36th International Electric Vehicle Symposium and Exhibition (EVS36)
Sacramento, California, USA, June 11-14, 2023

A Predictive Cabin Conditioning Strategy for Battery Electric Vehicles

Patrick Schutzeich[1], David Hemkemeyer[2], Kai Franke[1], Paul Hamelbeck[1]

[1]*Chair of Thermodynamics of Mobile Energy Conversion Systems (tme), RWTH Aachen University, Forckenbeckstraße 4, 52074 Aachen, Germany, schutzeich@tme.rwth-aachen.de*

[2]*FEV Europe GmbH, Neuenhofstraße 181, 52078 Aachen, Germany*

Executive Summary

In this paper, a model predictive control (MPC) approach for the cabin conditioning of battery electric vehicles (BEV) is presented. The new control algorithm aims to minimize energy consumption while maintaining passenger comfort and air quality. In a first step, a brief overview of model predictive controls and the respective fundamentals is given. Afterward, the modeling for the system dynamics is explained. The challenge for the system model considering humid air is discussed, and a first method for an implementation is presented. With the added equations for the air quality and humidity, a logic to prevent window fogging was developed to improve safety. Ultimately, Model-in-the-loop (MiL) investigations identified an energy-saving potential of up to 15.4% for cold and 39.7% for hot conditions compared to a rule-based strategy.

Keywords: BEV, air conditioning, control system, energy, simulation

1 Introduction

The European Commission has set itself the goal of reducing CO_2 emissions from passenger vehicles by at least 55% by 2030. To reach this and other climate and environmental protection targets, a far-reaching and comprehensive package of measures were adopted in the form of the Green Deal, which will significantly impact mobility in the future [2]. These plans are supported and endorsed by a majority of Europeans [3].

This is also made clear by the development of electric vehicle registrations in the European Union (Figure 1) [1]. The number of battery electric vehicles (BEV) and plug-in electric vehicles has increased from around 7000 in 2011 to around 1.7 million in 2021 for the EU-27 states [1]. Despite the positive development the share of electric vehicles will have to rise further in the future in order to meet the EU's self-imposed targets. To achieve this, customer acceptance and enthusiasm for electrified mobility must further improved. In particular, the range must be increased and charging times shortened to generate new purchasing impulses [4].

One way to tackle these aspects is the further development of thermal management systems and strategies. In particular, cabin air conditioning can reduce the range of BEVs by up to 50% compared to the manufacturer's specifications [5]. This is mainly due to the fact that the energy required must be taken directly from the battery in order to provide the necessary heating or cooling performance [6, 7]. The challenge is to minimize the energy required for cabin air conditioning while at the same time meeting the comfort requirements of the occupants.

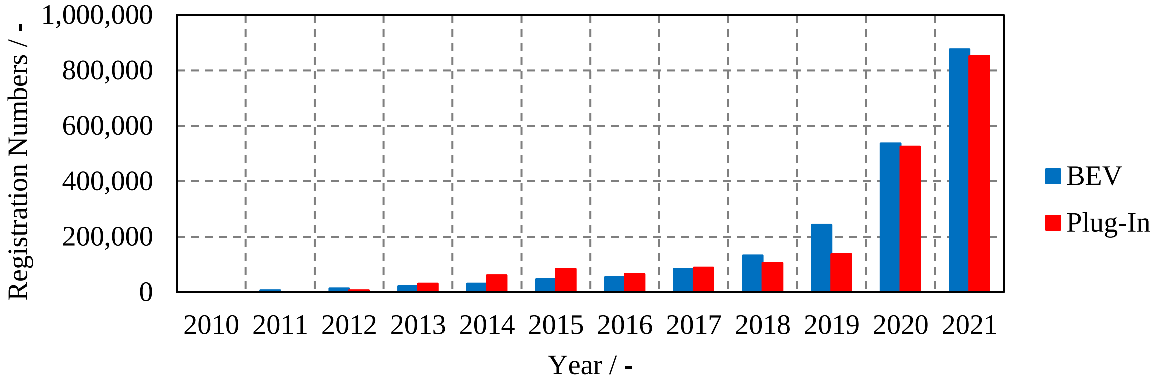

Figure 1: New registrations of electric cars, EU-27 (2011 - 2021) [1]

In this paper, a model predictive control strategy for the energy efficient air conditioning of BEVs is presented. In this approach, the air quality is measured in terms of CO_2 concentration and the comfort inside the cabin is ensured. In addition to the already published investigations [8, 9], a method is presented to consider air humidity and thus actively avoid windshield. For this purpose, the basic operating principle will be explained first. Then, the necessary adaptations for the implementation of air humidity are presented. Finally, first investigations on the control strategy will be shown.

2 Fundamentals of the model predictive control approach

In engineering, model predictive control (MPC) is gaining popularity. It offers mathematical solutions for the optimization of precisely formulated problems. Different decision, consequences, and constraints can be taken into account to determine a suitable operating strategy for the operation of a defined system. The objective evaluation criterion is expressed by a cost function J and minimized [10]. In this section, the basic principles of MPC approaches will be briefly discussed. Afterwards, the scope and specifications of the control strategy will be briefly discussed.

