Efficient Air Conditioning of Battery-Electric Multiple Units (BEMU): Modeling and Optimization

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Abstract. The power required for heating, ventilation and air-conditioning (HVAC) of the passenger compartment in BEMU strongly affects the capacity and lifetime of the battery. Accordingly, 11 different measures for reducing the energy demand of HVAC are presented in this paper. The measures are investigated using Dymola models of a thermal car body to determine the energy saving potential as well as the effects on the vehicle. Reducing the amount of fresh air while complying with CO_2 limits and using a heat pump are efficient measures to reduce the annual energy demand for the HVAC system by 62% or 48%, respectively. In addition, a control-based, catenary dependent HVAC operating strategy is being developed that decisively reduces the load on the battery during dynamic operation. This approach is particularly suitable for straightforward implementation since no design changes to the vehicle are necessary.

Keywords: railway vehicles · battery electric multiple unit · HVAC systems · thermal management · air conditioning · system modeling

1 Introduction

In the BMDV-funded (Federal Ministry for Digital and Transport in Germany) project MOSENAS, the German Aerospace Center (DLR) is working together with Stadler Rail to design and develop a modular and scalable battery storage system (see Fig. 1). This system is intended for use in battery-electric multiple units (BEMU) on partially electrified rail lines. Particular attention is also paid to the issues of operational suitability (e.g. usable range), cost-effectiveness and compatibility with the charging infrastructure.

The design of the battery capacity is largely dependent on the energy demand of the vehicle. This in turn is influenced by the auxiliary consumers, which account for up to 30% of the total annual energy demand [1]. The largest share of the auxiliary consumers is caused by the heating, ventilation and air conditioning (HVAC) of the passenger compartment, which is why research is being conducted into possibilities and

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Fig. 1. Modular, scalable energy storage in the MOSENAS project

technical innovations for reducing this energy demand [2, 3]. In the MOSENAS project, the energy demand for HVAC in rail vehicles was determined and new measures for reducing this energy demand were developed and evaluated.

2 Methodology – Definition of Measures and Modeling Setup

Definition of Measures

In the first step, 11 measures were defined that offer the potential to reduce the energy demand for the HVAC system. These measures are:

M1: Free cooling
M2: Passenger rate-dependent fresh air volume control via CO_2 content
M3: Direct use of recuperated energy for HVAC system
M4: Modified heat transfer through the outer wall of the car body
M5: Variation of leakage air flow to the environment
M6: Utilization of the temperature tolerance ranges of DIN EN 14750
M7: Change of setpoint temperature depending on catenary availability
M8: Variation of the vehicle category of DIN EN 14750 (A or B)
M9: Variation of the heat capacity inside the vehicle
M10: Use of a heat pump
M11: Waste heat utilization of the battery

The measures mentioned can be partially combined for the simulations, since similar parameters are changed. M1 investigates how an increased amount of fresh air to be introduced into the vehicle can be used for cooling at low outside temperatures. For that, fresh air is not processed by the HVAC system. M2 investigates to what extent the fresh air volume can be reduced without falling below the CO_2 limits, since current limits of the fresh air volume from DIN EN 14750 are fixed without taking the CO_2 content into account. Both M1 and M2 are consequently investigated by varying the amount of fresh air.

M3 investigates whether there are energetic advantages if the recuperation energy is used directly in the HVAC system. This avoids conversion losses in the vehicle.

M4 determines the effects of a different heat transfer coefficient, which can be realized, for example, by better insulation of the outer walls in the car body.

M5 explores how a modified air leakage flow affects the energy demand of the HVAC system. The leakage air flow enters and leaves the car body through several openings as it is not gas-tight.

M6 and M8 again investigate similar parameters. In M6, the variation of the setpoint temperatures is investigated using the characteristic curves from DIN EN 14750. Here, an upper and lower limit as well as a recommended curve are given (see Fig. 2 left). The characteristic curves also vary for vehicle categories A and B, so that the change in the curves due to the vehicle category is examined in M8. Category A represents regional trains while category B will be applied mainly to metro vehicles. Following M6 and M8, M7 considers the dynamic change of these characteristic curves under changing catenary availability in vehicle operation.

M9 investigates how varying the thermal capacity of the car body affects the energy demand. Thermal capacity indicates how much heat can be stored in the car body.

