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DELIVERABLE D5.1

STATE-OF-THE-ART REPORT FOR REGIONAL LINES ROLLING STOCK

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17/6/2025	Fabrizio Burro	F¢	² t1 [ŜaŘŜr	FiƴaƚăubYiăăioƴ

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Contributors

According to the FP6 FutuRe Grant Agreement, the D5.1 as part of the WP5, will receive contributions from SNCF, AZD, DLR, FT, ÖBB-PV, THP, PKP/IK and TRV.

The document will be shared to FP6 FutuRe Steering Committee for integration, review, and final approval before official release.

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Overview and description

This deliverable will provide, as specified in the Grant Agreement:

• A comprehensive report on requirement specification for rolling stock with a particular focus on mechanical architecture, mechanical parts, TCMS, traction/propulsion, modular interior, and train control,

• Suggestions on legislative changes/TSI updates (LOC&PAS, CCS, OPE) including operational and functional needs,

• A first concept for a lightweight, emission free rolling stock with modular interior.

Description of Methodology

The development of the D5.1 is based on the contribution given by Task 5.1, 5.2 and 5.3 to WP5.

The Task 5.1 is a preliminary approach of state-of-the-art, regulations and market, aiming to ensure that the specific needs of regional lines are considered regarding regulation and customer service.

The state-of-the-art analysis will help to understand technical and commercial success or failures from previous projects and adding that information to the current development.

Those studies will lead to define proper operational and functional requirements to create a working baseline for the Task 5.2, in charge of the specification development for a regional rolling stock.

Task 5.2 is subdivided in 3 parts:

5.2.1 Analysis for the development of the specifications for mechanical architecture of rolling stock,

5.2.2 Analysis for the development of the specifications for traction/propulsion and energy architecture of rolling stock,

5.2.3 Analysis of the concept relevant for other systems elements.

The task 5.3 provides an analysis of the state-of-the-art, and legal framework of multimodal fuelling station.

The WP5 tasks have also benefited from the collaboration with FP4-Rail4EARTH, sharing the aim to improve the existing sustainability performance of railways. An alignment has been explored in the rolling stock subsystem, namely propulsion and running gear systems.

Through the D5.1, the result of those tasks will be fed into WP10.

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List of abbreviations, acronyms, and definitions

Abbreviation / Acronym	Definition
AE	Affiliated Entity
ARB	Anti-Roll Bar
ATO	Automatic Train Operation
BEN	Beneficiary
CT5	Cooperation Tool 5
EMS	Energy Management System
ERA	European Railways Assocation
ERJU	Europe's Rail Joint Undertaking
ERTMS	European Rail Traffic Management System
ETM	Electrical Traction Motor
FEA	Finite Element Analysis
FP	Flagship Project
GA	Grant Agreement
GNR	Gasoil Non Routier
HRS	Hydrogen Refueling Stations
HVAC	Heating Ventilation Air Conditioning
LCA	Life-Cycle Cost Analysis
LFP	Lithium Iron Phosphate
LTO	Lithium Titanium Oxide
IPR	Intellectual Property Rights
MNC	Nickel Manganese Cobalt
ORE	Office for Research and Experiments of the International Union of Railways
PIVOT2	Performance Improvement for Vehicles On Track 2
PKP	Pulemyot Kalashnikova Pekhotny
PIS	Passenger Information System
PMSM	Permanent Magnet Synchronous Motor
PSD	Power Spectra of Density
SP	System Pillar
R&D	Research & Development
TCMS	Train Control and Management System
TCO	Total Cost of Ownership
TE	Traction Equipment
TSI	Technical Specification for Interoperability
WP	Work Package

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State-of-the-Art and Market Research

1.1. State-of-The-Art

1.1.1 Rolling stock data base

The following chapter describes the rolling stock that has operated in the past and is currently operating on under-utilized regional and branch lines. The selection is limited to vehicles with a maximum capacity of up to 100 seats (project constraint). To reflect the European character of the project, the state-of-the-art analysis took care to draw on references from as many different regions as possible.

The objective is to work out which vehicle concepts have proven to be advantageous and where the disadvantages lie. A database with a total of 29 vehicles was created for this purpose. This includes vehicles that have already been decommissioned, the current rolling stock as well as future vehicle concepts. The Figure 1 shows the timeline of the different vehicles.

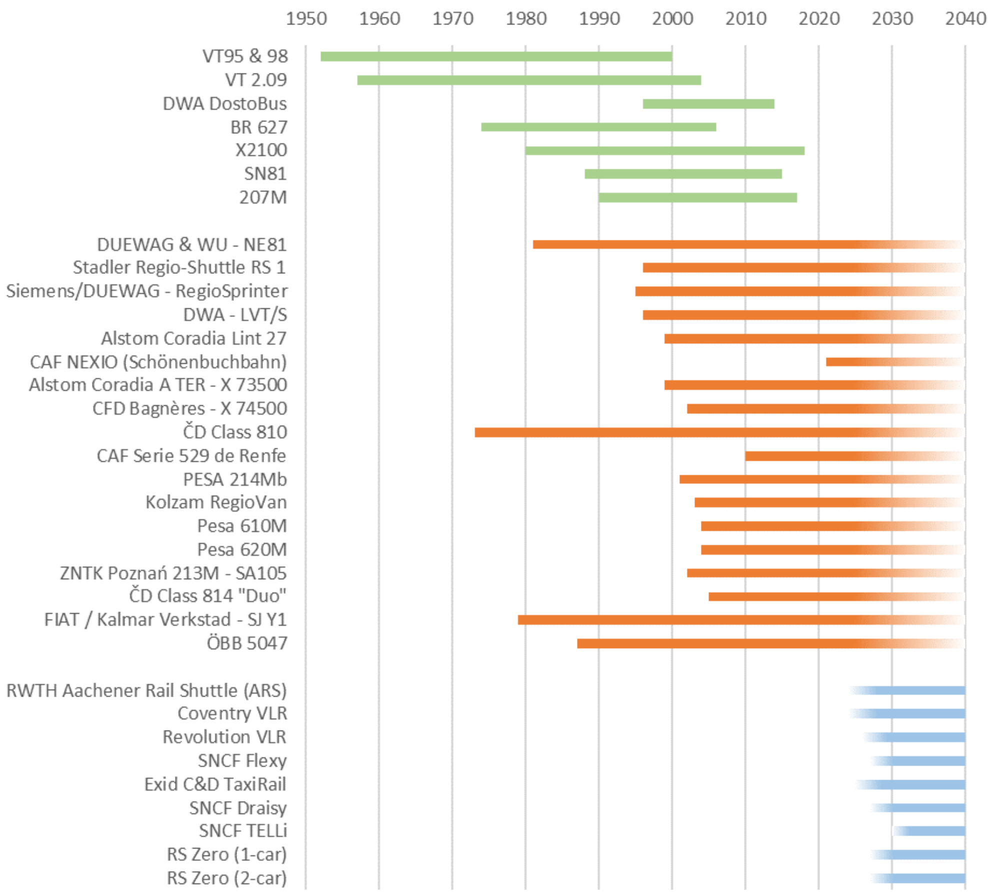

Figure 1 - Overview of the small railcars used in the past, today and in the future.

1.1.1.1 Discarded rolling stock

The discarded rolling stock includes all vehicles, the majority of which have been withdrawn from regular service. In some cases, a few vehicles that were sold on the used market may still be in service. The years from 1950 onwards were selected for the period under review.

The first generations of rail buses had running gears with single axles and were very light in design. The “Uerdinger” rail buses built in the 1950s and 60s (VT95 and VT98) are examples for this type of vehicle. The 13.3 m long vehicles had 60 seats and the driver's panel was located in the passenger compartment without a cab. Including licensed models, over 1000 railcars driving trailers and sidecars were built. They were primarily used in European countries, including Germany, Spain and Austria. The vehicles were withdrawn from regular service from the year 1970 onwards.[1]

Figure 2 : Uerdinger Schienenbus (VT98) and double-decker rail bus (Class 670) [2]

Following major accidents involving first-generation rail buses with heavy passenger and freight trains, the development of new vehicles with higher safety standards was commissioned. This was achieved, among other things, by increasing the longitudinal strength of the vehicle bodies, which is defined in DIN EN 12663. This is also reflected in the weight of the vehicles. To carry the higher weight, the vehicles were equipped with bogies instead of the previous single-axle running gear.[1]

[1] Reinhardt, W., Öffentlicher Personennahverkehr: Technik-Rechtliche und Betriebswirtschaftliche Grundlagen, Vieweg + Teubner, Wiesbaden, Germany, 2012.

[2] By MOs810 - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=31727120

Figure 3 : Autorail XB2142 [3]

In addition to the classic approaches in rail vehicle development, there were also attempts to find new approaches. Deutsche Waggonbau AG (DWA) developed two lightweight railcars in the 1990s. The DBAG Class 670 double-decker railcar and the DBAG Class 672 LVT/S. Both vehicles are single-unit diesel railcars with single-axle running gear. The Class 670 was designed without a coupler and the design aimed to use components from the road bus construction. For various reasons, most of the few Class 670 vehicles built were quickly withdrawn from service. The Class 672 remains in service.[4] [5] [6]

The Regiosprinter from SIEMENS/DUEWAG had a different approach. The vehicle consists of two end cars and a short middle car. Each end car has a driven axle at the end. A non-powered bogie is located under the middle car. The vehicle has a large low-floor section with a height of 575 mm which is located between the driven axles and is accessible from all doors. [6]

The vehicles already faced criticism in the early days. Among other things, the lack of space for baby carriages and bicycles as well as the lack of sanitary installations were criticized.[4]

The Regioshuttle RS1 from Adtranz (later manufactured by Stadler) was also introduced in the mid-1990s. The one-piece vehicle with four driven axles had approx. 70-100 seats and a low-floor entrance (600 mm above top of rail). It was sold around 500 times until 2013 mostly in Germany.[6]

1.1.1.2 Vehicles currently serving the regional lines

The focus of the state-of-the-art analysis was on vehicles with a capacity of up to 100 seats. For the sake of completeness, the last paragraph of this chapter describes the vehicles that are currently available on the market. However, these are larger vehicles with capacities of 120 seats or more.

[3] By Bruno Corpet (Quoique) - Gare-Callac-XB2142-2011.jpg auf commons.wikipedia.org, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=41974533

[4] https://signalarchiv.de/Meldungen/10003509; Access: 25.03.2024

[5] Deutsche Waggonbau AG, Schienenbus, 05/94, Verfügbar unter: http://www.lokmalanders.de/media/120f3081f961e5c4ffff801afffffff1.pdf. Access: 25.10.2024

[6] Hondius, H., Zehn Jahre Entwicklung einer neuen Generation Regio-Dieseltriebwagen: Übersicht über die neuen Fahrzeuge des SPNV in Dieselnetzen, Der Nahverkehr, 5, 2006, pp. 34–42.

The vehicles currently used in rural areas are predominantly diesel-powered and some have been in use for 30 or more years, which is why some have already undergone two modernization-cycles. The capacity varies from around 30 to 100 seats, although it should be mentioned that the configuration of the vehicles varies depending on their intended use.

The vehicle concepts vary, whereby vehicles with bogies and low-floor areas in the middle of the vehicle body have become the standard (for example Siemens Mireo [7]). The entrances of the newer vehicles are usually adapted to the platform heights of 550 mm or 760 mm above top of rail. Older vehicles often still have steps in the door area, which means that barrier-free access is not possible (for example DB Class 628 [8]). However, the level-like entrance height of the newer vehicles only allows barrier-free access to platforms of a corresponding platform height. Many platforms, especially in rural areas, have significantly lower platform heights, from 0 mm to 550 mm above the top of the rail. This makes access considerably more difficult for people with reduced mobility.[9] [10] [11]

In addition to the one-car vehicles discussed above, multiple units with two or more carriages now play a major role on branch lines. Almost all vehicle manufacturers offer multiple unit families with two or more carriages. In addition to the diesel-powered vehicles such as the Alstom Coradia Lint or Pesa Link, vehicles with alternative drive trains are now also available. One example is the Siemens Mireo, which is offered as a battery or hydrogen fuel cell vehicle.[7]

These multiple units have significantly larger capacities than the original one-car rail buses and railcars (Siemens Mireo 2-car & Alstom Lint 41; 120 seats), higher axle loads (Siemens Mireo Plus B 20 t; Alstom Lint 41 18 t) and are designed for speeds up to 160 km/h.[4]

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[7] https://assets.new.siemens.com/siemens/assets/api/uuid:f186839a-effd-4cef-a85b-00d84b0871fd/siemens-mobility-mireo-plus-b-mireo-plus-h-de.pdf; Access: 25.10.2024

[8] https://de.wikipedia.org/w/index.php?title=DB-Baureihe_628&oldid=249018003 ; Access: 28.10.2024

[9] https://press.siemens.com/global/de/pressemitteilung/mireo-plus-b-und-mireo-plus-h-neue-wege-im-fahrzeugdesign ; Access: 21.05.2024

[10] https://geovdbn.deutschebahn.com/isr ; Access: 21.05.2024

[11] https://hessen.vcd.org/startseite/detail/in-deutschland-gibt-es-sieben-verschiedene-bahnsteighoehen-von-weniger-als-38-cm-bis-zu-103-cm ; Access: 21.05.2024

1.1.2 Innovative approaches

Draisy

Draisy is a very light, non-interoperable, train designed by a French Consortium (SNCF, Lohr, GCK Battery, Stations-e and Railenium) to complement regional transport services.

Draisy targets routes in rural areas with low passenger traffic (G2 lines) and aims to boost their appeal by offering more frequent services than the currently available offer.

The rolling stock is designed to be modular and can accommodate up to 80 passengers, including 30 seats, as well as bicycles and micro-freight.

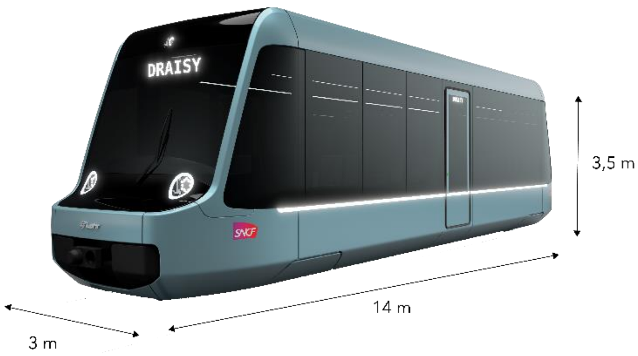

Figure 4 : Draisy

It is a very compact train, weighing 19 tonnes and measuring 14 meters, with 100% electric propulsion (batteries with a rapid charging system in stations). The development is focused on the economic aspect, using already existing road solutions (for example regarding the propulsion) with a frugal approach on CCS.

