vehicles

Review

Challenges in the (Re-)Connection of Peripheral Areas to the Rail Network from a Rolling Stock Perspective: The Case of Germany

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Abstract: Currently, in the course of the German mobility transition, an increasing number of disused rail lines are already being or intended to be reactivated in order to increase capacities, decrease transport-related emissions and reconnect rural areas to passenger rail services, thus creating a more comprehensive rail service. However, the use of state-of-the-art regional railcars on old rural infrastructure often leads to problems since they are often worn out and do not meet today's technical standards. This applies, for example, to the axle loads and dimensions of the vehicles but also to operational aspects, such as the vehicle's passenger capacity and accessibility. First, this work gives an overview of the available rolling stock and the given infrastructure, as well as an analysis of the (system) interfaces. Subsequently, various challenges for the re-connection of peripheral areas to the rail network were identified through data research and comparison of the vehicle and infrastructure parameters. In addition, the requirements related to possible autonomous operation and the related absence of the driver and crew personnel in the vehicle, which require new solutions in terms of safety, were taken into consideration. Orientation of future rolling stock generations towards the existing infrastructure and the required transport needs, including lower axle loads, accessibility and smaller capacities, can contribute to the economic operation of low-capacity lines and bring more passengers to public transport.

Keywords: rolling stock; rail infrastructure; reactivated rail lines; regional rail; branch line; accessibility

Citation: Hertel, B.; Pagenkopf, J.; König, J. Challenges in the (Re-)Connection of Peripheral Areas to the Rail Network from a Rolling Stock Perspective: The Case of Germany. *Vehicles* **2023**, *5*, 1138–1148. https://doi.org/10.3390/vehicles5030063

Academic Editors: Pedro Aires Montenegro, Hugo Magalhães and Pedro Antunes

Received: 16 July 2023
Revised: 9 August 2023
Accepted: 2 September 2023
Published: 9 September 2023

1. Introduction

The aim to shift the current transport system is accompanied by the need for new types of rail vehicle concepts. In rural areas, in particular, there are low-frequency and abandoned rail lines on which the operation of large and heavy railcars on a scheduled basis is not economically viable. However, the development of formerly closed or decommissioned branch lines has positive effects on the attractiveness of the regions. A reconnection to the rail network can represent, among other benefits, a locational advantage for the reconnected areas [1,2]. However, in order to create an attractive regional rail transport, it is also necessary to have a reliable system with good connections and service frequencies [3].

Since branch lines with the potential for reactivation are generally located in sparsely populated areas, vehicles with low capacities are needed to serve them. At the same time, vehicles are developing into modular, multiple-unit vehicle families that are intended to cover the widest possible range of applications. Due to high maximum speeds, crash and comfort requirements, as well as large passenger capacities, the weight and size of the vehicles have increased significantly since the introduction of rail buses in the 1930s to 1960s.

Current research mostly focuses on dedicated technical or operational problems in the general operation of railroads in rural areas, such as vehicle weight [4,5], alternative powertrains [6] or driverless operation [7,8]. The aim of this article is not to deepen individual technical and operational issues but to draw a holistic picture of the challenges involved in operating low-frequency branch lines and reactivating old lines, considering the various interfaces between rolling stock, infrastructure and passengers. For this, a systemic approach was chosen to elaborate on the challenges that arise when reactivating low-frequency rail lines and to illustrate the requirements that must be met by future generations of rail vehicles operating in rural areas.

In order to find out whether and which gaps exist in the current rolling stock portfolio for the operation of low-frequency routes, especially in peripheral areas, rolling stock currently in operation and market-available rail vehicles were first examined and compared with the infrastructural and capacity demand. The state-of-the-art vehicle research focused on single- and two-car units that are currently being used or have been used in the past on branch lines. Components of the analysis include the development of capacity, car body design and design speed over time and vehicle generations. In addition, various concept studies and demonstrators are included in the evaluation. On the infrastructure side, potential future fields of operation were identified. The focus is on lines where the use of market-available vehicles would most probably not be economically viable. Use cases were formed for the lines under consideration on the basis of reactivation studies and further technical data. Based on this, potential conflicts between the vehicle and the existing infrastructure were identified. Finally, based on the initial situation, the challenges that need to be considered in the development of future rolling stock for peripheral areas are highlighted.

