Improvement and Investigation of the Requirements for Electric Vehicles by the use of HVAC Modeling

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Abstract

Current activities in the field of vehicle electrification offer a great potential for contributing to climate change mitigation by reducing anthropogenic CO_2 emissions. Beyond the environmental strain, there is an economic one, too. It is therefore crucial for the European automotive industry to exploit not only the environmental benefits, but also the business opportunities, which come from the transition from conventional fuel powered to electrified vehicles. To capture these opportunities, electric vehicles must deliver better performance at a lower price, overcoming the constraints that are currently limiting their mass-market uptake. This paper presents the approach of the research and innovation action H2020 project QUIET to meet these stringent requirements by developing an improved and energy efficient electric vehicle with an 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.

Keywords: Environmental- and Economic Benefits; Increased Driving Range; User Centric Design; Lightweight Materials; Vehicle Energy Management.

1. Introduction

Current activities in the field of vehicle electrification offer a great potential for contributing to climate change mitigation by reducing anthropogenic CO_2 emissions. Beyond the environmental strain, there is an economic one, too. The automotive sector today accounts for 4% of EU GDP, employing approximately 12 million people in manufacturing, sales, maintenance, and transport sectors [1].

It is therefore crucial for the European automotive industry to exploit not only the environmental benefits, but also the business opportunities, which come from the transition from conventional fuel-powered to electrified vehicles. To capture these opportunities, electric vehicles must deliver better performance at a lower price, overcoming the constraints that are currently limiting their mass-market uptake. One of these is the limited driving range compared to conventional fuel vehicles, due to the still limited capacity and high cost of the battery systems. This aspect is exacerbated by cold and hot weather conditions and, more in general, by the variety of conditions that can be encountered in real-world driving. In fact, preliminary experimental tests from both the EU Commission and the US Department of Energy show a significant variation in the distance-specific energy demand of electric vehicles depending on the temperature, auxiliary systems load, and driving conditions [2, 3]. Figure 1 depicts the reduced driving range of a medium-sized EV with a conventional HVAC system in cold (winter) and hot (summer) weather conditions [4]. A significant detrimental effect can be seen when heating up or cooling down the passenger

compartment, quantifiable in up to 22% reduction of driving range in hot (+40 °C) and up to 60% in cold (-10 °C) weather conditions. The described scenarios also consider relative humidity (rH) and solar radiation (W/m²).
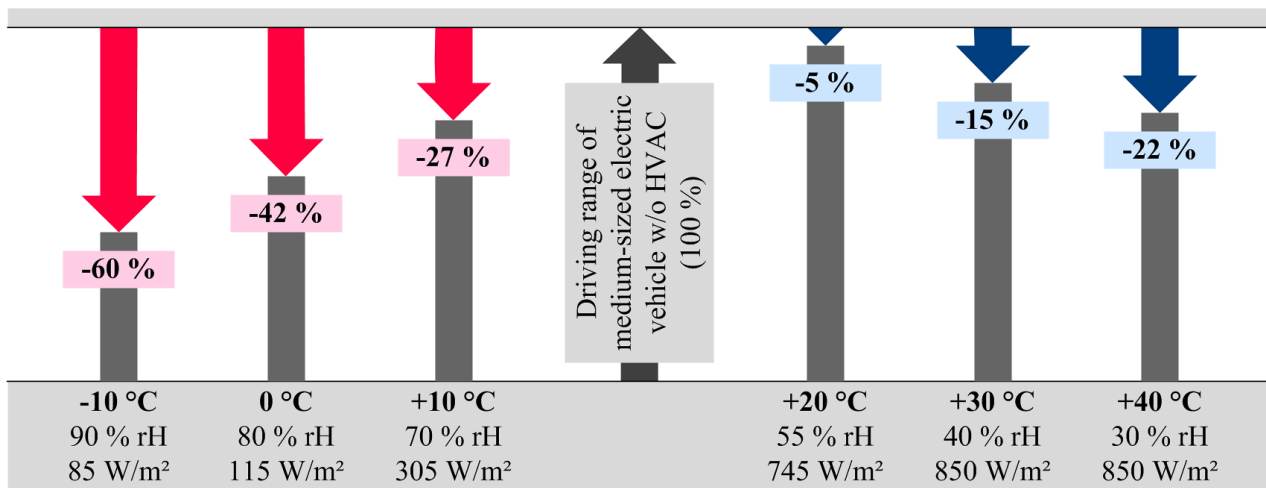

Figure 1. Driving range reduction of a medium-sized EV in cold (heating) and hot (cooling) weather conditions, applying a conventional HVAC system [4]

To address the challenge of enhancing driving range, 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 optimized vehicle energy management have been exploited.

Hence, the present work aims to reduce the energy needed for cooling and heating the cabin of an electric vehicle under different driving conditions, by at least 30 % compared to a state of the art (SotA) electric vehicle (EV), particularly a Honda Fit EV. Additionally, a weight reduction of about 20 % of vehicle components (e.g. doors, windshields, seats, heating and air conditioning) is also addressed. These efforts will lead at the end to a minimum of 25 % driving range increase under both hot (+40 °C) and cold (-10 °C) weather conditions.

