

## Full Length Article

# Cost-benefit analysis methodology for new rail vehicle concepts with alternative powertrain systems



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## ARTICLE INFO

## Keywords:

Cost-benefit analysis  
Reactivated railway lines  
Regional rail transport  
Rail bus

## ABSTRACT

There is currently an increased interest in the reactivation of secondary railway lines in Germany. These lines are mostly in bad condition and are not electrified. As diesel-powered vehicles are to be phased out in the future, in order to reduce greenhouse gas emissions, emission-free vehicles are required.

Market available vehicles are too large and not suited to the needs of low-frequency secondary lines. Due to the high cost of track electrification, vehicles with alternative drive systems are brought into focus. In addition, high infrastructure costs are incurred for track reactivation.

The aim of this work is to develop a comprehensive evaluation approach for a cost-benefit analysis to analyse the economic viability of low frequented railway lines and lines to be reactivated. The advantages of small rail vehicles were discussed on the basis of two tracks to be reactivated and two lines currently in operation. Based on these operational scenarios, cost analyses and cost-benefit analyses were carried out using four different types of vehicles. A sensitivity analysis was used to analyse the impact of passenger utilization and reactivation costs on economic viability.

The results show the significant influence of infrastructure-related costs associated with reactivating tracks, as well as track access charges and station fees for tracks in operation. Small vehicle concepts such as rail buses can contribute to cost-efficient operation on low-frequency secondary lines. This study aims to contribute to a better understanding of the factors influencing the economic viability of rail operations on lines with low passenger utilization rates.

## 1. Introduction

Of the more than 200 000 kilometres of railway lines in Europe, only about 57.4 % are electrified [1]. In Germany alone, 20 % of regional passenger rail transport is powered by diesel trains [2]. Many secondary lines have been closed over the last decades. Recent initiatives in many places in Germany and Europe aim to reactivate disused railway lines. As the infrastructure investment required for reactivation is high, alternatives to full track electrification are needed for low-frequented secondary lines which at the same time avoid greenhouse gas emissions in train operation. Battery-electric and hydrogen-powered

multiple units, which have already entered regular passenger service on various lines in recent years, are solutions [3,4].

Rising costs in rail transport and limited public spending are leading to cuts in regional rail services, particularly in low-density lines [5]. Reactivation projects are facing difficulties due to high infrastructure and personnel costs. Low demand for transport on secondary rail lines has created an application field for rail vehicles, that are smaller than the market available multiple units. Even the smallest vehicles available on the market are still too large for some of these low-utilized lines to keep costs sufficiently low. With the Next Generation Train (NGT) TAXI, the German Aerospace Center (DLR) is developing a new, small, and

*List of abbreviations:* BCR, Benefit Cost Ratio; CAPEX, Capital Expenditures; OPEX, Operational Expenditure; CRI, Charging and Refueling Infrastructure; BEMU, Battery Electric Multiple Unit; HEMU, Hydrogen Electric Multiple Unit; LCC, Life Cycle Costs; StaBW 2016+, German Standardisierte Bewertung 2016+; NGT, Next Generation Train; DLR, German Aerospace Center.

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<https://doi.org/10.1016/j.treng.2026.100422>

Received 24 September 2025; Received in revised form 21 November 2025; Accepted 17 January 2026

Available online 18 January 2026

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lightweight vehicle concept that focuses on reducing the Life Cycle Costs (LCC) [6]. Similar concepts are developed in a number of projects across Europe. The Europe's Rail Project FutuRe (FP6) [7], the Aachen Rail Shuttle [8,9], the Draisie and TELLi from SNCF [10] and the Revolution Very Light Rail [11] show what these small, innovative vehicles could look like.

In the field of small, lightweight rail vehicle concepts, studies on costs have been conducted by the developers of the concepts, (e.g. [12]). Climate-neutral alternatives to diesel multiple units have been evaluated on the basis of utility analyses and life cycle cost analyses [13–15]. In Germany, public stakeholders can use a standardised cost-benefit analysis to check whether the infrastructure investment in electrification via catenary or in refuelling and charging infrastructure for battery-electric or hydrogen-powered trains is worthwhile. It provides an established procedure for decision-making processes and determining the public funding eligibility for investment projects into non-electrified secondary railways (p. 189 [16]).

For investment projects to reactivate railroad lines, there are also procedures for decision-making and assessing eligibility for federal and state funding on a national level. In Germany, for investment projects over € 30 million, a welfare-economic cost-benefit analysis approach can be used (p. 6 [16]). Since this methodology is complex to apply, the “simplified procedure for reactivation projects”, which is a resource-based cost-benefit analysis approach that monetarily internalizes external effects, can be used for lower-investment projects to reactivate railroad lines (p. 211 [16]). Both approaches internalise external effects such as greenhouse gas emissions, the consequences of accidents and changes in travel times. The standardised assessments are collected in the German Standardisierte Bewertung 2016+ (StaBW 2016+) [16].

Cost-benefit analyses have mainly been used to assess the effectiveness of large investment projects [17]. Modifications of the method are available for rail freight services [18]. For new vehicle concepts, the cost-related methods Life-Cycle-Cost Analysis and Total-Cost-of-Ownership are usually sufficient. This paper combines various procedural approaches in order to evaluate investments into infrastructure for track reactivation, new vehicle concepts and alternative powertrain systems in a cost-benefit analysis. The procedural approaches for assessment refuelling and charging infrastructures and for the reactivation of railroad lines were combined with each other and detailed with regard to the capital expenditures (CAPEX) and operational expenditure (OPEX) of the vehicle. This ensures that both the life cycle costs from vehicle operation and external effects are included in the assessment and can be interpreted in the overall context of the transport effects and infrastructure CAPEX. With this evaluation approach, cost-benefit analysis for specific vehicle configurations in operation on specific railroad lines can be made. The individual costs and external effects and their interactions with each other will be transparent and this makes it possible to quantify the influence of new vehicle concepts and alternative drives on the possibilities for reactivating railroad lines and which lines provide potential business cases for the new concepts.

After presenting the method and the necessary data input and assumptions made, the paper looks at the costs on the vehicle side. In the presentation of the results, after a brief presentation of the overall result using an example case, the costs are discussed in detail by comparing the analysed variants.

## 2. Methodology and data

As a basis for the evaluation model, operating scenarios, track data, vehicle deployment as well as cost and utilization data were first determined via a literature search. Out of this data four scenarios were defined. When defining the scenarios, the focus was on covering a broad spectrum of local rail passenger transport, whereby four lines with low capacity utilization were selected, as these are particularly affected by economic efficiency problems. Two of these lines are tracks to be reactivated and two of the lines are in operation today. They are between 10

and 80 km long.

Initially, the area under consideration was defined and corresponding scenarios were compiled on the basis of lines and operating data (subsection 3.2). In order to achieve the highest possible informative value, four generic vehicles were created to operate the lines, each representing a spectrum of similar existing vehicles. For this purpose, parameters were determined for various vehicles of the same vehicle class and a generic vehicle was derived from the averaged values for each vehicle class. In order to identify influencing factors and their degree of efficiency for economic track reactivation, the four vehicles (Fig. 1), a small, lightweight battery electric rail bus, a one-car-battery electric (multiple) unit (BEMU-1) and a two-car-battery electric multiple unit (BEMU-2) as well as a one-car hydrogen electric (multiple) unit (HEMU-1) are examined in this study for the four lines.