In this paper, the MPC approach is used as an online optimization that determines the required control signals at a defined time step $\Delta\tau_s$. The optimization problem must be set up in such a way that the real-time constraints are satisfied. This implies that the time between the initiation of the optimization process and the output of the control signals must be correspondingly small in relation to the selected step size $\Delta\tau_s$ [10–12].

$$\min_{c} J(c) = \sum_{k=0}^{N-1} l(x(k), u(k), k) \qquad \text{Cost function} \qquad (1)$$

Under consideration of:

$$x(k+1) = f(x(k), u(k), k), k = 0, \dots, N-1 \qquad \text{System dynamic} \qquad (2)$$

$$h(x(k), u(k), k) \leq 0, k = 0, \dots, N-1 \qquad \text{Inequality constraint} \qquad (3)$$

$$G(x(k), u(k), k) = 0, k = 0, \dots, N-1 \qquad \text{Equality constraint} \qquad (4)$$

$$x(0) = x_0 \qquad \text{Initial conditions} \qquad (5)$$

The complexity of the problem does not allow to solve the optimization problem efficiently by analytical methods. For this reason, as is common for many other technical applications, numerical solution methods are used [10]. A direct solution method was selected which is characterized by the fact that the optimization problem is initially discretized on a defined time domain and can then be solved with static optimization methods. This type of solution method is currently widely used in MPC applications [10, 13, 14]. From the direct methods, the multi-shooting method was chosen, for its high accuracy while being well suited for real-time optimization [10, 13]. This solution method includes a discrete dynamic optimization problem whose formulation is shown in equations (1) - (5) [10]. This specific form of problem formulation is also known as non-linear programming (NLP) and is often used in this context. It takes into account the starting conditions of the system, the system dynamics, which is represented by a mathematical model, and the constraints. These can be used, for example, for limiting the state variables or the control variables [15].

The cabin conditioning can be defined as a nonlinear multivariable system under constraints. For this kind of systems the nonlinear MPC approach is suitable. The problem is solved on a fixed prediction horizon N_p taking into account the control objectives. These are, in the case of cabin air conditioning, the achievement of a target temperature in the interior and the minimization of the energy demand. For the entire prediction horizon, the vectors for the control variables are calculated for each time step. However, only the vector with the values for the current time is passed to the system to be controlled. The controller is reinitialized after one time step $\Delta\tau_s$ and the optimization problem is solved again. The prediction horizon is also shifted at this time by the time step $\Delta\tau_s$, which is why it is also called sliding prediction horizon [15].

For the implementation of the MPC in Matlab Simulink the acados framework was used, which is described in more detail in [16].This approach has already been used for applications of nonlinear MPC in the field of powertrain conditioning and its functionality has been proven [17].

3 Realization of the MPC control strategy in a Model-in-the-Loop (MiL) environment

After a short introduction to the basics of MPC, the implementation in MATLAB Simulink will be described in this section. For this purpose, the structure of the model-in-the-loop environment will be discussed first. Subsequently, the modeling of the system dynamics will be explained for the cabin conditioning and a method to include air humidity is presented.

3.1 Structure of the MiL environment

The MiL environment consists of three core elements - the plant model, the prediction function and the MPC. The plant model represents the system behavior outside the control structure and provides important state variables to the MPC and the prediction function. The plant model is replaced by the sensor interfaces during later implementation in the vehicle and is then no longer needed. For this purpose, the interface must be adapted accordingly. For the simulative considerations presented in this work, the plant model contains the same mathematical descriptions as the MPC. The model was validated using measurement data in different environmental conditions for an A class vehicle.

In the prediction function, the external conditions, such as the weather data, the route information, and the vehicle state are determined and predicted for the planned trip. The current set of predicted signals is then sent to the MPC along with the associated trajectories for the future. The latter are calculated from the current time step until the end of the prediction horizon. For the current executions a perfect prediction is assumed. This means that the actual system behavior does not deviate from the predicted system behavior. For the current evaluation of the potential of the functions this simplification is acceptable. However, the effects cannot be neglected in principle [10–12, 15]. This still needs to be investigated before the planned vehicle implementation.

The MPC processes the received information and sets up the optimization problem for the current time step. This is done using the acados framework [16]. The control signal for the current time step are forwarded to the plant model after the successful optimization.

3.2 Modelling of the system dynamics – Cabin conditioning

The MPC approach is particularly characterized by the fact that the system behavior is known and can thus be predicted. It follows that the modeling of the system dynamics is of highest importance for the quality of the control strategy. On the one hand, the behavior of the system must be reflected as accurately as possible and, on the other hand, the computing time must not be too long, otherwise, the real-time capability cannot be guaranteed. In a previous publication [8, 9], the basic modeling of the cabin conditioning and the special features have already been discussed. For this reason, these shall be briefly summarized. Subsequently, the extension for the consideration of the air humidity is to be dealt with.