2. Initial Position

2.1. Evolution of Rolling Stock in Branch Line Service

In the previous decades, there have been major changes in the field of rail rolling stock for branch line service, from light rail busses in the 1950s to heavy multiple units today. In the 1950s and 1960s, various versions of light rail buses—such as the VT 95/98 (Deutsche Bundesbahn in the Federal Republic of Germany (FRG)) or VT 2.09 (Deutsche Reichsbahn in the former German Democratic Republic (GDR))—were developed for use on branch lines. These small two-axle vehicles usually had about 60 seats. Due to their lightweight design dimensioned for a longitudinal compressive force of 500 kN at buffer level, they were very light vehicles (approx. 14–20 t, depending on the specific vehicle) [9]. Except for a few examples in museum operation, these vehicles are now retired.

In the mid-1970s, the single- and two-car DB class 627 and class 628 were introduced in Germany as replacements for the rail buses. As a result of serious accidents involving first-generation rail buses with heavy rail vehicles, the required longitudinal compressive force at the buffer level for new railcars was increased to 1500 kN. The increased safety requirements were reflected in a significant increase in vehicle masses (e.g., VT 95 with approx. 14 t and class 627 with approx. 34 t with comparable passenger capacity) [9].

A second generation of lightweight rail buses in Germany was developed in the mid-1990s. Two new vehicles, the DWA LVT/S and the DWA double-decker railcar, were introduced in 1996. Both vehicles had a low longitudinal compressive force of 600 kN or 400 kN, respectively. The reduced passive safety (lower longitudinal compressive forces) was compensated for by an increased active safety—among other things, through better braking technology. While some of the LVT/S are still in service with private operators today [10], the double-decker railcar is mostly withdrawn from regular service due to susceptibility to faults, among other reasons. Only a small number of both vehicles were manufactured [11,12].

Simultaneously with the lightweight vehicles, vehicles such as the Regio-Shuttle RS1, the class 650 from Stadler (formerly Adtranz) or the LINT 27 (class 640) out of the Coradia LINT family of Alstom entered the market, which in the long term have become established above all for branch lines. These vehicles are of conventional design with a longitudinal compressive force of 1500 kN. Compared with the first- and second-generation rail buses, they show higher specific masses per seat as well as higher axle loads than the rail buses [11].

Newer vehicle types used in regional and commuter services are generally derived from modular multi-unit train platforms. They are designed for higher speeds of up to 140 or 160 km/h. In order to be able to operate them on main lines and TEN-lines, they are equipped with high frame rigidity, just like the Regio-Shuttle RS1 or the Alstom Coradia LINT family. Traction units are usually classified in category P-II of the standard DIN EN 12663-1 [13] (TSI conform) and must resist a longitudinal compressive force on a buffer level of 1500 kN. DIN EN 15227 [14], issued in 2008, regulates the crashworthiness design of vehicles.

The further increase in safety requirements resulting from crashworthiness adapted design and vehicle designs for higher speeds (cf. Figure 1) has also led to a further increase in vehicle masses. Furthermore, the number of seats increased to up to 120 per vehicle.