To determine the benefits and costs of these scenarios, a resource-oriented approach of a cost-benefit analysis has been adapted and executed, which determines the benefits and costs of investment and operating secondary lines with new vehicle concepts. The CAPEX for the vehicles, infrastructure investments to reactivate the line and the costs for the refuelling and charging infrastructure are considered. The OPEX include costs for maintenance, energy consumption and personnel costs. The benefit side takes into account the following indicators:

- traffic benefits consisting of avoided car operating costs, benefits from travel time savings and benefits from additional mobility alternatives
- benefits from avoided consequential accident costs
- benefits from avoided CO2 emissions
- benefits from avoided emission costs
- public transport operating costs
- infrastructure maintenance costs

The benefits and costs of track reactivation (including regional rail services) are compared with the reference scenario (status-quo road-based public bus transport service). If the benefit-to-cost difference is positive (corresponds to a benefit-cost ratio >1), the project can be said to be economically viable.

Four scenarios are considered for the use cases, which differ in terms of length, passenger utilisation, track characteristics, status quo infrastructure condition and charging and refuelling infrastructure (CRI). Combined with the four vehicle types defined previously, these results in 16 different cases to be analysed. For the reactivation scenarios, the infrastructure costs and the transport performance of rail passenger transport can be varied as part of a sensitivity analysis. Fig. 2 schematizes the evaluated scenarios.

## 3. Technical and operational assumptions

This section describes the underlying technical and operational assumptions for the vehicle concepts. First, four generic rail vehicles with different seating capacities and powertrains are described, which were selected for operation on low-utilised secondary lines. Second, the selection of the analysed secondary routes is described, the respective operating scenarios are defined, and the methodology for determining

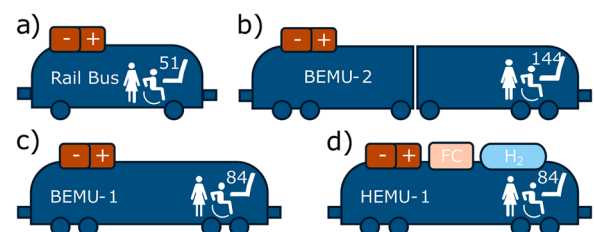


Fig. 1. Rail vehicle types a) battery electric rail bus, b) two-car BEMU, c) one-car BEMU, d) one-car HEMU.

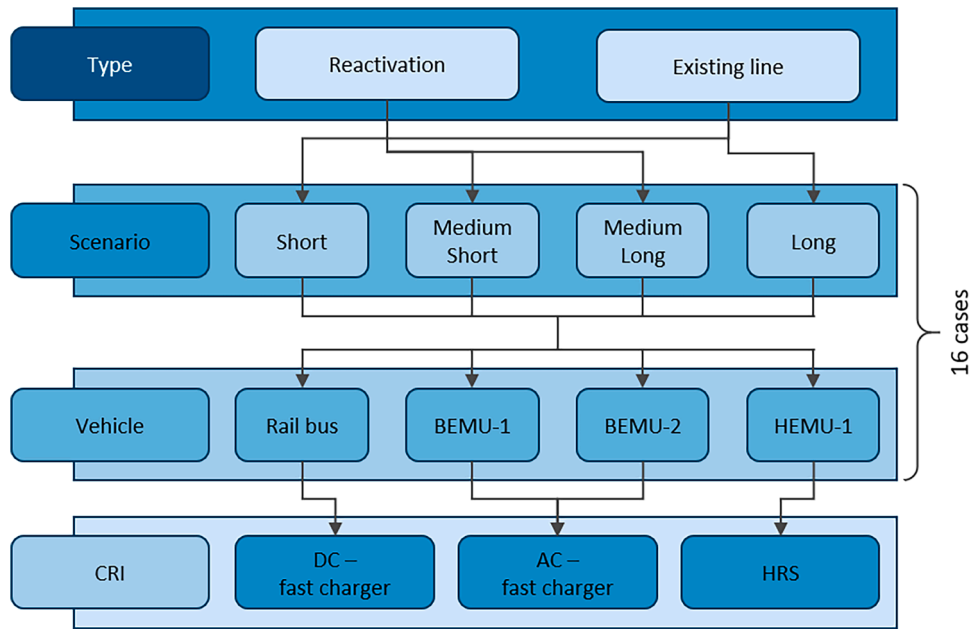


Fig. 2. Breakdown of the scenarios.

passenger demand, utilisation, and the required vehicle capacity is explained.

### 3.1. Vehicles

Four generic rail vehicles with different passenger capacities and energy supply systems are being evaluated for operation in the scenarios. The vehicles included in the study were selected based on the low utilisation on secondary lines. The focus is therefore on smaller vehicles.

In order to meet the requirements of a future-oriented mobility concept, the focus is on vehicles with locally emission-free powertrains that do not emit greenhouse gases. Furthermore, modern vehicles, with a low capacity are chosen to meet the demands of society on low frequented lines.

The smallest vehicle is a two wheel-set rail bus, which will be represented by NGT TAXI. The NGT TAXI is a vehicle concept currently being developed by the German Aerospace Centre (DLR) that is tailored for use on reactivated lines and low-frequency lines in rural areas. The multi-modular approach of the vehicle concept allows, among other things, a modular length that can be configured according to capacity requirements. This study examines the longest version (NGT TAXI Large) with 44 seats [6]

The next larger vehicle is a single-car rail vehicle with two bogies powered by batteries (BEMU-1) or hydrogen fuel cells (HEMU-1). Its size is based on existing diesel-powered vehicles such as the Alstom LINT 27 [19], Stadler Regio-Shuttle RS1 [20] and the future Stadler RS ZERO [21]. The largest vehicle considered in this study is a two-car BEMU of conventional design with Jacobs bogie (BEMU-2), such as the Siemens Mireo Plus B [22] or Stadler Flirt Akku [23]. These are currently the smallest rail vehicles available on the market for operation on standard-gauge tracks. Table 1 shows the key vehicle parameters. The key parameters for the generic BEMU-1, HEMU-1 and BEMU-2 vehicles were derived from different real vehicles of similar type. The vehicle data is presented in Table 1.

### 3.2. Lines and scenarios

The following section introduces the lines and scenarios, the infrastructure and vehicle capacity utilization and the number of vehicles. This data will be evaluated in the course of this work.

Table 1  
Vehicle data.

Vehicle		Rail bus	BEMU-1	HEMU-1	BEMU-2
Number of cars		1	1	1	2
Number of wheel sets		2	4	4	6
Length	m	16.7	27	27	46
Seats		44	75	75	125
Seats + 15 % standees*		51	84	84	144
Service weight	t	22	55	55	95
Max. weight	t	32	69.4	69.4	115
Max. wheelset load	t	16	17	17	19
Energy supply		DC	AC 15/25 kV	Hydrogen	AC 15/25 kV

\* The maximum passenger capacity is calculated based on the number of seats plus 15 % standing passengers [24].

#### 3.2.1. Introduction to the evaluated lines

Four lines were selected for the application of the model. Two of these are tracks that need to be reactivated and two lines which are currently in operation. All lines have the characteristics of secondary lines in rural areas in Germany. When selecting these lines to be examined, attention was paid to ensure that they cover a broad spectrum with respect to length and passenger loads.