Figure 5 : Draisy (3D)

TELLi

TELLi is an interoperable light train (G1 lines) conceived by a French consortium (SNCF, CAF, Alstom, Thales, Texelis, Cerema, Ektacom, Wabtec, Railenium, Ferrocampus, Capgemini) to replace the diesel powered X73500. Electric (an H2 version is to be developed later), and compliant to the TSIs, the TELLi is to measure 30 meters and weight less than 70 tons.

TELLi targets regional line with a moderate passenger's traffic and will allow to upgrade the actual offer. Despite being a "light train", this rolling stock can be operated on a mixed traffic line (freight, national trains…).

The TELLi train will be equipped with GOA2 technology and ready to be retrofitted for GOA3 when available. This train is also compatible with multiple units using (up to 4 vehicles).

The main technologies developed for TELLi are:

- Independent wheels and adaptative suspension to fit different platform highs.
- Electric propulsion system (battery/charging by pantograph).
- New driver cabin design.
- A whole car-body with modular interior design.
- Onboard infrastructure monitoring.

Figure 6 : TELLi

The project is also developing a new regional CCS to offer "on shelf" solutions for various regional lines situations.

Figure 7 : TELLi (3D)

Flexy

Flexy is a rail-road vehicle designed for closed regional lines. To this day, there are almost 5700 km of closed or not operated lines in France. This vehicle aims to run on a very small line (30 km) and to offer an alternative to individual car in rural areas.

With 14 seats and a range of 200km (battery powered), this vehicle is at crossroads between a minibus and a very very light train.

The specific "rail-road" wheels enable road services to be provided to communities located close to the railway line, using a level crossing transformed into road junctions and increase the density of services. Bikes and micro-freight can also be loaded. This project is also a use case to create a new safety regulation for rail-road vehicles.

Figure 8 : Flexy

Taxi Rail

Taxi Rail was also a very light train project (G2 lines) aimed to be equipped with GoA4. It was designed to accommodate up to 40 passengers, 2 wheelchairs users and 2 bikes. The propulsion was to be Hybrid Hydrogen/Electric and it should have allowed multiples unit with a platooning system. On the 10th of July 2024, the project has been abandoned. [12]

Revolution VLR

The Revolution Very Light Rail (RVLR) demonstrator vehicle (Figure 9) was developed in England by a consortium of Transport Design International (TDI), Eversholt Rail, the Rail Safety and Standards Board (RSSB), WMG at the University of Warwick, Cummins, Prose, RDM Group, and Transcal Engineering. The consortium completed the build and integration of the demonstrator vehicle in August 2021 and in September 2021 the vehicle successfully completed the initial functional tests. First vehicle ready for passenger operation is planned in 2026.

[12] https://www.ville-rail-transports.com/ferroviaire/le-train-leger-taxirail-ne-verra-pas-le-jour/

Figure 9 : Revolution VLR

The main goal of Revolution VLR project is proposed as a cost-effective and sustainable rolling stock solution for planned standard gauge railway lines reopening and network extensions. Vehicle of this project is designed to demonstrate a new innovative, lightweight, energy-efficient vehicle that can primarily operate on short routes where the use of heavy rail or tram systems is economically unviable.

Because of that, vehicle is designed as self-propelling, with battery-only or diesel-battery hybrid traction propulsion, with lightweight composite bodyshell, modularity at system and sub-system level what maximised through-life operational flexibility and approach facilitates reconfiguration to meet specific customer needs of vehicle layout options.

Figure 10 : Revolution VLR

This vehicle, with a length of 18,5 [m], can accommodate up to 56 seated passengers, 1 wheelchair user and 26 standing persons. For entrance, passengers can use 2 single-leaf sliding plug doors per side, with dimensions of 855x1905 [mm]. Lightweight bodyshell, with a factor of 1,34 [t/m] and maximal axle load 8,1 [t] for vehicle, include welded steel chassis, composite side panels and aluminium/composite cabs and roof. Train can be charging by lineside fast charging and recuperation systems and is capable for moving with maximum speed of 100 [km/h].[13]

[13] www.revolutionvlr.com

Coventry VLR

Coventry Very Light Rail (CVLR) is a research and development project, using the latest automotive expertise to develop an innovative track design and vehicle, and deliver an affordable light rail system for small cities.

The demonstrator vehicle (Figure 11) was ready to functional tests on test track at the Very Light Rail National Innovation Centre (VLRNIC) in Dudley in November 2023 and service with passengers is planned in 2025-2026.

As part of the CVLR project, a new tram track was also created, which laid just 300 [mm] within the road's surface, minimising the need to relocate pipes and cables.

Figure 11 : Coventry VLR

A key motivation for the CVLR project is to make urban light rail more affordable to install, making it available as widely as possible.

Public transport as an element of fight climate change with a battery-powered vehicles means zero emission at point of use. Its use of regenerative brakes also reduce energy consuming in service. Battery-powered trams also means absence of catenary along the standard tramline and ability to turn 15-metre radius curves means that in most places, track could be laid in the existing road, minimising the need to change road layouts. As an element of innovation and implementation of new technologies, it is assumed that introducing autonomy in a rail-based CVLR system will be simpler than introducing autonomy in cars.

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www.transportdesigninternational.com/portfolio/revolution-vlr

www.railway-technology.comprojectsrevolution-vlr-demonstrator-vehicle

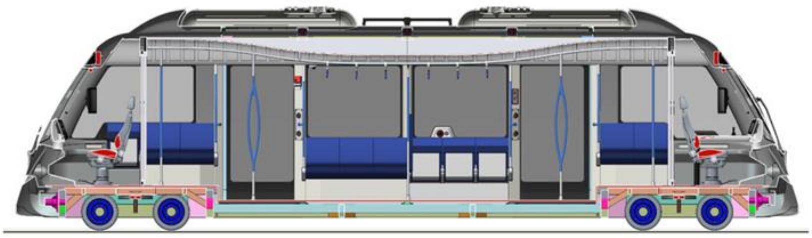


Figure 12 : Coventry VLR

This demonstrator can carry up to 70 passengers, including 20 seated and 1 wheelchair user. For passengers' access to the vehicle 2 single-leaf sliding plug doors per side are provided, with dimensions of 900x1950 [mm]. This vehicle has the maximum speed of 70 [km/h] and is being prepare for autonomous operation in the future. Lightweight bodyshell, include steel, aluminium, and composites panels. Tare weight of 11 [t] and length of 11 [m] means a very low factor of mass per length of the vehicle at 1,0 [t/m].[14]

[14] www.coventry.gov.uk/verylightrail

www.transportdesigninternational.com/portfolio/coventry-vlr

www.theengineer.co.uk_A. Wade_2023_sky blue thinking: Coventry VLR takes shape

Aachen Rail Shuttle

The Aachen Rail Shuttle is being developed at the Institute for Rail Vehicles and Transport Systems (IFS) at RWTH Aachen University as part of the FlexSbus-LR project. The vehicle is an autonomous, single-car rail vehicle for rural areas. The vehicle has a capacity of around 90 passengers, including approx. 34 fixed seats. The vehicle is equipped with a battery-electric drive train. The maximum vehicle speed is 100 km/h.[15] [16]

The vehicle has a lightweight construction and a longitudinal strength of 800 kN on buffer level. The vehicle is designed according to category C3 for collision design in accordance with EN 15227. The lower passive safety is compensated for by increased active safety through more powerful brakes comparable to BOStrab equipped vehicles which allows a higher deceleration. [16]

In addition to passenger transport, the vehicle concept is also intended for use in freight transport. To make this possible, all the components required for driving are built into the chassis so that the passenger cabin can be removed for freight transportation. In the event of a collision, the energy is absorbed by the chassis so that the passenger cabin serves as a survival space.[15]

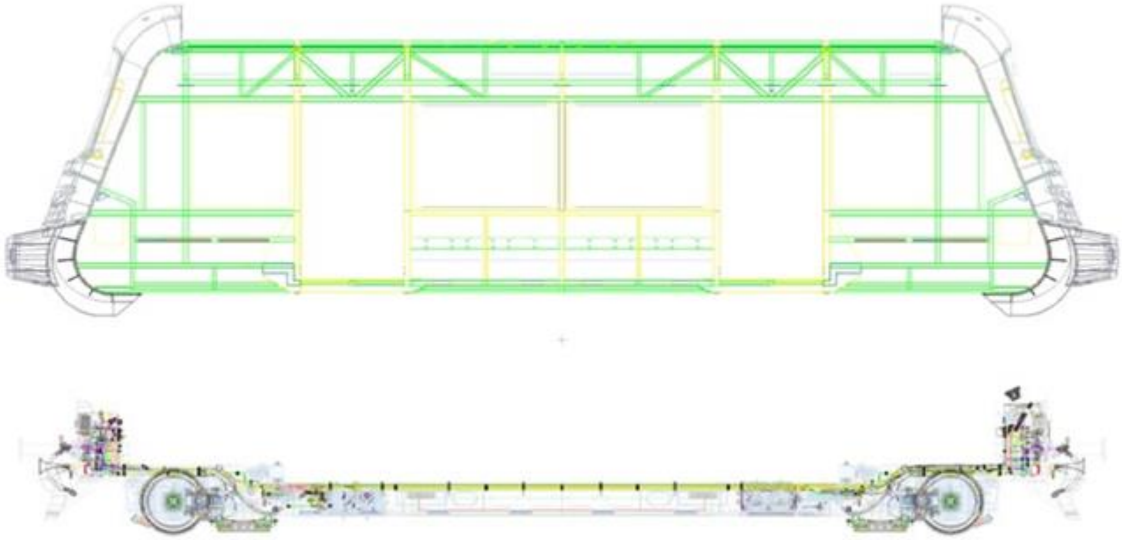


Figure 13: Modular design of the Aachen Rail Shuttle – IFS [15]

[15] Frohwein, C., 'Aachener Rail Shuttle: Entwicklungsstand heute', DER NAHVERKEHR, 9/2023, pp. 38-41

[16] Schindler, C., 'The Aachen Rail Shuttle ARS - Autonomous and energy self-sufficient feeder transport', Journal of Rail Transport Planning & Management, Vol. 21, 2022, https://doi.org/10.1016/j.jrtpm.2022.100299

NGT-TAXI (DLR)

The DLR is currently working on a small, lightweight, automated rail vehicle with a catenary-independent drive, the Next Generation Train (NGT)-TAXI. The field of operation includes less frequented routes in rural areas and revitalized lines.

Figure 14 : NGT-TAXI Small and Large (DLR)

The investigated routes lead to different requirements for the vehicle. Depending on the intended use and the corresponding requirements, the vehicle structure and propulsion system are adapted using a multimodal vehicle design. The NGT-TAXI is designed with a modular length to serve the different passenger volumes on the individual routes. This results in a minimum and a maximum length variant, with possible in-between sizes. All variants offer a large multipurpose area in the entry module. Depending on requirements, the multipurpose area can be equipped to provide large standing spaces, wheelchairs, bicycles, baby carriage parking, etc. The vehicle capacities have been determined based on analyses of different scenarios on routes addressed by the NGT-TAXI.

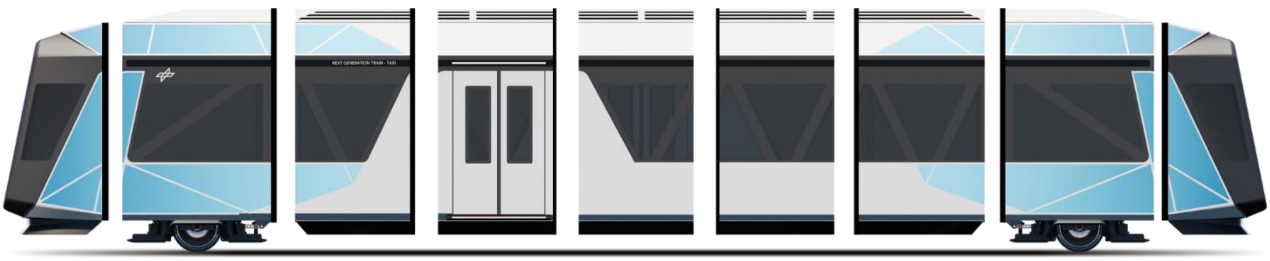


Figure 15 : NGT-TAXI Large with three middle segments (DLR)

The different length derivatives of the NGT-TAXI are identical in terms of width, height and front design and differ only in terms of their length and propulsion system. The length of the vehicle is fixed during manufacturing. Each vehicle is equipped with two front modules, two chassis modules and two entry modules. A maximum of three middle segments enables length modularity for capacity adaption. Virtual coupling allows several vehicles to be linked together to form a larger unit, enabling flexible adaptation of capacity over the course of the day. The vehicle is equipped with two single-wheel individual running gears, which allows stepless, level walk-through access. The maximum entry height is 550 mm.

To reduce costs, the control and safety technology (LST) will be adapted to the track-specific requirements. In mixed operation with other vehicles, the usual LST (ETCS) is used. In operation exclusively with the NGT-TAXI on one route, a simplified but nonetheless safe LST is used. Automated operation and the vehicles' virtual coupling capability allow capacity to be quickly adapted to the demand during the day - with the perspective of on-demand operation.