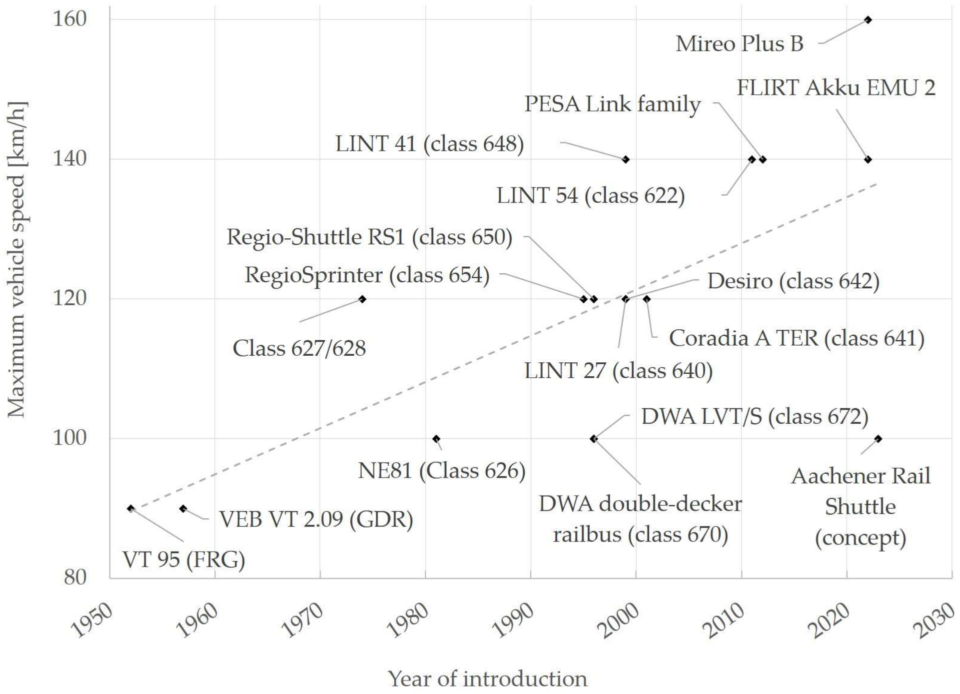

Figure 1. Development of maximum vehicle speeds over time (Reference: various publicly available information from OEM and other sources).

Figure 2 shows the development of axle loads and seating capacities of regional rail vehicles over time. It can be seen that the seating capacities, as well as the axle loads of the vehicles, have increased over time. Vehicles for branch lines had maximum axle loads of between 10 and 14 t until the 1980s. This allowed them to be used on all current line categories. With 14 t up to 18 t, vehicles developed in the 1990s—such as the Stadler Regio-Shuttle RS1 (14 to 15 t depending on the series) or Alstom LINT 41 (18 t)—have a significantly higher mass. Vehicles with an axle load of over 16 t can only be operated on class B lines or higher. Current multiple units have maximum axle loads of between 18 t (diesel multiple units such as the Pesa Link II) and 20 t (battery electric vehicles such as the Mireo Plus B from Siemens), depending on the type of traction. Due to the high axle loads, operation on some branch lines is no longer possible. Other reasons for an increase in weight include changes in comfort requirements and additional HVAC and passenger information systems.

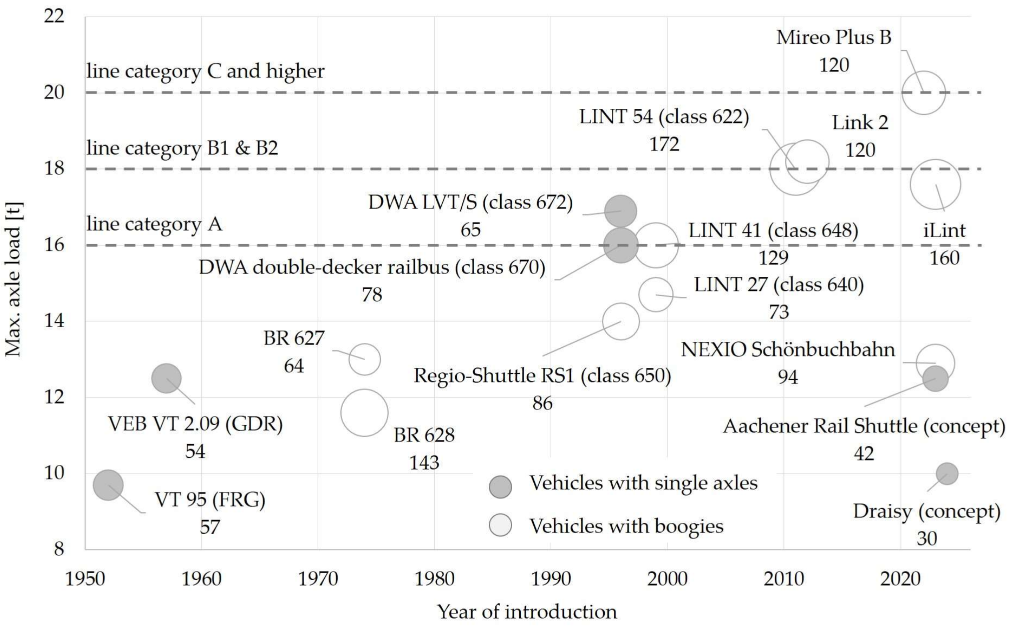

Figure 2. Development of axle loads and seating capacities (bubble size and number) of regional rail vehicles in Germany; variations due to different vehicle series possible (Reference: various publicly available information from OEM and other sources).

