Thermal Management in E-Carsharing Vehicles—Preconditioning Concepts of Passenger Compartments

Daniel Busse, Thomas Esch and Roman Muntaniol

Abstract The issue of thermal management in electric vehicles includes the topics of drivetrain cooling and heating, interior temperature, vehicle body conditioning and safety. In addition to the need to ensure optimal thermal operating conditions of the drivetrain components (drive motor, battery and electrical components), thermal comfort must be provided for the passengers. Thermal comfort is defined as the feeling which expresses the satisfaction of the passengers with the ambient conditions in the compartment. The influencing factors on thermal comfort are the temperature and humidity as well as the speed of the indoor air and the clothing and the activity of the passengers, in addition to the thermal radiation and the temperatures of the interior surfaces. The generation and the maintenance of free visibility (ice- and moisture-free windows) count just as important as on-demand heating and cooling of the entire vehicle. A Carsharing climate concept of the innovative ec2go vehicle stipulates and allows for only seating areas used by passengers to be thermally conditioned in a close-to-body manner. To enable this, a particular feature has been added to the preconditioning of the Carsharing electric vehicle during the electric charging phase at the parking station.

Keywords Carsharing · Thermal management · Thermal comfort · Electrical vehicle · Passenger compartment · Preconditioning of vehicle interior · Heat to passenger · Heat to seat

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1 Introduction

The recent development and market introduction of battery electric or hybrid vehicles as an alternative to traditional gasoline- or diesel-powered vehicles is being driven by politics and also by the automotive industry now for several years. After an initial euphoria and first successes in cities and regions with strict environmental regulations and generous funding programmes, the current discussion is more characterized by a balance between benefits and costs of a system change in automotive drive concepts (AMS 2011). In addition to numerous other issues, the identification of appropriate initial markets is crucial to give all parties the opportunity to develop sensible vehicles, usage models and support frameworks.

The focus of this paper is on the subject of Carsharing fleets for the integration of electric mobility: Concepts of cars with shared use offer interested customers the opportunity to test vehicles without having to bear the high cost. In addition, it may allow a faster penetration of electric drive technology to speed and economy of electric vehicles can be improved by minimizing downtimes. Furthermore, Carsharing has developed to a very dynamic market in recent years and it suggests itself to a change in the mobility behaviour of broad social layers. Signs of a trend away from the car as a 'status symbol' for the flexible use of vehicles and transportation to their suitability for the currently planned trip purpose can be recognized and supported by various studies (ISI 2011).

For electric vehicles the air conditioning and thermal management of the vehicle represents a major challenge (Ackermann 2011). Classic solutions which are used in conventional vehicles with internal combustion engines such as belt-driven refrigeration compressors, electric windows and seat heaters can only be used very partially in electric vehicles due to the electrical charging of the traction battery, as draining the electric battery for these uses would be counterproductive for the driving range (Ackermann et al. 2013). Therefore, innovations in the field of temperature and climate management are essential for electric vehicles especially in Carsharing applications.

2 The Thermomanagement Concept

The Carsharing climate concept stipulates and allows for only seating areas used by passengers to be conditioned. Heating of the whole interior is not always energetically sensible. Tight surface heating compensates for the lowered interior temperature. The basic idea of the close-to-body conditioning (Heat to Passenger) saves energy by reducing the average interior temperature of the vehicle and increases the comfort by a demand-controlled individual seat heating. The use of surface heating (Heat to Seat) includes seat and backrest, floor mats, armrest, steering wheel, headrest, seat belt, even slices. According to the usage profile, the response time of the heating elements is very fast. The concept of close-to-body temperature control may also include the concept of eClothing, a climatic seat belt and air headrest. Vacuum insulation panels are used in the vehicle body elements on the basis of high-performance foams from polyurethane, which provide an up to seven times better thermal performance (heat, cold) compared to conventional polymer insulating materials. Infrared-reflective films in the glazing reduce the heating up of the vehicle interior, and infrared-reflective coatings and pigments in exterior paint and interior reflect heat radiation from the sun and light. Transparently, coloured photo cells generate enough electricity for a continuous air flow in the interior of the Carsharing vehicle at high sunlight. The climate centre is displaced from the dashboard to the proximal areas of the occupants. The comfort can be produced by simple controls and customized comfort elements can thus be taken into account.

3 Benchmarking of Thermal Management Parameters of Electric Vehicle

For subsequent validation of simulation models, a detailed benchmark of the university's research vehicle, a Mitsubishi i-MiEV, was performed. In addition to the electrical energy flows in the drivetrain and in the auxiliaries, the thermodynamic behaviour of the drivetrain as well as the vehicle compartment was analysed.

Temperature was recorded at eight different measuring points: four temperature measurement points were set up in the engine cooling circuit (the drive motor, the power electronics, the battery charger and the DC/DC converter), two in the heating circuit, one ambient temperature measuring point and one in the passenger compartment. Electric current was measured at three measuring points.