M10 studies the effects of heat pump use. Here, the heat pump can be used for the full part of the heating capacity, or only for conditioning the outside air.

M11 considers to what extent waste heat from the battery can be used to heat the passenger compartment.

Definition of Boundary Conditions

In order to investigate the measures presented, the boundary conditions for the simulation must be defined. The climatic boundary conditions for rail vehicles are specified in DIN EN 50591. For this purpose, 16 operation points (OP) are defined, which consist of the ambient temperature, ambient humidity, solar radiation and passenger rate. In addition, time periods are specified as to how often these OPs occur annually in order to determine an annual energy demand. In addition to the normalized OP, three further points were defined to investigate extreme climatic conditions. These points, as well as the two extreme climatic cases from DIN EN 50591 can be found in Table 1.

Table 1. Operating points for extreme weather conditions

OP	1*	2**	3	4	5
Ambient temperature in °C	−10	35	40	−20	−20
Ambient relative humidity in %	90	50	90	90	90
Solar radiation in W/m^2	0	700	0	0	0
Passenger rate in %	0	100	100	100	0

* OP1 and ** OP7 of DIN EN 50591

The boundary conditions on the vehicle side were specified by Stadler. A 3-car BEMU serves as the reference vehicle. The target values for fresh air and temperature control are based on DIN EN 14750 (see Fig. 2 left). While many measures were investigated in stationary simulations, dynamic simulations had to be used for M7 and M9. A daily driving cycle of a regional train in northern Germany was selected as the trackside boundary condition.

Modeling Approach

A thermal car body model (TCBM) from the German Aerospace Center (DLR) was used to investigate the measures presented. The model is created in Dymola and is based on a validated TCBM from Shift2Rail project FINE-2 [4]. The overview of the model is shown in Fig. 2 on the right. Centrally, the cross-section of the car body is shown. Here, the vehicle-side parameters are defined. On the left side are the model inputs in the form of the climatic boundary conditions. The output parameter is the electrical energy demand of the car body. The model is used for both stationary and dynamic simulations. In the dynamic simulations, the velocity-dependent convection at the outer wall of the car body leads to a dynamic behavior. For this, the trajectory of the vehicle has to be given as a further model input.

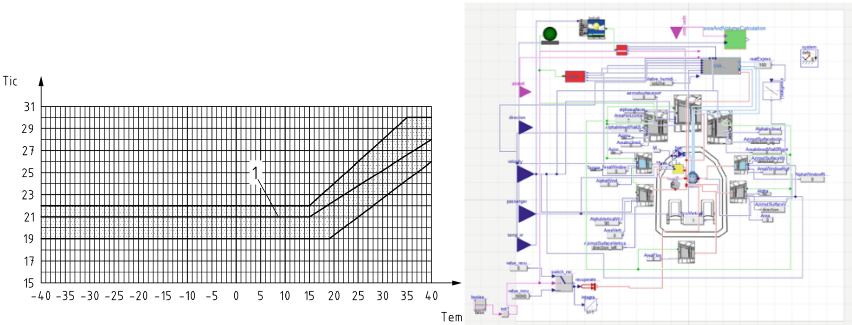

Fig. 2. Left: Set point for the temperature in °C in the passenger compartment (Tic) as a function of the outside temperature (Tem) in °C – Upper, recommended (1) and lower curve of DIN EN 14750, Right: Dymola surface of the thermal car body model (TCBM)

3 Results – Evaluation of the HVAC Optimization Measures

The measures presented to optimize the HVAC systems in BEMUs are evaluated below. For this purpose, the energy demand of the HVAC system was calculated in both stationary and dynamic simulations.

During the investigations, it was found that in the reference vehicle the recuperated energy can be completely absorbed by the batteries during the braking phase. Likewise, qualitative investigations of M11 revealed that the utilization of the battery waste heat is probably only possible in a meaningful way on the car on which the battery and the battery thermal management system are concentrated, which is only one car in the reference vehicle. Transferring the heat to all the other cars is critical in terms of moving hydraulic lines and heat losses along the length of the line. Accordingly, measures M3 and M11 have no or very little influence in the present case, so that they will not be described further in the following results.

Stationary Evaluation of Energy Efficiency Measures

The evaluation of the measures is based on the annual energy demand for HVAC. The measures can be divided into control-based measures and design-based measures. The control-based measures M1, M2, M6 and M8 do not require any physical changes or new components for implementation. However, measures M4, M5, and M10 can only be implemented if design changes are taken on the vehicle and thus tend to be costlier than the control-based measures.

