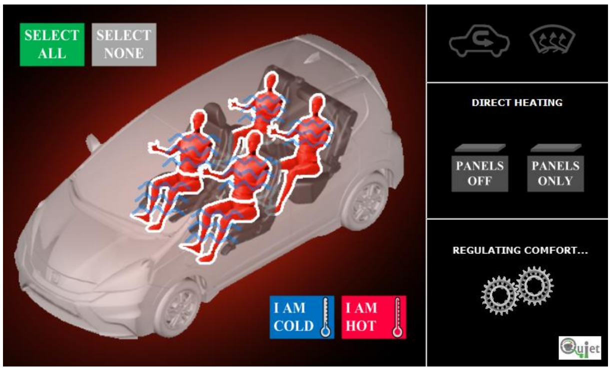

Figure 23: HMI visualization of whole cabin cooling

Most users understood the visualization and appreciated that the system regulated automatically. Nevertheless, users would have liked to have the possibility to stop the regulation (e.g. because they would like to open a window, or the range is low). Colour coding in the summer scenario was more confusing than in the winter scenario for some users, because the red colour was very prominent so that the visuals conveyed the impression of heating and not cooling.

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7. Summer scenario – Driver is feeling cold, passenger is feeling hot

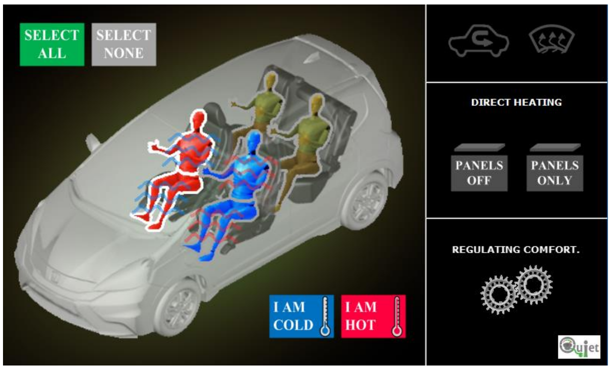

Figure 24: HMI visualization of parallel heating and cooling

Although most users were able to solve the task, perceived mental workload was high and many operation steps were needed. Especially deselecting passengers that were not manipulated in the planned operation generated high complexity.
Selecting whole passengers should be easier, automatic/intelligent (de)selection is needed.

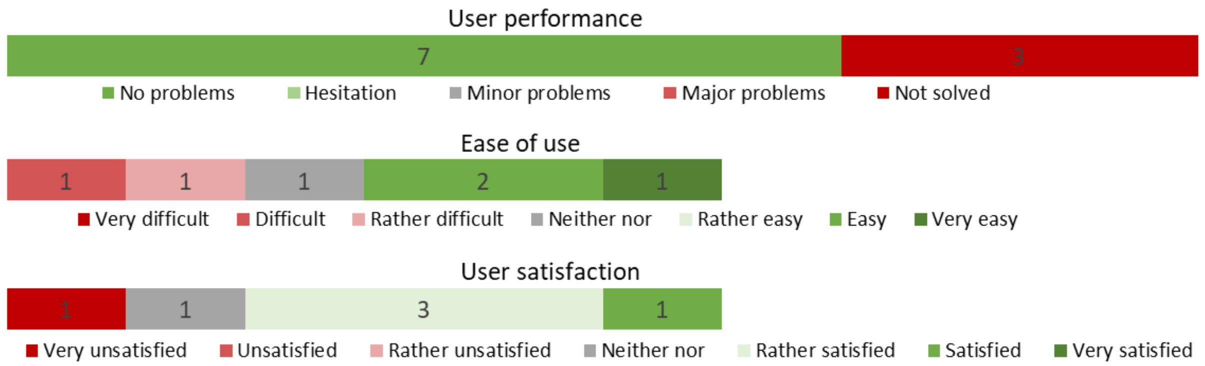

Figure 25: Performance and subjective user rating for use case 6

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4.3.3. Usability findings

With the use case-based study design, performance ratings and subjective user ratings as well as qualitative feedback, a usability list was developed showing the issues that should be resolved in order to improve the usability and user experience.

The usability issues can be allocated into three different categories:

1. Function-related issues: Usability problems caused by functions that are missing or not working as expected
   - Users did not find an option to stop the current regulation when the comfortable climate was reached, and the HVAC was still regulating

2. Operation logic-related issues: Usability problems caused by an unintuitive or inconsistent operation logic when solving a use case
   - Users struggled with the logic of selecting and deselecting body parts. Users rated use cases as inconvenient and mentally demanding where they had to deselect body parts first
   - Users were unsatisfied with the number of operation steps they had to do in order to select a whole body or multiple bodies
   - Users accidentally selected wrong body parts because they hit the outstretched arm of the mannequin

3. Visualization-related issues: Usability problems that occurred due to unclear, missing or hidden visualizations on the screen
   - Users did not understand the panels at all. The functionality location as well as the operation was unclear. Most users did not use them during the use cases. The title "direct heating" did not support understanding
   - Users mostly didn't recognize the background colour indicating energy efficiency of the current HVAC regulation. The users who recognized the colour were not able to understand the meaning
   - Users understood the meaning of the "regulating comfort" visualization with the rotating cogwheels, but they did not see the need or benefit to display it
   - Users misinterpreted the "Select none" button as an option to stop the current HVAC regulation
   - Due to the unfamiliar design of the new HVAC concept, users had initial difficulties to identify the screen as an HVAC HMI
   - Users didn't like the appearance of the mannequins. Their design is regarded as unfriendly and prototypical
   - Users mostly did not recognize that there were different intensity levels for "I am hot" and "I am cold"

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4.4. HMI usability summary

4.4.1. Overall usability (SUS-Score)

The result of the SUS (System Usability Scale) shows that the overall usability of the new HVAC HMI concept was regarded as "OK". To improve the usability some issues regarding visuals and operation logic should be resolved.