In addition, the battery voltage of the vehicle was recorded and evaluated.

In the high voltage (HV) electrical system, the voltage of the drive battery and the electrical power to the interior heating, air conditioning compressor and power train were also documented. In addition to the thermal behaviour of the drivetrain at different load profiles, heating and cooling curves of the interior were recorded (see Fig. 1). The data sets were evaluated and used to validate the thermal management model.

4 Carsharing Specific Thermal Management Requirements

To ascertain requirements and user profiles for Carsharing of relevance to actual usage, evaluation data of Carsharing provider *Cambio Mobility Services* in Aachen were used. Their (as of 2014) 9 e-vehicles in a fleet of about 100 vehicles are in use. From the usage data provided, information such as average distance travelled, time of booking, etc. were provided. Furthermore, a user survey among approximately 700 participants was conducted amongst Carsharing customers. These data were

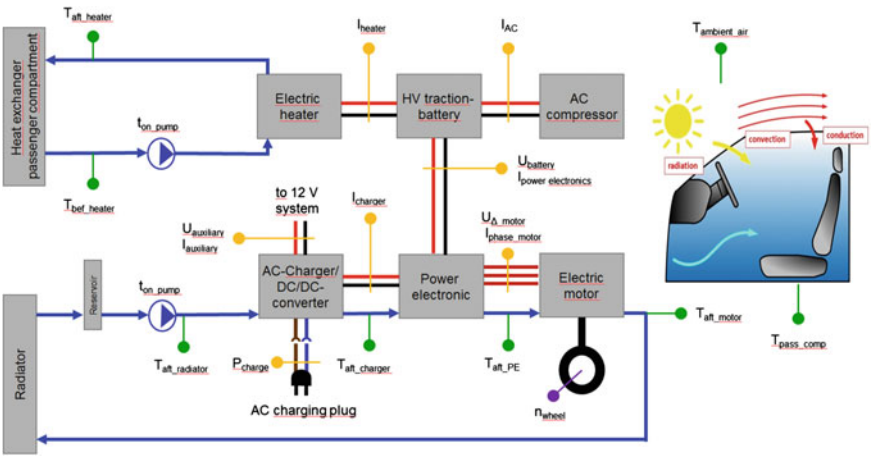

Fig. 1 Measuring positions during benchmark investigations of the Mitsubishi i-MiEV vehicle

used to interpret and evaluate the Carsharing specific potentials. The survey results and the user data of Carsharing customers analysed were then evaluated at the vehicle level with respect to thermal management and drivetrain with respect to the user requirements. The following identified key data parameters have been taken as a decisive basis in the conceptual design:

- in terms of *distance travelled per user*, in 58 % of cases this ranged from 0 to 20 km
- the *average distance travelled per user* was 13.9 km
- in terms of *frequency of use of Carsharing*, 62 % of customers used it less often than three times per month
- the *average use time/vehicle booking duration per user* was 2.5 h
- in terms of *predictability of bookings*: only 8 % of trips of each ride are known only less than 1 h before use
- in terms of highway usage, 58 % of users said that they seldom to never go on the highway with a *Carsharing vehicle*.

4.1 Load Profiles of Drivetrain

In order to establish the longitudinal dynamics model for the subsequent concept evaluation, a requirement profile was defined as a vehicle profile. These requirements are similar to the performance of the university's research vehicle and shall comply with requirements representing a small zappy town car for Carsharing use. From these data profiles, a requirement design cycle has been generated to test the parameterized models (see Table 1).

Table 1 Requirements of vehicle performance for Carsharing purpose

Acceleration		Elasticity	
0–30 km/h	3 s	30–50 km/h	2.5 s
0–50 km/h	5 s	50–70 km/h	4 s
0–100 km/h	15 s	70–100 km/h	10 s
v_{max}	120 km/h	100–120 km/h	10 s
Gradeability		*Body parameter/weights*	
4 %	100 km/h	Tare weight	900 kg
20 %	30 km/h	Gross vehicle weight	1260 kg
30 %	20 km/h	c_W	0.35
35 % (max)	1 km/h	Front surface	2.5 m^2

For the longitudinal dynamic evaluation of the concepts the New European Drive Cycle (NEDC) was used as reference. With its 11.007 km length an NEDC cycle corresponds approximately to the average travel distance of a Carsharing user per booking. Furthermore, for a more detailed validation of the longitudinal dynamic model a real reference route through Aachen (Aachen City Cycle, ACC) was defined. Various benchmark measurements for different traffic situations have been conducted with the university's research vehicle (see Table 2).