The lines examined are all standard-gauge, non-electrified and single-track, assuming that there are possibilities for train crossings so that a 60-minute service can be implemented. For the area under investigation, the line lengths were limited to a maximum of 80 km. These represent > 85 % of the non-electrified lines in Germany [25]. Scenarios were constructed for each of the selected lines (Table 2).

#### 3.2.2. Infrastructure and vehicle capacity utilization

To calculate the line and vehicle utilisation, the passenger demand of the individual line sections was first determined. Data from public transport plans, including those from the German states Lower Saxony [26], Brandenburg [27], and Thuringia [28], were used for this. Fig. 3 shows the passenger demand accumulated in both directions over the course of the line in passenger kilometres per day in relation to the distance. The transport performance  $P$  [pkm/day] of each scenario has been determined from the passenger demand of the individual line

**Table 2**  
Scenario data.

Scenario		Short	Medium Short	Medium Long	Long
Type		In Service	Reactivation	Reactivation	In Service
Length	km	9.9	20.4	46.1	79.3
Line stops each way	-	5	6	11	18
Avg. distance between stops	km	2	3,4	4,2	4,4
Travel time one-way	hh:mm	00:17	00:24	01:03	01:20
Round-trip time	hh:mm	01:00	01:00	03:00	04:00
Travelling speed*	km/h	35.3	51.0	43.9	59.5

\* One-way trip, average speed including intermediate stop times.

segment  $D_{Si}$  [passenger/day] and the length  $l_{Si}$  [km] of the respective sections.

$$P = \sum D_{Si} \cdot l_{Si} \left[ \frac{pkm}{day} \right] \quad (1)$$

The time dependent utilisation  $u(t)$  [%] of the individual line sections over the course of the day was determined using a daily hydrograph. Fig. 4 shows daily hydrographs extracted from literature [29–31]. The arithmetic mean of the hydrographs has been used for all future calculations. Due to variations in the different timetables at the beginning and end of the day, the passenger utilisation of the non-operating hours was distributed among the surrounding trips.

The required passenger capacity  $C_{Si}$  [passenger] of the vehicle for the individual line section can be determined multiplying the passenger demand  $D_{Si}$  [passengers/day] with the maximum utilization rate  $u_{max}$  [%] and divide it by half for the demand in one direction. It is assumed that the same number of passengers travel in both directions throughout the day.

$$C_{Si} = \frac{D_{Si}}{2} \cdot u(t) \quad (2)$$

The vehicle capacity  $C_{s(max)}$  [passenger] is determined based on the maximum passenger capacity throughout the day and along the line. A summary of the calculated values is shown in Table 3.

### 3.2.3. Number of vehicles required and mileage

Based on the calculated required capacity, the number of trips that need to be served by multiple-train units is determined according to the different vehicle types, using the number of seats available in the vehicle. The operating kilometers were calculated based on the track length, number of trips and the average train length. The number of vehicles per type in the various scenarios was determined using two criteria. First, the minimum required number of vehicles was determined that can serve all scheduled trips, including multi-unit trains. It was then checked whether the mileage of the individual vehicles for operating the timetable plus 5 % margin for service and shunting did not exceed a maximum mileage of 175 000 km and, if necessary, the number

of vehicles was increased so as not to exceed this limit. The mileage limit was chosen to keep vehicle mileage within a range typical for regional rail transport.

## 4. Cost rates used for the valuation

In order to assess the economic viability of the transport scenarios examined, it is necessary to systematically determine all relevant cost and benefit components according to the presented assessment method. This section describes the methodological approach. The cost components consist of three categories, vehicle-related costs including CAPEX and OPEX, energy-related costs including energy consumption, CO<sub>2</sub> and pollutant emissions and infrastructure costs for renewal or reactivation

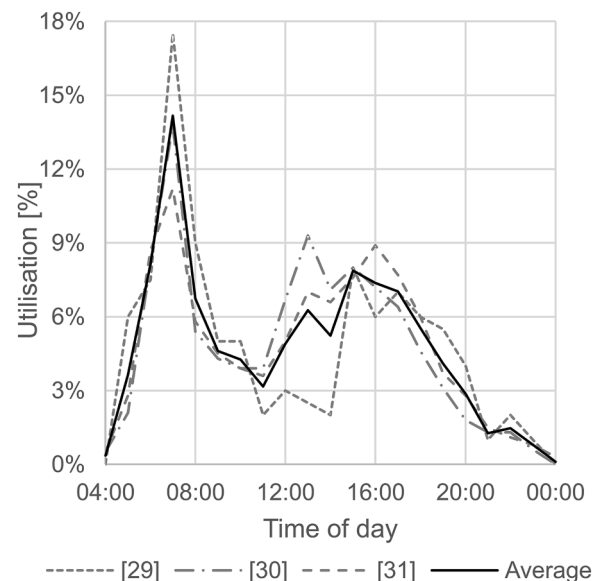


Fig. 4. Utilisation over the course of the day .

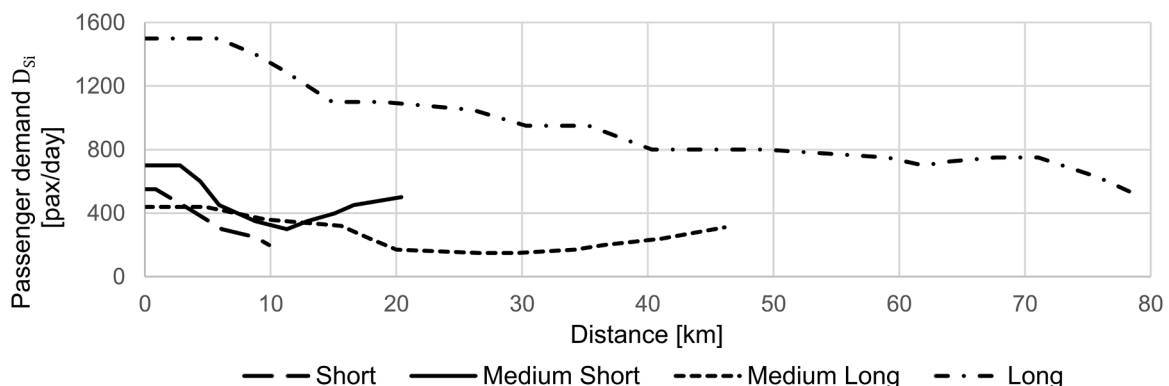


Fig. 3. Line traffic load profiles.

**Table 3**  
Line utilisation and required vehicle capacity.

Scenario			Short	Medium Short	Medium Long	Long
Passenger demand	$P$	$pkm \text{ per day}$	3 250	14 000	12 000	54 150
	$p$	$\frac{pkm}{track - km} \text{ per day}$	328	588	260	691
Required passenger capacity	$C_{s(max)}$	passenger	78	57	71	106

of track infrastructure and provision of CRI.

#### 4.1. Vehicle-related costs

The evaluated vehicle-related costs include both the CAPEX for the acquisition of the vehicle fleet and the maintenance costs incurred during the operating period. As some of the vehicle concepts examined are not yet available on the market, the values had to be determined using comparison and scaling methods.

