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Effects of Implementing Weather Data in Life Cycle Cost Calculation of Passenger Trains with Alternative Powertrains

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Abstract

In this study we computed energy demand of heating, ventilation and air conditioning for generic battery electric multiple units, in regards to varying local climate conditions for four locations in Germany. We compared the results to approaches common in cost calculations. We propose a model chain that automatically integrates local weather data into the energy assessment of multiple units with alternative drivetrains. The approach includes a geodata model that generates driving profiles, a longitudinal simulation, a vehicle energy model and a thermal car body model. Weather data is sampled based on the vehicle's location and time from a reanalysis data set. We compare the resulting energy requirements of this approach with those obtained using the specifications of DIN EN 50591 and the German Standardized Assessment. We demonstrate the implications for cost planning by executing a cost calculation for battery-electric multiple units. The approach is carried out on four locations in Germany. The annual energy consumption per vehicle for heating, ventilation and air conditioning ranges by location between 49.2 to 55.9 MWh. This compares to a variation of 12.1 % due to locate climate variability. DIN EN 50591 accounts to 76.1 MWh respectively. Regarding the overall annual energy consumption per vehicle, the location specific modelling approach results in 495.4 to 502.1 MWh. Overall energy costs differ by approximately 5 to 9 €ct/kWh depending on the energy price.

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Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Railway vehicles with alternative drivetrains are increasingly entering the rolling stock market. There are strong developments, specifically in the application of fuel-cell electric multiple units and battery-electric multiple units. There is little experience with the energy costs associated with operating these vehicles. Hence, energy demands are often assessed during decision-making processes regarding a certain powertrain technology. Power and energy demand

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of vehicles are often determined by applying longitudinal simulations. To account for the required energy demand for heating and cooling, studies often use a static heating and cooling load (e.g. Streuling et al. 2023; Streuling et al. 2021; Herwartz and Kühlkamp 2022; Kühlkamp et al. 2022; Zhang et al. 2019). This is usually derived from the specifications of the European regulatory framework DIN EN 50591, which provides parameters for a range of predefined weather conditions across different climate zones.

This is useful for design cases such as the dimensioning of drivetrain components. However, when evaluating energy consumption, for instance, as an input parameter for operational expenditures (OPEX) calculations embedded in a Life Cycle Cost (LCC) analysis, the standard DIN EN 50591 might not serve this purpose well. Regional passenger rail operations are typically subject to long-term service contracts with limited financial margins, leaving operators exposed to rising energy costs under changing climatic conditions. This urges us to progress towards a more sophisticated acquisition of vehicle energy consumption. To achieve this, we propose a model chain that automatically integrates local weather data into the energy assessment of multiple units with alternative drivetrains.

We present a geodata model that generates driving profiles based on timetables, geodata of the railway network, and station locations. It parses track parameters from OpenStreetMap (OpenStreetMap contributors 2024) and samples elevation profiles from a digital elevation model (DEM, (JAXA 2016)). This serves as the foundation for simulating traction energy demand. To determine the energy needed for heating and cooling, weather data along the route is sampled based on the vehicle's location and time, as determined by the timetable. The sampled weather conditions are fed into a thermal car body model, which outputs the thermal power requirements. We compare the resulting energy requirements of this approach with those obtained using the specifications of DIN EN 50591. We demonstrate the implications of various heating, ventilation and air-conditioning (HVAC) calculation methods for OPEX cost planning by executing a cost calculation for battery-electric multiple units (BEMU). This model-based approach enables a comparison of regional results without the data noise inherent in empirical datasets, often caused by variations in vehicle configurations, operational characteristics, driving patterns, and other influences.

2. Methodology

This section describes the methodical approach and describes the steps carried out to establish study results. In general, the methodology is carried out by combining a set of simulation tools and models to determine HVAC energy consumption in regards to climate variability. These results are then compared with the results of established approaches for the same vehicle and operational conditions. The concepts used for comparison are namely the DIN EN 50591 and the German Standardized Assessment (INTRAPLAN Consult GmbH and VWI Verkehrswissenschaftliches Institut Stuttgart GmbH 2023). Figure 1 illustrates the methodical approach.