2. Methodology of the QUIET Project

To increase the driving range of an EV, reducing the energy required for the thermal management system while preserving or even increasing thermal passenger comfort at the same time is a potential method. Hence, effort must be put into the design of novel and innovative components to reach this goal. For the groundwork all components which are relevant (e.g. doors, seats, windshield, heating- and cooling modules and the overall vehicle) are modelled in a simulation tool, validated and optimized to meet the desired criteria also under various environmental conditions. Furthermore, the developed simulation models are the basis for analyzing the integration of the components into the vehicle e.g. by investigating their interaction and the synergetic effects of the different subsystems, and to estimate the entire EV's energy consumption.

The acquired data of the research demonstrator (i.e. Honda FIT EV) and the resulting baseline performances are used to validate the modelled components and to identify improvement potentials of the Honda Fit EV. The analysis of the potential and the feasibility of possible innovations is initially performed by using mathematical equations and 1D models of the analyzed systems.

The design and simulation phases are followed by assembling the components and subsystems on test beds to test and optimize them individually until all modules are satisfying the required criteria. Further topics which are investigated in this work are novel refrigerants 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.

Further focus is put on lightweight glasses and composites for windows and chassis, as well as light-metal aluminium or magnesium seat components. The thermal performance of the vehicle is additionally enhanced by optimized energy management strategies, such as pre-conditioning and zonal cooling/heating the passenger cabin as well as user-centric designed cooling/heating modules.

This holistic approach enables finally to qualify and realize an improved QUIET demonstrator used for proof of concept, vehicle testing, and comparison with the reference EV regarding thermal comfort and entire vehicle energy consumption.

3. Requirement Definition and Simulation Approach

The measured vehicle data and the resulting baseline performances were the first benchmark for conceiving the requirements for novel solutions, leading to the targeted efficiency improvements of the vehicle and therefore to an enlarged usable electric driving range.

To find improvement potentials of the Honda Fit EV, a virtual analysis of the potential of innovations was performed by means of 1D Modelica models created in Dymola [5], a software tool which allows to create any kind of multi-physical models based on ordinary, algebraic differential equations.

3.1. Modelica Vehicle Model

In Figure 2 a screenshot of the developed Modelica vehicle model is depicted, which was realized in the simulation environment Dymola. The implementation represents the entire vehicle model of a fully electric driven Honda Fit EV consisting of several sub-models which are interconnected via mechanical and electrical connectors and interfaces and a bus system.
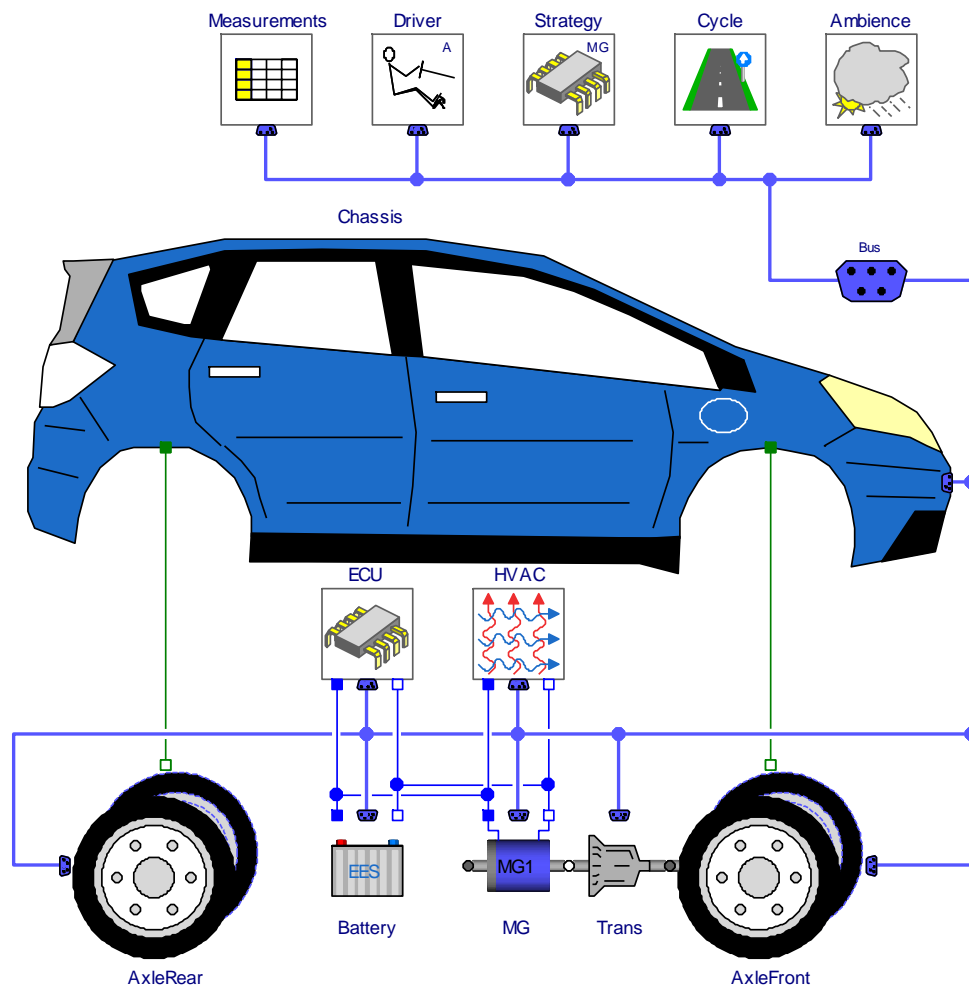