The overall objective of the model is to determine the heat up and cool down behavior of a vehicle cabin and the energy required. For this purpose, a single-zone model of the vehicle cabin was built and coupled with corresponding thermal masses for the interior equipment. The basis for this model was available measurement data for an A class vehicle. The model was extended by the representation of the HVAC and the influence of solar radiation on the interior and cabin air. The airflow provided by the HVAC can be taken either from the environment (fresh air mode) or from the cabin interior (recirculation mode). The user can steplessly vary between the two modes. In addition to the described relationships, the impact of passengers on the cabin in terms of heating and CO_2 production is also be taken into account. The latter has an influence on the air quality. For the investigations in this work, a limit value of 1200 ppm in the interior was selected according to the recommendations in[18]. Furthermore, the model was extended by taking into account radiant panel heating. It has already been demonstrated in [19] that this can save energy during heating. This makes it necessary to evaluate the comfort in the interior separately in addition to the air temperature. This was fulfilled by the implementation of the equivalent temperature. The necessary correlations can be found in [20–23]. For a more detailed description of the modeling, please refer to [8, 9]. In the work published so far, the assumption has been made that the air is always dry. The humidity of the air was therefore not taken into account. For real systems, however, it has a significant influence on energy demand and comfort [5]. The prevention of window fogging is also an important aspect, which must not be neglected due to its relevance to safety [5, 24]. For this reason, the system modeling is to be extended by a consideration of the air humidity, which is explained in the following.

In a first step, the state variables for the cabin were extended by taking into account the air humidity, respectively the amount of water inside. This is accounted for by the water quantities of the incoming and outgoing air flows. In addition, it had to be taken into account that the occupants also emit water into the interior through breathing and sweating. The necessary parameters and formulas were taken directly from [5] and [25]. The biggest challenge in implementing the humidity was the adaptation of the HVAC model. The active heating and cooling of the airflow directly affects the humidity. For example, cooling the air can cause water to precipitate and thus actively reduce the humidity of the air stream after the subsequent heating [5, 25]. The extended functionality of the HVAC model is described in more detail below.

The HVAC System determines the conditions of the air entering the cabin. These properties can be adjusted via the control variables, which correspond to each individual component within the HVAC system. The summary of all control signals for the HVAC is presented in (6). The airflow itself is provided by a blower fan which is actuated by r_{Blower}. The control values for $r_{Cooling}$ and $r_{Heating}$ determin to which extend the air is heated up or cooled down by the system. The last variable $r_{Redirect}$ expresses which proportion of the air flow is redirected from the cabin to the HVAC. If the value is $r_{Redirect} = 1$ the cabin conditioning is running recirculation mode. In contrast, a value of $r_{Redirect} = 0$ indicates a fresh mode operation of the HVAC.

$$u_{HVAC} = [r_{Blower}\ r_{Redirect}\ r_{Cooling}\ r_{Heating}] \tag{6}$$

For the simplification of the calculations the relation between the current air mass flow and the control variable is linearized to the following equation.

$$\dot{m} = \dot{m}_{max} * r_{Blower} \tag{7}$$

The value $\dot{m}_{max}$ is defined as the maximum mass flow the blower can provide. The energy consumption of the blower P_{Blower} is defined by the following equation.

$$P_{Blower} = P_{Blower,Max} * r_{Blower}{}^{2} \tag{8}$$

The relation between the increased mass flow and energy consumption is quadratic in nature due to the kinetic energy [24].

The airflow provided by the blower consists of a mixture of ambient and cabin air. The ratio of ambient and cabin air is determined by the control variable $r_{Redirect}$. The calculations used to determine the changes in the temperature of the mixed air flows T_{mix} as well as the resulting CO_2 concentration $x_{mix,CO2}$ and water concentration $x_{mix,H2O}$ is shown below [24].

$$T_{mix} = \frac{r_{redirect} * c_{p,1+x,Cbn} * T_{AirCbn} + (1 - r_{redirect}) * c_{p,1+x,Amb} * T_{Amb}}{r_{redirect} * c_{p,1+x,Cbn} + (1 - r_{redirect}) * c_{p,1+x,Amb}} \tag{9}$$

$$x_{mix,H2O} = r_{redirect} * x_{AirCbn,H2O} + (1 - r_{redirect}) * x_{Amb,H2O} \tag{10}$$

$$x_{mix,CO2} = r_{redirect} * x_{AirCbn,CO2} + (1 - r_{redirect}) * x_{Amb,CO2} \tag{11}$$

The specific heat capacity $c_{p,1+x,i}$ the heat capacity of humid and the other parameters are determined for either the ambient or the cabin proportion of the air flow[24, 25]. All fluid properties for the model have been taken from [26] or [27]

In addition, for the calculation of the values at the evaporator a distinction was needed between the case with condensation and the case without condensation. Therefor no direct calculation of the resulting temperature was possible. Instead in a first step, the enthalpy of the exiting airflow was calculated [25].

$$h_{cool,out} = h_{cool,in} - \frac{\dot{H}_{cool,Max} * r_{Cooling}}{\dot{m}} \tag{12}$$

The enthalpy of the entering air $h_{cool,in}$ is calculated using the following general formula [25].

$$h_i = c_{p,1+x,i} * (T_i - T_0) + x_{H2O,i} * H_0 \tag{13}$$

To determine if condensation occurs within the evaporator, the water load of the incoming stream $x_{H2O,in}$ gets compared to the maximal water load at the evaporator outlet $x_{H2O,dew}$ [25].

$$x_{H2O,out} = \begin{cases} x_{H2O,in} & if\ x_{H2O,in} < x_{H2O,dew} \\ x_{H2O,dew} & else \end{cases} \tag{14}$$

Using this relationship the amount of condensing water can also be calculated. It is assumed that the liquid water instantly leaves the system and can therefore not be reabsorbed later [25]. The variable $x_{H2O,dew}$ is dependent on the enthalpy at the evaporator outlet. Using lookup tables a function can be fitted to approximate the relationship between $x_{H2O,dew}$ and $h_{cool,out}$ [24].