Various lightweight vehicle concepts for different applications are currently being developed throughout Europe. In addition to the Coventry Very Light Rail (VLR), which is being developed as a novel light rail concept, activities are primarily focused on the development of small vehicles to maintain operations on low-demand lines and reconnect rural areas to the rail network. One example is the *Aachener Rail Shuttle* (ARS), which is being developed at the Institute for Rail Vehicles and Transport Systems (RWTH Aachen). The ARS is an autonomous, battery electric vehicle (concept) in lightweight construction with a comparatively low passenger capacity of 90 passengers (seated and standing) and a maximum speed of 100 km/h [15,16].

Vehicle concepts such as the Taxi Rail in France are vehicles that are specifically oriented to the conditions of routes to be reactivated [16]. This is in line with the plans to reconnect peripheral areas to the rail network and to shift more traffic from road to rail. France's national railway company, SNCF, is currently working on three different vehicle concepts with its partners. Flexy, Draisy and Innovative Light Train each represent individual concepts with capacities ranging from nine to eighty seats. All of them are designed to revitalize rural areas [17].

The class 455 electric multiple unit for the Schönbuchbahn is already on the rails but has not yet been certified. In order to replace the existing Stadler Regio-Shuttle RS1, a vehicle procurement tender was issued in 2013. However, all bids showed significant deviations from the requirements (vehicle weight, energy demand and capacity in relation to the vehicle length). Due to that, the Spanish manufacturer CAF was awarded the contract with a tram-train approach based on the NEXIO platform. The vehicle, which was originally planned according to LNT guidelines, has an axle load of only 12.3 t despite being fully loaded, which is a significantly lower axle load compared to other currently available traction unit families [4].

Since class 455 cannot be approved for every line according to the LNT guideline, and instead only according to the EBO, the braking system now has excessively high deceleration values, which is not allowed according to the EBO but would be necessary to fulfill the LNT requirements with the reduced carbody loads compared to the usual trains. The approval of the vehicles is now to be route-specific [18].

2.2. Potential Areas of Application and Derivation of a Use Case

2.2.1. Data Base

In order to meet the goal set out in the current German coalition agreement from 2021 of doubling local passenger transport services by 2030 and reactivating closed lines, among other things, an increasing number of disused lines are being reactivated, and operations resumed [19]. In addition, efforts are being made to operate existing lines, which were previously served by diesel vehicles, with locally emission-free vehicles in the future. Based on this situation and the state-of-the-art rolling stock described, the question arises which routes can be served with the available vehicles and for which new concepts are required. For this purpose, the infrastructural and operational framework conditions of the routes being considered were first described in a use case.

In order to create the use case on specific deployment scenarios, the use case was created on the basis of routes foreseen for reactivation. In addition to the infrastructure characteristics, the expected passenger potential on the lines is one of the main factors determining the requirements for such vehicles.

In order to be able to make a prediction about the required passenger capacities and, therefore, about vehicle sizes, studies of the potential for reactivating disused lines were used. A study with a comprehensive database is the "*Potenzialanalyse zur Reaktivierung von Schienenstrecken in Baden-Württemberg*" [20]. In addition to route information, this study analyzes the respective passenger potential of the individual routes, broken down by route sections between stops. In order to estimate the passenger potential, the study considered the catchment area of the route and used this to produce, among other things, a forecast of the number of passengers boarding the train and the maximum cross-sectional load for each route section. For further consideration, the selection of routes available from the study was further narrowed down. Routes that could potentially be served by modern, available vehicles were not included in the analysis.

The study focuses, in particular, on the potential passenger volumes as well as operational parameters. This is important in order to make a statement on the worthiness of reactivation but does not provide a sufficient basis for considering the interfaces of the vehicles and infrastructure for compatibility. Therefore, further data on line and station infrastructure, as well as current or planned operations, were gathered. The data were compiled from documents published by the rail infrastructure companies in charge, such as the *Collection of Operational Regulations* (*Sammlung betrieblicher Vorschriften*) (SbV) or the *Network Statement* (*Schienennetz-Benutzungsbedingungen*) (SNB), which can be accessed on the "*Schienennetz-Nutzungsbedingungen (SNB)-Portal*" of the Federal Network Agency (*Bundesnetzagentur*) [21].