##### 4.1.1. Vehicle capex and maintenance

CAPEX for the rail bus were estimated based on comparable vehicles as there are currently no comparable vehicles on the market. The one car tram Moderus Gamma LF 10 AC BD, which was built in a small series of 4 units for a small German tram network [32], and the tender [33]. for a similar vehicle, which is also to be delivered by Modertrans Poznan in 10 units, served as the basis. This vehicle was selected because it is a new development and also a lighter vehicle. To align the costs with the rail bus, different assumptions were made:

- Surcharge for longer vehicle
- Additional costs for traction battery system
- Additional costs incurred for vehicles in main line operation

This results in total costs of approximately € 2.5 million for the rail bus. The acquisition costs for vehicles BEMU-1, HEMU-1, and BEMU-2 were determined based on the values specified in [16]. and an internal DLR database. In reality, these also depend on the size of the fleet to be acquired and the vehicle model. Models that are manufactured in large quantities may be cheaper than tailor-made vehicles. An overview of the costs of the vehicles is shown in Table 4.

In order to determine the overall economic viability of the scenarios discussed in combination with the vehicle variants, cost assumptions are required for the vehicles, the track infrastructure investments and the costs for the refueling and recharging infrastructure. Vehicle costs include CAPEX and maintenance costs and are defined in the model as mileage-based annuities. The determining variable is the annual mileage of the vehicles in accordance with the scenario. The maintenance costs are based on a time-dependent and mileage share (Table 5), which are calculated based vehicle mass and vehicle-km, calculated from parameter sets given in appendix 1 [34]. of StaBW 2016+.

Table 6 shows the mileage-related vehicle costs, including CAPEX and maintenance. The vehicle CAPEX were determined based on the acquisition costs and vehicle mileage. The annuity factor used for the vehicles was derived from the StaBW 2016+ (appendix 1 [34]).

##### 4.1.2. Energy and CO<sub>2</sub>-emission costs

The energy consumption for each vehicle type and line was calculated according to the method presented in StaBW 2016+ [16]. which calculates track- and stop-specific energy consumption based on line specific parameters for each vehicle variant. The line-related energy

**Table 4**  
Vehicle CAPEX (base year 2025).

Vehicle type	Rail Bus	BEMU-1	HEMU-1	BEMU-2
Vehicle acquisition cost	2.5 M€	4.5 M€	5 M€	7.5 M€

**Table 5**

Maintenance cost assumptions for each vehicle variant based on StaBW 2016+; Appendix 1, B11 [34].

Vehicle type	Maintenance (run time) [€/t <sup>a</sup> ]	Maintenance (mileage) [€/1000 tkm]
Rail Bus	540	5.8
BEMU-1 / BEMU-2	540	5.8
HEMU	590	8.8

**Table 6**

Vehicle costs as the example for the medium long line.

Vehicle type	Vehicle CAPEX [€/km]	Vehicle Maintenance [€/km]
Rail bus	0.810	0.229
BEMU-1	1.172	0.606
HEMU-1	1.302	0.707
BEMU-2	1.953	1.046

consumption is calculated from the specific energy consumption of the line [kWh/km] or [kg<sub>H2</sub>/km] and the mileage per year [vehicle-km/year]. The energy consumption of the rail bus is assumed to 1.5 kWh/km based on simulation-based analysis, as no vehicle of this size is given in the model vehicle types. Scaling the energy requirement solely on the basis of the vehicle mass would lead to strong distortions compared to the 1- and 2-car vehicle configurations.

The energy costs for each powertrain configuration are calculated from the energy consumption and the powertrain-specific prices assuming an electricity prices of € 0.12/kWh and hydrogen prices of € 5/kg<sub>H2</sub>, as given in the StaBW 2016+ [16].

As the standard vehicle data given in StaBW 2016+ appendix 1 [34]. does not include the required cost data assumptions of the examined vehicle concepts, maintenance costs, CO<sub>2</sub> and pollutant emission rates have been calculated based on a mileage- and operating time dependent approach given in the general procedure of StaBW 2016+ [16].

CO<sub>2</sub> emissions and pollutant costs are determined based on the energy consumption of the respective vehicle variant and energy carrier specific emission rates. In this case, the battery-electric powertrain variants were based on electricity supplied from the conventional power grid (German electricity mix). In the StaBW 2016+, the use of exclusively green hydrogen is assumed for hydrogen-powered vehicles, which distorts the comparability with battery-electric vehicles. For this study, the corresponding emission factor was assumed for hydrogen production from grid electricity. CO<sub>2</sub> emission costs were calculated using a cost rate of € 670/tCO<sub>2</sub> (StaBW 2016+, Appendix 1 [34]) for all vehicle configurations. Table 7 summarizes the results of the energy and cost calculations.

#### 4.2. Infrastructure-related costs

This section expands on the vehicle-related costs described above to include the expenses associated with the necessary infrastructure. It covers CAPEX and OPEX in CRI and the costs of reactivating the rail lines.

**Table 7**

Vehicle, emission and pollutant related costs as the example for the medium long line (EU: kWh for battery electric vehicles and kgH<sub>2</sub> for hydrogen powered vehicles).

Vehicle type	Energy	Energy consumption		Energy costs		CO <sub>2</sub> costs		Pollutant costs	
		[EU/km]	[EU/stop]	[€/km]	[€/stop]	[€/km]	[€/stop]	[€/km]	[€/stop]
Rail bus	electric	1.5	0.000*	0.180	0.000*	0.446	0.000*	0.016	0.000*
BEMU-1	electric	1.815	1.193	0.218	0.093	0.503	0.215	0.017	0.007
HEMU-1	hydrogen	0.121	0.080	0.605	0.259	1.398	0.599	0.048	0.021
BEMU-2	electric	3.135	2.061	0.376	0.161	0.869	0.372	0.030	0.013

\* The energy consumption of the one-car rail bus is assumed based on longitudinal simulation, therefore the total energy demand is entirely given per vehicle km. This approach differs to the other discussed vehicles because the StaBW does not provide data for vehicles of the size of a rail bus.

**Table 8**

CRI data.

		AC-Battery Charging	DC-Battery Charging	H <sub>2</sub> Refueling Station
Reference model		Furrer und Frey Voltap	Furrer und Frey Rapid Charger (Coventry) & all in one	-
Charging Power	kW	2400	450	-
CAPEX (2025)	M€	2.25	0.8	7.5
Life span	years	30	20	30
References		[39,40]	[37,38]	[13,41,42]

#### 4.2.1. Charging and refueling infrastructure

For the vehicles included in this study, different charging and refueling options are considered (Table 8). For the conventional rail vehicles BEMU-1 and -2, commercially available overhead line recharging systems, such as the Voltap fast charging system from Furrer and Frey [35], are selected. Two vehicles can be charged simultaneously at each charging station with a combined maximum charging power of 2.4 MW. Charging the BEMU-1 and -2 via catenary is also possible if sections of the track are connected to the rail traction power supply.

The rail bus is charged using direct current. As there are currently no commercially available charging systems for DC rail vehicles, the Rapid Charger from Coventry VLR [36], will be used as a reference. The energy is transferred via an inverted pantograph with a charging power of up to 450 kW. Each charging station can charge one vehicle at a time. To determine the costs, the costs of similar systems for charging road buses were used as a reference [37,38].