$$x_{H2O,dew} = a_1 * \exp(-a_2 * h_{cool,out}) + a_3 + a_4 * h_{cool,out} \tag{15}$$

The temperature of the airflow leaving the evaporator can now be calculated with equation (16) [25].

$$T_{cool,out} = T_0 + \frac{h_{cool,out} - x_{H2O,out} * H_0}{c_{p,1+x,i}} \tag{16}$$

After the evaporator, the airflow enters the heater. The temperature changes within the heater are calculated using equation (19) [25].

$$T_{Heating} = \frac{\dot{h}_{Heating,Max}}{\dot{m}_{max} * c_{p,1+x,Heating}} * r_{Heating} + T_{Cooling} \quad (19)$$

The determination of the temperature and the concentrations of CO_2 and the amount of water within the airflow is done accordingly to the evaporator. Although, they typically do not change during the heating process. With these calculations the properties of the airflow entering the cabin can be calculated.

As mentioned before window fogging has to be prevented at any time. Obstructed view due to condensation on the windshield is a safety related issue. Therefore, cabin humidity needs to be kept below the critical humidity for condensation at the windshield. This limit is calculated based on the temperature of the windshield and external boundaries. The windshield temperature needs to be calculated, using an approximation based on the heat flow between cabin air and the ambient [24]. A detailed study of the mechanisms behind windshield fogging by Leriche et al. [28] showed that solar radiation is an important factor for the fogging threshold. However, the influence of solar radiation is neglected in this approximation. This is possible, without risking unexpected condensation occurrence, since solar radiation can only result in an increased window temperature, compared to no solar radiation. Therefore, solar radiation is neglected for this part of the model. The correlations of the windshield temperatures lead to a critical humidity value which is then used as a threshold for the MPC control strategy [24].

The methods presented here show some of the adjustments made to account for humidity. In addition, adaptations to the cost functions and the calibration of the models were also necessary, which will not be explained further at this point.

4 Investigations to determine the effectiveness of the MPC approach.

In contrast to the previous studies, the focus of this publication is on demonstration of the operation of the MPC, taking into account the humidity of the air. For this reason, as already indicated in the previous chapters, the investigation were carried out in Matlab Simulink. Here, both cold and hot ambient conditions were taken into account. The focus should be on compliance with the fogging limits and the impact of humidity on the energy consumption. For this purpose, the MPC was compared with a rule-based strategy. This was adapted to the current state of the art compared to previous publications. The exact boundary conditions will be described below before the results are presented.

4.1 Description of the rule-based control strategy used as the basis for the assessment

The comparison strategies used in past publications were highly simplified. They could not represent an automatic control of the recirculation rate. However, this is of great importance for the investigation of the impact of humidity and air quality. For this reason, the comparison strategy has been adapted. In [24], an operating strategy is presented that is based on the current state of the art. It can also take into account the CO_2 concentration inside the cabin and adjust the recirculation rate accordingly. This was used as a basis and implemented for the comparison carried out here in a separate model. The principles of operation will be briefly summarized in the next section.

In a first step, the airflow is controlled based on the deviation of the current cabin temperature from the desired set point temperature. The smaller the deviation, the lower the actuation of the fan. However, a minimum air flow is always ensured. Reducing the air mass flow when the desired temperature is reached ensures that a stable control can be achieved. The basic control strategy aims to operate the system in recirculation mode as long as possible. It is possible to steplessly vary the recirculation rate between 0.1 and 0.9. The maximum value is maintained until the CO_2 limit of 1200 ppm is reached. From this point on, 90% of the air is drawn from the ambient. This means that the system is in fresh air mode. In this phase, the fan speed is also increased again to achieve a noticeable improvement in air quality. After reaching a lower threshold of 600 ppm, the system switches back to recirculation mode and resumes the original fan strategy. The cooling and heating of the air flow is ensured by a PID control. It was necessary to ensure that the system reacts sufficiently to the ventilation phases in the calibration of the PID. Automatic dehumidification of the air flow via cooling and heating of the air flow is not part of the strategy, as in [24].

4.2 Simulation results at -10 °C

For cold ambient conditions a heat up of the cabin at -10 °C is simulated. For the duration a period of 3600 s was selected. This equals a drive of two consecutive WLTC cycles. The desired temperature in the cabin was set to 20 °C and as a target for the CO_2 concentration 1200 ppm was chosen. A deviation from both target values is penalized by the cost function. The temperature set point is used as a target value for the equivalent temperature. The radiant heating panels were not activated for this first investigations. As additional ambient conditions a relative humidity of 0.9 and a solar radiation of 0 W/m^2 was assumed.

When looking at the recirculation rate (dotted lines) and the CO_2 concentration (solid lines) for the rule based Approach (RB/red) and the MPC approach (blue) in Figure 2, the difference in the approaches becomes clear.