4.2 Load Profile Vehicle Interior

Since for E-mobility climatic conditions have a major impact on vehicle performance (range), temperature profiles were sought to evaluate, design and optimize the thermal system performance. From the idea of a Carsharing vehicle for the use in urban areas and to analyse the potential for optimization with regard to the specific usage requirements, it was decided to use the weather data of Aachen, representing a typical central European city. With respect to the thermal requirements the daily values of temperature of the German Meteorological Service (Deutscher Wetterdienst, DWD) weather station 10501 Aachen (located at 50°47′N006°05′E) were evaluated over the time period between 1991 and 2010. From the DWD source, the following values were specified for each month in the mentioned period: Minimum temperature, mean daily minimum temperature, mean temperature and mean maximum temperature, as well as maximum temperature. The day referred to here is a 24-h calendar day without distinction between day and night. From this

Table 2 Comparison of used driving cycles

Cycle	Driving distance (km)	Driving time (s)	Average velocity (km/h)	v_{max} (km/h)
NEDC	11.007	1180	33.6	120
ACC	24.2	Appr. 3600	28–31	100

temperature data three design points for use in warm ambient temperatures (*summer*, S1–S3) were defined, as well as three for cold ambient temperatures (*winter*, W1–W3). For the design point *summer* the values of the period 01.04–30.09 were considered, and for *winter* accordingly 01.10–31.03. The mean daily maximum temperature, averaged over the summer months of April to October, is defined as the first design point for the summer (S1), and the second design point (S2) is the mean of the average daily maximum of the months of April to October. The absolute daily maximum has been determined as the highest design limit for this time period. For summer design points the thermal requirements on warm summer days, for example at noon, should be reflected. For the winter design points this was translated accordingly (see Table 3).

In addition to the expected temperature, solar radiation is important. For central European latitudes such as Aachen one can expect a solar radiation of 600–1000 W/m^2 on a summer day with clear skies (see Table 4).

4.3 Simulation Tools and Procedures

To determine the purpose of analysis and the optimization potentials, vehicle submodels have been constructed. As a simulation tool, in this case GT-Suite by Gamma Technologies was chosen. With its programme modules GT-Power and GT-Cool it offers, among others, options, the possibility of simulating the vehicle's

Table 3 Evaluation of the weather data of the Aachen DWD weather station (from 1991 to 2010)

Point	Name	Evaluated by	Temperature value (°C)
S1	Average summer day (01.04–30.09)	Average of median daily maximum summer days	20
S2	Average summer extremes (01.04–30.09)	Average of the maximum temperature summer days	28
S3	Absolute extreme summer (01.04–30.09)	Extremum 1991–2010	37
W1	Average winter day (01.10–31.03)	Average of median daily maximum winter days	0
W2	Average winter extremes (01.10–31.03)	Average of the maximum temperature winter days	−4
W3	Absolute extreme winter (01.10–31.03)	Extremum 1991–2010	−16

Table 4 Solar radiation for central Europe (http://www.wetterstation-bremen-nord.de/index.php?inhalt_mitte=content/solar.inc.php)

Season	Heavy overcast to cloudy foggy (W/m^2)	Light to medium clouds (W/m$^{2)}$	Clear to slightly diffuse sky (W/m$^{2)}$
Summer	100–300	300–600	600–1000
Winter	50–150	150–300	300–500

longitudinal dynamics as well as the thermodynamic behaviour of different vehicle systems (engine, interior, cooling …). Thus, a longitudinal dynamic model of the drivetrain, and a model of the vehicle interior have been built and validated.

4.4 Vehicle Cabin

With the thermal model of the passenger compartment the required heating or cooling capacity for achieving the comfortable temperature environment at predetermined conditions is detected. The model simulates the driving environment in all material respects and consists of eight interrelated concentrated point masses. All the doors of the vehicle are represented by a single mass, as are all door panels, all side windows and the entire interior. Further individual masses represent the roof, the windscreen and the rear window. Besides the weight, the components are characterized by their surface described by thermal conductivity, by emissivity and absorption coefficient and by transmittance (only for glass). For the heat exchange between the vehicle components and the indoor air or the ambient air, the heat transfer is taken into account by convection. For the sake of simplification, a constant heat transfer coefficient is defined between an interior side and environment side heat transfer. The heat conduction within the individual masses is taken into account by a constant thermal conductivity. View factors for the roof, doors and windows are also considered.

4.5 Interior Ventilation

The layout of the heating and ventilation system of the model was largely inspired by one of the conventional vehicles. Both a fresh air mode and a recirculation mode can be simulated. During the standing and charging phase of the vehicle a recirculation mode of the ventilation system effects to save energy and to accelerate the warming or cooling of the interior is applied. In the subsequent preparation phase and during the trip a fresh air mode takes place. Both in recirculation mode and fresh air mode, the air current operates a fan into the passenger compartment with a constant flow rate of 150 m^3/h. The function of the air speed of the vehicle is neglected in order to simplify the simulation model. The graph (Fig. 2) shows the cabin model with the air circuit and the control elements in the simulation environment GT-Cool.