Figure 2. Reference vehicle model of the Honda Fit EV modelled in Dymola/Modelica

Since the Honda Fit EV car is available as study subject, a large amount of measurement data is available to ensure validity of the vehicle model but also to provide real-life data (like driving cycles, velocities, etc.) as realistic target values for the simulation. This data is available in the 'Measurements' block whereas different data sets can be loaded before simulation starts. Different driving cycles (e.g. WLTP cycle [6]) can be used in simulations to predict relevant performance values such as energy consumption and losses of transmissions, electric engines, batteries, auxiliaries (like heating, ventilation and air conditioning systems 'HVAC', etc.).

A parameter extraction script developed in the numerical computing environment MatLab was applied to measurement data (like vehicle speed, rotational speed and torque of the e-machine as well as voltage and current of the e-machine and the battery) to get relevant parameters for the vehicle model and its sub components. The most important parameters which have been extracted were (i) the driving resistance coefficients, (ii) the e-machine- and inverter parameters and their operating maps and (iii) the battery parameters.

3.2. Thermal Vehicle Model – HVAC Modeling

The importance of proper thermal management is highlighted by the fact that heating in cold winter conditions or cooling in warm summer conditions (e.g. at an ambient temperature of -10 °C and +40 °C, respectively), can consume up to 60 % of the batterie's capacity, which in turn reduces the maximum driving range of the vehicle by 60 % (cp. Figure 1). To deal with this issue, protracted real life test can be used for designing and testing new HVAC systems and components. Another, more cost time-saving option (i.e. economic benefit) would be to base the design of the HVAC system or its operating strategy on simulation models. Hence, this work addresses also the design the HVAC system by using a model-based design approach to increase on the one hand the efficiency of the conventional (air-based) HVAC system and on the other hand by adapting novel technologies such as infrared heating panel.

In order to investigate the operating behaviour of the HVAC system in different application scenarios (i.e. heat pump operation at low ambient temperatures and cooling operation at high ambient temperatures), an entire Propane-based (R290) HVAC model has been implemented in Dymola/Modelica using components from the model library TIL Suite [7]. TIL is a commercial library for steady-state and transient simulation of thermodynamic systems. The thermodynamic properties are obtained through TILMedia, a library for the calculation of thermophysical substance properties, providing an interface with the Modelica Media library (MSL). The TIL library includes a variety of models for thermodynamic components (e.g. heat exchangers, pumps, expanders). The implemented HVAC model is depicted in Figure 3.
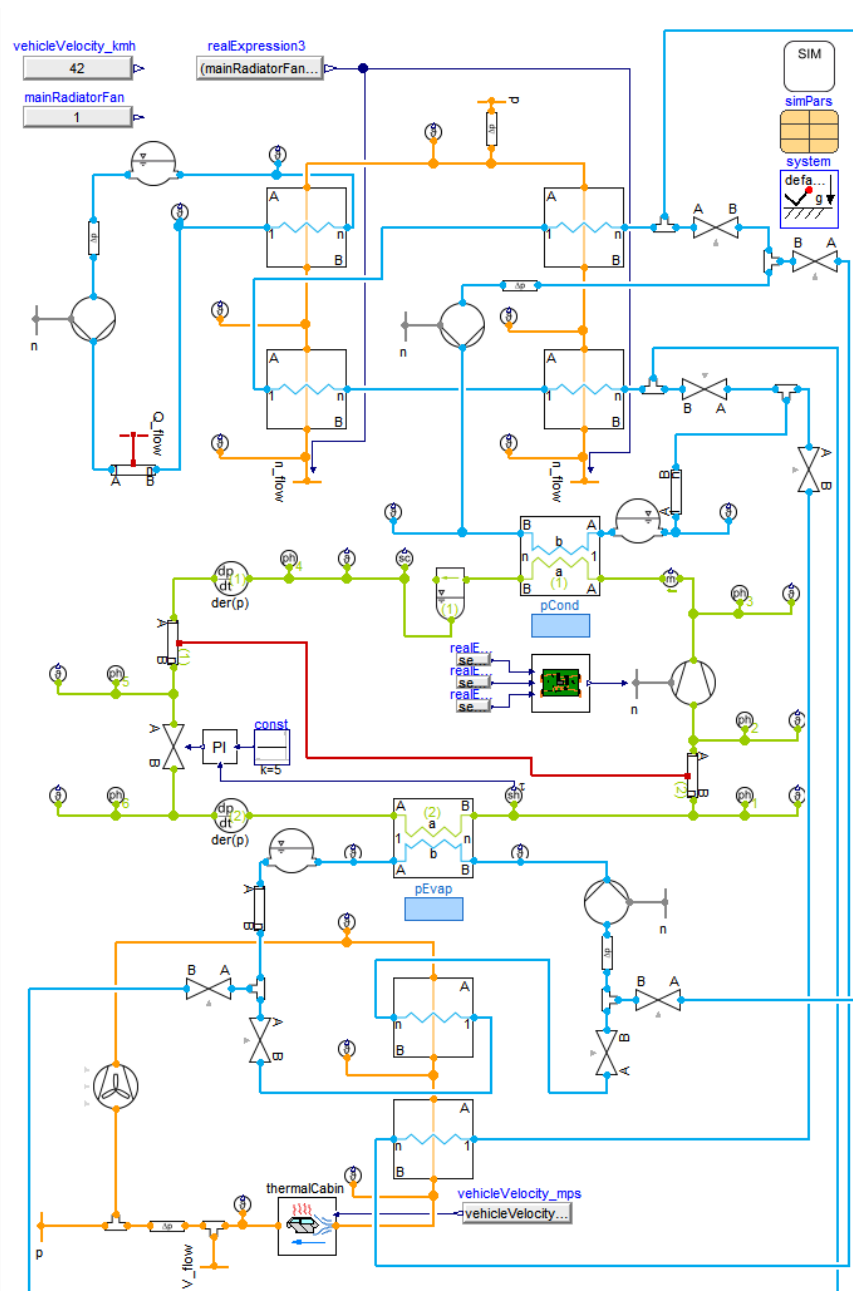