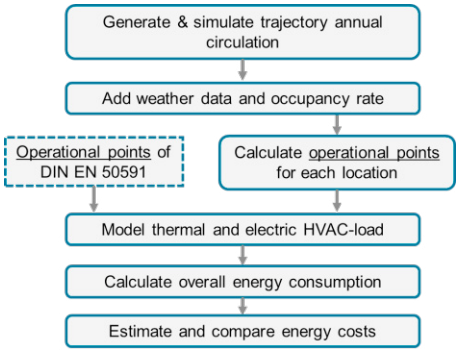


Fig. 1. Flowchart of the methodical approach.

The first step in the study was to generate and simulate a full year-trajectory of a BEMU operating in a regional railway passenger network. This is based on a circulation plan, which is a generic operational plan representing typical operation of German regional railway networks. The circulation plans consist of 30 service days, assuming the railway operator rotates vehicles throughout the circulation. The circulation is then repeated to fulfill 365 service days. Each

service day consists of a set number of trips. Station names, locations, arrival times and departure times are queried from the national timetable (OpenData-Plattform ÖPNV) and concatenated according to the circulation plan. Each trip is parsed through an established geodata model (Streuling et al. 2023) to parse track attributes such as maximum speed, tunnel, bridges, electrification and elevation from OSM. The so generated driving profiles are fed into a longitudinal simulation tool (Schenker et al. 2020). The resulting trajectories yield the energy at wheel level. These trajectories are then fed into a vehicle energy model (Herwartz-Polster et al. 2024) to yield vehicle energy consumption. The service day trajectories are concatenated to the full year operation.

The resulting service year is enriched with weather data from a reanalysis data set (COSMO REA6; (Bollmeyer et al. 2015)). For any given entry in the service years trajectory the time and location are known. With this information, weather parameters (temperature, relative humidity, solar radiation) are sampled and written into the trajectory. Based on the time and date, occupancy rates are estimated and also written into the service year trajectory. After the trajectory has been appended with this information it is grouped into operational points. Operational points consist of the temperature, solar radiation, relative humidity, occupancy rate and the cumulated duration in which they occur over the course of a year.

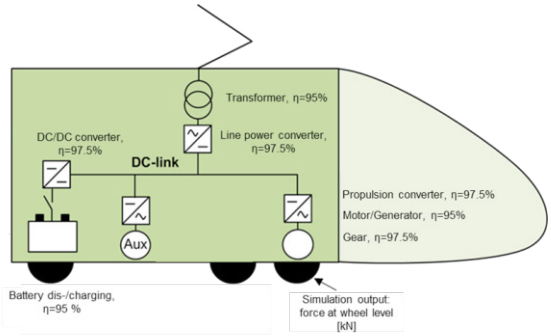
Finally, the operational points of the trajectory are fed into a thermal car body model (Wieser et al. 2025), yielding the annual HVAC energy consumption. This is also performed for the operational points defined in DIN EN 50591 for climate zone 2 (DIN EN 50591, pp. 44–45) . The costs of the HVAC-consumption and the rest of the vehicle's energy demand are calculated and compared.

2.1. Models

The approach facilitates a series of models to establish vehicle energy consumption. The geodata model generates driving profiles from infrastructure data (inclination, speed limits, bridges, tunnels, electrification) and operational data (arrival and departure times). These driving profiles are then used to simulate traction energy demand. The resulting trajectory is fed into a vehicle energy model to model the power and energy at DC-Link, battery, and pantograph. The assumed vehicle specifications of the generic 2-car battery electric multiple unit are specified in figure 2.

Parameters for longitudinal simulation *	
Length	42 m
Mass (seated)	97.5 t
Passenger seats	120
Maximum velocity	140 km/h
Max. de-/acceleration	1 m/s²
Max. power at wheels	1000 kW
Battery: installed energy	500 kWh

Schenker et al 2020



Vehicle Surface Area		
Car Body	Area [m²]	Heat Transfer Coefficient [W/(m²*K]
Wall	100	1.62
Floor	113	1.23
Windows	31	1.83
Roof	79	1.32

Thermal Car Body Model**		
Convection Coefficient Outside	21.9	W/(m²*K)
Target inside Temperature	22	°C
Target Inside Relative Humidity	40	%
Fresh Air per Person	15	m³/(Person*h)

**Wieser et al (2025)*

Fig. 2. Vehicle specifications of the generic 2-car battery electric multiple unit.