In *Temperature Control* all subcomponents are combined, regulating the heating or cooling the indoor air and the air delivery. The change of air circulation mode to fresh air operation is dependent on the duration of the individual phases of operation. The heating or cooling of the vehicle interior air comfort temperature and maintaining the comfort temperature can be controlled by a PID (proportional-integral-derivative) controller. The PID controller determines this function of the

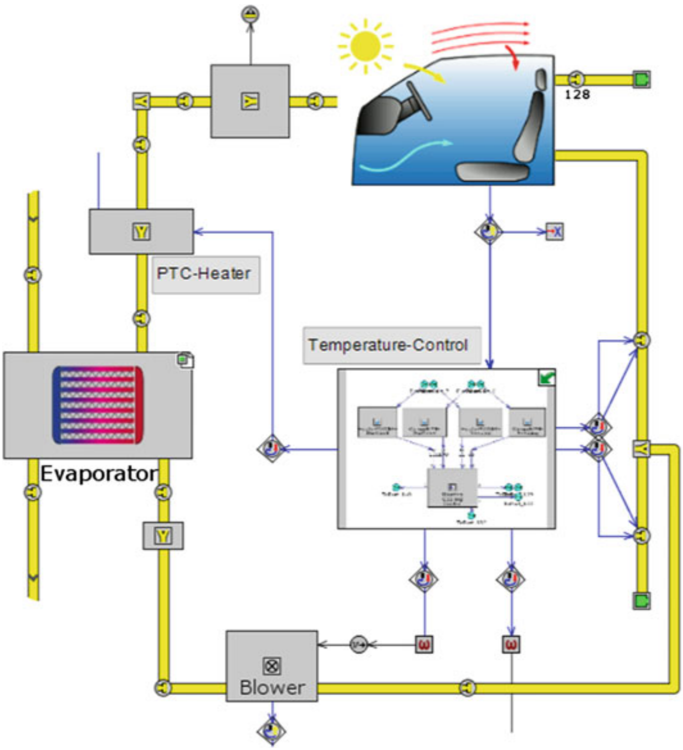

Fig. 2 Model of interior ventilation and heating in GT-Suite environment

instantaneous average indoor temperature, the required heating power of the *PTC Heaters* or the required speed of the compressor. For heating the indoor air, a PTC (positive temperature coefficient) heater is used, which is mounted in the air circulation downstream of the *Evaporator*. The heat thus passes directly through the ventilation system (*Blower*) into the interior.

4.6 Cooling Circuit

The cooling circuit model consists of the components of an electric compressor, a condenser, a TX valve (TXV), an evaporator, a receiver/dryer and refrigerant pipes. A refrigerant R134a is used. The selected compressor is a positive displacement compressor (positive displacement type). The simulation model of the compressor is based on map data. The map comprises a function of the compressor speed-reduced to the reduced mass flow rate, the pressure ratio of the refrigerant and the efficiency of the compressor. The compressor speed is controlled according to the case study of PID controllers depending on the indoor temperature in different

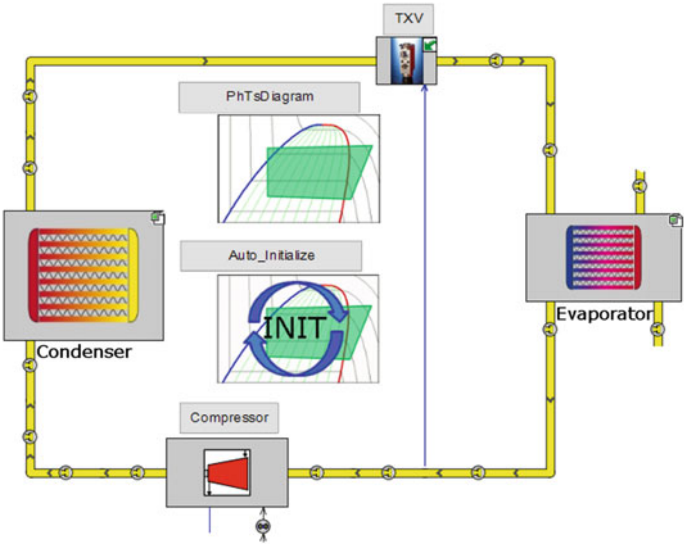

Fig. 3 Model of the cooling circuit of the passenger compartment

speed ranges. The used amount of energy to drive the compressor, depending on the load point, is taken from the battery. For the modelling of the condenser, the software tool COOL3D was used. With the help of COOL3D the condenser was initially mapped three-dimensionally, and then generated as a discrete one-dimensional model. Similarly, the evaporator was imaged. This makes a detailed illustration of the condenser possible. The discretized 1D model of the condenser is integrated into the overall model. The TXV was depicted as a four-quadrant model which reproduces the real behaviour of the thermal expansion valve. Figure 3 shows the coolant circuit in the simulation environment of GT-Cool.

4.7 Experimental Validation of the Models

The vehicle longitudinal and thermal models were validated by means of measurements on the research vehicle Mitsubishi i-MiEV from the aforementioned benchmark (Eckstein et al. 2011). The consumption of the drivetrain was calibrated by the model with the measurement results from the i-MiEV under laboratory conditions in the NEDC on the chassis dynamometer as well as in real driving in Aachen City Cycle (see Table 5).