Figure 3. Implemented HVAC model in Dymola/Modelica using components from the model library TIL Suite

Each single component has been parameterised separately. Therefore, measurement data has been used. The boundary conditions, such as pressure and temperature, in different operating points have been defined based on the measurements. Then, characteristic quantities that are relevant for the respective component (i.e. mass flow, heat transfer, outlet temperature, outlet pressure) have been analysed during simulation. Based on the comparison between measured and simulated values, the quality of the chosen model parameters was determined by using an automated adaptive tree search algorithm for parameter tuning tasks which has been implemented by the AIT. Afterwards, the parameterized single models have been connected step-by-step to get the final HVAC model which is depicted in Figure 3.

The model is structured in three different parts: refrigerant cycle (green), water cycles (blue) and air cycles (orange). The refrigerant cycle considers the compressor, condenser, separator, internal heat exchanger, expansion valve and evaporator. The water cycles (for cooling power electronics and for HVAC system) consist of the water side of the condenser, evaporator and front heat exchanger, a PTC heater, pumps and valves. By switching the water cycle valves the refrigerant cycle can be either used in cooling or in heat pump mode. The air cycle considers the front heat exchanger (the heat exchanger is divided into four parts, where one quarter is used for the power electronics and three quarters are used for the HVAC system), the cabin heat exchangers (heater core and low temperature radiator), the front vehicle fan and cabin fan and a cabin volume.

4. Comparison of Simulation Results with Measurement Data

4.1. Validation of the Modelica Vehicle Model

With the vehicle model depicted in Figure 2 a detailed identification of the energy flows of the reference and the improved QUIET vehicle has been carried out. Thereby, possible energy-saving potentials have been determined and validated with measurement data gained from worldwide harmonized light vehicles test procedures (WLTP). The WLTP cycle used for validation and verification of developed simulation model (i.e. identification of reference Fit EV vehicle) is a class 3 cycle aimed for high-power vehicles classified by a power-weight ratio PWr > 34 kW/t [6]. The cycle (cp. Figure 4 can divided in four parts for low, medium, high, and extra high speed and is periodically applied to the entire vehicle model during different ambient conditions (norm @ +23 °C, cold @ -10 °C, hot @ +40 °C) and different operation modes (i.e. without HVAC, heating mode, cooling mode).
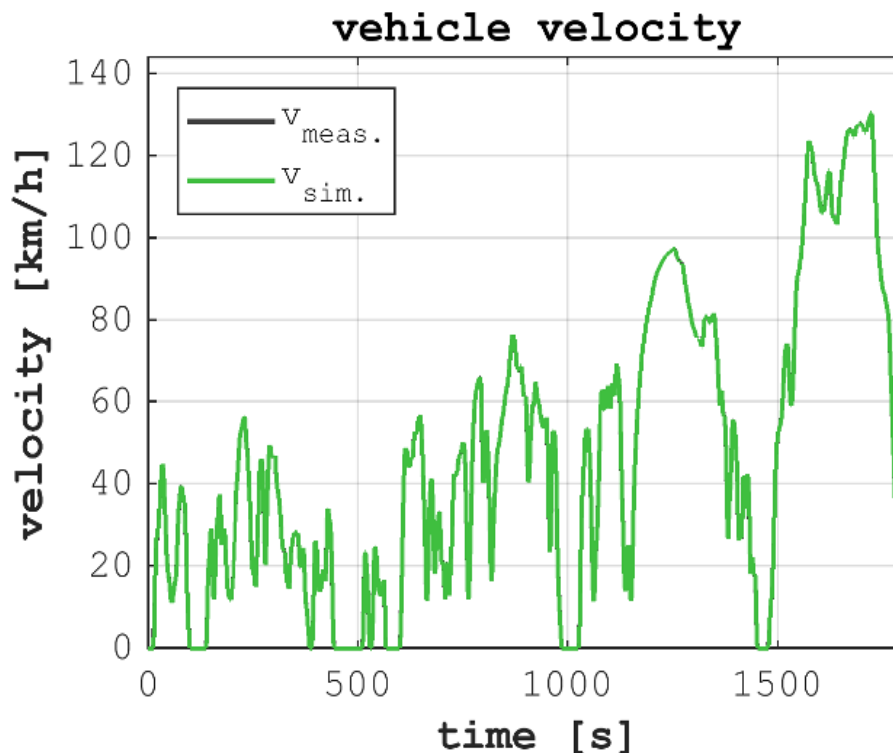