Stadler RS Zero

The RS Zero is the successor of the Stadler RS1 and offers two options regarding traction energy: battery (BEMU) and hydrogen (HEMU). It can accommodate 59 to 165 seated passengers depending on the chosen configuration (one or two cars, with or without toilet onboard). With 18 tons per axle, this train can be operated on most regional lines while being TSI compatible. [17]

Figure 16 : Stadler RS ZERO - Exterior View (Stadler)

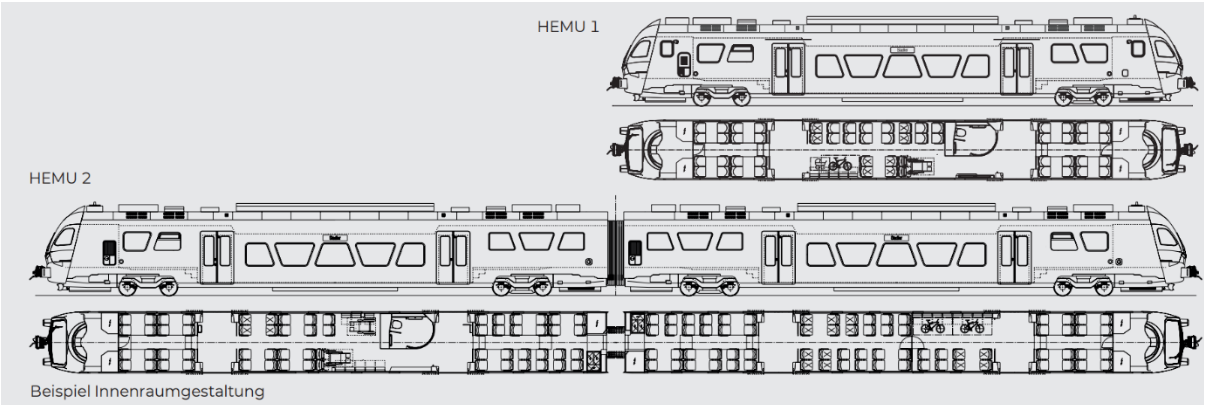


Figure 17 : Stadler RS ZERO – Floor Layout [17]

[17] Stadler, RS ZERO HEMU, https://events.stadlerrail.com/wp-content/uploads/2024/09/RSZHEMU_0924_de.pdf, Access : 20.10.2024

1.1.3 ATO State of the Art

Autobahn (Austria)

AutoBAHN is a research project led by the University of Salzburg and the Wels University of Applied Sciences in Austria, in collaboration with the University of Linz and Siemens Österreich.

In addition, the Open.Rail.Lab research centre, which brings together RUs and industry to carry out studies into rail transport, has adapted the Oberwart-Friedberg line (Styria) to turn it into a test track for autonomous trains. The 25.5 km line includes eight stops, twelve junctions and a 524 m long tunnel. The track entered service in June 2018. The Ministry of Infrastructure (BMVI), the Land and industry have invested around €11 million in the project. In addition, the BMVI will be subsidising research projects on autonomous trains to the tune of €5 million a year.

Autohaul De Rio Tinto (Australia)

Rio Tinto is an Anglo-Australian multinational mining group and the world's leading aluminium producer. In 2012, Rio Tinto launched the "Autohaul" project and invested €459 million to automate the existing rail network (1,700 km in the Pilbara, Western Australia), which links the group's fifteen mines to its three seaports, and thus create the world's first network of autonomous long-distance freight trains. The objectives of the project were to:

- Increase production capacity and productivity through greater flexibility in train scheduling and the elimination of driver changeover times
- Optimise fuel consumption, resulting in lower energy costs and carbon dioxide emissions per tonne of iron ore produced
- Improve the safety and efficiency of operations controlled centrally in Perth.

Rio Tinto has not acquired new rolling stock but has equipped the existing fleet (175 locomotives and more than 10,000 wagons) with new on-board systems such as cameras, radar and track mapping.

DB Projects (Germany)

At a press conference in May 2016, the Chairman of DB stated:

"We don't want to come after the car industry, but before it, and run autonomous trains by 2020-2023". The plan is to introduce autonomous trains gradually:

- Firstly, on lines with no mixed traffic.
- Then on lines where freight trains, ICEs and commuter trains run.

In 2016, tests were carried out on the tracks of DB's Erzgebirgsbahn subsidiary: freight and shunting locomotives were fitted with automatic pilots. Camera and location sensor systems were also tested.

DB then installed trackside sensors and beacons and equipped a Siemens Desiro 642 series train (a diesel multiple-units for commuter traffic) with cameras, laser scanning systems and tracking systems. The train was travelling at a maximum speed of 80 km/h and the laser scanned the track within a 400 m radius, with a braking distance of 382 m.

Prorail Projects (Netherlands)

Project in collaboration with Rotterdam Rail Feeding and Alstom Utrecht

ProRail, the Dutch rail infrastructure manager, and Rotterdam Rail Feeding are collaborating with Alstom Utrecht on a first trial of driverless goods trains on the Betuwe line linking Rotterdam to the German border (160 km), solely for freight purposes; in 2009 Alstom equipped the Betuwe freight locomotives with its Atlas ERTMS system. ProRail and Alstom are working together to develop the ATO.

As a first step, GoA2 trials took place in November 2018 with a train from Rotterdam Rail Feeding, to test various ATO functionalities and study the transition from ERTMS Level 1 to ERTMS Level 2 and automatic train zoning. The partners have obtained approval for these tests from ILT, the Dutch rail safety authority. Rotterdam Rail Feeding is the Dutch subsidiary of the American company Genesee & Wyoming Inc. and provides shunting and freight services in Belgium and the Netherlands

Project in collaboration with Lineas and Alstom

In 2020 and 2021, Prorail, the Belgian freight company Lineas and Alstom will be testing automatic shunting of freight trains at the Oosterhout marshalling yard. The aim of these tests is to increase feedback on the use of ATO. Alstom will equip an HLD77 diesel-hydraulic shunting locomotive with the necessary technology.

Project in collaboration with Arriva

Talks are currently under way with the transport authorities in Groningen (northern Netherlands) for trials, this time involving passenger trains, on a line operated by Arriva, a subsidiary of Deutsche Bahn, from 2019. If everything goes according to plan, these first passenger trains, made by Alstom, would begin regular service in 2023.

Project in collaboration with DB Cargo

In 2021, DB Cargo signed a letter of intent with ProRail for an autonomous freight train project on the Betuwe on the Dutch side, between Kijhoek and Valburg. The Betuwe route is seen as particularly suitable for such tests, as it has no level crossings and is equipped with an ETCS system. In addition, almost 72% of freight traffic between Rotterdam and Germany is carried via this route.

Automatic Train Test By Nederlandse Spoorwegen (Netherlands)

In December 2019, the Dutch national operator Nederlandse Spoorwegen (NS) carried out trials of an automatic train in GoA2 mode on the Hanseatic line in the north of the Netherlands, a passenger line with very high traffic density.

A new-generation CAF Sprinter electric train was used for this test (without passengers) and equipped with an on-board computer that communicated with the train's operating system. CAF Signalling provided its ATO system on ETCS. The

Traction and braking performance were in line with expectations, as was the train's predefined position and stopping time alongside the platform.

Siemens Tram Without Driver

In collaboration with Verkehrsbetriebe Potsdam, Siemens Mobility presented an autonomous tram project in October 2018. 450 trials were carried out across the city of Potsdam next to Berlin, with a Combino tram without passengers, with a driver to prepare for any eventuality, in real traffic conditions; the trams are equipped with a lidar scanner, nine cameras (side and front), three radar laser systems and the "Siemens Tram Assistant" collision warning system used notably on the Avenio M tram in Ulm and including a camera and radar as well as an audible alert warning any pedestrians who might be knocked down. Machine-learning software enables the tram to interact with pedestrians, cars and "other urban obstacles"; Siemens refers to this as "artificial intelligence functions": the system exploits the performance "learned" from previous journeys and the tram responds to signals at the edge of the track and stops at each stop. If a person is too close to the tracks, emergency braking is applied and the driver must restart autonomous operation. The scanner checks the track 100 m downstream of the train, giving enough margin for full braking at 50 km/h (tram speed).

Trials Of Automated Trains by SBB (Switzerland)

Swiss Federal Railways (SBB) tested a digital assistance system on the line between Bern and Olten. In the presence of a locomotive engineer, the pilot train was subjected to automatic braking and acceleration, in GoA2. The train is a Flirt duplex from Stadler, fitted with a new driver assistance system based on the European ETCS Level 2 system and the adaptive control system (ADL) developed by SBB to promote energy-saving driving. The test runs took place over three nights, outside the normal timetable, with no passengers on board. The research will continue, and autonomous driving trials should take place on lines equipped with ETCS level 1.

The project is part of the SmartRail 4.0 programme, which aims to progressively digitise and automate various services. SmartRail 4.0 brings together the Swiss railway companies (Lötschbergbahn (BLS), Südostbahn, Rhaetian Railway (RhB), SBB) and the Union of Public Transport. The SmartRail 4.0 activity report considers the widespread use of fully autonomous trains (GoA4) unlikely, but the advent of trains operating in GoA3 highly probable, with trains calculating their own route envelope on the basis of geographical, meteorological, operational and technical data.

Db Cargo Tests (Switzerland)

At the beginning of 2021, DB Cargo carried out a practical "ATO on ETCS" test on the Swiss mainline rail network. SBB Infrastructure and suppliers Thales, Siemens, Alstom, AZD Praha and Hitachi (formerly Ansaldo) also took part in the test, which took place on the 16 km stretch between Sierre and Sion; a Bombardier Traxx AC1 locomotive was used in combination with fourteen Eanos wagons loaded with gravel, the whole weighing 1,274 tonnes and measuring 240 m in length.

The test was originally scheduled for summer 2020 but was delayed by six months due to the pandemic. DB Cargo Swizerland had to cope with snow, rain and temperatures of -20°C at night, which was an additional challenge but allowed the systems to be tested successfully in all circumstances.

Thameslink (Great- Britain)

The Thameslink comprises 225 km of lines and 115 stations serving a Bedford-Brighton route via London and, in particular, St Pancrace International, used by 40 million passengers a year. Since 2019, it has been operated by Govia Thameslink Railway, a subsidiary of Govia, a joint venture between GoAhead and Keolis.

Thameslink includes an 8km central section in the heart of London, which has undergone an intensive £6bn (€6.7bn) upgrade programme to cope with very heavy peak hour traffic. From December 2018, capacity on this section was increased from 16 trains per hour per direction to 24 trains, with the possibility of 30 trains per hour if required, thanks to the first deployment of ATO in conjunction with ETCS Level 2 on a mainline railway. On this section of the line, the ETCS can handle very short-block traffic; the transition is easy, with the system indicating to the driver that the ATO is available and the driver choosing whether or not to opt for ATO operation for the train, in GoA2.

Crossrail (Great- Britain)

CrossRail, renamed Elisabeth Line, is a London commuter line in GoA2, linking West and East London, to be operated by MTR Corporation with a planned frequency of 24 trains / h in central London at peak times. The line finally entered service on 24 May 2022. Part of the line (Western section) is equipped with ETCS level 2 with fixed-block operation, the central section is equipped with a CBTC with moving blocks (the Siemens Trainguard MT) and the third part (Eastern section) with a conventional AWS / TPWS (Automatic Warning System / Train Protection and Warning System) with fixed blocks. The three sections of the line are equipped with different interlockings.

Train Autonome by SNCF (France)

Train Autonome brings together several projects organized in different consortia. Those projects explore different challenges such as the retrofit of autonomous equipment on an existing rolling stock (the project Train de Fret Autonome uses a prototype based on a BB427000), the development on native equipped rolling stock and the remote control of a train. In 2022, Train Autonome teams has demonstrated the feasibility of automatic driving with the ATO over ETCS solution, adapted to operate via visual perception of lateral signalling.

Project MARS of SNCF's research on autonomous train and aims to produce a reconnaissance vehicle to monitor high-speed line every morning instead of using a TGV pulled from the commercial service.

1.1.4 Evaluation of the innovativ approaches

1.1.4.1 Categories

In the analysis of different ongoing projects, two primary categories of regional trains have been identified: Type A (smaller) and Type B (bigger). These categories are distinguished on key factors such as speed, passenger capacity, length, crashworthiness, and compression capabilities.

Type A: Those trains are designed for longer distances and have a maximum speed of 120 km/h, making them suitable for G1 lines and main regional routes. They have a higher passenger capacity (from 56 to 80 seats, depending on the model) and can offer more comfort (for example: toilets).

Crashworthiness in this category is G1/C1.

Type B: Those trains are typically designed for shorter routes and frequent stops. They are characterized by lower speeds (up to 100 km/h). These trains have a smaller passenger capacity (up to 42 seats), suitable for less densely populated routes or for services that run frequently enough to avoid overcrowding. The length of small trains is inferior to 20 meters, allowing them to fit into smaller platform lengths.

Regarding crashworthiness, Type A train are often C3/P3 according to TSI's standards. This allows a lighter design but prevent them to access to the G1 lines and main network. However, some countries like Germany have adopted specific (LNT rule) to grant those trains access on main lines using a regulation framework. Those rules are applied to the CAF Nexio and the Karlsruhe tram for example.

The classification of regional trains into Type A and Type B allows us to classify rolling stock according to G1 and G2 lines needs but do not resolve the problem of the connections regarding a Type A rolling stock unable to reach a main train station even if it is a few kilometres away from the end on the G2 line. For such situations and to help passengers to travel easily, the German example can be of interest.

1.1.4.2 Automation

In the current landscape of regional railway projects, the question of automation seems not to be a shared goal. This trend can be attributed to several factors, including regulatory challenges, high initial costs, and the complexity of integrating automated systems into existing rail infrastructure.

Despite advancements in technology and the potential benefits of it, only one remaining project (since the abandon of Taxirail) is aiming at GOA4 for its deployment and its specificities need to be developed.

The Stadler RhW has been commissioned by the Appenzeller Bahnen for the Rheineck-Walzenhausen line. The rolling stock will be GOA4, allowing a driverless operation of the train.

Nevertheless, this project cannot be compared to any other regional rail since the line is:

- A rack rail,
- Operated with a CBTC command-control,
- 1,96 km long.

Other projects like TELLi aims to a GO2 to 3 goals for the commercial launch and work toward a retrofit to GOA4 when the technology will be ready.

1.1.5 Evaluation of current and decommissioned rolling stock

1.1.5.1 Accessibility and TSI PRM

Rail vehicles from the past often have little or no accessibility. Many vehicles have a high access of 550 mm to 800 mm measured from the top of the rail. Old vehicles also have additional steps to access the vehicle. In addition, the infrastructure shows a very inhomogeneous picture of platform heights. These vary not only by region but also within stations along individual lines.[18]

This incompatibility of vehicle and infrastructure means that access to the vehicle is not easily possible for people with limited mobility. In many vehicles, wheelchair access is only possible via ramps and lifts. These are operated by staff and often must be ordered several hours or even days in advance. This makes independent mobility extremely difficult. Access is also made difficult or impossible for passengers with large luggage, strollers, or bicycles.

These issues are addressed by the technical specifications for interoperability relating to accessibility of the European Union's rail system for persons with disabilities and persons with reduced mobility, in short TSI PRM. This regulation "enhance[s] the accessibility of rail transport" for "any person who has a permanent or temporary physical, mental, intellectual or sensory impairment which, in interaction with various barriers, may hinder their full and effective use of transport on an equal basis with other passengers or whose mobility when using transport is reduced due to age."