For the cost assessment of the hydrogen refueling station, various projects and studies were used as a reference. The costs determined varied significantly between € 1 million and € 19 million. The actual costs depend on various factors such as the dimensions required in relation to the size of the vehicle fleet and fuel consumption, or the location of the filling station. Additional uncertainty arises from the fact that this is not an established technology. For this study, costs of € 7.5 million were assumed.

#### 4.2.2. Cost for reactivating rail lines

The costs of reactivating railway lines vary greatly. Different factors, such as the shape of the track and stations, the number of level crossings, or the topography, affect the costs. For the purposes of this study, a range of cost assumptions per reactivated track kilometre was assumed for standardisation purposes, ranging from € 0.5 million/km to € 2.5 million/km [43]. In specific cases, the infrastructure investment can be significantly higher, for example due to tunnel structures. For the method used, these costs were divided into different categories. For each of these categories, a corresponding value for the annuity factor and a factor for maintenance costs are assumed. These factors can be used to determine the annual CAPEX and maintenance costs. The factors were derived from [16].

## 5. Results

Following the results of the overall economic calculations, this section focusses at vehicle costs, infrastructure costs and energy costs. Additionally, a sensitivity analyses has been carried out for important input factors.

### 5.1. Overall economic results

In the cost-benefit assessment, all effects of the variants considered are monetized and compared to the reference case (line bus service case without rail service). Fig. 5 shows the benefit and cost ratio (BCR) of the four vehicles considered for the Medium Short scenario. If the benefit difference exceeds the cost difference, the project is advantageous. In the scenario shown in the figure, this is the case for the first two variants.

The infrastructure CAPEX and maintenance costs for the reactivation of the railroad line as well as the traffic benefits are the same in all variants. The rail bus variant has the best benefit-cost ratio of 1.37, followed by the BEMU-1 variant with an BCR of 1.21. The main difference is composed of the public transport operating costs, which are lower for the rail bus compared to the BEMU-1. As the energy demand of the light rail bus is lower, the internalized benefit from the lower CO<sub>2</sub> emissions is also higher. The larger BEMU-2 has a lower BCR due to the significantly higher operating costs. The HEMU-1 shows the worst result, as the CAPEX for the refueling and charging infrastructure (CRI) is particularly high and there is no advantage in lower CO<sub>2</sub> emissions compared to bus service due to the poor efficiency of hydrogen production. As mentioned at the beginning, this cost-benefit analysis approach was chosen in order to be able to interpret the sensitivity of the influence of new rail vehicle concepts and alternative powertrain systems on the overall result of infrastructure CAPEX in line reactivations.

### 5.2. Cost analysis

In order to obtain a more accurate overview of the costs, these were analysed individually. The first step involved analysing the vehicle-related costs. This was followed by a discussion of the influence of the infrastructure-related costs and energy costs.

#### 5.2.1. Vehicle cost analysis

As the transport benefits and the costs for investment and maintenance of the rail infrastructure are the same for all scenarios, the costs of the different four vehicles are presented in this subsection. To evaluate the costs, the individual cost components were considered first. Fig. 6 shows the breakdown of vehicle-related costs across all scenarios and vehicle types. For comparability reasons, the specific costs per kilometre are shown. The non-integer number of vehicles (n-vehicles) is based on percentage surcharges for provisioning trips, maintenance, and the annual mileage limit for the vehicles. The number of vehicles has not been rounded up, as this would result in very different percentage surcharges across the scenarios and vehicles, which would affect the result accordingly. Furthermore, it can be assumed that the vehicle fleet is used across multiple lines. This means that reserve vehicles in the fleet can be used across multiple lines.

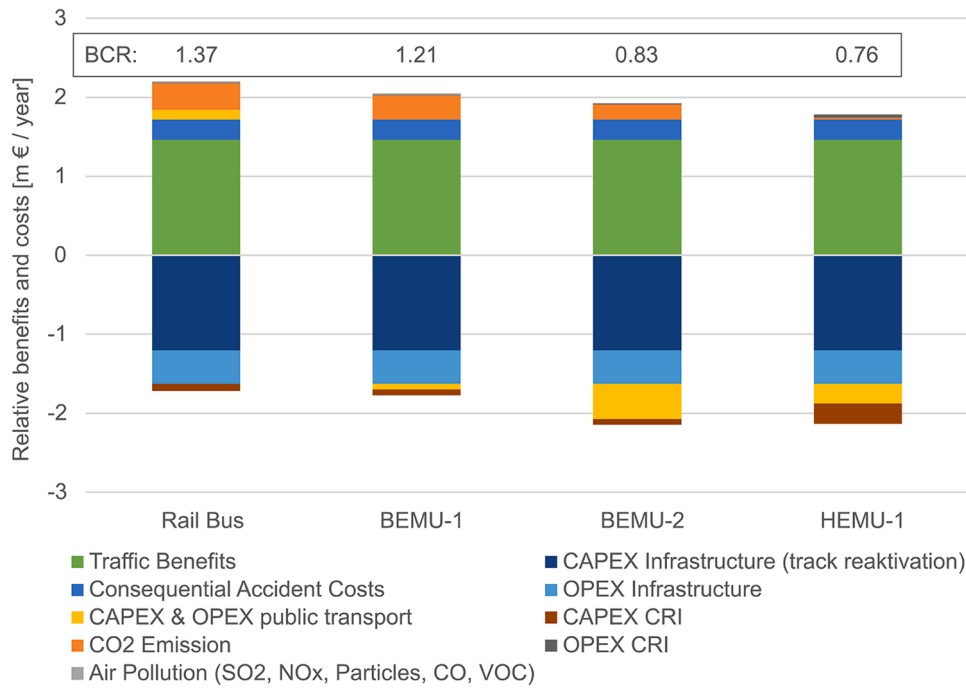


Fig. 5. BCA for the scenario Medium Short; 15,000 pkm (735 pkm/km) per day; CAPEX Infrastructure 1.5 M€/km. The bars show the balance relative to line bus public transport.