Figure 4. Single WLTP cycle

Table 1 summarizes the performed validation for all different driving modes based on the applied WLTP cycle and for the additional modes MAX heat-up and MAX cool-down (both carried out at 40 km/h constant vehicle speed). The simulated values show only minor differences compared to the measured ones which could be achieved by recursive improvements of the vehicle simulation model during its development and due to suitable selection of different iteration algorithms provided in Dymola.

**Table 1. Measured vs. simulated (baseline) driving ranges**

Driving mode	Driving range (measured)	Driving range (simulated)	SOC remaining (measured)	SOC remaining (simulated)
WLTP norm	155.56 km	155.56 km	0.00 %	1.86 %
WLTP cold	68.40 km	68.43 km	0.00 %	4.86 %
WLTP hot	137.00 km	135.74 km	0.00 %	1.01 %
MAX heat-up*	43.64 km	43.64 km	22.9 %	25.07 %
MAX cool-down*	35.37 km	35.37 km	80.5 %	81.96 %

*Constant vehicle speed (40 km/h)

To identify the energy flows of the reference EV and the improved QUIET vehicle, the validated entire vehicle model was used to fine-tune various key parameters (e.g. reduction of the energy consumption of auxiliaries or weight reduction of vehicle components, etc.). By varying systematically, the key parameters (e.g. the weight of vehicle components) the maximum driving range could be identified, and outperforming impacts became visible.

4.2. Validation of the HVAC Model

The total cycle of the HVAC model has been validated as a whole system. Therefore, again, the measurement data has been compared to the simulation results. The Validation has been performed for one operating point in cooling mode (at 40 °C ambient temperature) and for one operating point in heat pump mode (at -10 °C ambient temperature), respectively. The compressor speed was controlled to fit the measured high pressure after the compressor, while the expansion valve was controlled to guarantee 5 K superheating after the evaporator. The validation of the HVAC model based on the pressure-enthalpy (p,h) diagrams can be seen in Figure 5 for the cooling (blue) and heating (red) mode. In the figure, the grey line is the saturation line of propane, the dashed lines represent the measurements and the solid lines represent the respective simulation results. The results show a very good coherence between the measurement and simulation.
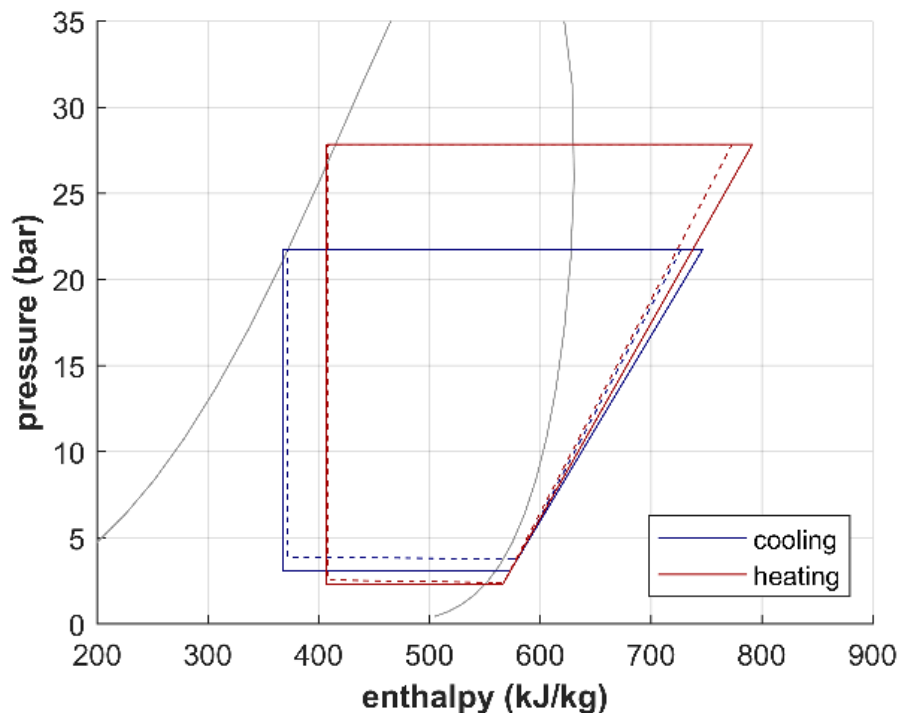
Figure 5. p,h diagram for model validation in cooling and heating mode