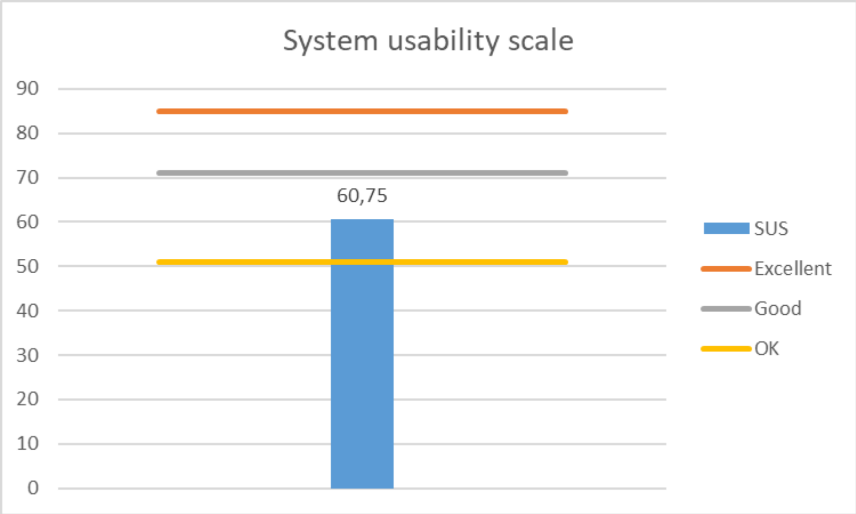

Figure 26: HMI SUS score

The SUS score items show that users perceived the system as unnecessarily complex, cumbersome to use and inconsistent in some parts. Nevertheless, users also indicated that they would like to use the system frequently. This means the overall concept was accepted by users, but the complexity of operations (e.g. too many operation steps, too many unnecessary steps) was too high for a good usability. Furthermore, perceived inconsistencies occurred like the difference between the left and right side of the screen regarding design and operation.

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4.4.2. Improvement proposals for QUIET Demonstrator

Although expert feedback was continuously fed back into the HMI development, new aspects were discovered during the initial user study. Many helpful comments were collected and categorized from the conducted interviews.
The communicated issues with the current version of the new HVAC HMI can be separated into two main categories.
This section shall cover usability complication which were caused by design flaws of the new HMI. We expect, that these items can be solved easily until the final HMI evaluation during WP5.

Functions

- Adding dedicated touch buttons for
  - Turning the HVAC completely off
  - Stopping the comfort adjustment by keeping current cabin conditions as new target value

Operation logic

- Changing logic for selection of body sections
  - Allowing selection of full body with a single touch operation
  - Reducing or removing need to deselect previously selected body section
- Reduced active touch areas on the occupants in areas, where graphics are overlapping

Visualisations

- Clear headline for the touchscreen (e.g. "Advanced Climate Control")
- Statement "Regulating Comfort" should be changed to an abstract status bar, showing the current cabin condition compared to the set target condition
- Replace graphics for vehicle occupants with a more friendly or reduced version
- More pronounced visual distinguishing of selected discomfort levels ("I am hot"/"I am cold")
- Exchange the wording "Panel" with a less technical term (e.g. "Eco Heating")
- Exchange the icon of the heating panels with a more intuitive graphic, which could indicate the positon and role of the panels
- More helpful feedback regarding the energy consumption of the currently used HVAC settings

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4.4.3. Improvement proposals for future applications

Other experienced issues with the HMI usability were caused by system limitations. On the one hand, these arose from limitations of the carry-over HVAC components of the Honda Fit EV baseline car. Other issues were caused by the limited implementation scope, which is possible to realise in a Horizon2020 collaborative research project. However, it will be necessary to address the following items when working towards future applications.

Functions:

- Individual selection of different air flow intensities
- Integration of seat heater operation into HVAC HMI
- User-friendly options to manipulate the automatic model to individual needs
- Detailed energy efficiency visualisation for technically interested users
- Automatic activation of "Eco mode" in case of low range
- Seat occupation detection by seat belt detection, in order to remove the need to deactivate heating manually for empty seats

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5. Conclusions

For the implementation of the QUIET demonstrator car, a suitable control strategy for the novel HVAC strategy has been created. This development control strategy was conducted within the project QUIET and was described in D2.2. At the end of D2.2 an initial formulation of this operation strategy was demonstrated in a simulation environment. This enables the initial assessment of the resulting behaviour of the main components of the novel HVAC system. These cases were used for the first-level assessment in this deliverable. Overall, it could be confirmed that high efficiency gains can be expected from the new HVAC implementation in comparison to conventional HVAC systems. At the same time, some secondary issues appeared. These should be addressed and re-evaluated before implementing the final operation strategy in the demonstrator vehicle.

Additionally, to the operation strategy, a thorough assessment of the novel HMI was performed. The results of a small, internal user study were analysed and summarized. In general, the novel HMI scored 'OK' in the presented form. From the interview, several improvement items were identified and documented. For the majority of these items, only little implementation effort would be required. The HMI system can therefore be easily updated, before the HMI is finally implemented into the demonstrator vehicle. This process has already been started.

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7. Acknowledgment

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4	**QPD**	qpunkt Deutschland 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