The cabin model was calibrated for each temperature point regarding heating and cooling. As a criterion the time-dependent behaviour by heating/cooling curves was compared. Second, the required heating/cooling power in the steady state was adjusted to maintain the temperature constant between model and real vehicle. In

Table 5 Comparison of measured energy consumption of i-MiEV vehicle in different cycles and weight configurations with longitudinal dynamics model

	Aachen City Cycle (sporty driving style)	Aachen City Cycle (restrained driving style)	NEDC
Distance	24.2 km	24.2 km	11.022 km
Time	2809 s	3086 s	1180 s
Average vehicle speed	31 km/h	28.2 km/h	33.6 km/h
ec2go (900 kg and altitude profile)	11.26 kWh/100 km	8.95 kWh/100 km	13.34 kWh/ 100 km
ec2go (1260 kg and altitude profile)	14.15 kWh/100 km	10.96 kWh/100 km	15.26 kWh/ 100 km
i-MiEV (1160 kg)	15.69 kWh/100 km	13.45 kWh/100 km	17.55 kWh/ 100 km
ec2go simulation		*i-MiEV*	
• Energy consumption from battery		• Energy consumption from socket	
• Altitude profile included		• Only to drive required auxiliary loads in service	
• No electrical consumers			

Figs. 4, 5, 6 and 7, measured values on the research vehicle i-MiEV and the simulation results are plotted against each other. The model was adjusted to reflect the different vehicle body geometry and the other components of the selected i-MiEV compared to ec2go design. The Mitsubishi i-MiEV features—in contrast to ec2go concept—a coolant fluid heater. A PTC heating element is warming up a coolant fluid which is pumped to the coolant–air heat exchangers in the interior. The ec2go concept provides a PTC air heating which guides the warmed up air directly into the interior. This difference was not adjusted for in the comparison, and this explains the sluggish response of the heating of the i-MiEV vehicle compared to the ec2go model during the first 270 s.

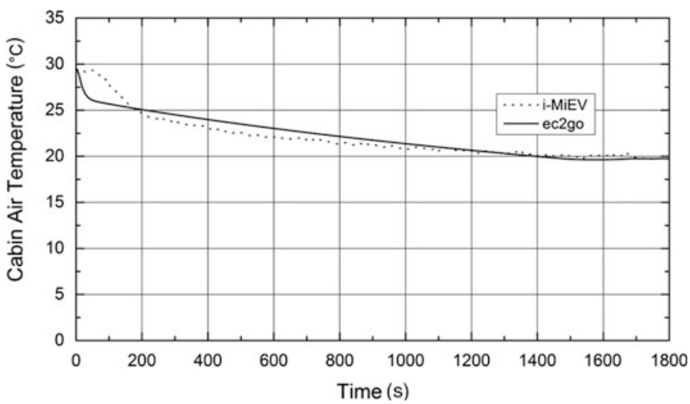

Fig. 4 Compare cooling behaviour of the ec2go model and the i-MiEV research vehicle

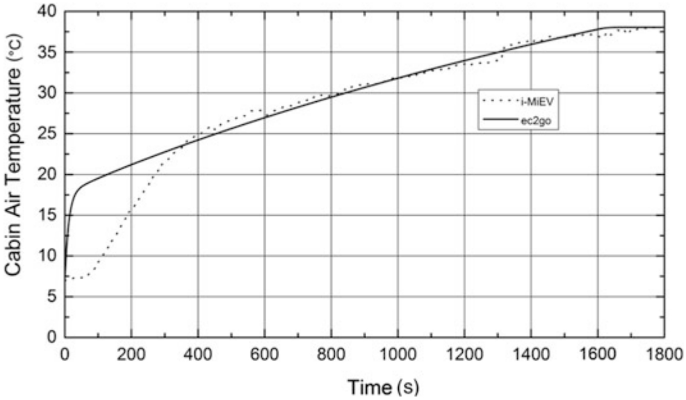

Fig. 5 Compare heating behaviour of the ec2go model (PTC air heater) and the i-MiEV research vehicle (PTC water heater)

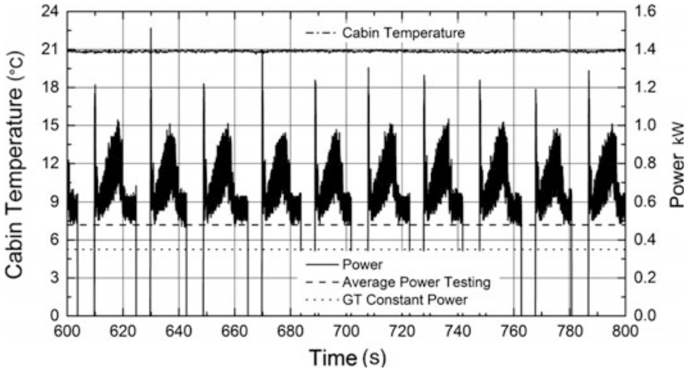

Fig. 6 Compare cabin temperatures and electrical power of the compressor at 30 °C ambient temperature