[18] Hertel_2023_ Challenges in the (Re-)Connection of Peripheral Areas to the Rail Network from a Rolling Stock Perspective: The Case of Germany

This not only concerns rolling stock itself but also infrastructure, operational aspects, and telematics applications. For example, the infrastructure must be designed in a way, that every facility within the rail transport system must be accessible without obstacles like ramps or stairs as much as possible. The station and the trains must provide enough space for people with wheelchairs, so minimum space requirements shall be adhered to concerning passages, doors, waiting areas and the interior of the trains. Passenger information shall be as easy and clear as possible using pictograms and announcements. The train itself shall be fitted with priority seats, PRM toilets, wheelchair spaces, wide doors, and audible and tactile guidance systems. [TSI PRM]

1.1.5.2 Anticipating evolution in energy sources and policies

The European Union is actively working to phase out diesel in railway transportation as part of its broader strategy to reduce greenhouse gas emissions and combat climate change. Several key initiatives and regulations illustrate this commitment.

The European Green Deal aims for Europe to become the first climate-neutral continent by 2050, with reducing emissions from transportation, including railways, being a crucial part of this plan. Additionally, the Shift2Rail initiative focuses on research and innovation to accelerate the development of sustainable and competitive rail transport. This initiative promotes the adoption of clean technologies and supports projects aimed at reducing dependency on diesel.

Meanwhile, the Alternative Fuels Infrastructure Directive (AFID) sets targets for the deployment of alternative fuels infrastructure across Europe, including the promotion of electric and hydrogen-powered trains to replace diesel engines. The EU's Hydrogen Strategy, launched in 2020, also aims to develop hydrogen as a key energy carrier for the future, with hydrogen fuel cells being seen as a clean alternative to diesel engines in rail transportation.

Various European countries have their own plans and targets to phase out diesel trains. For instance, Germany plans to significantly reduce the number of diesel trains by promoting electrification and hydrogen trains, so is France where SNCF works to ban diesel trains by 2035.

1.1.5.3 Crash and strength compatibilty with TSI

The TSI Loc&Pas includes a chapter on strength of vehicle structures (4.2.2.4) which regulates the approach to provide static and dynamic strength to a vehicle body. It refers to the norm EN 12663 which specifies and regulates different load cases, forces and qualification methods to different rail vehicle categories to ensure safe operation of mechanical structures on rail vehicles. Furthermore, the TSI includes a chapter for passive safety (4.2.2.5), which ensures maximum safety for passengers and freight in case of a collision. For this purpose, it refers to another norm EN 15227, which specifies different collision scenarios for different vehicle types and areas of application and the necessary precautions to prevent injuries and casualties as much as possible. These precautions include:

- limiting deceleration,
- maintaining survival space and structural integrity of the occupied areas,
- reducing the risk of overriding,

- reducing the risk of derailment, and
- limiting the consequences of hitting a track obstruction.

Figure 18 : Voith Galea train head[19]

In modern rail vehicles these precautions are implemented in strong car bodies. Especially the front end of rail vehicles beyond the crash area is highly strengthened, so that the space for passengers and drivers remains stable and free of obstacles. This is implemented using a-pillars and structures with high strength and anti-penetration walls. Additionally, energy absorption devices are used to limit the deceleration of the vehicle. These are partial places within the coupling, buffers and in the front of the car body structure. The front end of trains and especially the structure in the buffer area is designed in a way that prevents the car body from being lifted out of the track in case of a collision. To achieve this, they are fitted with anti-climbers which avoid an overriding of the car body during a collision. In addition, the front end is equipped with structures, that holds the car body in its vertical position, so any movement up and away from the rail is prevented. The bogies and driving gear of trains can furthermore be fitted with substitute guidance mechanisms to keep the train in the track in case of a derailment. An Example of such a vehicle head and its crash safety systems is shown in Figure 19.

Beside the crashworthiness requirements the strength of the car body according EN 12663 has a significant relevance for the car body. The operational and exceptional loads are defined here, according to the category of the vehicle. The loads are generalized for each category whereby the loads on the coupler area have a dominant effect on the mechanical car body design, the structure, and the weight. This force is 1.500 kN respective 2.000 kN for mainline trains according to the TSI Loc&Pas. Further categories, which are considered in the standards but not in the TSI, have less loads, based on the specific frame conditions and requirements for the respective categories and use case. The use of vehicle categories which can run on mainlines but with smaller loads, is suitable here even if this is currently not considered in the TSI.

[19] Schienenfahrzeuge: Voith präsentiert neues Fahrzeugkopf-Konzept Galea auf der InnoTrans 2012, Voith Turbo GmbH & Co KG, 17.09.2012, Last checked: 25.10.2024, https://voith.com/corp-de/news-room/press-releases_39460.html

The enabling reason is based on the approach of the FutuRe-project (for example the division in G1 and G2-lines) and the corresponding vehicle which could fulfill the requirements for the use of reduced loads (e.g. tram train approach).

1.1.6 Market prices

The cost per seat had been raising for the last two decades due to several circumstances: inflation and technology/regulation development (See Appendix 1 and 4).

After the 2008 economic crisis, and a crash of raw materials prices, a boom occurred followed by a continued inflation. This is combined to a shift on the market pricing for plastic and petrol-based products: before 2008, their prices were usually correlated to oil price. Since the economic recovery post-2008, product petrol-based has their own fluctuation and are no-longer priced following the oil barrel: this is a market on its own and the demand for plastic is continuously increasing (for example: in automotive industry, plastic is generally used instead of certain metal alloys in the engine bay since mid-2000, creating a new need for this material among many others). The re-use of plastic can only partially cover it (regarding plastic packing, in Europe in 2018, 42% of them were re-used, for automotive industry, the share of re-used plastic is around 19%).

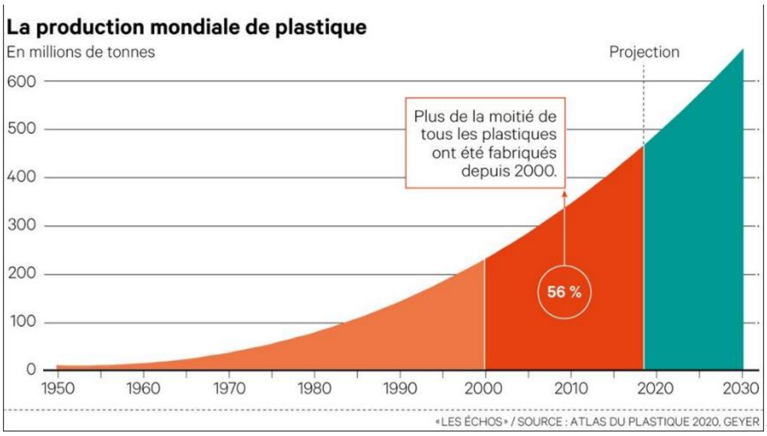


Figure 19 : International plastic production / in millions of tons per year

Meanwhile, the need for safety, the shift toward 0 emission and the demand for comfort lead to a train equipped with more components and/or expensive ones (bi-standard CCS components, battery or hydrogen propulsion instead of diesel technology, better air conditioning and heat management, but also for example individual charging socket for passengers, onboard Wi-Fi, screen for passengers' information…).

The railway industry has also its own characteristics. Production volumes are smaller compared to automotive or aircraft industries, and there is no European "scaling" in production management due to the specificities of each national market or even each regional demand. This increase production costs regarding the lack of consolidation.

For example, the AGC (Automotrice Grande Capacité) made by Bombardier was a commercial success (700 trains bought by SNCF) but the company has to produce:

- 4 variations for propulsion
  - Diesel
  - Electric 1500 V and 25 kV
  - Dual mode 1500 V
  - Dual mode 1500 V and 25 kV
- Each propulsion variation could be a 3 or 4 cars train (except for the dual-mode/dual-current that must be in 4 cars)
- Several interior layouts were offered including different seats and colours to accommodate regional requirements.

In the end, more than 20 variants of the AGC were available, resulting in a semi-customised production.

Figure 20 shows the price development of different multiple units for the use on regional rail lines on the European market. Due to the strongly varying vehicle capacities (from 58 to 165 seats), the specific acquisition costs per seat were calculated and illustrated. The data is based on sources publicly available on the Internet. As shown in the figure, prices have risen significantly in recent years. An additional increase in acquisition costs can be seen in vehicles with alternative propulsion systems and bi-mode vehicles (the Alstom iLint is powered by a hydrogen fuel cell, the Newag 36WEh Hybrid is a bi-mode vehicle with pantograph and diesel engine, the Siemens Mireo Plus B is an electric multiple-unit with traction battery for approx. 80 km). In addition, the costs for the Siemens Mireo Plus B also include maintenance and energy costs for a contract term of 29.5 years.[20]

[20] https://vm.baden-wuerttemberg.de/de/service/presse/pressemitteilung/pid/land-bestellt-erstmals-batterieelektrische-zuege/; access: 25.10.2024

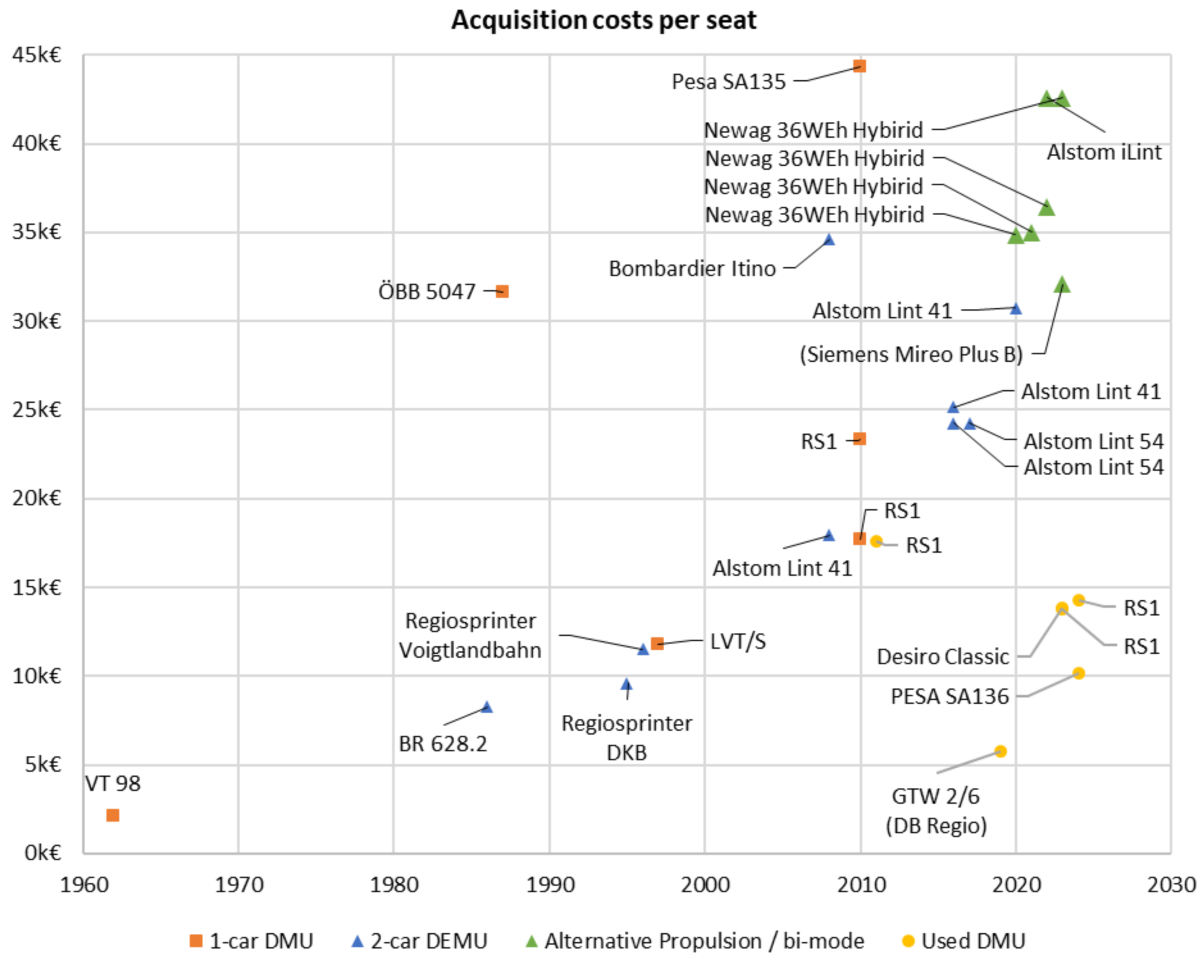


Figure 20 : Cost per Seat for new and used vehicles

1.1.7 Market available rolling stock (based on market research)

Currently available vehicles are mostly based on modular multiple unit vehicle families. The smallest vehicles currently available on the market are 2-car, around 42-45 m long multiple units with Jacobs bogies and around 120 seats. Examples include the Mireo Plus B from Siemens and the Stadler Flirt Akku.[21]

The next larger vehicle category are two-car traction units with four bogies, a length of around 55 m and 150-180 seats. Examples are the Stadler Flirt Akku, Alstom iLint, or Škoda RegioPanter BEMU.

[21] https://assets.new.siemens.com/siemens/assets/api/uuid:1cdbf355-fa91-4fca-8917-5e04e9419e17/mors-b10022-00dbmireoplusortenau-72_original.pdf

https://stadlerrail.com/static/img/flirt-akku/fnah0922_de.pdf

Most vehicles can be ordered with different traction options, e.g. with overhead line, battery, hydrogen or, in some cases, diesel propulsion.[22]

But apart from new vehicle designs, solutions based on current constructions are also sought. As example could be the three-car Class 230 train, retrofitted from vehicle D78 Stock, which has batteries charged in 3.5 minutes at the one return station, introduced in March 2024 for a 12-month trial on the 7.72 km West Ealing - Greenford route in West London.[23]

1.1.8 Use cases

To provide a comprehensive overview of the system's intended functionalities, several use cases has been studied. Due to the confidential nature of some of the network data and different level of public availability, Sweden, Germany, and France couldn't provide the same amount of information.

In Appendix 3 a spreadsheet introduces a series of use cases that categorize vehicle operations based on parameters such as track length, travel time, axle load, and designated route types. The classifications are as follows:

- Light (G2),
- Heavy Short (G1S),
- Heavy Long (G1L),
- Heavy Unlimited (G1U).

[22] https://stadlerrail.com/static/img/flirt-akku/FADBBEMU1023d.pdf

https://www.now-gmbh.de/wp-content/uploads/2022/11/2.-Plattform-Schiene_Einsatz-von-Brennstoffzellenzuegen-in-Niedersachsen_Nawrocki-LNVG.pdf

[23] https://news.gwr.com/news

1.1.9 Discussing the right propulsion system depending on the necessary range

As shown in the Use Case, over the day the vehicles are often running over 400-800 km. This correlates to the range of the existing diesel-powered vehicles. The vehicles which are used currently on low-frequency branch lines are mostly diesel-powered vehicles due to the lack of electrification. Infrastructure work to electrify those line is not always a financially viable operation.