Occupancy rates were assumed over weekdays and weekends and national holidays. Table 1 describes the assumptions underlying the occupancy-rate function. The assumptions were then randomized over each day in normalized distribution within predefined ranges.

Table 1. Occupancy Rate by Day and Time.

Time	Time	Occupancy rate	
Weekdays (Mon – Fri, excl. holidays)	06:00 – 08:00	70 – 100 %	Commuter traffic
	09:00 – 15:00	40 – 70 %	Regular demand
	16:00 – 18:00	70 – 100 %	Commuter traffic
	Other hours	10 – 40 %	Low demand
Weekends and public holidays:	07:00 – 09:00	20 – 50 %	Low mobility
	10:00 – 17:00	50 – 80 %	Leisure traffic
	18:00 – 21:00	20 – 50 %	Evening activities
	Other hours	5 – 20 %	Minimal usage

The HVAC energy demands are calculated for each operational point in the service year trajectory. We grouped the operation by one degree Celsius steps, 10 %-steps for relative humidity, 50 W/m²-steps for solar radiation and 10 %-steps for the occupancy rate. This yielded in various thousand operational points depending on the location. For the location Kiel, 5043 operational points were created (in comparison, the DIN EN 50591 provides 16 points, fig 3.

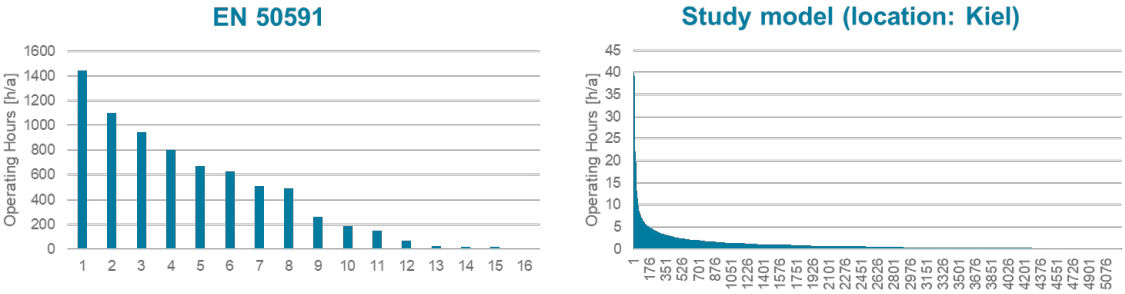


Fig. 3. Operational points of DIN EN 50591 and of the study model.

In addition to the energy demand for traction, the energy demand for HVAC is calculated in a thermal car body model (TCBM, (Wieser et al. 2025)). The TCBM calculates the energy required to condition the air flowing into the cabin and to compensate for heat transfer through conduction, convection and radiation via the outer walls. The HVAC system ensures that the state of thermal comfort within the cabin is maintained in the form of the inside temperature and humidity. The ambient conditions, the track profile and the vehicle parameters are used as input parameters for calculating the energy demand for HVAC. In the case of the ambient conditions, the ambient temperature, ambient humidity, solar radiation and the passenger rate are used to describe an operating point in accordance with DIN EN 50591. The vehicle parameters used in the TCBM are described in Figure 2. In the cabin, the setpoint condition is defined via the inside temperature and humidity, as well as via a fresh air volume flow. To calculate the heat transfer to the environment, the outer areas of the car body including the heat transfer coefficients are specified.

The assessment of energy costs is a critical component in evaluating the economic viability of rail transportation systems. However, energy costs are affected by various factors, including fluctuations in electricity prices. These prices are often influenced by long-term contracting agreements between operators and energy suppliers, but also by the global political situation. Electricity costs also vary based on the supply system, i.e. proprietary rail traction power system or public electricity grid, as well as the national energy mix and energy taxation and duties.

Recent studies in Germany have reported a broader range of electricity prices, spanning from 12 €ct/kWh to 16 €ct/kWh (Klebsch et al. 2020; Stephan et al. 2022) for electricity from rail traction power grid to about 23 €ct/kWh (Stephan et al. 2022) for electricity from the public electricity grid, with additional national taxation and levies applied. According to the German Standardized Assessment (INTRAPLAN Consult GmbH and VWI Verkehrswissenschaftliches Institut Stuttgart GmbH 2023)), a standardized method to evaluate the eligibility of funding for public transport infrastructure projects, electricity prices are assumed to 12 €ct/kWh or 14 €ct/kWh (excluding taxes and duties) depending on the share of renewable energy. Furthermore, future electricity price procurement will be subject to increased uncertainty. Taking these uncertainties into account, energy costs are calculated for three distinct electricity price levels: 14, 18, and 22 €ct/kWh.