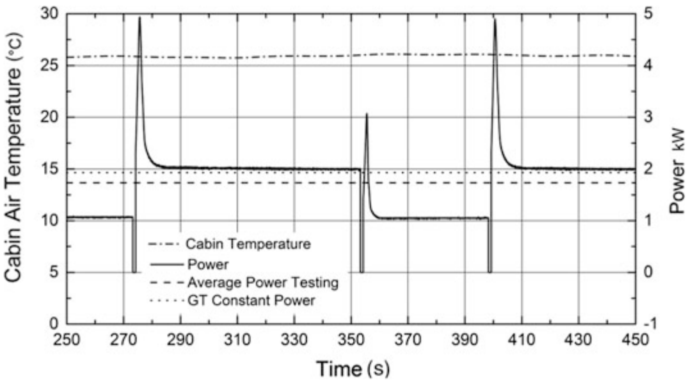

Fig. 7 Compare heat output at 7 °C ambient temperature

4.8 Thermomanagement Interior

The task of the concept is to be as user-oriented and energetically favourable as possible to provide a feeling of satisfaction and also to ensure driving safety aspects such as good visibility. To minimize the influence of climatic conditions on the performance, a thermal management concept was created based on the specific terms of use of a vehicle with exclusive use in a Carsharing application. This concept is to exploit the optimization potential at the expected service as fully as possible for a Carsharing vehicle. The concept features were optimized and evaluated in the following by means of simulations.

4.9 Preconditioning in Electric Vehicle

The electric vehicles are parked in Carsharing stations and connected to the electricity grid to recharge the battery. During charging, the energy is used from the grid to keep the vehicle continuously at a predetermined temperature level of the booking system. The difference between the temperature level during the preconditioning and the comfort temperature for the user is selected so that the vehicle can reach the final heating or the final cooling within the limited preparation phase quickly. If the vehicle is booked, the booking system is calculating the beginning of the final heating and final cooling depending on the prevailing weather. While driving, the internal temperature of the preheated vehicle is only going to keep on comfort temperature. Since the energy for heating/cooling need not be provided by the vehicle battery, the energy storage in the vehicle can be made smaller, or the range of the electric vehicle can be increased.

4.10 Inclusion of Booking Data and Carsharing Station

To underline the brand's trademark ec2go, special Carsharing base stations are possible in the form of solar carports. Affixed on the carports, solar panels provide clean energy for charging the electric vehicle, underscoring at the same time the ecological brand image of Carsharing. Furthermore, the solar carports offer summer protection from direct sunlight on the electric vehicle and its interior surfaces. Sheltered from direct sunlight the average indoor temperature can be kept stable on the outside temperature level only through venting and less AC power will be needed. Out of the Aachen Carsharing benchmark data it is known that in 92 % of all cases the booking of vehicles takes place more than an hour before each ride. In case of a sensibly selected mean indoor temperature for the preconditioning phase, there is thus sufficient time for the final heating or the final cooling of the vehicle to the desired comfort temperature of the respective user.

4.11 Lowering the Interior Temperature When Using Surface Heating Systems

The analysis of usage data from Cambio showed an expected predominant use of vehicles for short distances. This means that the heating of the entire vehicle interior is not deemed appropriate in many cases. By the application of a targeted more favourable surface heating, controlled energetically, a comfort feeling appears with the passengers already at a low mean interior temperature in winter. A possible energy requirement of such a system that consists of contact surfaces, heating surfaces of the short range and of the long range, is a total of 700 W at steady state after a few minutes. The temperature of the heating surface is then 37 °C. By means of a control strategy, areas can be switched off with rising interior temperature gradually. This allows for further reducing the energy demand in the steady state per seat to 120 W (Ackermann et al. 2013).

4.12 Potential Analysis Through Simulation

Along with the design of electric vehicles and its energy storage systems it must be ensured that there is enough energy available to cool the vehicle interior or sufficient to heat it both in winter and in summer. This is necessary both for ride comfort and for the safety of the driver. Here, the heating or cooling is very energy consuming directly after starting the car. The use of energy for preconditioning and temperature variation of the vehicle interior to the final temperature when charging with the energy from the electrical supply grid brings significant savings on energy consumption whilst driving. Furthermore, the Carsharing user benefits from comfort and safety advantages with each ride. Also, the vehicle is always immediately ready to drive at temperatures below 0 °C, and possibly a removal of snow and ice is not necessary.

4.13 Potential Analysis of Thermal Preconditioning of the Interior

In the following, the determined energy consumption is compared after driving the electric vehicle with and without previous conditioning under winter and summer ambient conditions. The total power consumption is the portion that is taken from the vehicle battery. It consists of the drive energy and the heating and cooling energy and is the average specified per 100 km driving distance. The individual energy components also contain the energy levels of the corresponding energy consumer. As winter ambient conditions, the design points defined are the design points W1 and W2, and as summer ambient conditions the design points S1 and S2 are chosen.