Table 1 lists different types of vehicles that are commonly used in Europe on these lines with their fuel consumption, tank capacities and ranges. The vehicles usually have a diesel capacity of 500-1800 l, which enables a range of 500 km up to 1200 km. Route characteristics such as speed, elevation and curves also affect fuel consumption.

It is important to note that the development of a battery-powered train, with a range of few several hundred kilometres, will have an impact on regional timetables and production methods.

Table 1 : Overview of the fuel consumption of different small DMU for regional lines

Vehicle	n-cars / wheel arrangement	Seat capacity	Fuel capacity	Fuel consumption	Specific fuel consumption	Range	References
			[l]	[l/100 km]	[l/seat*100 km]	[km]	
ÖBB 5047	1-car / 2'B'	62	700	117	**1**,887	600	[24]
Alstom Coradia A TER / X73500	1-car / (1A)(A1)	77	900	87	1,130	920	[25], [26]
Pesa 214Ma (SA103)	1-car / B'2'	70	840	60	0,857	1000	[27], [28]
Kolzam Regiovan 212M (SA109)	2-car / A'1'+1'A'	73	500	63	0,863	790	[29], [30]
Alstom Lint 41 (LNVG)	2-car / B'2'B'	120	1600	76	0,633	2100	[31]
Siemens Desiro (ÖBB 5022)	2-car / B'2'B'	117	600	120	1,026	500	[32]
Bombardier Itino	2-car / Bx' (2) By'	119	1800	150	1,261	1200	[33]
Average				**96,14**	**1,094**		

[24] https://www.tuwien.at/index.php?eID=dumpFile&t=f&f=163947&token=f3ce947b96e3aed4b562e63ba097369e85be2224, Access : 29.05.2024

[25] http://fbrisou.free.fr/RAIL21/FicheX73500.pdf, Access : 29.05.2024

[26] Schlussbericht Machbarkeitsstudie Pilotprojekt Einsatz von H2BZ-Triebwagen in Thüringen (thueringen.de) , Access : 29.05.2024

[27] https://web.archive.org/web/20140204032933/http://www.pomorskie.eu/res/BIP/UMWP/zamowienia_publiczne/zamowienia/2009/39_09_zalacznik_nr_6_do_siwz___informacja_o_pojazdach_zmodyfikowana.pdf, Access : 29.05.2024

[28] Marciniak J. "Autobusy szynowe III generacji"; TTS, 2012, R19, nr 9, Access : 29.05.2024

[29] https://web.archive.org/web/20140204032933/http://www.pomorskie.eu/res/BIP/UMWP/zamowienia_publiczne/zamowienia/2009/39_09_zalacznik_nr_6_do_siwz___informacja_o_pojazdach_zmodyfikowana.pdf, Access : 29.05.2024

[30] https://kd2-my.sharepoint.com/personal/sylwia_pabian_kolejedolnoslaskie_eu/_layouts/15/onedrive.aspx?id=%2Fpersonal%2Fsylwia%5Fpabian%5Fkolejedolnoslaskie%5Feu%2FDocuments%2FDSUDTRP5&ga=1, Access : 29.05.2024

[31] https://www.now-gmbh.de/wp-content/uploads/2022/11/2.-Plattform-Schiene_Einsatz-von-Brennstoffzellenzuegen-in-Niedersachsen_Nawrocki-LNVG.pdf, Access : 29.05.2024

[32] https://www.vor.at/fileadmin/CONTENT/Bilder/Projekte/ATHU114_Low_Carb_Mobility_Endbericht_Energiewirtschaft_extern.pdf, Access : 29.05.2024

[33] https://www.fahma-rheinmain.de/projekte/odenwaldbahn/technische-daten/, Access : 29.05.2024

1.1.10 Capacity Requirements

Various studies have indicated that a seating capacity of 10 to 70 seats is required. The lowest capacity of 10 seats is the result of preliminary analyses of various reactivation studies with a focus on reactivating routes in Germany that correspond to G2 lines with a 60-minute interval. The largest capacity of 70 seats is based on capacity studies for on-demand services and transit through a major city.

This vehicle size range is in line with the status of research activities with similar approaches, e.g. ARS (34 seats), Draisy (30 seats) and Revolution VLR (56 seats).

Based on this data, the consortium has agreed on a capacity range for the G2 and G1 vehicles. The minimum capacity for the small vehicle is 12 seats and the maximum capacity for the large vehicle is 40 seats.

1.2. User research

FutuRe seeks to deliver novel and innovative technical solutions and services with the overarching goal of enhancing the cost efficiency of regional rail systems, while concurrently adhering to safety standards and augmenting the reliability, availability, and capacity of the railway network. This necessitates an exploration beyond purely technical considerations to encompass the user perspective. It is imperative to recognize that solutions deemed technically sound may not automatically enjoy the highest levels of user acceptance. Thus, striking an optimal balance between technical viability and achieving maximum user acceptance is essential. This equilibrium is crucial to ensuring that regional trains are utilized to the extent envisioned by the project.

Therefore, the following chapter constitutes of four parts: Part 1.2.1. describes the results of focus group discussions, Part 1.2.2. concerns the results of a survey with passengers traveling with regional lines, Part 1.2.3. integrates and discusses the results of the user research and Part 1.2.4. describes respective design implications.

1.2.1 Focus Group discussions

1.2.1.1 Introduction

To gain insights into users' requirements and parameters of comfort in regional lines, focus group discussions (FGDs) were implemented. The FGDs focused on the interior design of current regional train carriages to identify potential acceptance barriers and improvement options.

1.2.1.2 Methodology

A series of four FGDs was conducted in July 2023, with a total of 24 German participants, including 13 females. The participants use regional trains at least one to three times per month: 9 participants use regional lines one to three times per month, 7 participants one to three times per week and 8 participants daily. All FGDs were held online and were limited to a maximum duration of two hours each. The primary focus of these discussions was the execution of a comprehensive user journey analysis, specifically targeting the evaluation of user satisfaction and dissatisfaction regarding the interior design of regional train carriages. The user journey analysis encompassed various phases, beginning with the passengers' initial entry onto the train, followed by the exploration for seating or standing space, and the experience of sitting or standing during the journey while engaging in typical passenger activities. The analysis was concluded with insights gained during the alighting process. The FGDs were recorded, and these recordings were transcribed and subjected to analysis using MAXQDA software, employing the inductive-deductive approach to extract meaningful insights from the data.

1.2.1.3 Results

To prepare the participants for the following two hours, the FGDs started with a broad and more general question. The participants were asked to name the most important aspects of the design of regional train carriages for them personally. The most important aspect according to the participants was hygiene with eight votes, followed by workplace configuration with seven and storage space with six votes, respectively. Comfort and accessibility without barriers were valued moderately with five votes each, while safety, more personal space and air conditioning were brought up the least with two and single votes on the last two aspects.

Subsequently ten more specific questions with an open format were asked. The valence of the answers was administered and categorized into positive, neutral/wish and negative.

1.2.1.3.1 How is the boarding and alighting being evaluated ?

In the *positive category* one aspect was mentioned one time “Door signal in colour”. The most voiced answer in the *neutral/ wish category* was the wish for “Level boarding for entry and exit” with six votes. Followed by “Automatic door opening” with five votes, “The ramp should be automatic” and “System, for example, a traffic light, that indicates: let passengers alight first” with two votes each. Lastly “Better a small gap than steps between train and platform” and “Separate doors for entry and exit” were both important to one participant each. The most mentioned answer in the *negative category* was “Accessibility” with eleven votes, followed by “Crowding”, “Separate doors for entry and exit”, “Door opens too slowly/ late”, “Doors close before everyone could alight” with two votes each and finally the question was answered once with “Too narrow”, “Doors are hard to find” and “Warning button to indicate that you want to alight”.

1.2.1.3.2 How is the seating situation evaluated ?

As can be seen in Figure 1 the most two mentioned and only registered answers in the *positive category* (green colour) were “Folding seats are good” and “Seats and backrest comfortable”, which were both mentioned four times. “Favourite seating area: Four-seater“ was the answer leading the *neutral/ wish category* (yellow colour) with five votes, followed by “Favourite seating area: Double seat” with two votes. “At night, prefer transverse folding seats: safer “, „Standing place with backrest”, “Make more seats foldable”, “More seats instead of standing places” were mentioned once each.

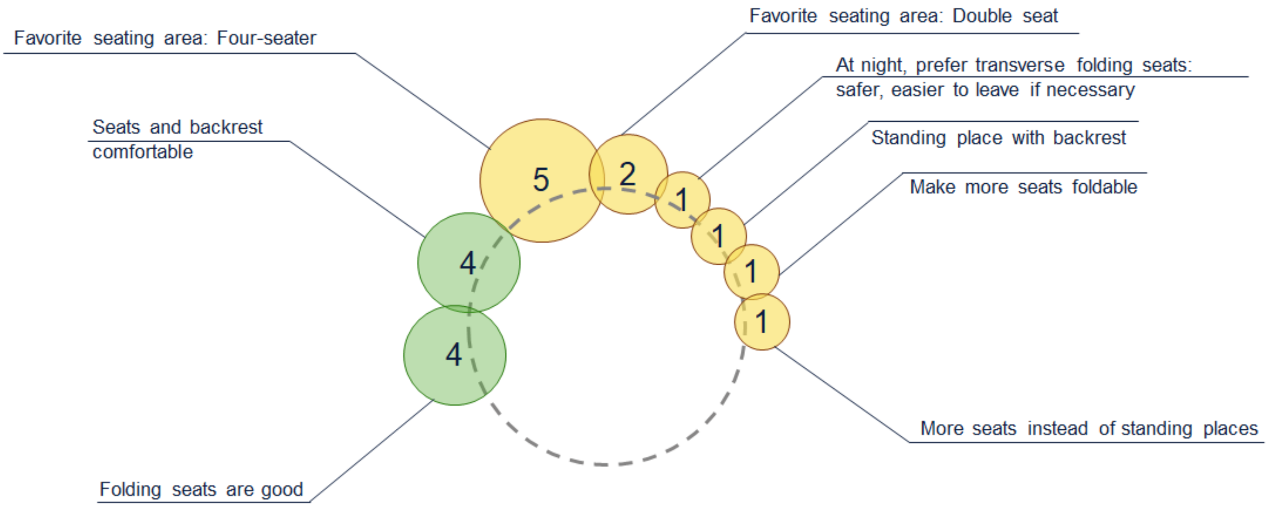


Figure 21 : Positive and neutral remarks on the question: How is the seating situation evaluated?

As can be seen in Figure 2. the most voiced answer of the *negative category* (red colour) was “Wanting to sit in the direction of travel: you never know beforehand” with six votes and “Folding seats uncomfortable", "Privacy (prefer to sit alone, two-seater is more private, have to face others in a four-seater)", "Hardly any power sockets" with five votes. "More legroom" had been mentioned four times, while "Uncomfortable headrest", "Make seats adjustable", "Seats uncomfortable", "Too few workstations" and "Folding seats only for short Journeys" were voiced two times. "Folding seats too close together" and "Make the armrest adjustable" were communicated the least with one vote, respectively.

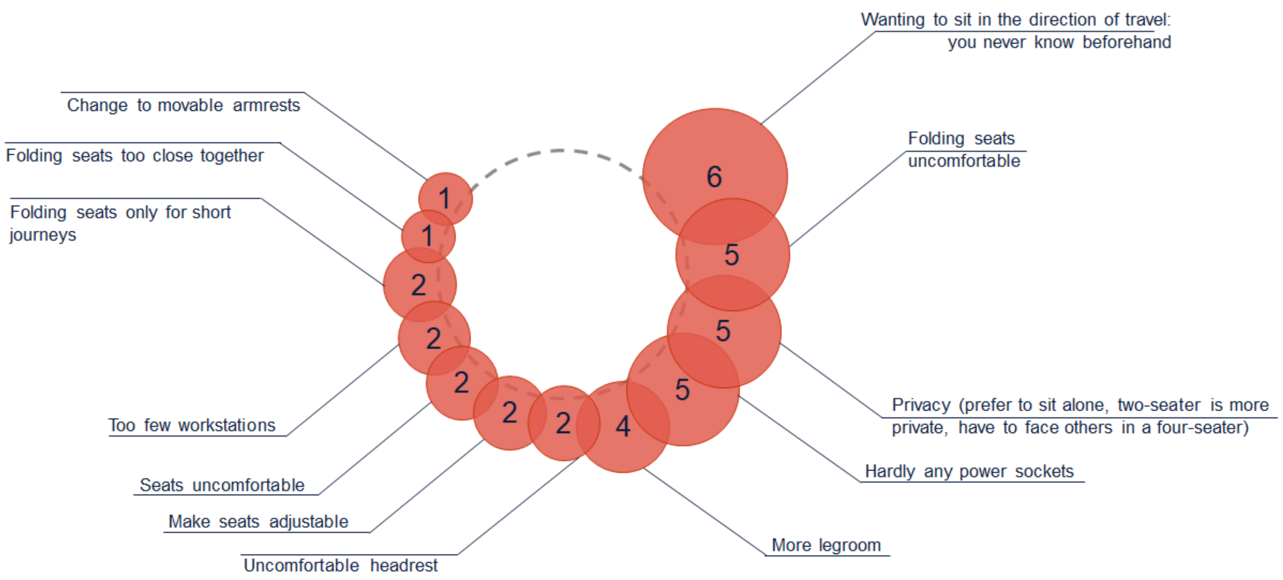


Figure 22 : Negative remarks to the question: How is the seating situation evaluated?

1.2.1.3.3 How are different handrail/handhold options evaluated ?

While there were no *positive* remarks, in the *neutral category* participants *wished* for "More handrails to hold onto" six times and mentioned "Handles on seats desired" three times. "Handle bars to high" and "Too many bars" were noted three and two times in the *negative category*.

1.2.1.3.4 How are different aspects of the interior design of regional trains evaluated ?

The sole *positive* answer concerning this aspect was "Prefer double-decker trains (better view, better distribution)" while being mentioned twice. With no *neutral/ wish* answers the *negative* responses consisted out of "Poor colour design/ change it" four times, "Too old-fashioned" twice and "Use calming colours" and "Ceiling is too low" one approval each.

1.2.1.3.5 How are various information systems/displays evaluated ?

No *positive* remarks were made, but it was *wished* for "Touchscreen: the ability to search for things yourself" and "Display: where staff, assistance" once, respectively. Eleven participants agreed that "Display board should be larger, more informative, more often available, and clearer" on the *negative* side.