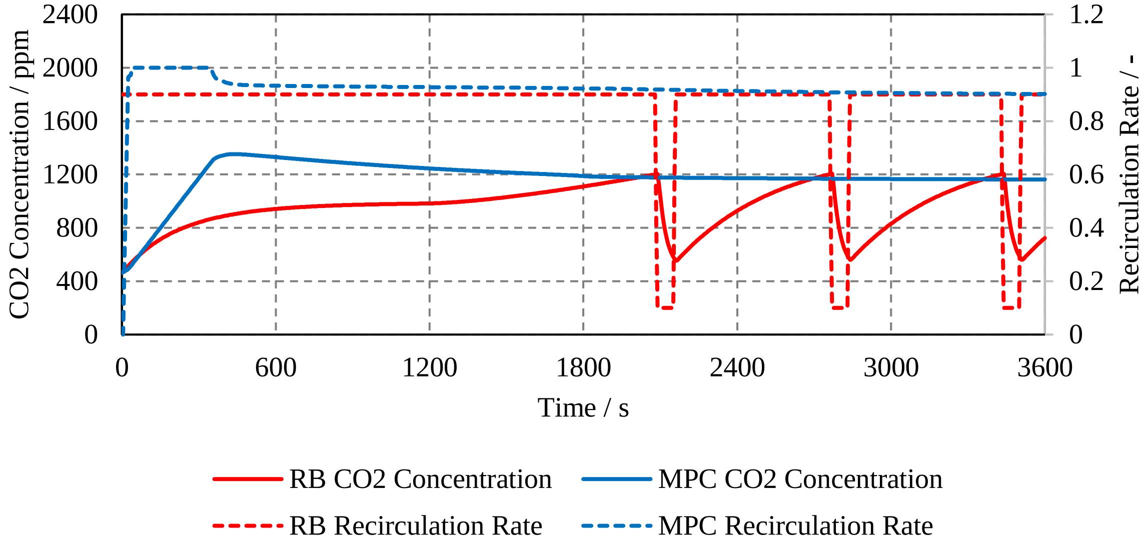

Figure 2: CO_2 concentration in the cabin and recirculation rate for a cabin heat up at -10°C

The maximum for the recirculation rate of the MPC is not limited to 0.9 and goes up to 1. The CO_2 concentration at the start rises faster due to the higher recirculation in comparison to the rule based approach. After the limit of 1200 ppm is exceeded the recirculation rate stays high for a certain period of time. After that it is slowly reduced by the MPC to get below the limit again. The MPC values the energy costs at the beginning of the heat up process higher than maintaining the CO_2 limits. This could be adapted by changing the cost function for higher requirements towards air quality. Nevertheless, this is not considered efficient as a slide overrun of the threshold should not be considered harmful for the passengers [18, 29]. The CO_2 level for the rule based approach increases much slower due to the maximum recirculation rate of 0.9. As soon as the limit is reached the fresh air mode is activated. The process is repeated three times during the simulation.

Due to the low response time of the electric air heaters the air entering the cabin is quite dry already at the start of the simulation. Therefore the actual humidity stays below the threshold value which indicates the risk of windshield fogging. In both cases, the humidity in the cabin is reduced quickly. Therefore not other actions have to be taken into account. In other use cases it could be observed that the MPC uses active dehumidification to stay below the humidity threshold. This method is very energy intensive and only used when window fogging cannot be prevented by other measures. The results can also be seen in Figure 3. It can be noted that the humidity for the MPC application is slightly lower at the beginning of the simulation. This can be explained by the fact that the rule-based approach gets 10% of the air flow from the environment at the start. The ambient humidity is very high. Therefore the humidity inside the cabin also stays higher at this time. This effect could be neglected it the upper limit for the rule based-approach could be also set to 1. For more critical boundary conditions this could lead to an increased risk of windshield fogging.

As there is no further logic to prevent that this could be unsafe in the operation. The plots for the cabin temperatures are not shown here as the results are comparable for both control strategies.

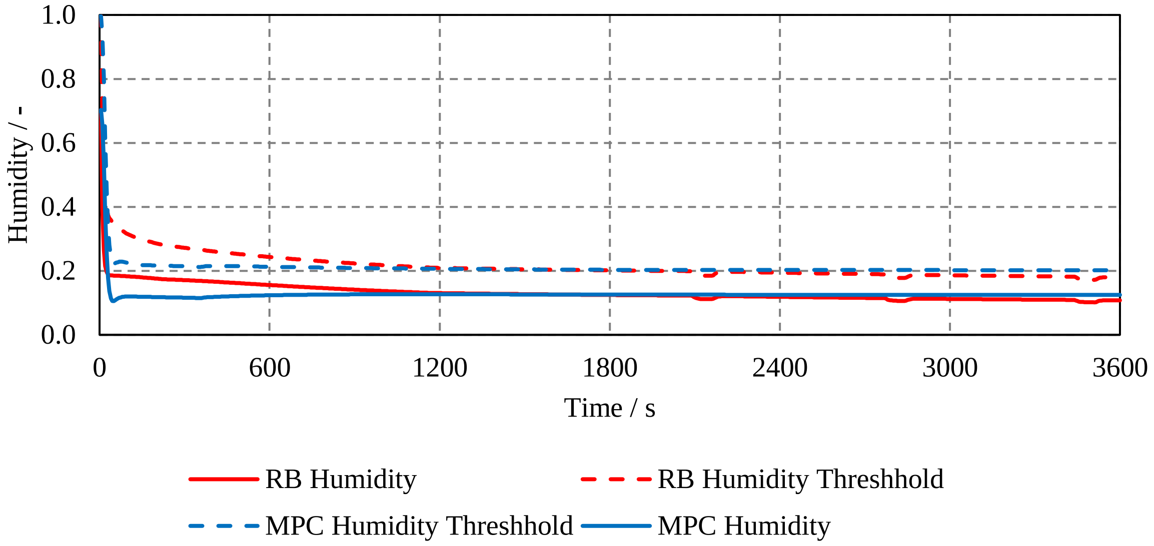

Figure 3: Humidity inside the cabin and upper humidity limit for a cabin heat up at -10°C

Comparing the energy consumption of both approaches it can be seen that the MPC saves up to 15.4% during the simulation. Especially at the end of the run while the cabin temperature has to be maintained the MPC can show his real advantage by maximizing the recirculation rate.