The HVAC model will be used also for determining and validating an optimal vehicle energy management strategy using model reduction and optimization methods [8-10]. The model is crucial for the development of the electronic control unit which is required to integrate the vehicle energy management strategy, and which is acting as an interface between the modules for heating and cooling and the user. Hence, special focus is laid in the further course of the QUIET project on the development of a human machine interface. A user-centric designed user interface is provided via a touch screen to the user by forwarding its input stimuli (e.g. desired comfort temperature) to the electronic control unit as new conditions for the embedded (optimised) energy management strategy.

5. Determination of Improvement Potentials of the Reference EV

With the developed simulation model different combinations of settings, components (e.g. variation of their geometries and physical attributes) were investigated to identify systemic weaknesses, and vice versa, their corresponding improvement potentials.

To determine the improvement potentials (e.g. reduction of the energy consumption of auxiliaries or weight reduction of vehicle components, etc.) of the reference EV and to enhance its driving range, the vehicle model can be used to investigate the resulting beneficial effects. Hence, the expectable improvement potentials were classified and clustered in different areas:

- AREA I addresses the user centric design. Here an expected energy consumption reduction of 10 % compared to current State of the Art (SotA) thermal and energy management systems should be achieved;

- AREA II deals with lightweight components and optimized thermal insulation. The expected reduction of energy consumption in AREA II from these factors is around 10 %;

- AREA III addresses innovative cooling and heating concepts. Here the energy consumption should be reduced by 10-15 % for either heating or cooling through optimized thermal insulation and weight reduction of the HVAC system.

By systematically varying the key parameters (as envisaged and graphically depicted by the AREAS in Figure 6) in the vehicle model, the potential of these beneficial effects can be estimated.
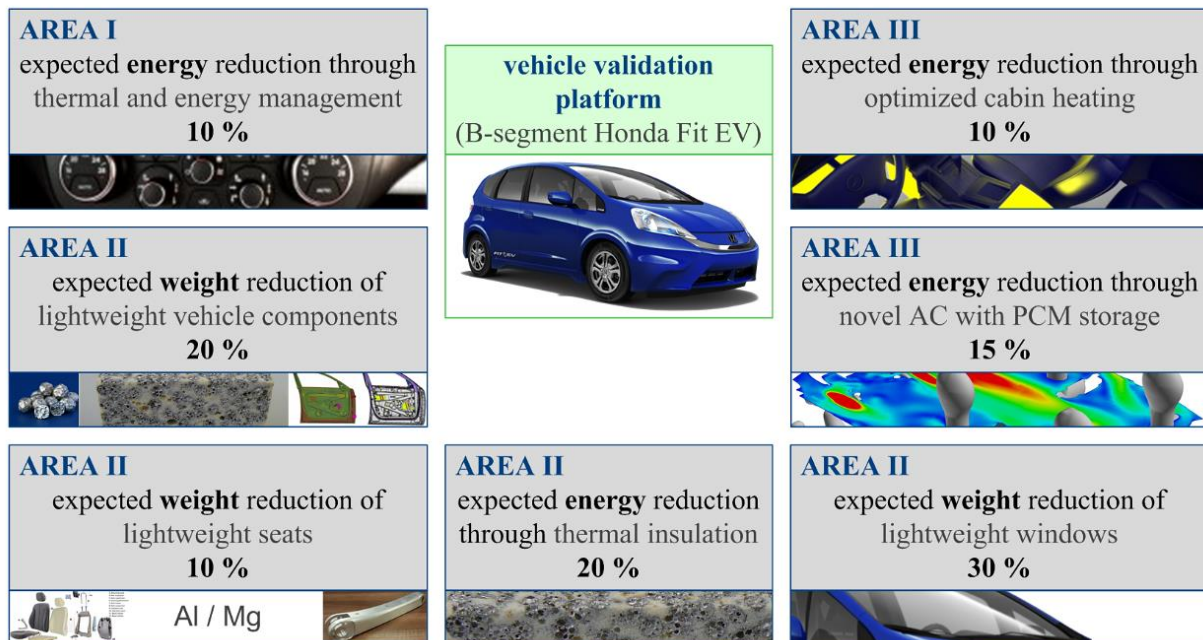
Figure 6. Expected reduction of energy consumption and weight in each of the three areas of the QUIET project

Starting point is the Honda Fit EV 2017 baseline for which a driving range increase of at least 25 % is prescribed (accompanied by enhanced thermal comfort and maximized energy efficiency) by means of following enhancements, specified by:

- An energy reduction of at least 30 % for cooling and heating of the vehicle cabin and (covered by the AREAS I & III);

- A weight reduction by approximately 20 % of the vehicle components (covered by AREA II).