1.2.1.3.6 How are the toilets rated ?

As can be seen in Figure 3. “Toilets are large enough” was found to be a *positive* answer (green colour) three times. Two participants *wished* for “Toilets on the commuter train” and one participant asked for “Disinfectant” (yellow colour). On the *negative* side (red colour), fifteen participants shared the opinion that the toilets are “Dirty”, ten agreed on “Too narrow” and it was mentioned once that the toilets are “Often broken or blocked”.

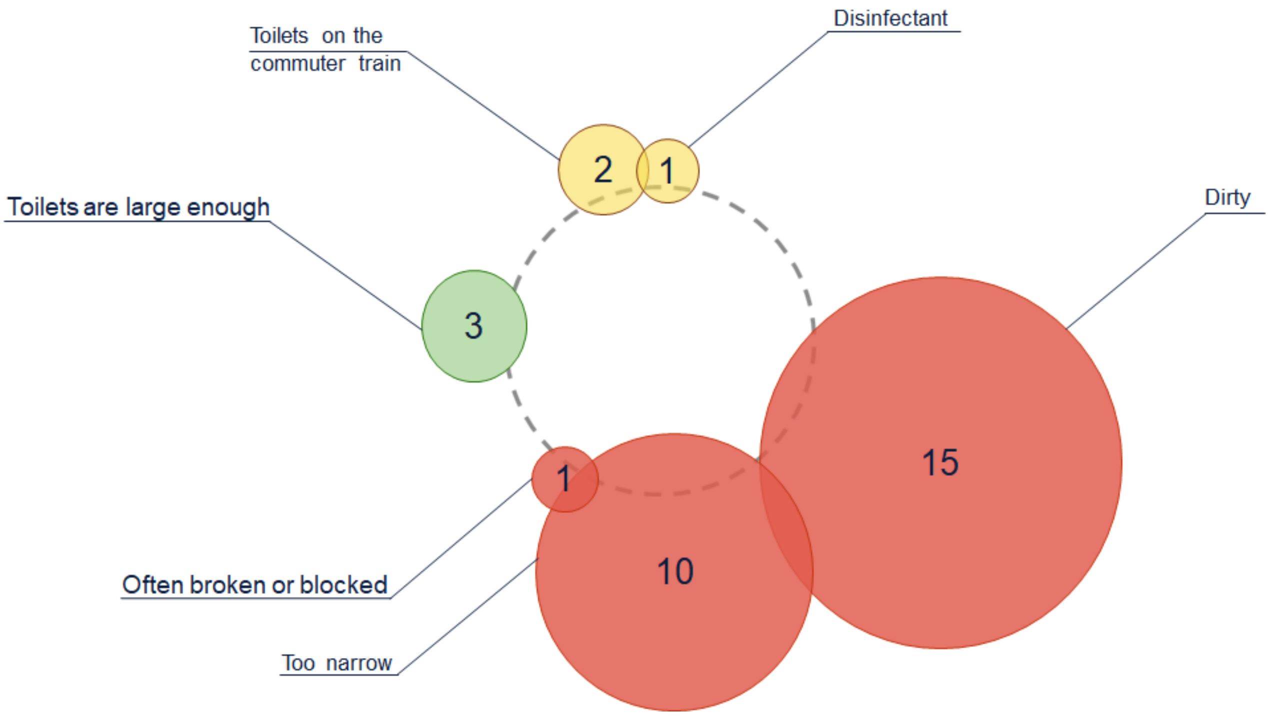


Figure 23 : Remarks to the question: How are the toilets rated?

1.2.1.3.7 How is hygiene rated ?

“Leather covering/ wipeable” was mentioned as *positive* by two participants. It was *wished* for “Disinfectant/ wipe dispensers” by three participants and “Bars are not a problem” and “Buttons are not a problem” were assessed to be *neutral* twice, respectively. On the *negative* side five participants valuated “Buttons are not touched/ unhygienic“, three mentioned “Cushions/ coverings are unhygienic” and two participants answered with “Handrails and handles are not touched/ unhygienic”.

1.2.1.3.8 How is the interior space rated ?

On this regard, only *negative answers* were given. Equally strong advocated for with eight acknowledgements each were “Too narrow” and “Bicycles: not enough space, blocking seats, no secure fastening options, separate area”. Followed by “Crowded” with two votes and “Fewer seats in the entrance area” with a single vote.

1.2.1.3.9 How is the luggage storage evaluated ?

As in the prior occasion, only *negative answers* were given (see Figure 4.). The most emphasized ones being "Luggage storage space is lacking" being mentioned by five participants and "Overhead luggage compartment is hard to reach" and "Luggage takes away seats" being mentioned by three participants each. "Luggage security" was voiced twice while "Luggage racks in the line of sight are missing" was voiced one time.

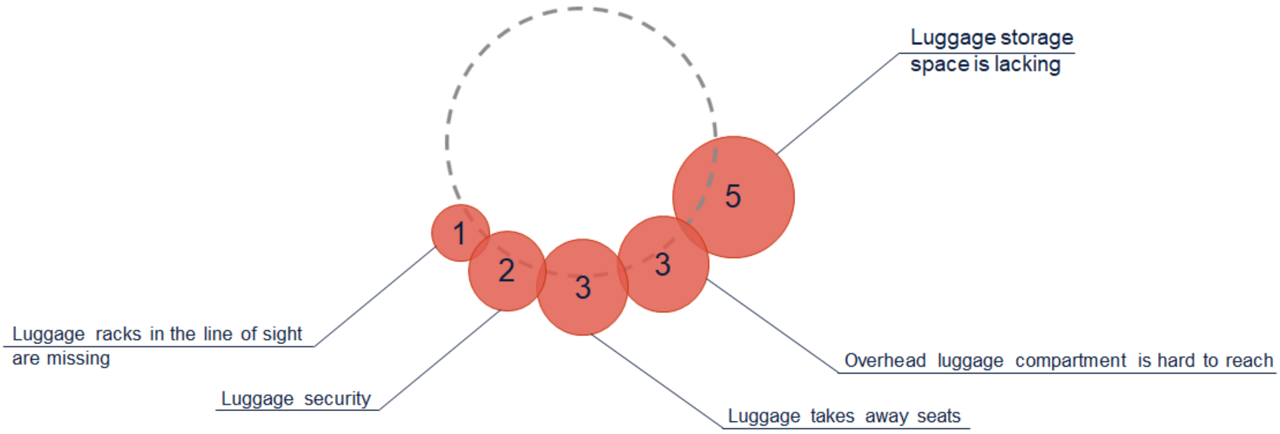


Figure 24 : Remarks to the question: How is the luggage storage evaluated?

1.2.1.3.10 How is the safety evaluated ?

As can be seen in Figure 5., four participants answered *positively* (green colour) with "No safety concerns". Five participants *wished for* "More security personnel/ contact persons", while two participants advocated "Against security personnel: already present/ not necessary" in the *neutral* category (colour yellow). Another two votes went to the *wish* for "Emergency button to the driver". "More compartments" and „A continuous train: better visibility" were mentioned one time, respectively. *Negative* aspects of safety (red colour) were "Slippery/ uneven floor" and "Distance between train and station is too far" with two votes and "Lack of handrails/ handles" and "It's difficult to pass with a table" with single votes.

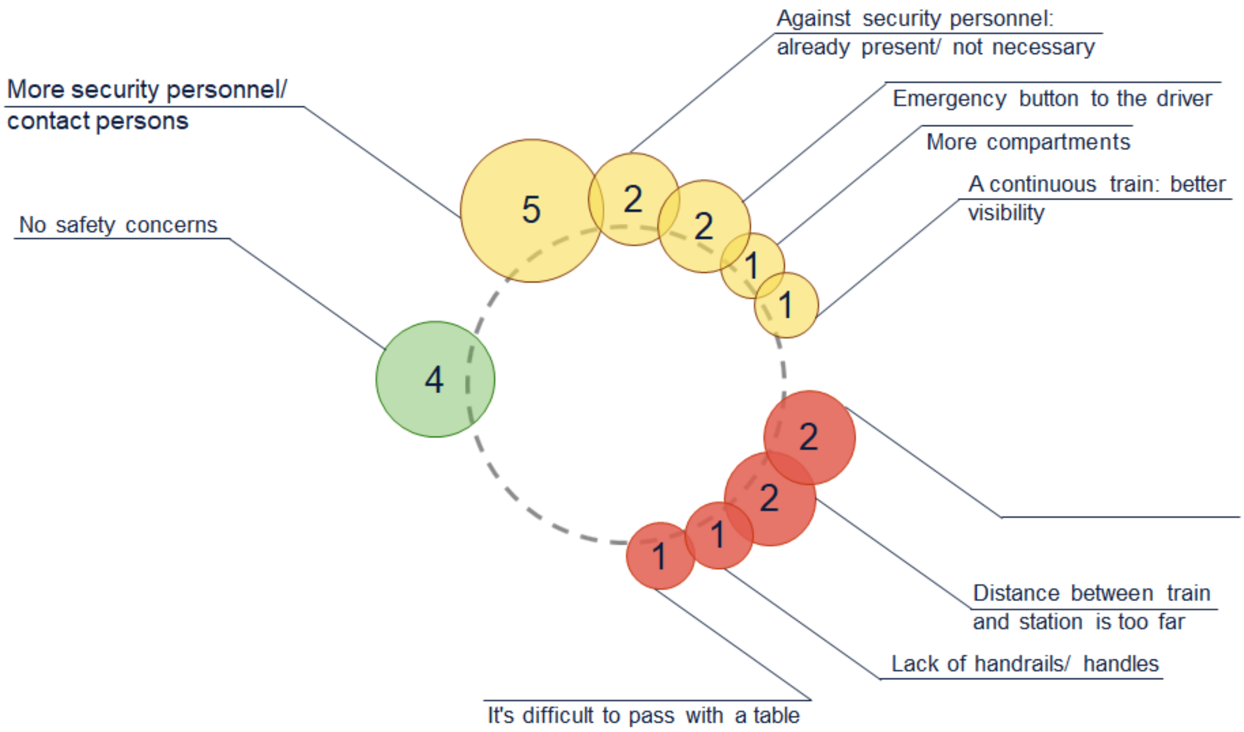


Figure 25 : Remarks to the question: How is safety evaluated?

1.2.1.4 Discussion

The first thing noticeable when looking at the results of the ten valanced questions asked, is that the responses were vastly *negatively* connotated. Only a few questions even featured remarks with *positive* valence. Out of these questions, some also featured the semantical opposing remark, which often was supported by more people. A second remarkable aspect are the various *wishes* for the design of regional trains. The most *wishes* came for the topics of boarding and alighting, seating modes, hygiene and safety, which also had been featured in the answers to the question about the three most important aspect of regional train design beforehand.

1.2.1.4.1 Positive remarks

Out of the ten questions, six *positive* remarks have been made, while only once have there been multiple *positively* connotated responses.

The second question was the question with multiple *positive* responses and also had the most advocates overall with eight. Concerning seating, participants evaluated the seats and backrests to be comfortable as well as folding seats to be a good idea. While these opinions are severely contradicted by the *negative* remarks made, it can be assessed that the folding seats are a seating mode with a lot of potential as participants included them in both their *wishes* and their *positive* remarks. They seemed to generally like the concept and saw some opportunities in how folding seats may be used or bettered.

The *positive* remark on different aspects of the interior design of regional train carriages was that double-decker carriages were the preferred train model. This should come as no surprise as double-deckers.

can enhance the enjoyment of train trips with a better view from above and also add to a less stressful and more private travelling experience because of better distribution of passengers (on both levels) on the train.

Toilets were found to be spacious enough by three participants. This stands in contrast to ten participants assessing the space as too narrow. While it certainly is an individual perception of space for each participant, it seems that toilets generally are rather too small than just fine.

On the subsequent topic of hygiene, it was stated that leather coverings and wipeable coverings are good. Aligning with differently valanced remarks, coverings that are easy to clean seemingly add to a perception of better hygiene on regional trains. This may be because either the probability of it looking clean and being clean could be higher or/ and the expectation of an easily cleanable surface being cleaned more often than surface harder to clean.

The last question about safety revealed that there was a larger quantity of *wishes* for safety and *negative* responses to safety compared to *positive* remarks about the topic. However, some participants indicated they have ‘No safety concerns”. This could be, as mentioned in other categories before, since there are individual perceptions of safety. While some participants (in the FGDs mainly male) mentioned no safety concerns using regional trains, for other user-groups that might be the case. As the *negative* remarks mainly evolved around the difficulty to move safely inside the train, it could be an indicator that the circumstances inside regional trains are not ideal for people to maneuver that lack the necessary physical requires to use the structures in place. These groups could consist out of women, the elderly, and children. While the structures to secure a stable stance may be harder reachable for these groups, they may also more often lack the necessary strength to hold onto the holding options in the first place which leads to significant danger of injury. Furthermore, for the group of women, another lack of safety is adamant. Women are way more likely to be victims to harassment, especially sexual harassment, being initialized by other passengers, mostly male. This was reflected by safety concerns mainly mentioned by women and shows a fundamental usage barrier of regional trains.

1.2.1.4.2 Neutral remarks / Wishes

The *wishes* concerning the first question mainly addressed making processes automatic and improving accessibility without barriers. New modes of accessing regional trains were also proposed. People seem to be stressed by finding and accessing doors on the trains. This part of a ride with a regional train seems to need a more structured concept, that takes cognitive load off the users and makes embarking and alighting easier for everyone. This could be achieved through strict rules on who embarks or alights first, using e.g. some sort of traffic light, and fixed stopping points for the doors of the train as can be observed in for example Asian countries as China.

The *wishes* for the seating situation mainly revolved around the arrangement of seats and the different seat models. The four-seater had many supporters as well as the double-seater. Four-seaters may be as popular, as they offer more space and hold a variety of options it can be used for, e.g. travelling in groups, eating, and working. In the case of the double-seater the popularity may be for the relative privacy enhanced. Transverse folding seats were said to be used at night for safety reasons by women. This could be for spatial reasons as leaving the double-seater at the window is not as easy as simply leaving a folding seat. While there are differences in the preferred seating area, it seems to be the case that a *wish* for more seats in general is conveyed. The reasons for that might be either overcrowding of regional trains in general or the aligning need for a private and singled-out seating option (which is not given in case of overcrowding). What needs to be addressed in these remarks is the difference in usage of the seating options. This could imply a multifunctional design which focuses on different user needs and (could) be implicated in favor of a more generalist approach. As now, multifunctional areas for bicycle-users, wheelchairs and foldable seats are all incorporated together, future designs might investigate giving each user-profile its' own designated areas. Areas for families are a good example of this or silent areas on long-distance trains. Options for people preferring to sit alone could be realized as well as areas for larger groups. Thus, making travelling with regional trains a more desirable experience for everyone through separating and addressing different needs at the same time.