2.2.2. Vehicle Interfaces with the Surroundings

To create the use cases, the interfaces between the rail vehicles and the elements of the "rail system" are regarded. These are in particular:

- **Track infrastructure:** especially superstructure and substructure, including the track system, elevated and underground structures such as bridges or tunnels, as well as level crossings and signaling systems.
- **Station infrastructure:** The relevant parameters are platform height and length, with the former being decisive in terms of accessibility.
- **Power supply:** Classically by continuous contact wire or diesel at the filling station, and also via electrants, catenary island systems, charging stations or hydrogen filling stations in the future.
- **Train control and signaling systems (TCSS):** Depending on the line, the equipment varies widely, from deconstructed systems to modern ECTS systems. On less frequented secondary lines, only simple equipment such as PZB tends to be available.
- **Passengers:** In order to create acceptance of the vehicle, certain minimum requirements must be met in various areas, such as safety (security), accessibility, service frequency and comfort.

2.2.3. Derivation of the Use Case

The passenger and infrastructure data were the base for the creation of a generic use case, which is intended to represent a cross-section of potential fields of application (set of characteristic routes). From the pool of data, the governing parameters were chosen so that the use case would include as many application fields as possible. However, outlier values were not included to avoid stretching the technical requirements too far.

The use case covers low-frequency routes in rural areas for which current vehicles have too-high passenger capacities or too-high mass. A connection to the higher-level regional rail network is guaranteed at one or both ends of the line. The technical parameters of the line and the stations, as well as the transportation requirements, are listed in Table 1. The parameters result from an analysis of different sources, including [20], as well as an analysis of the corresponding SbV and SNB of different railroad infrastructure companies [21].

Table 1. Use Case Parameters.

Trackside Infrastructure Parameters of the Use Case		
Importance of the line		Secondary/branch line
Max. track length	[km]	30
Distance betw. stops (min.-max.)	[km]	2.4 (1.2–3.4)
Electrification		no
Number of tracks		Singe track
Speed limit	[km/h]	60 (80)
Line category		A
Minimum curve radius	[m]	140
Max. gradient	[‰]	32
Loading gauge		EBO G1
Station infrastructure		
Platform height		Wide range of platform heights (0–550 mm above rail level)
Platform length		Partially less than 30 m
Service requirements		
Capacity per hour and direction		10–60 (peak time)
Travel time (average/max)	[min]	12/40
Extended mobility needs		Wheelchairs/rollators, strollers, (e-)bikes, luggage, etc.

Service (transport) demand was approximated by the maximum cross-section volume, assuming a load ratio of 3:1 from peak to off-peak hours. The determined required capacity at rush hour serves as a guideline for determining the required passenger capacity. The travel time was roughly determined using a constant travel scenario with constant acceleration and deceleration. Energy saving driving modes would increase the minimum travel time.

On some of the lines studied, there is currently no traffic, while on other lines, there is freight traffic and/or occasional passenger traffic (including seasonal traffic). The equipment standard of the TCSS and the operating procedures used vary greatly. In some cases, the TCSS have already been completely dismantled.

3. Development Premises for Rail Vehicles on Reactivated Lines and Low-Frequented Branch Lines and Discussion of the Results

Based on the use case, various challenges and requirements for future rail vehicles can be derived. These mostly result from the infrastructural conditions. Many of the examined lines have not been adapted to the current state-of-the-art design for years or decades. As a result, some of the track systems and stations are in a heavily antiquated condition.

Besides the technical challenges, however, it is also important to consider the economic factors. From the 1950s to the 1990s—and in some cases even beyond—numerous passenger services were discontinued on branch lines with low-capacity utilization. This was usually justified by excessive costs, and the service was replaced by bus transportation. However, bus services alone do not offer the same transport quality, comfort, etc., as rail services. A connection of a locality to the rail network can contribute to the upgrading of a region and influence the choice of a place of residence. Therefore, an attractive public transport system requires an integrated concept of bus and rail services that complement each other [1].

3.1. Accessibility

With a view to future transport services in rural areas, it is important to ensure an attractive and non-discriminatory public transport mobility for passengers in all life situations. This also results in technical challenges for the design of rail vehicles. An elementary aspect of implementation is an overall system that is as accessible as possible, including not only the vehicle itself but also the transitions between the transport stations and the next traffic medium. Particularly, rail transportation offers advantages over other modes of transport, such as buses, due to the greater space available in the vehicle or the fact that vehicles often have level floors.