5.1. Improvement Potentials Through Energy Reduction of Cooling and Heating and Through Lightweight Vehicle Components

The correlation of these enhancements to possible improvement potentials for the reference EV was elaborated by carrying out variation simulations (i.e. by varying the energy consumption parameters for cooling and heating by assuming a weight reduction of 20 %). Table 2 summarizes the expected increase of the driving range for different driving modes (hot weather conditions: +40 °C vs. cold weather conditions: -10 °C) based on the applied worldwide harmonized light vehicles test procedure (WLTP) by varying the vehicle weight and by varying the energy

consumption needed for cooling (AC mode) and for heating mode, respectively. The highlighted values within the blue cells are representing the driving range increase in percent. Under the assumption of an achievable weight reduction of the vehicle of about 75 kg the simulation results have shown, that reducing the cooling energy by 45 % (in hot weather conditions: +40 °C) would lead to a driving range increase of about 10 % (baseline driving range is 137 km). Reducing the heating energy by 40 % (in cold weather conditions: -10 °C) would lead to a driving range increase of about 27 % (baseline driving range is 68 km).

The highest improvement potential to increase the vehicle driving range of about 25 % can be reached if merely a reduction of the heating energy of about 40 % will be realized. When supposing a weight reduction by approximately 20 % of the vehicle components (i.e. a further vehicle weight reduction of more than 75 kg due to introduction of lightweight materials [11-14] for doors, seats, and polycarbonate glazing) the target results have been exceeded for hot conditions (range increase over 27 %).

Table 2. Expected increase of the driving range (cp. blue cells, in percent) under different driving conditions

driving cycle	reference driving range		reduction of energy consumption of AC mode [%]							weight reduction [kg]
name	measured	simulated	0	-10	-20	-25	-30	-35	-45	
WLTP hot	137.00	137.00	0.00	2.85	4.67	5.51	6.12	7.42	8.60	0
			0.25	3.66	5.45	5.85	7.18	7.88	8.99	-25
			2.61	4.49	5.79	7.15	7.78	8.47	9.44	-50
			3.55	4.93	6.96	7.65	8.41	8.85	9.98	-75

driving cycle	reference driving range		reduction of energy consumption of heating mode [%]					weight reduction [kg]
name	measured	simulated	0	-10	-20	-30	-40	
WLTP cold	68.40	68.07	0.00	6.55	12.91	18.67	26.09	0
			2.60	6.58	13.52	19.22	26.30	-25
			2.92	6.86	13.66	19.89	26.53	-50
			3.00	7.23	14.16	20.95	26.85	-75

5.2. Improvement Potentials through Energy Reduction by Improved Thermal Insulation

The presented HVAC model was used for assessing the cooling and heating performance in the passenger compartment for different application scenarios (e.g. to determine the lost thermal energy at different vehicle surfaces like chassis and windows, cp. Figure 7) and to assess for instance improvement potentials by improved thermal insulation effects, cp. Figure 7 (a) vs. Figure 7 (b). Figure 8 (a) depicts different vehicle surfaces (A1 to A7) whereas glazed surfaces are accentuated in color blue and the other relevant surfaces in color red. The highest thermal losses were identified at the side windows (A4), the least thermal losses were determined for the vehicle floor (A7). This can be explained by the fact that the battery pack is mounted on the vehicle floor and acts as an insulator. The results show a potential to replace the existing glass windows with polycarbonate glazing in order to reduce thermal losses at the problematic surfaces (A4, A5, A6).
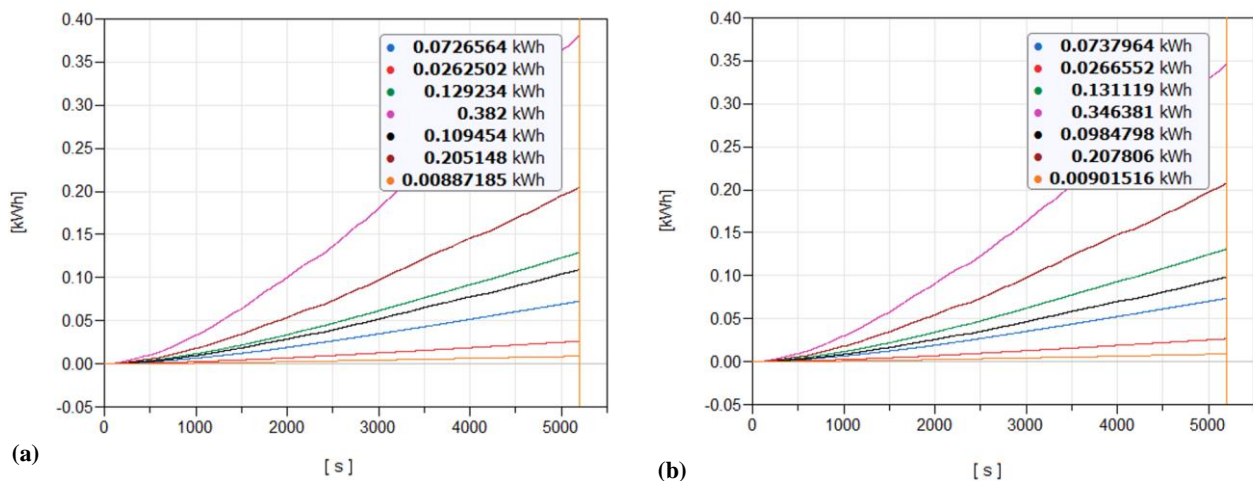