As far as handrails are concerned, the participants wanted more handrails, especially on the seats. Even though some participants also said that there were too many handlebars on trains, it seems that the options to hold on should be placed in spots that are sensible and desired by the users and in the quantity required. Otherwise, passengers are potentially seriously endangered when not being able to hold onto something while/ when the train is accelerating or decelerating.

Some participants could agree on the fact that there is not enough information on their respective train ride while being on the train. They suggested a type of display or touchscreen on which they would be able to freely search for information and look for assistance or the staff. Interestingly, the mode the participants voiced was a digital one and not a personal as staff providing information. This might be since people on regional train rides like to decide for themselves when to engage in personal interactions and when to go for the more private digital interactions with a machine. Furthermore, such a digital device promises to cover many different types of information.

Wishes concerning toilets were more toilets on regional trains and disinfectant. On the one hand these *wishes* indicate a need for a higher standard of hygiene on trains. On the other hand, the users' requirements concerning sanitary needs in general on regional trains are not met. This is an inconvenience that should not be the case in modern times train travel as a (clean) toilet being aboard on every public transport should be the standard. If this standard is not reached, it could lead to less individuals using trains in general and regional trains to be more specific. Furthermore, health complications can emerge, especially for groups that are particularly vulnerable to infections, and such caused by insufficient hygiene, e.g. women and children.

Subsequently, on the question of hygiene it was *wished* for disinfectant and wipe dispensers. The other remarks made were two of the few *neutral* remarks. As the participants stated that touching the handlebars and the buttons are not a problem. While some hygienic standards apparently need to be raised, some participants had the perception that the hygiene in some areas is sufficient. This is another situation of differences in opinion.

For the last question the participants gave their opinion on security personnel. While more participants could agree on more security and contact people being needed, some people stated the opposite. This could imply that for some participants there is no need for more personnel or that the personnel in place are not effective. Either way the security concept does not seem to be sufficient or adequate. In addition, there were some more design proposals such as an emergency button to the driver, more compartments, or a continuous train for better visibility. All these propositions can be seen as continuances to the matter of an insufficient security concept and an unpleasant, unsecure atmosphere aboard a train for its' users.

1.2.1.4.3 1.2.1.4.3 Negative remarks

Starting with the first question, the concerns voiced by the participants can be summarized into the point of view, that it seems to be rather difficult to board a train comfortably, with enough personal space, without hurrying and barrier free. This seems to be the case because the doors and the entry area are not fit for the task. Specifically, the tallies and the mechanics of the doors are mentioned to make boarding or alighting especially hard. Doors seem to be too small, too hard to find and do not leave the passengers with enough time to enter or leave the carriage. Therefore, a need for new door concepts addressing these problems seems to be immanent, especially for people that are not as mobile, e.g. the elderly, people with physical incapacities, people in wheelchairs, caregiving people with strollers, and children.

The second question, which was concerned with the seating options, had a variety of *negative* responses. All of which can be patterned roughly into the three subcategories comfort, personal space and functionality of the seating options. While comfort was addressed with general complaints like an overall lack of comfort, remarks were made about specific areas of the seating like lack of legroom, making seats individually adjustable and changing singled out parts of the seats like the headrest. It can be assessed that the standard seating option does not seem to fit the needs of the participants. A need for an adjustable, overhauled version is implicit. For the topic personal space, it is asked for more personal space and an individual and private transportation experience. The folding seats being too close together and the general space concept with four seaters and a table seem to be the main issues here. The last aspect that surfaced was the functionality of the seating option with many participants stating too few options to charge electronic devices or the lack of workstations altogether. The point that was brought up the most was the preference to always sit in the direction of travel, which does not seem to always be possible right now. This could be both a comfort and a functionality issue.

The *negative* remarks to the third question about handrail/ handhold options were made about there being either too many handlebars on the regional train or the handlebars being too high to reach. While this could mean that the number of handlebars impairs the usage of the train interior for one, it also implies the handhold options to be installed only for people who are tall enough to reach them and not for everyone. Shorter people, e.g. women, shorter men, and children, or passengers with physical incapacities as well as the elderly would therefore either endanger themselves while riding regional trains or find themselves excluded from their use altogether because of potential safety concerns or actual safety risks.

On the fourth question the participants were mainly criticizing the looks of the interior design of regional train carriages. While the colors used did not seem to fit their taste or were not calming, it was also noted that the current design was out of time. A new design should be implemented that fits these needs. It should be designed as ‘timeless’ as possible and in a more foresighted approach to be adaptable with design elements and tastes changing throughout the time. Another *negative* remark was that the ceilings are too low. This could also be a reason for an uncomfortable travel experience as too little space can make passengers feel cramped up inside the vehicle.

The *negative* things pointed out about the information systems/ displays can be summarized as the fact that the service in place simply was not good or sufficient. The participants *wished* for it to be larger, better, clearer, and more in general. This part of the design of regional trains can thus be viewed as underdeveloped. A better information service should be mandatory in the future to fulfill the needs for information concerning the respective journey.

Evaluating the toilets on regional trains, most of the participants agreed on the sanitary facilities being too narrow, mostly dirty and sometimes even broken and unusable. As the opinion was rather unanimous, clean and functioning sanitary facilities can be seen to be of great value to travelers and their dissatisfaction with the service as a great disappointment to a level of discomfort that is not acceptable. This should not be the case on a regional train ride and might endanger some passengers’ use of regional trains altogether.

Adding to the concern of sanitary standards, the response to the evaluation of the hygiene onboard mainly resonated in a revulsion towards surfaces that need to be touched on a regular basis during a train ride. A reluctance to touch buttons, handrails and cushions was stated because they did not seem to match the hygienic standards applied by the participants. For one, this could be due to the recent pandemic and the increased awareness concerning hygiene in public spaces and transport. Another valid possibility could be that passengers notice a lack of cleaning in the interior of regional trains as has already been the case with toilets. Even though the opinions were not as strongly supported and unison as with the toilets, it still seems to be a topic that concerns the participants regularly and therefore should be addressed.

Now addressing the topic of interior space, the participants mostly agreed there was too little of such and the space available being too narrow or being often blocked by e.g. bicycles. On the topic of bicycles, it was *wished* for better options to securely store them or a separation of usage altogether. Adding to this theme was the *wish* for less seats in the entrance area. What can be taken out of these responses logically adds up with the points already being made about the demands for a calmer and more private mode of travel on regional trains. With too little space and a mixed usage of this scarce resource, it seems to have a *negative* effect on the passengers’ satisfaction with the service provided.

Penultimately, the luggage storage was assessed purely *negative.* It was either viewed as not secure enough, because of for example its’ positioning out of the customers’ sight. Or accessibility was an issue as the storage seemed to be out of reach and too high above or lacking in the first place in the participants' eyes. In this context the remark was made that luggage is taking seating space, which could be the case if the destined space is missing. These concerns are all voicing a clear dissatisfaction with the current situation and are showing that customers are not even able to use the luggage storage options in place. This is pointing in the direction of luggage storage of the future that should be close to the customers and be easily accessible in size and form or height, respectively.

Lastly, some negative remarks about the safety on regional trains have been made. Interestingly, the topics addressed concerning safety were of quite a variety. The access to the train was assessed as suboptimal because of the large distance between station and train, missing handrails to hold onto, slippery or uneven floor and a lack of space in areas with tables was noted. Nevertheless, this category was one of the few which was not solely negatively connotated. However, the negative remarks had been made in other categories before and should therefore be taken very seriously.

1.2.1.5 Conclusion

The results of the FGDs give a deeper and detailed perspective on user experience riding regional trains in Germany and their perception of the interior design of regional train carriages. The most important services while using regional trains were assessed by applying a user journey starting from the moment of embarking over crucial facets of user needs like seating options, safety during rides, sanitary facilities, and luggage storage to the alighting off the vehicle.

The picture painted throughout this process depicted room for improvement in the services of regional trains as the remarks were vastly *negatively* connotated or fell into the *neutral/ wish category*. While there were some *positive* comments on a few of the topics mentioned above, in most of the cases the interior design either did not fit the users' needs accurately or the desired services were found to be missing altogether. The results of the FGDs show a variety of shortcomings in the interior design of regional trains that impair its' use. Especially some distinct groups are currently not able to use the service to its' fullest, these being women, caregiving individuals, elderly people, people with physical incapacities and children. While these insufficiencies sometimes make the ride with regional trains uncomfortable for said user groups, it often seems to be an unpleasant, at times unacceptable and even endangering experience. As FutuRe aims to gather information about such deficits and is committed to enhance sensible and necessary change in the field, the FGDs conducted should be a useful source of insight and can lead to qualitative as much as quantitative change in the design of regional trains in Europe and arguably worldwide.

1.2.2 Survey research

1.2.2.1 Introduction

Instytut Kolejnictwa (IK - Railway Research Institute) in cooperation with PKP S.A. participates in the international project entitled "Delivering innovative rail services to revitalize capillary lines and regional rail services", the overall objective of which is to ensure the long-term viability of regional rail. The project also aims to increase customer satisfaction and make rail an attractive and preferred mode of transport.

One of the elements of the tasks carried out by the IK in this project is to conduct surveys among regional railway passengers regarding their expectations in the scope of the interior equipment and construction solutions of the rolling stock dedicated to serving regional traffic. As part of this task, the IK conducted a survey among passengers travelling on regional trains operated by Łódzka Kolej Aglomeracyjna Sp. z o. o. and POLREGIO S.A. on the Tomaszów Mazowiecki - Opoczno / Drzewica / Spała routes.

1.2.2.2 Place of conducting survey research

The project included three quantitative surveys on the following samples:

− sample of 60 persons on the Tomaszów Mazowiecki – Opoczno – Tomaszów Mazowiecki route,

− sample of 37 persons on the Tomaszów Mazowiecki – Drzewica – Tomaszów Mazowiecki route,

− sample of 22 persons on the Tomaszów Mazowiecki – Spała – Tomaszów Mazowiecki route.

A total of 119 completed questionnaires were obtained for further analysis. Above mentioned regional railway routes are located in the central of Poland in the Łódź Voivodeship (Figure 1.) and include the following cities:

− Tomaszów Mazowiecki: a city with approximately 59k inhabitants (according to data of 31.12.2021),

− Opoczno: a city with approximately 21k inhabitants (according to data of 31.12.2019),

− Drzewica: a city with approximately 3,8k inhabitants (according to data of 31.12.2019),

− Spała: a small town with approximately 500 inhabitants (according to data of 31.12.2019).

Figure 26 : Regional railways around Tomaszów Mazowiecki, Opoczno, Drzewica, Spała

Data concerning infrastructure, rolling stock and the time of conducting surveys are included in Table 1 and in the figures Figure 2 to Figure 4.

Table 2 : Data concerning infrastructure and rolling stock (Source: https://portalpasazera.pl., self-verification)

Route	Date of the survey	Route length	Number of intermediate stops	Rolling stock	Carrier
Tomaszów Mazowiecki – Opoczno	31.05.2023	26, 2 km	5	36WEha	ŁKA Sp. z o. o.
				214Mb (SA135)	POLREGIO
Tomaszów Mazowiecki – Drzewica	13.06.2023	36 km	5	L-4268 (2-car)	ŁKA Sp. z o. o.
Tomaszów Mazowiecki – Spała	29.07.2023	8,6 km	0	36WEha	ŁKA Sp. z o. o.

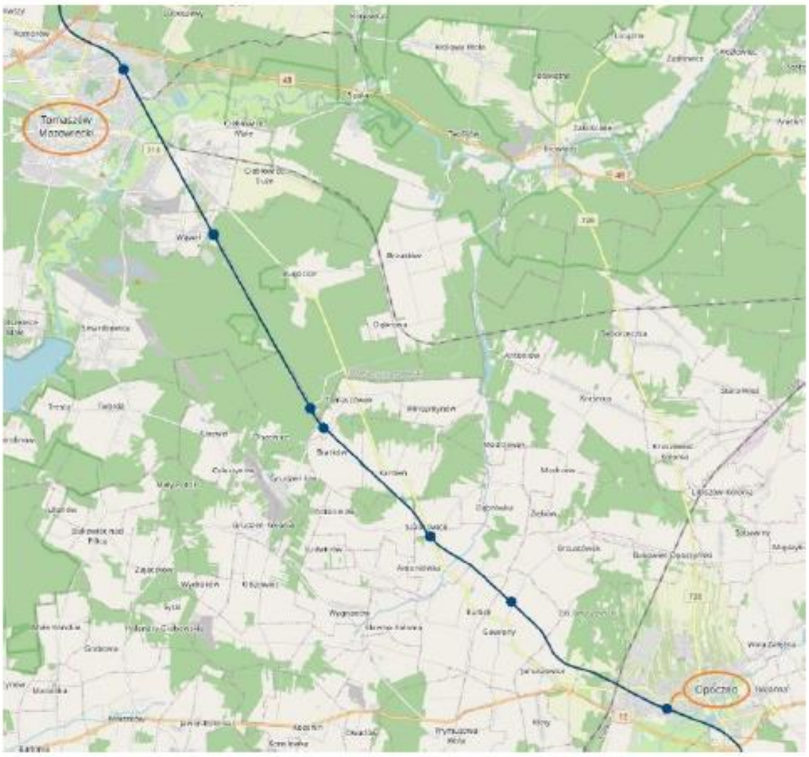


Figure 27 : Route Tomaszów Mazowiecki – Opoczno

Figure 28 : Route Tomaszów Mazowiecki – Drzewica

Figure 29 : Route Tomaszów Mazowiecki – Spała

1.2.2.3 Surveys

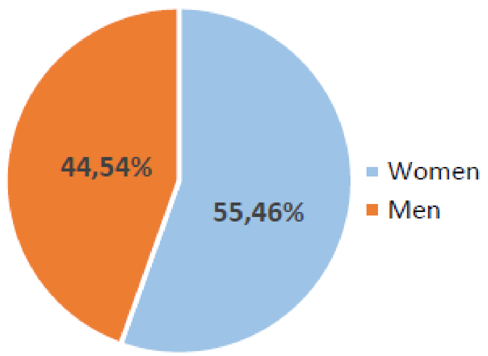
The survey questionnaires, were completed independently by travellers or by interviewers based on the answers provided by respondents. In the first part, the interview form consisted of a personal information sheet, the purpose of which was to find out the gender and age of the respondent with additional question regarding any possible disability and included purposes for which she or he was traveling by train. To get to know the preferences of travellers, 15 questions with the choice of proposed answers and the possibility of own comment, as well as a few supplementary questions regarding the evaluation of the current journeys were used.