To enable accessible boarding of the vehicle, the floor and platform must be kept at the same level (as well as the distance from the vehicle to the platform as small as possible). However, platform heights vary widely in Germany, especially in rural areas. While the traffic stations of highly frequented lines have standardized platform heights of 550 mm or 760 mm, according to TSI, and are thus compatible with many of the modern commuter trains, platforms at stations and stops in rural areas often still have heights of 0 to 380 mm above rail level. In the long term, as part of the standardization process, platforms are expected to be adjusted to 550 mm or 760 mm *. However, these changes will take some time and will take place on lines that are more heavily used first. Therefore, solutions must be found that will allow accessible use of all transport stations even in the short term. Currently, mostly mobile ramps, among other things, are used to overcome small changes in height from the platform to the vehicle. However, in practice, these do not allow independent use of public transport, and although they comply with the regulations due to gradients of up to 18 percent (TSI PRM [22]), they are a serious hurdle to using public transport for many people [23].

* The current target platform heights from the platform height concept (*Bahnsteighöhenkonzept)* of Deutsche Bahn AG (DB AG) at the federal level and those of the states vary. DB AG aims to standardize all platforms to a height of 760 mm. Many federal states, on the other hand, have recently raised platforms to 550 mm or are in the process of doing so since this is in line with the boarding heights of most modern regional rail vehicles, especially double-decker cars [24].

The boarding heights of present vehicles have heights between 550 mm and 800 mm (see Figure 3). This is consistent with the standardization concept for platform facilities but does not provide accessibility options at many of the existing infrastructures.

Also, the vehicle interior design must be oriented to the mobility needs in different phases of life and offer sufficient space. This requires, for example, sufficiently dimensioned and easily accessible multi-purpose areas that offer sufficient parking and securing options for baby carriages, wheelchairs, walkers, as well as (e-)bikes and luggage. The TSI PRM provides guidance for implementation [22].

Figure 3. Boarding heights of different regional passenger transport vehicles used in Germany (floor height in the door area) (Reference: various publicly available information from OEM and other sources).

3.2. Driverless Driving

One way to reduce operating costs and provide a solution to staff shortage is to operate driverless, which is a significant issue, especially for vehicles with a smaller passenger capacity than the usual existing one. However, this raises new technical and operational challenges at various levels. On the technical level, solutions must be found to operate the vehicle safely over an unsecured guideway. Existing driverless vehicle systems have so far operated on secured routes, such as subway systems, for example, in the German city of Nuremberg. The route of a regional rail vehicle, on the other hand, has additional points of contact with other modes of transport, e.g., at level crossings, but also an increased risk of objects on the tracks, such as fallen trees, individuals or animals [25].

Driverless driving of vehicles in mass transit is the subject of various development and demonstration projects. Using "driving on sight," the Aachener Rail Shuttle of the Institute of Rail Vehicles and Transportation Systems (RWTH Aachen University) is also able to operate outside secured tracks. Research has been carried out, among other things, to determine the influence of track parameters, such as curve radius and loading gauge, as well as braking performance on safe travel speeds [7].

In addition to the technical safety of the rail vehicle (safety), the security of passengers inside the vehicle in relation to other passengers (in-vehicle security) must also be considered. Passengers consider in-vehicle security to be a very important factor when choosing a mode of transport. Even today, in vehicles that have driving and service personnel, the fear of being subject to attacks has a decisive influence on the choice of mode choice. The complete absence of personnel in the vehicle further increases the actual as well as perceived insecurity. Other concerns about driverless operations include increased pollution and vandalism, as well as a lack of support options. In order to create sufficient acceptance of the vehicle, it is necessary to address these issues and create solutions that restore safety as well as educate passengers [26,27].

3.3. Train Meets

Many reactivation projects or low-frequency lines are single-track lines with no or few passing places. This considerably reduces the performance of the lines. If a traffic offer with higher frequency or even demand-responsive transport is aimed for, train meets will unavoidably occur. For these situations, technical or operational solutions must be found to create ways of taking evasive action.

3.4. Energy Supply

Usually, reactivation studies and routes proposed by transport associations for reactivation are non-electrified branch lines. In order to establish a locally emission-free operation, infrastructural measures are, therefore, required to supply the vehicles with energy. Due to the development of battery- and hydrogen-powered vehicles, electrification of the entire line is no longer necessary for locally emission-free operation. The energy supply for the operation of battery-powered vehicles can be provided in various ways, e.g., via charging points at stations or partial electrification of the line. For the operation of hydrogen-powered vehicles, hydrogen refueling stations are required [28].