4.3 Simulation results at 35 °C

For hot conditions an ambient temperature of 35 °C was chosen at a relative humidity of 0.4, and a solar radiation of 800 W/m^2. All additional settings and boundaries are kept unchanged in comparison to the cold conditions.

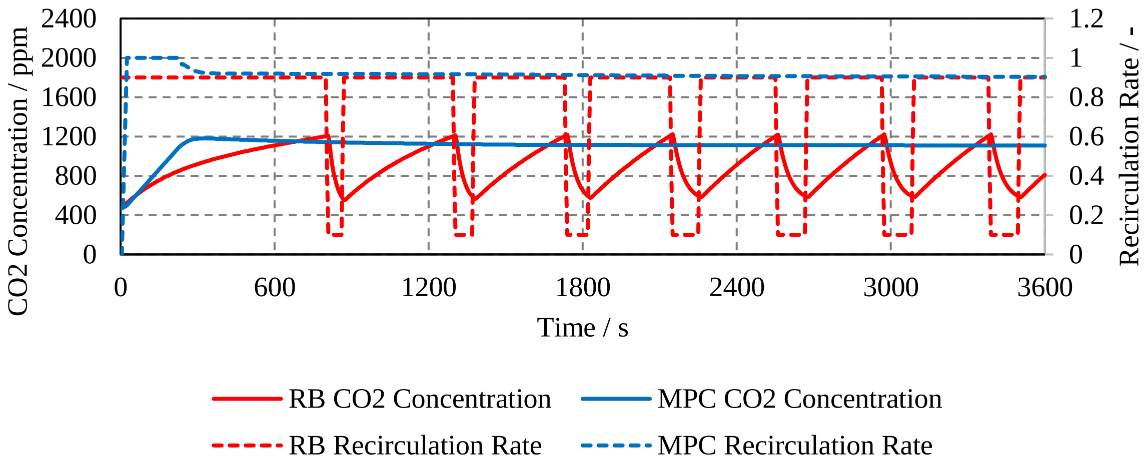

Figure 4: CO2 concentration in the cabin and recirculation rate for a cabin cool down at 35 °C

Figure 4 shows the CO_2 concentration (solid line) and the recirculation rate (dotted line) for the MPC (blue) and the rule-based approach (RB/red). It gets obvious that the rule based approach is forced to switch to fresh air mode much more often than for cold conditions. Both strategies maintain the limitations and reach the temperature targets comparably fast (not shown in diagram).

When looking at the humidity (figure 5) the threshold values for the prevention of windshield fogging cannot be seen as they are higher than 1. This seems not to be plausible on the first sight as the relative humidity is limited to 1. The values has to be interpreted as a theoretical representation of the limit value. It symbolizes that at the given windshield temperature the humidity must theoretically exceed 1 to cause window fogging. That means that it is practically impossible to have window fogging at this status because of the high windshield temperature.

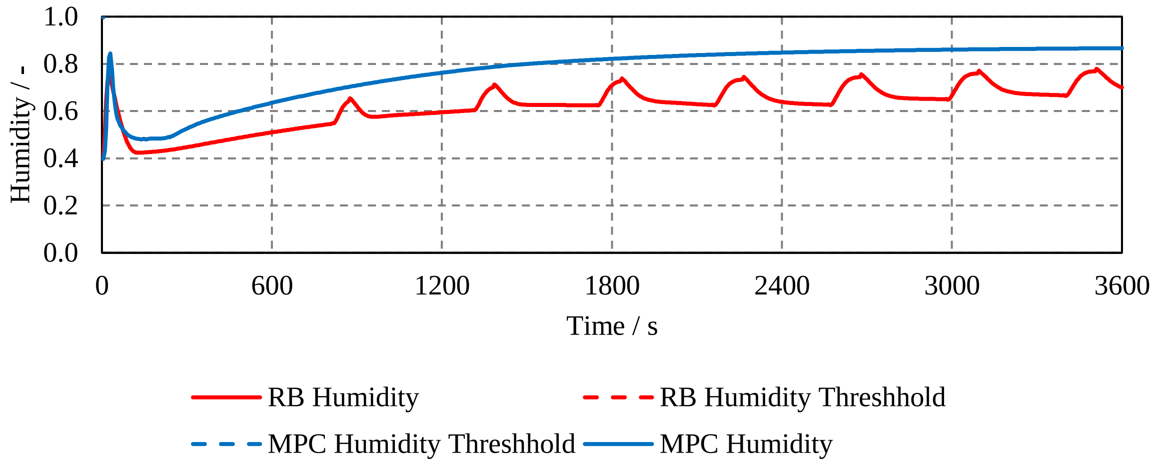

Figure 5: Humidity inside the cabin and upper humidity limit for a cabin cool down at 35 °C

Comparing the energy consumption of the rule-based approach and the MPC, an energy saving potential of 37.9% can be identified. This mainly achieved again by exploiting the possible recirculation rate as much as possible.