The total energy consumption of a not preconditioned vehicle before driving is a reference value for the relative power consumption of a preconditioned vehicle. In the simulations in not preconditioned condition it is ensured that by a standing phase at the beginning of the simulation the vehicle temperatures can adapt to the ambient conditions. For the case of ‘summer’ the heating by the sun is taken into account, in winter it has been derived from an overcast sky without energy entry by solar irradiation.

Next follows the ride in the driving cycle and the beginning of the vehicle conditioning to comfort temperature. For each ride all the energy required for this is removed from the battery. The simulation of the preconditioned ride is divided into three areas. It also begins with a standing phase in which the vehicle heats up on account of the surroundings terms or cools and at the same time the first preconditioning of the vehicle on the interior temperature T1 occurs. Subsequently, the preparation phase for the final heating or final cooling to comfort temperature T2 and the drive at this constant interior temperature takes place. For all scenarios the comfort temperature of 20 °C is applied for ease of comparability. During the standing and preparatory phase, the required energy is drawn from the grid, so that by the beginning of the cycle the battery is fully charged.

The NEDC driving cycle is used which will be traversed once according to the user analysis. In not preconditioned simulations carried out with the beginning of the cycle, a fresh air mode with a constant volume flow of 150 m^3/h and the conditioning on the comfort temperature of 20 °C is applied. The solar radiation is taken into account in the summer points S1 and S2 with a constant value of 850 W/m^2, and neglected under the winter design points. Furthermore, the standing phase lasts an hour for the winter points, and 2 h for the summer points. The preparation phase lasts 1 h for all design points.

First, the energy consumption of the not preconditioned vehicle is considered for the design point W1. After the end of the standing phase a vehicle temperature of 0 °C is set up. With the start time of the NEDC the blower and PTC heater begin to heat up the vehicle interior by fresh air mode. Before entering into the passenger compartment, the intake of cold air is heated up to 64 °C by the PTC heater. The warm air then exchanges heat with the components of the passenger compartment, and heating them. At the same time the average temperature of the passenger compartment air increases, and reaches after 1178 s 20 °C. When preconditioned, the passenger compartment is brought to comfort temperature in two steps before beginning the NEDC. In the first step, during the standing phase, the average temperature of the passenger compartment air is preconditioned at 10 °C and kept at a constant level. In the second step, with the beginning of the preparation phase, the final heating is at comfort temperature. At the beginning of the cycle, the passenger compartment is fully preheated with its components (see Fig. 8).

The heating of the vehicle not preconditioned (PC-Off) to comfort temperature is compared with the preconditioned vehicle (PC-On) only during the drive. In this case, the PTC heater is operating under maximum power output to speed up the heating process. Only when the temperature of the passenger compartment air of comfort temperature approaches comfort temperature, the power output of the PTC heaters

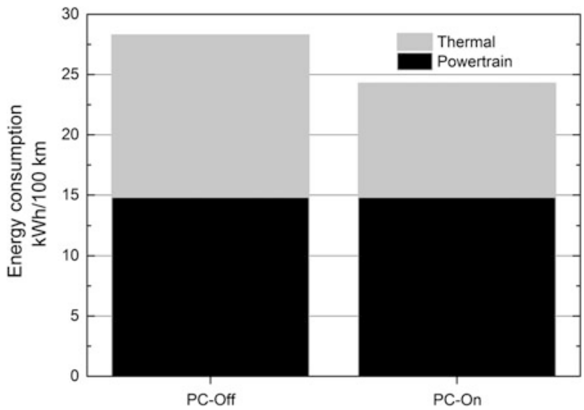

Fig. 8 Total electric energy of a not preconditioned (*PC-Off*) and a preconditioned vehicle (*PC-On*) after driving the NEDC in relation to the energy consumption of the drive at 0 °C outdoor temperature in winter (W1)

decreases. In the preconditioned passenger compartment the PTC heater has the task to keep the temperature constant and thus has a lesser power output. The energy required for heating the vehicle interior represents a non-negligible share of total energy expenditure. Its share is 48.3 %. The energy consumption of the drive—including the electrical load required at a minimum—is 51.7 %. In the case of preconditioning (PC-On) and heating of the vehicle interior through the use of electrical energy from the utility grid, the heating energy consumption in the NEDC can be reduced by up to 27 %. Without heating or cooling the maximum range of the vehicle is 126 km. This range is reduced down to 65.4 km by heating the interior. By preconditioning in winter at 0 °C outdoor temperature, the range increases to 75.2 km.