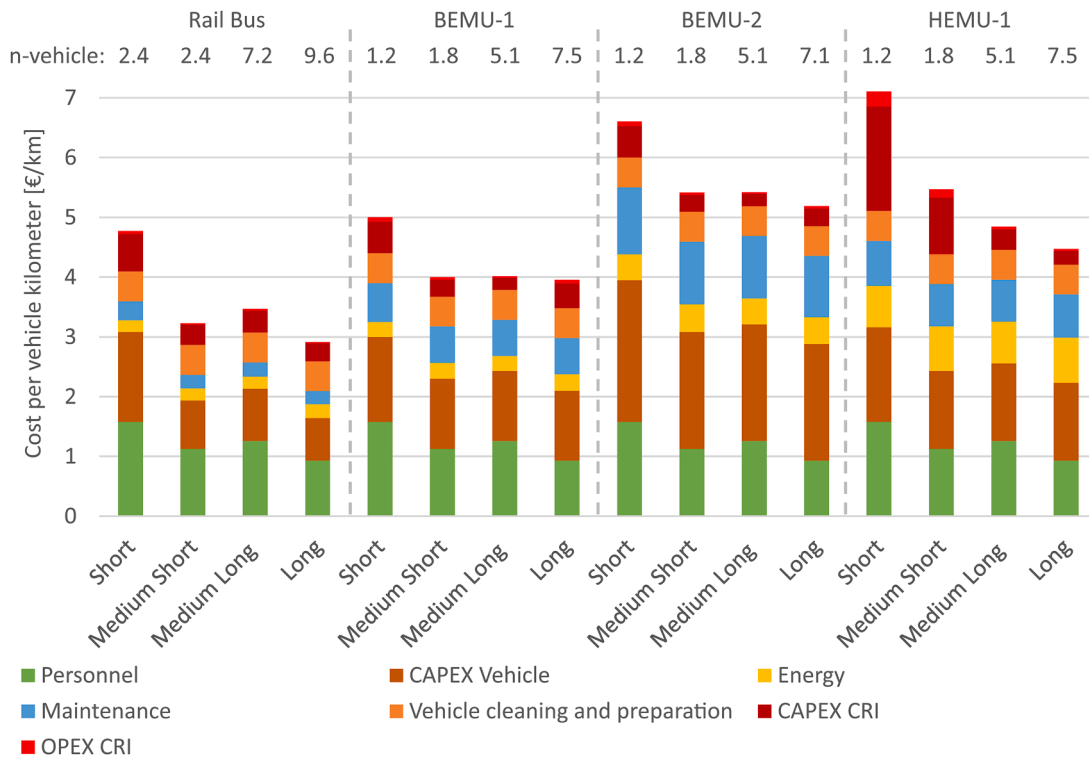


Fig. 6. Breakdown of the vehicle-related costs over all scenarios and vehicles.

The figure shows that costs vary not only for different vehicles on a line, but also for a vehicle on different lines. There are several reasons for this:

- The comparative analysis shows that the difference in relative infrastructure costs is due to the different mileage of the vehicles per line and the traffic volume. Non-recurring CAPEX for the entire

system, such as a cost-intensive hydrogen filling stations for the HEMU, have a much greater impact on short lines.

- Vehicle investment costs are strongly determined by the number of vehicles required. This is related to the operating concept and the utilization of the line. There is therefore no simple correlation between line length and vehicle costs.

- Personnel costs vary depending on the travel speed and operating hours.
- Vehicle-specific costs are relatively higher across all vehicles for short lines. This is because the vehicles have relatively long standstill times and low mileage due to the short line length.
- Personnel costs vary between 7 and 12 % of total vehicle-specific costs
- Vehicle CAPEX account for the largest share of vehicle-specific costs
- Maintenance costs are constant across all scenarios for the respective vehicle, as they are calculated using mass and mileage-specific parameters.
- The CAPEX and OPEX of the CRI are strongly related to the number of vehicles used, mileage, charging and refueling times, battery chemistry, and the resulting operating concept.

5.2.2. Accounting for infrastructure-related costs

In addition to the vehicle related costs, the costs for infrastructure utilisation are now also included (Fig. 7). These are split into track and station charges. An amount of € 6.5/km was assumed for the track charges and € 1.75/km for the station charges. The values are averaged values from [44,45]. In the cases examined in this study, infrastructure costs account for approximately 75 % of total costs, when considering the cases with the lowest vehicle related costs (rail bus, long scenario) and 50 % of total cost for the case with the highest vehicle related costs (HEMU-1, short scenario).

The results show that a less utilized track operated by a small vehicle will incur these relatively high infrastructure charges. However, the cost considered only represents the average values from the track access charge system of DB InfraGo and German station charges (various Infrastructure managers). The costs for individual track access charges can vary significantly case by case.

5.2.3. Impact of rising energy costs

As energy costs have risen continuously in recent years and also vary depending on the energy source, the impact on total vehicle costs was examined (Fig. 8). For the purpose of comparability, a one-car train was used for this analysis of energy cost variation, as this is available with both battery and hydrogen powertrains. The medium-long scenario was chosen as it provides average energy costs in comparison with the other scenarios.

The baseline energy price in this study is € 0.12/kWh and € 5/kgH<sub>2</sub>. The literature currently quotes a price for green hydrogen starting at € 1.5/kgH<sub>2</sub> [46]. Values from projects currently being implemented are often closer to € 10/kgH<sub>2</sub>. The energy costs were calculated in four stages (50 %, 100 %, 150 % and 200 % of the baseline price), both for the hydrogen and electricity prices, based on this price range.

The increase in energy costs for hydrogen has a significant impact on

overall costs. In the baseline scenario, energy costs amount to approximately € 0.70/km. If the price of hydrogen rises, energy costs will already be around € 1.4/km, which accounts for approximately 11 % of total vehicle-related costs. In comparison, the share of energy costs in vehicle related costs is significantly lower in the case of battery electric vehicles.

5.3. Sensitivity analysis

A sensitivity analysis is used to examine the influence of different characteristics of selected input variables of a track reactivation on the economic efficiency of the project. This is shown by the benefit-to-cost difference (BCD). All combinations of the following sensitivity parameters are examined for the Medium Short and Medium Long scenarios:

- Traffic performance: 9 000, 12 000, 15 000, 18 000, 21 000 [pkm/day]
- Infrastructure capital expenditures: 0.5, 1.5, 2.0 [M€/km]

For a simplified classification of the traffic performance level in relation to the total length of the line, this was divided by the track length driven. The resulting dimension pkm/track-km shows the traffic performance in the following diagrams (operational efficiency).

5.3.1. Reactivation scenario medium short

To begin with, the impact of the transport performance and the level of infrastructure capital expenditures on the benefit-cost difference of the Medium Short reactivation scenario with a length of 20.4 km is examined. Four scenarios are considered, which differ in the choice of rail vehicle. Fig. 9 shows the resulting benefit-cost difference according to the input parameters.

For the baseline infrastructure CAPEX of € 1.5 million/km (dashed line) all of the vehicles reach their point of profitability. Due to the low vehicle CAPEX and maintenance cost the rail bus reaches the point of being economically viable already at around 550 pkm/km, if the BCD is greater than zero (brake even). The BEMU-1 needs an around 18 % higher passenger demand to reach this point (650 pkm/km). The BEMU-2 and HEMU-1 need even higher passenger demand. The changes in the gradient of the BCD over the course of the passenger demand are caused by the varying number of vehicles (n-vehicle). Since the change in the number of vehicles does not occur at the points specified in this study, the changes in passenger numbers do not show any sudden changes over time, but only changes in the gradient.