5 Summary & Outlook

In this paper, a model-predictive approach for the cabin conditioning of BEVs was presented. The focus was on the consideration of the air humidity in the control strategy and the prevention of windshield fogging. It could be shown that it is possible to include the air humidity appropriately and thus to add an additional safety level for the optimization of the control strategy.

Also the impact of the air humidity on the energy demand was examined. MiL investigations identified an energy saving potential of up to 15.4% for cold and 37.9% for hot ambient conditions.

As a next step, additional comfort-dependent limitations for humidity will be introduced and added to the MPC control strategy. Furthermore an investigation of the MPC in a co-simulation environment with high fidelity models is planned to improve the quality of the method. With this platform additional use cases and boundary conditions shall be examined to further develop the MPC control strategy for cabin conditioning.

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement 628 No 824295.

References

[1] EUROPEAN ENVIRONMENT AGENCY: *New registrations of electric vehicles in Europe*. URL https://www.eea.europa.eu/ims/new-registrations-of-electric-vehicles. – Aktualisierungsdatum: 2022-10-26 – Überprüfungsdatum 2023-01-30

[2] EUROPÄISCHE KOMMISSION: *Mitteilung der Kommission an das europäische Parlament, den Rat, den europäischen Wirtschafts- und Sozialausschuss und den Ausschuss der Regionen* : *„Fit für 55“: auf*

dem Weg zur Klimaneutralität – Umsetzung des EU- Klimaziels für 2030. URL https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:52021DC0550&from=DE. – Aktualisierungsdatum: 2021-07-14 – Überprüfungsdatum 2022-04-27

[3] EUROPÄISCHE KOMMISSION: *Special Eurobarometer 513 - Climate Change* : *Report*. URL https://ec.europa.eu/clima/system/files/2021-07/report_2021_en.pdf. – Aktualisierungsdatum: 2021-07-05 – Überprüfungsdatum 2022-04-27

[4] GÖTZ, Konrad ; SUNDERER, Georg ; BIRZLE-HARDER, Barbara ; DEFFNER, Jutta: *Attraktivität und Akzeptanz von Elektroautos* : *Ergebnisse aus dem Projekt OPTUM ; Optimierung der Umweltentlastungspotenziale von Elektrofahrzeugen*. Frankfurt am Main : ISOE, 2012 (ISOE-Studientexte 18)

[5] GROßMANN, Holger ; BÖTTCHER, Christof: *Pkw-Klimatisierung* : *Physikalische Grundlagen und technische Umsetzung*. 3. Aufl. 2020. Berlin, Heidelberg : Springer Berlin Heidelberg, 2020 (VDI-Buch)

[6] VDI UND VDE: *Brennstoffzellen- und Batteriefahrzeuge* : *Bedeutung für die Elektromobilität*. URL https://www.vdi.de/ueber-uns/presse/publikationen/details/brennstoffzellen-und-batteriefahrzeuge. – Aktualisierungsdatum: 2019-06-07 – Überprüfungsdatum 2022-04-27

[7] AUER, Markus: *Ein Beitrag zur Erhöhung der Reichweite eines batterieelektrischen Fahrzeugs durch prädiktives Thermomanagement*. Wiesbaden : Springer Vieweg, 2016

[8] SCHUTZEICH, Patrick ; PISCHINGER, Stefan* ; HEMKEMEYER, David ; WAHL, Alexander ; FRANKE, Kai: *A Model Predictive Control Strategy for Advanced Passenger Compartment Air Conditioning in Vehicles with Electrified Powertrains* : *2022 SAE Thermal Management Systems Symposium , Plymouth, Michigan , USA , 2022*. Video, 2022

[9] MANNS, Patrick ; HEMKEMEYER, David ; LINSE, Daniel: *Predictive Cabin Climatization for Electric Vehicles*. In: *ATZ worldwide* 124 (2022), Nr. 10, S. 36–39

[10] PAPAGEORGIOU, Markos ; LEIBOLD, Marion ; BUSS, Martin: *Optimierung* : *Statische, dynamische, stochastische Verfahren für die Anwendung*. 4., neu bearb. u. erg. Aufl. 2015, S. 343-427. Berlin, Heidelberg : Springer Berlin Heidelberg, 2015

[11] SCHWARZKOPF, Stefan: *Echtzeitfähige optimierungsbasierte Regelung von Stofftrennprozessen*. Magdeburg, Otto-von-Guericke-Universität Magdeburg, Fakult¨at fur Elektrotechnik und Informationstechnik. Dissertation. 2012-10-16. URL https://d-nb.info/1054135266/34 – Überprüfungsdatum 2023-01-24

[12] ADAMY, Jürgen: *Nichtlineare Systeme und Regelungen*. 3., bearb. u. erw. Aufl. 2018, S. 227 - 280. Berlin, Heidelberg : Springer Berlin Heidelberg, 2018

[13] DIEHL, Moritz ; BOCK, Hans Georg ; SCHLÖDER, Johannes P.: *A Real-Time Iteration Scheme for Nonlinear Optimization in Optimal Feedback Control*. In: *SIAM Journal on Control and Optimization* 43 (2005), Nr. 5, S. 1714–1736

[14] VÖLZ, Andreas: *Modellprädiktive Regelung nichtlinearer Systeme mit Unsicherheiten*. Wiesbaden : Springer Vieweg, 2016 (SpringerLink Bücher)