Other energy savings could be obtained by using potential surface heating in the form of heaters that are mounted in the near and far fields around the driver and passenger. For this purpose, surface heating in the seat and backrest, floor mats, armrest, steering wheel, headrests and seat belt are conceivable. In the winter, heating the cold interior surfaces to the level of the body temperature, the heat output from the body to the surrounding components is reduced and the feeling of comfort is increased. Thereby, the mean interior temperature of the vehicle could be lowered by a few degrees Celsius, without reducing the feeling of comfort. For the preheated interior and an ambient temperature of 0 °C (design point W1), this results in a saving of 0.75 kWh/100 km in the NEDC when a reduction in the average indoor temperature by 2 °C is applied. This corresponds to a constant power output of 250 W over a driving cycle. A possible power consumption of a radiant heating system is 120 W per seat in steady state, depending on the switched surface elements.

For summer ambient conditions, design point S1 and a constant heat radiation of sun are taken into account with a value of 850 W/m^2. In not preconditioning case, the air inside the passenger compartment in the middle is at 31 °C, after standing for 2 h. Then the NEDC starts and also the cooling of the passenger compartment is initiated. The comfort temperature of 20 °C is reached after 700 s, and maintained for the remaining journey time. In the case of the preconditioned ride, it is actively

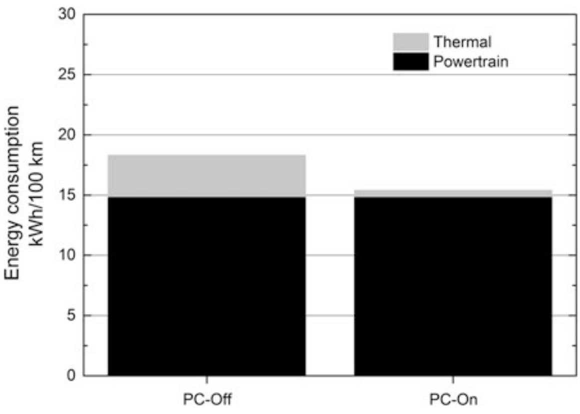

Fig. 9 Total electric energy of a not preconditioned and a preconditioned vehicle after driving the NEDC in relation to the energy consumption of the drive at 20 °C outdoor temperature in summer (S1)

cooled during the standing phase, when the interior temperature of the vehicle exceeds 25 °C. By booking request for the vehicle takes place during the 1 h-long preparatory phase, further cooling the passenger compartment on the comfort temperature of 20 °C takes place (see Fig. 9).

The results obtained by simulation for the overall determined energy consumption for the not preconditioned case splits to 21.2 % in the cooling energy and 78.8 % in pure driving power, including the minimum required auxiliary equipment. The low proportion of electricity consumed for cooling the passenger compartment is to be expected for the design point S1, since the outside temperature is 20 °C and the heat is supplied to the passenger compartment only by the sunlight. A preconditioning reduces energy costs for cooling the passenger compartment significantly by 82.5 %. The range of the vehicle in the not preconditioned case is 100.3 km. By preconditioning the design point S1 the range is increased to 121.7 km.

Under extreme environmental conditions, as defined for the design points W2 and S2, the average consumption of electric power for the heating or cooling of the passenger compartment increases during the passage of an NEDC. During the cooling circuit at the elevated ambient temperature 1.26 kWh/100 km more energy is needed, though the energy increase by heating at lower outdoor temperatures is negligible. By preconditioning the passenger compartment a saving at the design point W2 of 15.6 and 16.1 % at the design point S2 due to heating and cooling energy savings can still can be achieved.

As expected, simulations show that for the sequence of two NEDCs after the other, the average energy consumption of a not preconditioned passenger compartment sinks with fairly long distance. In this case, this is due to the heating or cooling energy. By preconditioning the passenger compartment before driving there are still significant savings in electrical energy at the design points W1 and S1. The simulation results for twice the NEDC show that the energy consumption for heating or cooling the vehicle interior by preconditioning, can be reduced at the design point W1 by 21 % and at the design point S1 by 11 %. The advantage of preconditioning decreases with increasing travel distance.

5 Conclusions

The simulation shows that the direct optimization of thermal management for the vehicle interior to the respective e-Carsharing use has a lot of potential. Due to the electric drive waste heat is hardly available, and if so on a much lower temperature level than in internal combustion engines. Also, existing heating/cooling concepts of vehicle interiors are highly influenced by the internal combustion engine. The simulation models have targeted some potential concepts of E-mobility, and in particular the use of Carsharing. A particular feature has been added to the preconditioning of the vehicle during the electrical charging phase in the parking station. There, the vehicle is continuously heated to a bookable value. The required start of final heating or final cooling, depending on the prevailing weather, is adjusted in a customized fashion according to the Carsharing reservation system. Thus, energy is saved by a volume of more than 21 % in winter whilst driving through preheating or precooling at a—for example—solar-powered Carsharing station (maximum operating range improvement by 21.7 % in the summer NEDC load profile). Applying this thermal preconditioning of the vehicle, a reduction of the energy storage capacity is possible. This represents a considerable convenience and also results in safety benefits compared with previous system solutions for personal mobility. In addition to the bookable internal temperature, interior smells and music packages can be individually preordered. For the future, a test of concept ideas would be desirable in a small series by vehicle data analysis and user surveys.

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