With an infrastructure CAPEX of € 0.5 million/km all of the vehicles can operate at an economically viable point. Infrastructure CAPEX of € 2.5 million/km require a service that is high in demand and are only economical for a rail bus from 950 pkm/line-km and above. All other

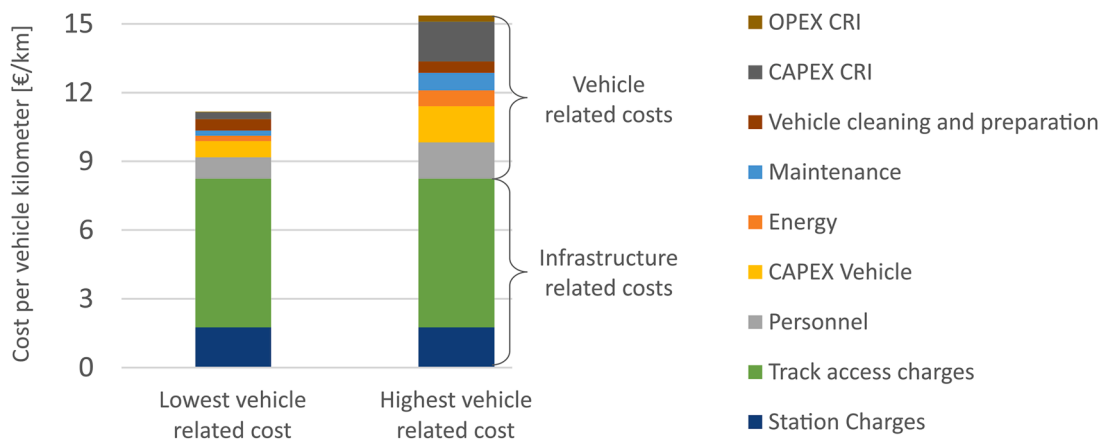


Fig. 7. Total train costs including track access and station charges (showing lowest and highest cost for the range).

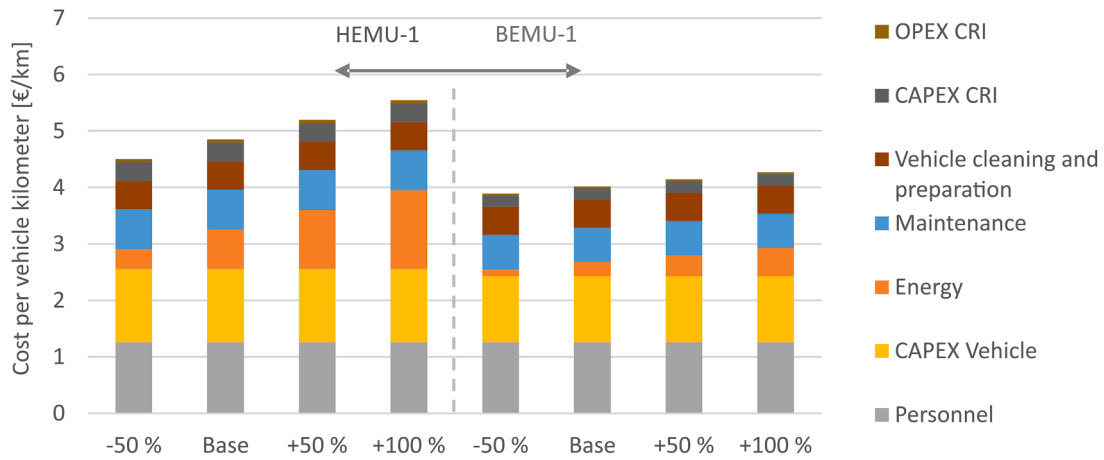


Fig. 8. Energy cost variation.

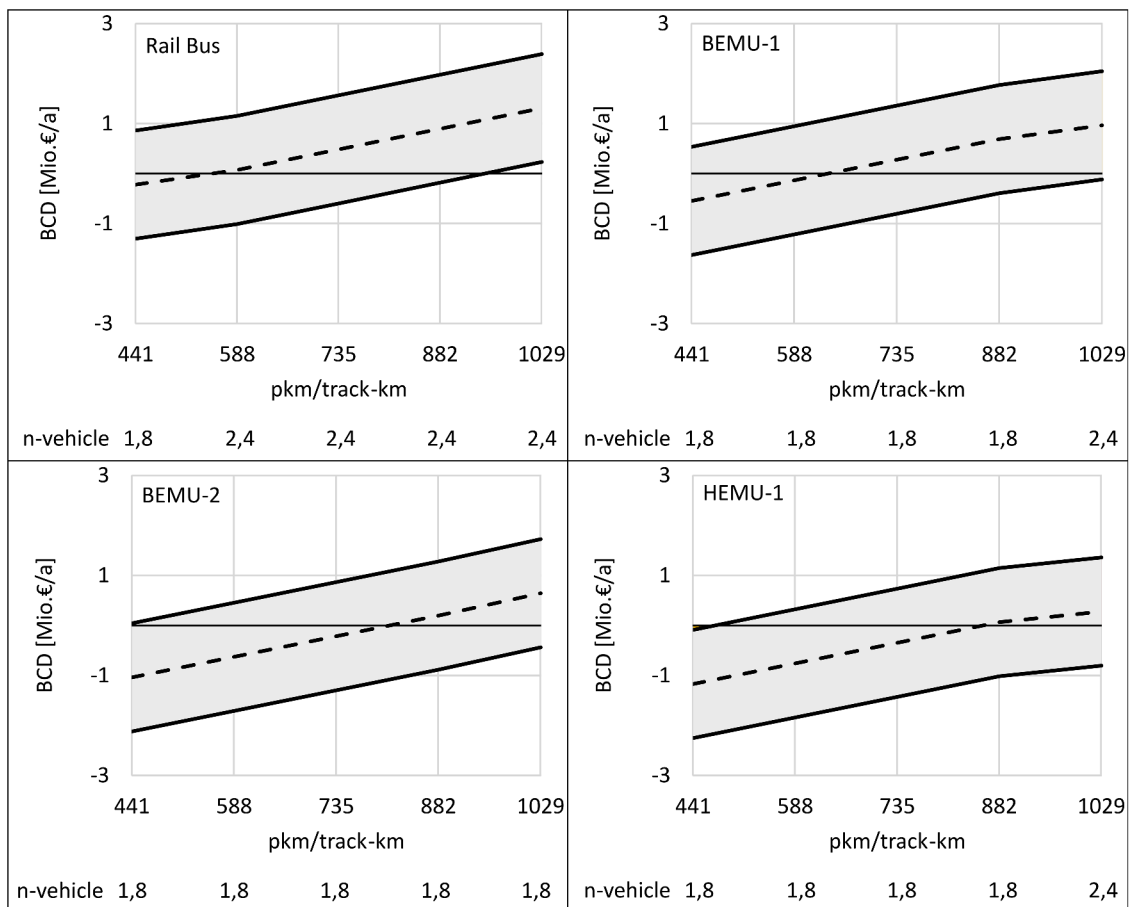


Fig. 9. Sensitivity analysis for the Scenario Medium Short; BCD for different infrastructure CAPEX from 0.5 M€/km (top line), 1.5 M€/km (dashed line) to 2.5 M€/km (bottom line).

vehicles need a demand that is higher than investigated in this paper in order to be profitable.

5.3.2. Reactivation scenario medium long

The same input values have a different effect in the Medium Long scenario of 46.1 km. The low traffic performance per track-kilometer in combination with high investment costs for track reactivation due to the long line leads to a negative benefit-cost difference in most cases (see

Fig. 10). In addition to the high infrastructure costs, this scenario also requires more vehicles due to the long line, which further increases costs.