3.5. Vehicle Homologation

Strict requirements apply to the approval and operation of rail vehicles and infrastructure to ensure safe operation. However, rigid regulations, standards and laws can also slow down innovative solutions on the railways. New types of vehicle and operating concepts, which are tailored to a specific purpose and deviate from current operating structures, can fall through the existing grid of regulations and standards. In addition to the rededication of rail lines to light rail lines, other measures for the realization of simplified rail vehicles are conceivable. An isolated operation, separated from heavy rail traffic, can allow room for new safety concepts adapted to the circumstances.

3.6. Vehicle Mass and Axle Load

The majority of rail lines in Germany are designed for high axle loads. With 86%, line class D4 (22.5 t wheelset load, 8 t/meter load) is the most widely represented in the DB Netz network (as of 2021) [29]. Many lines are also being upgraded for route category D4 in the course of reactivation projects in order to make the lines suitable for freight traffic. However, some lines are still classified as category A or B2. On these lines, the use of BEMU vehicles with wheelset loads up to 20 t is not possible.

Even though the operation of heavy commuter railcars such as the Siemens Mireo Plus B with a wheelset load of 20 t is possible on many lines, it does entail some disadvantages. With a heavy vehicle structure, the demand for traction energy increases. This is particularly noticeable on regional rail lines where frequent acceleration is required due to short stopping distances. In the case of BEMU or HEMU vehicles, which are to replace diesel railcars on branch lines in the future, this also increases the need for energy storage capacity in the form of batteries or hydrogen tanks, which further increases the vehicle weight. In addition to the energy requirement, the maintenance costs for the track superstructure also increase with increasing wheelset load [30].

From a technical and economic point of view, therefore, there are a number of reasons in favor of lighter vehicles. On the other hand, however, there are high requirements for the vehicle design in terms of car body strength and crashworthiness. The TSI LOC&PAS [31] regulates the application of EN 12663 and EN 15227 which defines the strength requirements and crashworthiness for car bodies depending on the vehicle category.

4. Conclusions

The identified challenges illustrate the tension between the large number of requirements for the vehicle and the pressure to be as cost-efficient as possible in terms of acquisition and operation.

The evolution from small and light vehicles designed for operation on branch lines to modular vehicle families, which are supposed to cover as many operational scenarios as possible, is creating a gap in the vehicles currently available on the market. The infrastructure and passenger requirements cannot be met with these vehicles due to, for example, their high axle loads, capacities and lack of accessibility to the existing infrastructure. In addition, there is the cost pressure, which is on the modes of transport in general, but especially on low-utilized services. The energy supply of the vehicles must also be rethought if local emission-free operation is the goal.

Technical innovations such as driverless operation can help realize cost-effective operation but raise new challenges in the area of safety and in-vehicle security. To date, there is no autonomous rail vehicle approved in Germany for unsecured rail operations, and the physical absence of staff on board can lead to further uncertainty among passengers.

In order to re-establish a widely spread rail transport system in rural areas, new vehicle concepts are needed that can be adapted to the requirements of the infrastructure and the mobility needs, as well as low costs in acquisition and operation. In combination with new operating concepts, coordinated with connecting transport modes such as buses, a widespread coverage of rail-bound public transport can also be created in rural areas.

The content of this paper primarily represents the situation in Germany. However, similar questions also arise in other (European) countries, such as the Czech Republic or France. Due to the historically individually evolving infrastructures of the respective countries and regions, the requirements may partly differ from the requirements elaborated in this paper. An individual analysis of the specific requirements of the respective regions is therefore necessary in future work.

DLR is currently working on a new vehicle concept. Using a systematic approach that considers the operating concept, infrastructural aspects and a demand-oriented design of the vehicle, the aim is to create a small, lightweight, optimized, multi-modular, automatic driving rail vehicle with local emission-free propulsion.

Author Contributions: Conceptualization, B.H.; methodology, B.H. and J.P.; validation, B.H., J.P. and J.K.; formal analysis, B.H.; investigation, B.H., J.P. and J.K.; data curation, B.H.; writing—original draft preparation, B.H.; writing—review and editing, J.P. and J.K.; visualization, B.H.; supervision, J.P.; All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Helmholtz Association of German Research Centres on behalf of the Federal Ministry for Economic Affairs and Climate Action. The work was carried out as part of the Project VMo4Orte within the framework of DLR basic funding.

Data Availability Statement: Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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