Figure 7. Lost thermal energy at different surfaces like chassis and windows: (a) Standard glazing; (b) Polycarbonate glazing

Figure 7 depicts the cumulated lost thermal energy at different surfaces (i.e. chassis and windows, A1 to A7) for standard glazing Figure 7 (a) and for polycarbonate glazing Figure 7 (b). The energy values outlined in Figure 7 are corresponding with the numbering of the surfaces (e.g. top-value: A1, bottom-value: A7, etc. with related color-labels/colored curve profiles).
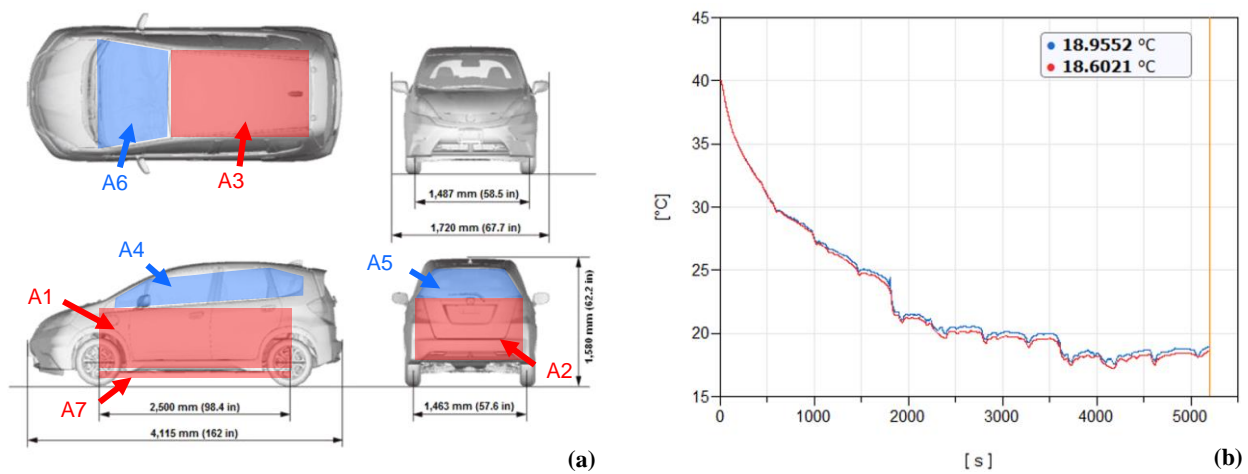

Figure 8. (a) Relevant surfaces for thermal losses; (b) Cabin temperature comparison between standard- and polycarbonate glazing

The improvement potential by using polycarbonate instead of glass windows is depicted in Figure 8 (b) comparing the cabin air temperature of the vehicle with standard glazing (blue) with the cabin air of the vehicle with polycarbonate glazing (red). The results show that the novel glazing can lead to lower cabin temperatures in summer conditions by approximately 0.5 °C.

6. Conclusion

This paper has provided simulation models of the QUIET vehicle demonstrator (Honda Fit EV) and simulation models of the entire HVAC system for this car. The models have been parameterized based on measurement data at the component level. Parameter extraction scripts and an optimization routine helped to reduce the necessary amount of time to adapt the model parameters to fit the measurements. The parameterized models have been used to implement the Modelica vehicle model and its entire HVAC system model, which were validated using measurement data. The validation showed that the models can reproduce the operating behaviour and, with the developed thermal vehicle HVAC model, the improvement potential by using polycarbonate instead of glass windows was elaborated.

Under the assumption of an achievable weight reduction of the vehicle of about 75 kg, the simulation results have shown that reducing the cooling energy by 45% (in hot weather conditions: +40 °C) would lead to a driving range increase of about 10% (baseline driving range is 137 km). Reducing the heating energy by 40% (in cold weather conditions: -10 °C) would lead to a driving range increase of about 27% (baseline driving range is 68 km). The highest improvement potential to increase the vehicle driving range by about 25% can be reached if merely a reduction of the heating energy of about 40% will be realized. When supposing a weight reduction by approximately 20% of the vehicle components, the target results have been exceeded for hot conditions (range increase of over 27%).

7. Nomenclature

EV	Electric Vehicle	GDP	Gross Domestic Product
HMI	Human Machine Interface	HVAC	Heating Ventilation and Air Conditioning
PTC	Positive Temperature Coefficient	rH	Relative Humidity
SotA	State of the Art	WLTP	World-wide harmonized Light-duty Test Procedure
QUIET	QUalifying and Implementing a user-centric designed and EfficienT electric vehicle		

8. Funding

9. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

10. References

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