The slightly negative gradient of the benefit-cost difference observed for rail bus, between 325 and 455 pkm/track-km, is due to the increase in the number of vehicles required and the number of charging stations as a result of the increase in traffic performance. Due to the percentage surcharge for the distance driven for preparation and shunting, the

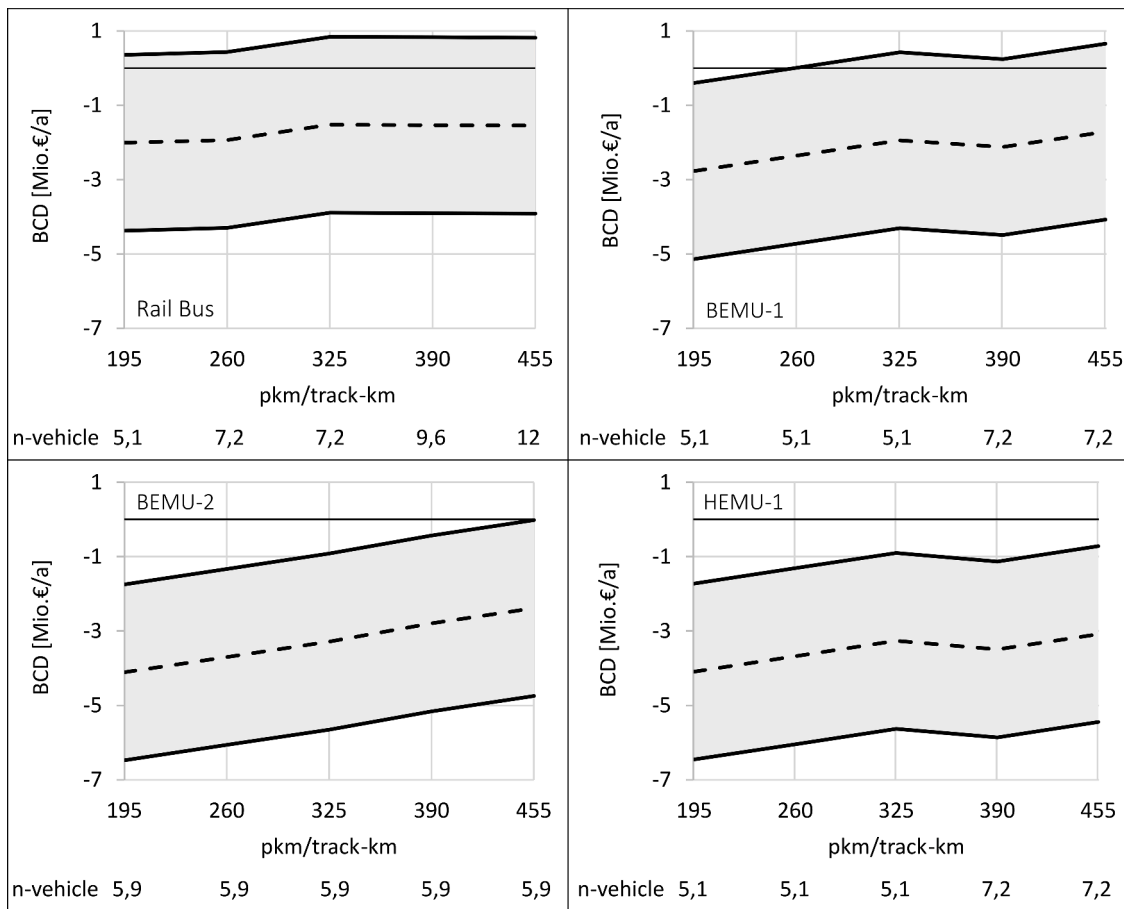


Fig. 10. Sensitivity analysis for the Scenario Medium Long; BCD for different infrastructure CAPEX from 0.5 M€/km (top line), 1.5 M€/km (dashed line) to 2.5 M€/km (bottom line).

number of vehicles increases more than proportionally with the increase in passengers. The slight positive trend in the first step in passenger numbers is therefore already negative in the last two steps. As in the Medium Short scenario, the size of the two-part BEMU-2 allows a constant number of vehicles across all traffic volumes considered.

For low infrastructure CAPEX of € 0.5 million/km the rail bus is economically viable for all investigated traffic performances. The BEMU-1 reaches this point at 260 pkm/km and the BEMU-2 at 455 pkm/km. The HEMU-1 does not reach economic viability in this scenario for the investigated traffic performance. If the investments for the infrastructure increase, none of the vehicles will be economically viable in operation.

6. Discussion

The method developed allows compare different vehicle types on various operating scenarios and to determine the sensitivities of individual influencing factors in the cost-benefit analysis for reactivating lines. Further fine-tuning and expansion to aspects such as railway automation for future consideration with this method is possible and sensible.

For the necessary investments in the case of track reactivation, a value range in M€/km was assumed. The project specific infrastructure requirements may vary by magnitude, so that a case-by-case assessment considering local circumstances and the condition of the track is always necessary.

The energy prices for electrical energy and hydrogen included in the assessment are below the current standard prices. As shown in 5.2.3, this has a significant impact on the total costs, particularly in the case of

hydrogen as an energy carrier. In addition, there are national regulations and taxes that can affect prices for energy and air pollution control depending on the region in focus and may have an influence on the result. Further assessments should also include a more in-depth differentiation between fossil and renewable energy sources, which also have an impact on energy prices.

The automation of train operations has not been taken into account in the analysis so far. However, automation can be of great benefit, especially on low-traffic secondary lines [47]. For a comprehensive analysis, detailed concepts must first be developed to show what automated train operations on secondary lines could look like. In addition to the technical equipment for the vehicles and infrastructure, this includes new control centers and remote train operation workspaces, as well as concepts for safety and security.

7. Conclusion and outlook

Previous studies have examined the overall economic viability of investments in the reactivation of railway lines or in refuelling and charging infrastructure for alternative drive systems. There are also analyses of innovative vehicle concepts, such as small, lightweight rail vehicles (rail buses). This paper presents assessments that combine these evaluation approaches in order to identify business cases for novel rail vehicle concepts with locally emission-free drive trains for use on reactivated lines.

It has become apparent that concepts such as rail buses have a significant influence despite the high share of infrastructure CAPEX in the overall result and should therefore be considered by stakeholders. In this regard, it seems helpful to combine different assessment approaches in

order to create transparency regarding the influence of the various factors.

In terms of total costs (vehicle acquisition and operation, excluding infrastructure use), rail buses result in cost savings of 18 % compared to BEMU-1 and 40 % (average across the analysed operating scenarios) compared to BEMU-2. Rail buses and BEMU-1 offer significant cost savings compared to larger vehicles, especially on short and medium-length secondary lines. Further cost savings could be achieved if track access charges were levied based on vehicle weight, to take into account that light vehicles require a less robust infrastructure.

Some of the input parameters used in this study are subject to considerable fluctuations in reality (e. g., infrastructure CAPEX), which also have a significant impact on the model's output. An attempt was made to counteract this through sensitivity analysis.

Future work will include further adapting the evaluation methodology with regard to automating operations, including the necessary infrastructure enhancements, integrating new demand-oriented operating concepts, and assessing the impact of increasing service frequency, which is particularly feasible with small vehicles such as rail buses. Consideration should also be given to how rail transport on low-frequency secondary lines can be made more economically viable. This could be achieved, for example, by adjusting infrastructure charges to reflect the actual costs generated.

### CRediT authorship contribution statement

**Benedikt Hertel:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Evnika David:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Johannes Pagenkopf:** Writing – review & editing, Supervision, Investigation. **Benedikt Scheier:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Christoph Streuling:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization.

### Declaration of competing interest

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

### Data availability

No data was used for the research described in the article.

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