To incorporate weather data into the trajectory, we used reanalysis data COSMO REA6 (Bollmeyer et al. 2015) provided by the German Weather Service (Deutscher Wetterdienst, DWD). This dataset provides hourly historic data in 2 m above ground. The reference year in this dataset is 2018.

2.2. Study area

The approach is carried out on four locations in Germany (figure 4). At those locations BEMU-operation is in place or tendered. The locations are chosen to represent a wide span of local climate conditions in Germany. Kiel has an oceanic climate with mild winters and relatively cool summers due to its proximity to the Baltic Sea. Eberswalde has a more continental climate, characterized by colder winters and warmer summers compared to western Germany. Coesfeld experiences a temperate climate influenced by prevailing westerly winds that bring in moist and relatively mild air from the Atlantic Ocean. Mühldorf is influenced by alpine weather patterns, experiencing colder winters and relatively more precipitation, especially in winter.

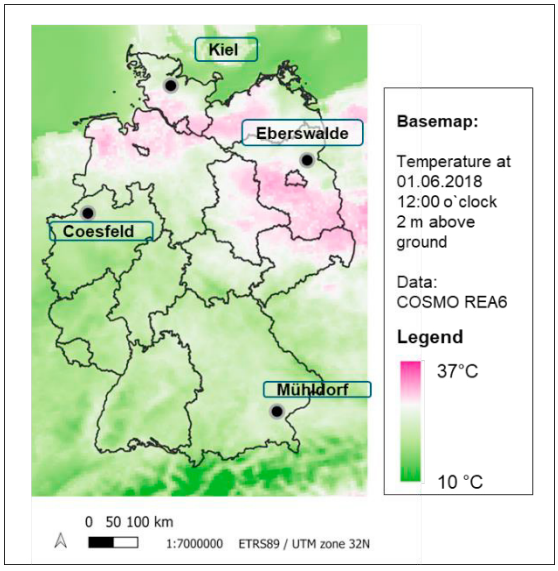


Fig. 4. Study area.

3. Results

The service year trajectory consists of 1.3 million data points, each attributed with the vehicle energy demand and momentary power consumption of the drivetrain components. Operational characteristics of the generic railway network are shown in table 2. The operational hours during commercial operation result from the timetable. The operating hours during non-commercial operation are oriented at DIN EN 50591 operational points. During this mode

vehicles are stationary and the HVAC system operates as it would during commercial service, however no passengers are on board. We assigned hours surrounding the commercial service times to this mode based on the assumptions made in DIN EN 50591. The annual traction energy demand of one vehicle is 446,182 kWh, with an annual mileage of 162,312 km. The vehicles are on average 12.1 hours in commercial operation, however there are service days with as little as two hours of operation (i.e. days where the only planned operation consists of support trips for multiple traction).

Table 2. Operational characteristics of the generic regional passenger railway network.

Operational characteristics		
Service day with the longest distance	788	km
Service day with the most operating hours	19.1	h
Train mileage (per year)	162,312	km/a
Average daily distance	444	km/d
Operating hours during commercial operation	4425.5	h/a
Avg operating hours during commercial operation	12.1	h/d
Operating hours during non-commercial operation	1352.4	h/a
Avg operating hours during non-commercial operation	3.7	h/d
Traction energy demand		
Commercial operation	405,620	kWh
Non-commercial operation	40,562	kWh

Table 3 shows the annual HVAC energy consumption of each study region in comparison to the approaches of DIN EN 50591 and German Standardized Assessment. The annual HVAC energy consumption results in 49.2 MWh to 55.9 MWh based on the presented model-based approach and the four locations, whereas DIN EN 50591 account for 76.1 MWh and the approach with constant HVAC power for 104.2 MWh respectively. Due to locate climate variability the HVAC energy consumptions of the investigated model locations show a difference of 12.1 %. Regarding the overall energy consumption, the location specific modelling approach results in 495.4 MWh to 502.1 MWh. The calculation based on DIN EN 50591 accounts for 522 MWh. The modelled HVAC energy consumption of Coesfeld (the location with the lowest HVAC demand) is 35.4 % lower than the DIN EN 50591 HVAC consumption. As the HVAC consumption is only a fraction of the vehicle's entire energy demand, this difference reduces to 5.2 % when considering the overall energy consumption. Assuming there are 30 vehicles rotating, the energy consumption of the entire fleet is approximately between 14,861 MWh and 16,779 MWh. The fleet`s HVAC consumption ranges between 1476 MWh and 3125 MWh.