[15] GRAICHEN, Dr.-Ing. Knut: *Methoden der Optimierung und optimalen Steuerung* : *Skriptum (Wintersemester 2012/2013)*. URL https://vdocuments.site/skriptum-methoden-der-optimierung-und-optimalen-steuerung-c-prof-dr-ing.html?page=1. – Aktualisierungsdatum: 2019-08-05 – Überprüfungsdatum 2023-01-25

[16] VERSCHUEREN, Robin ; FRISON, Gianluca ; KOUZOUPIS, Dimitris ; FREY, Jonathan ; VAN DUIJKEREN, Niels ; ZANELLI, Andrea ; NOVOSELNIK, Branimir ; ALBIN, Thivaharan ; QUIRYNEN, Rien ; DIEHL, Moritz: *acados—a modular open-source framework for fast embedded optimal control*. In: *Mathematical Programming Computation* 14 (2022), Nr. 1, S. 147–183

[17] WAHL, Alexander ; WELLMANN, Christoph ; KRAUTWIG, Björn ; MANNS, Patrick ; CHEN, Bicheng ; SCHERNUS, Christof ; ANDERT, Jakob: *Efficiency Increase through Model Predictive Thermal Control of Electric Vehicle Powertrains*. In: *Energies* 15 (2022), Nr. 4, S. 1476

[18] ANGELOVA, R. A. ; MARKOV, D. G. ; SIMOVA, I. ; VELICHKOVA, R. ; STANKOV, P.: *Accumulation of metabolic carbon dioxide (CO 2) in a vehicle cabin*. In: *IOP Conference Series: Materials Science and Engineering* 664 (2019), Nr. 1, S. 12010

[19] HEMKEMEYER, David: *Thermomanagement im elektrischen Personenkraftwagen unter Nutzung der Abwärme des Antriebs*. Aachen, RWTH Aachen, Lehrstuhl für Verbrennungskraftmaschinen. Dissertation. 2017-10-09 – Überprüfungsdatum 2022-04-27

[20] ASHRAE (FIRM): *Standard 55-2013 user's manual* : *ANSI/ASHRAE standard 55-2013, thermal environmental conditions for human occupancy*. Atlanta, GA : ASHRAE Research, 2016

[21] *DIN EN ISO 14505-2:2007-04, Ergonomie der thermischen Umgebung_- Beurteilung der thermischen Umgebung in Fahrzeugen_- Teil_2: Bestimmung der Äquivalenttemperatur (ISO_14505-2:2006); Deutsche Fassung EN_ISO_14505-2:2006*

[22] SHAW, E. W.: *Thermal Comfort: analysis and applications in environmental engineering, by P. O. Fanger. 244 pp. DANISH TECHNICAL PRESS. Copenhagen, Denmark, 1970. Danish Kr. 76, 50*. In: *Royal Society of Health Journal* 92 (1972), Nr. 3, S. 164

[23] YE, Guodong ; YANG, Changzhi ; CHEN, Youming ; LI, Yuguo: *A new approach for measuring predicted mean vote (PMV) and standard effective temperature (SET∗)*. In: *Building and Environment* 38 (2003), Nr. 1, S. 33–44

[24] SCHAUT, Stefan ; SAWODNY, Oliver: *Thermal Management for the Cabin of a Battery Electric Vehicle Considering Passengers' Comfort*. In: *IEEE Transactions on Control Systems Technology* 28 (2020), Nr. 4, S. 1476–1492

[25] LUCAS, Klaus: *Thermodynamik* : Springer Berlin Heidelberg, 2008

[26] KRETZSCHMAR, Hans-Joachim ; WAGNER, Wolfgang: D2.1 Thermophysikalische Stoffwerte von Wasser. In: STEPHAN, Peter; KABELAC, Stephan; KIND, Matthias; MEWES, Dieter; SCHABER, Karlheinz; WETZEL, Thomas (Hrsg.): *VDI-Wärmeatlas*. Berlin, Heidelberg : Springer Berlin Heidelberg, 2019 (Springer Reference Technik), S. 201–218

[27] *VDI-Wärmeatlas*. Berlin, Heidelberg : Springer Berlin Heidelberg, 2013

[28] LERICHE, Maryline ; ROESSNER, Wolfgang ; REISTER, Heinrich ; WEIGAND, Bernhard: Numerical Investigation of Droplets Condensation on a Windshield: Prediction of Fogging Behavior. In: *SAE Technical Paper Series* : SAE International400 Commonwealth Drive, Warrendale, PA, United States, 2015 (SAE Technical Paper Series).

[29] ZHANG, X. ; WARGOCKI, P. ; LIAN, Z. ; THYREGOD, C.: *Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance*. In: *Indoor air* 27 (2017), Nr. 1, S. 47–64

Presenter Biography

Patrick Schutzeich (born Manns) studied mechanical engineering at the RWTH Aachen University (Germany). The topic of thermal management and cabin air conditioning accompanied him early on in his studies. After completing his master's degree in automotive engineering and transport at RWTH Aachen, he worked for one year as a project engineer at FEV Europe GmbH. At the beginning of 2019, he moved to RWTH Aachen University as a research assistant and has since been pursuing his PhD in predictive thermal management for electric vehicles. The focus of his research is on cabin and battery conditioning.