When varying the amount of fresh air in M1 and M2, it can be seen that the increased amount of fresh air in M1 due to free cooling results in a drop in the energy demand by 14% of the reference value for OP3 and OP4 of DIN EN 50591. These OP are particularly suitable for the application of free cooling, since here the temperature difference between the interior car body and the environment is relatively small. In M2, lowering the fresh air volume flow beyond the DIN EN 14750 limits to 4 m^3/h per person shows a reduced annual HVAC energy demand by 62%. With the volume flow of 4 m^3/h, the calculations show a CO_2 concentration below 5000 ppm, which is the defined boundary in the technical specifications for interoperability (TSI).

M6 shows that using the lower temperature setpoint curve of category A results in a reduction of the annual HVAC energy demand by 22%. An optimized temperature setpoint curve that selects the lower setpoint heating cases and the upper setpoint in cooling cases reduces the HVAC energy demand even further by 32%. Combining this measure again with M8 and selecting vehicle category B with an optimized temperature setpoint curve reduces the annual HVAC energy demand by 36%.

When examining the design-based measures, M4 shows that reducing the heat transfer coefficient by 26% of the baseline value reduces the annual HVAC energy demand by 18%. M5 shows that completely preventing leakage in the car body reduces the annual HVAC energy demand by 16%. The use of the heat pump represents the design-based measure with the greatest potential savings by reducing the annual HVAC energy demand by 48%.

Dynamic Evaluation of Developed HVAC Operation Strategy

As described above, the evaluation of measures M7 and M9 requires a dynamic approach. Accordingly, they were combined with measures M6 and M8 to form an optimized control strategy for the HVAC system in the vehicle. The temperature setpoint is adjusted depending on the catenary availability and the ambient temperature. Under catenary, the HVAC power is maximized by selecting the maximum setpoint curve in the heating case and the minimum setpoint curve in the cooling case. In this way, the car body can be "charged" within the thermal comfort and store thermal energy for the catenary-free operation (CFO). In the CFO, the minimum HVAC power is demanded. This is implemented through the use of the minimum setpoint in heating mode and the maximum setpoint in cooling mode (see Table 2). The goal of this strategy is not necessarily to reduce the overall energy consumption from the catenary, but mainly to reduce the energy demand at the battery storage as battery costs and aging are a highly sensitive parameter for the BEMUs.

Table 2. Optimized control strategy for the HVAC system depending on catenary availability

Catenary	Heating case	Cooling case
Available	Max. setpoint temperature	Min. setpoint temperature
Not available	Min. setpoint temperature	Max. setpoint temperature

The implementation of the optimized HVAC control strategy HVAC in the simulations shows that the energy demand for the HVAC system in OP1 to OP5 decreases between 1.3% and 4.3% compared to the reference operation of the HVAC system for extreme weather conditions (see Table 3). At the system level, it can be seen that the energy demand for the vehicle in increases minimally in OP2, despite the reduced HVAC energy demand. This is related to the increased system losses due to the power increase from the catenary. Overall, however, it shows a reduction of up to 2.6% in the equivalent full cycles in the battery storage system. Thus, it is shown that the optimized HVAC operating strategy contributes to the relief of the battery storage.

Table 3. Comparison of the energy consumption with and without optimized HVAC control strategy for the HVAC system only and the overall vehicle in the daily driving cycle

OP (see Table 1)	1	2	3	4	5
Energy consumption HVAC	−3.9%	−1.3%	−2.7%	−4.3%	−3.0%
Energy consumption vehicle	−0.9%	+0.2%	−0.4%	−1.1%	−0.8%

Conclusion

There are a variety of measures to reduce HVAC energy demand in BEMU. The reduction of the fresh air volume depending on the CO_2 concentration is the most promising control-based measure among the presented ones with a reduction of energy demand by 62%. For this, however, the set points for fresh air flow in DIN EN 14750 must be reset. The use of a heat pump represents the most promising design-based measure with a reduction of energy demand by 48%, although it is costlier to implement. The optimized dynamic HVAC operating strategy depending on the catenary availability also offers the possibility of decisively relieving the battery storage, while complying the boundary conditions from DIN EN 14750.

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