Table 3: Annual HVAC energy consumption of each study region and for various approaches.

Modelling approach	HVAC-consumption [MWh]	Share of overall vehicle energy consumption [%]	Vehicle energy consumption [MWh]	Specific vehicle energy consumption [kWh/km]
EN50591	76.14	14.6	522.32	3.22
Study Model Locations				
Mühldorf	55.93	11.1	502.11	3.09
Kiel	50.30	10.1	496.48	3.06
Eberswalde	54.91	11.0	501.09	3.09
Coesfeld	49.19	9.9	495.37	3.05

Constant HVAC-power (21,4 kW*)	104.18	18.9	550.36	3.39
German Standardized Assessment**	/	/	559.30	3.45

*Streuling et al. 2024

**German Standardized Assessment 2016+ (2022)

The impact of different energy consumption modelling approaches and energy prices on the overall energy costs has been assessed (figure 5). Accounting for the variability in electricity prices, electricity costs are calculated based on three distinct price levels: 14, 18, and 22 €ct/kWh. The modelled energy costs range from about 40 €ct/km to above 70 €ct/km, given the assumed energy price levels. The different HVAC energy modelling approaches differ by approximately 5 €ct/km to 9 €ct/km in overall energy costs (incl. traction energy consumption).

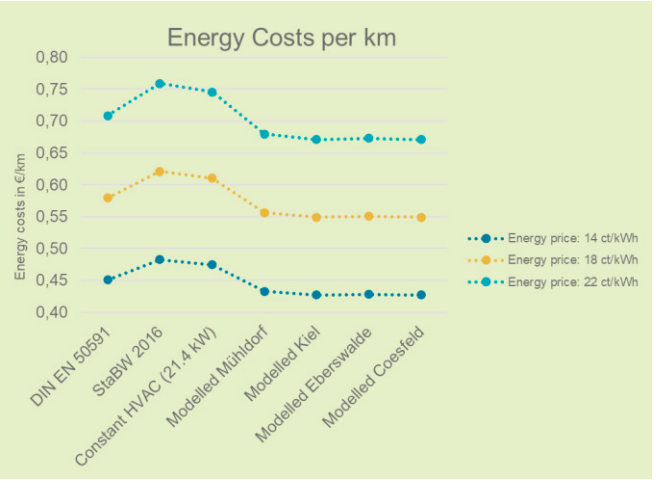


Fig. 5. Energy costs for different HVAC modelling approaches and electricity price levels.

Given energy price and annual weather variations, energy costs may vary substantially throughout the train's life time of multiple decades. Thereby, transport operators face the risk of increasing operating costs particularly driven by fluctuations in electricity prices. This underscores the importance of considering long-term energy cost implications in rail transportation system planning and operation.

4. Conclusion

In this study we computed HVAC-energy consumption for generic battery electric multiple units, in regards to varying local climate conditions for four locations in Germany. We compared the results to approaches common in cost calculation studies. Static approaches tend to overestimate energy costs, potentially multifold. While these static approaches are justified for other tasks, in energy cost calculation it is likely to make false assumptions. The results from the study locations correspond well to the requirements of DIN EN 50591. Therefore, we conclude that the DIN EN 50591 is a reasonable approach to estimate energy costs for LCC studies. However, with changing operational conditions, cost predictions deviate stronger for certain locations. Location-based evaluation of HVAC energy demands can be conducted with manageable effort while it helps designing HVAC systems specific to local requirements or provide insight for appropriate vehicle procurement. Actual regional climate conditions are likely to deviate considerably from the assumptions made in this study, as they are often deployed across both northern and southern Europe. Depending on national regulations and energy prices, HVAC-related energy consumption may

become a significant cost driver over the vehicle's lifetime. The presented methodology can be applied to account for these regional differences.

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