1.2.2.4 Results of the conducted surveys

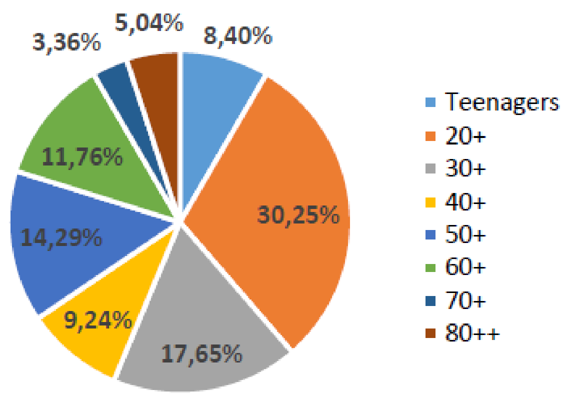
The answers contained in the survey were transferred to the Excel program. After ordering the answers, a percentage analysis was performed and shown in the Graphs.

1.2.2.4.1 Structure of the survey sample

The surveys were completed by 119 persons, 55% of whom were women and 45% men (Graph 1). The respondents were persons of various ages, ranging from teenagers to seniors over 80 years old (Graph 2).

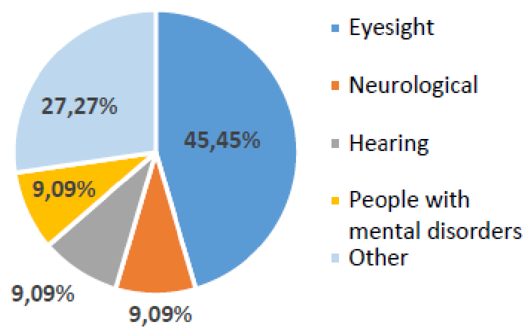


Graph 1. Gender of respondents



Graph 2. Age of respondents

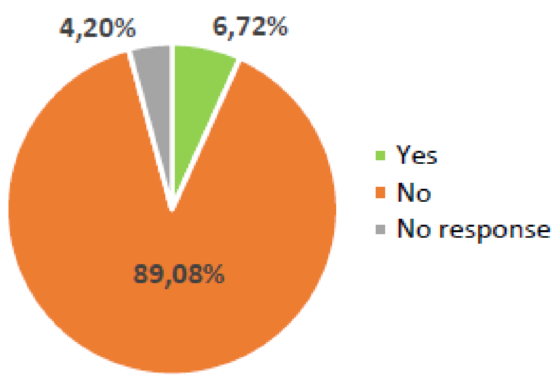
Eleven people indicated disability, which constituted less than 10% of the entire study sample. Graph 3 shows categories of disabilities indicated by passengers.



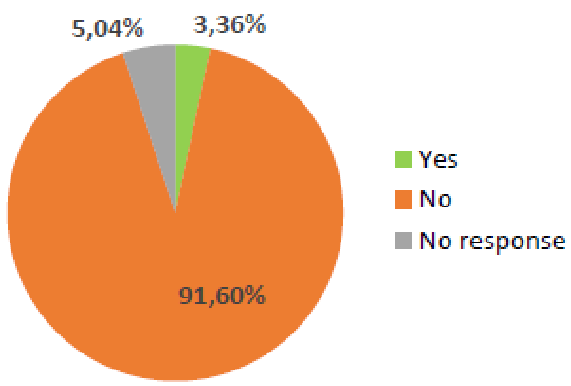
Graph 3. Disabilities of the respondents

Passengers with specific expectations

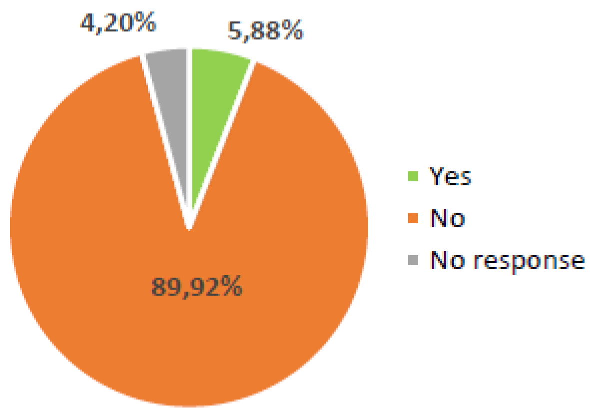
The group of passengers with specific expectations includes, among others, people with disabilities, carers travelling with children and prams or people traveling with bicycles (Graphs 4 to 6). In total, during three surveys, there were 15 persons travelling with a child, pram or bicycle, which is 12%. Three of these 15 persons, which is 20% of them (and 2.5% of all respondents), indicated that they travel with both a child and a bicycle.



Graph 4. Persons travelling with a child



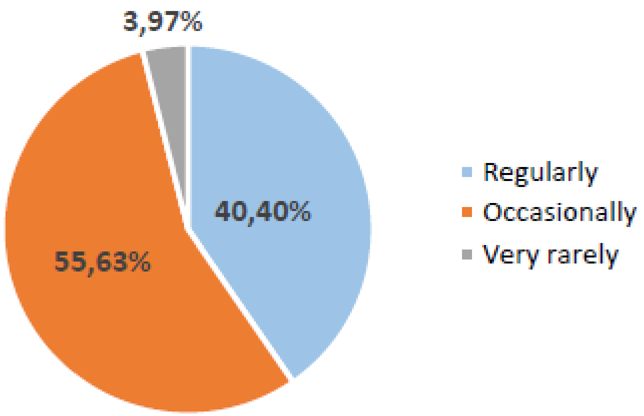
Graph 5. Persons travelling with a pram



Graph 6. Travelling with a bicycle

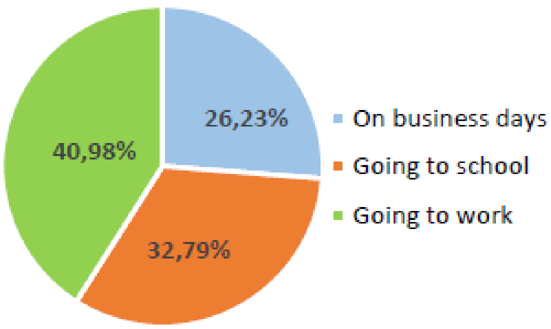
Frequency and purpose of travel

Among the respondents, more than half, i.e. 56%, travel by rail occasionally, 40% use this mode of transport regularly, and only 4% of respondents very rarely (Graph 7).

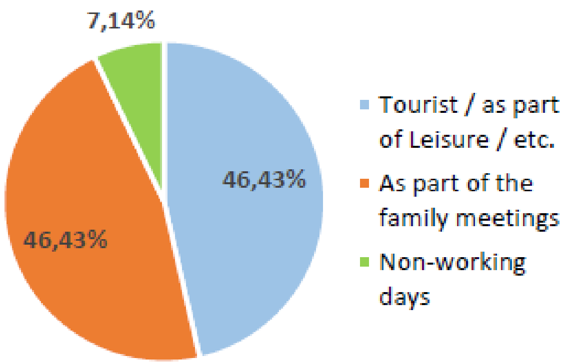


Graph 7. Frequency of travel by train

According to the respondents' answers, regular travel results mainly (less than 74%) from the need to realize everyday duties, like travelling to school or work (Graph 8). On the other hand, occasional travel (Graph 9) are mainly caused by the need to travel for tourism and leisure purposes and to keep family contacts, each of them 46%.



Graph 8. Reasons for travelling regularly



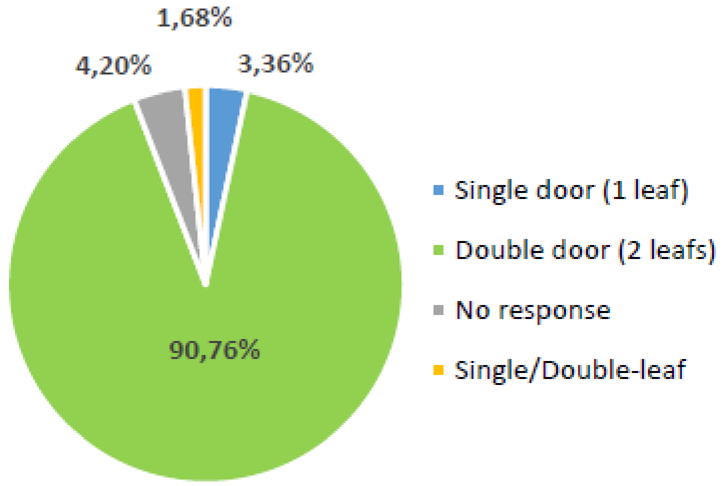
Graph 9. Reasons for travelling occasionally

1.2.2.4.2 Passengers expectations to the design and interiors solutions of the vehicle

The main part of the survey included questions about passengers' preferences related to boarding and alighting the vehicle, travel comfort and additional amenities.

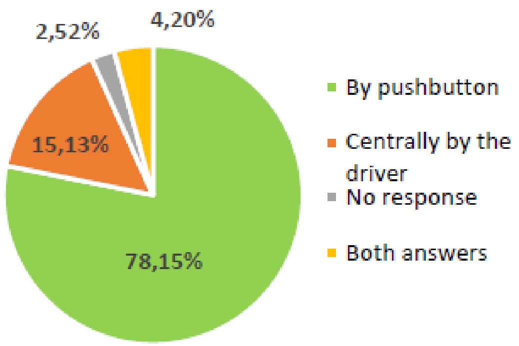
A – Boarding and alighting

The first questions in this part of the questionnaire concerned the entrance door system. The vast majority of respondents, over 90%, would prefer to use double-leaf doors, just over 3% prefer single-leaf doors, for the rest of the respondents it does not matter or did not give any answer (Graph 10).

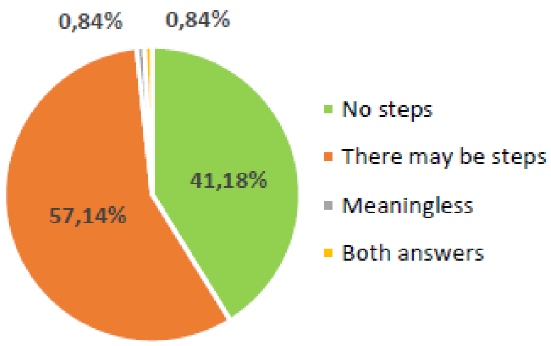


Graph 10. Door width

From the answers given by passengers regarding preferred way to open entrance door (Graph 11) it can be seen that a large majority of respondents (78%) prefer doors to be opened using dedicated pushbuttons, while only 15% of respondents prefer central opening by the driver. For the remaining less than 7% of passengers, this issue is less important.



Graph 11. Preferences to way of opening the door

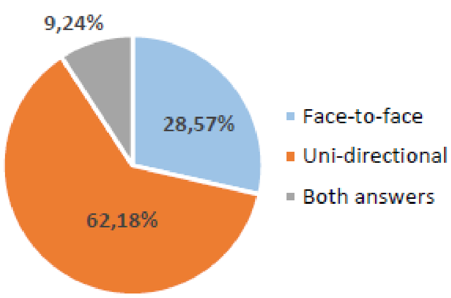


Graph 12. Preferences to entrance step

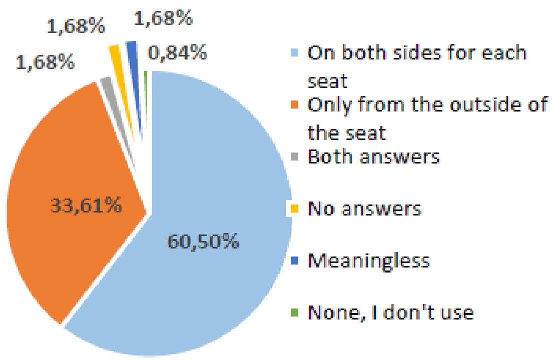
As Graph 12 shows, the presence of steps into the vehicle is accepted by less than 58% of travellers, with just over 41% indicating the need for a stepless/level boarding and alighting.

B – Seats

Seat preferences on the train are included in the answers to two questions. They concerned the positioning of the seats relative to each other and equipping them with armrests. Out of 119 respondents, 74 persons answered that they preferred uni-directional seats (>62%), 34 people chose face-to-face seats arrangement (>28%), while 11 surveys (>9%) indicated both answers (Graph 13).



Graph 13. Arrangement of passenger seats

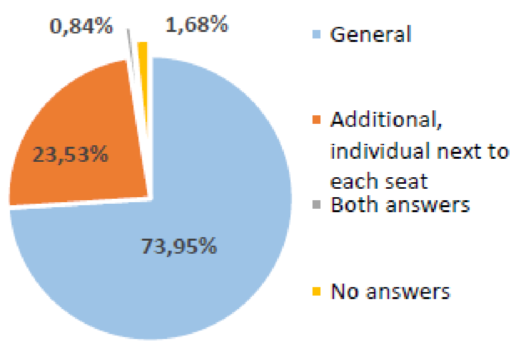


Graph 14. Location of armrests

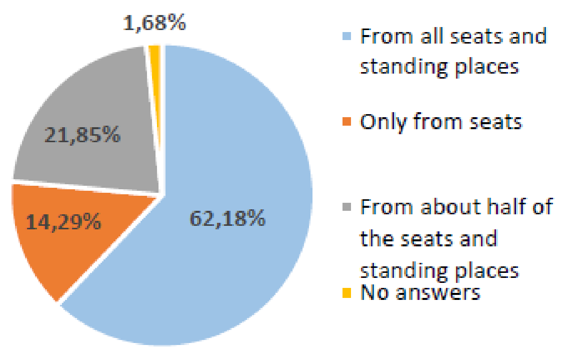
When asked about the location of armrests on seats (Graph 14), 60% of respondents said that they prefer armrests on both sides of each seat, which is most likely related to the feeling of having their own, separate space, and thus increasing travel comfort. Almost half less of the respondents (less than 34%) indicate that the armrests are sufficient only on the outside of the seat, and the remaining less than 6% of the respondents do not pay attention to their placement.

C – Interior lighting and visibility of information displays

In the opinion of almost 74% of respondents, lighting inside the train can only be achieved using general lighting (Graph 15). However, just over 23% of travellers indicate the need to install additional, individual lamps for each seat.



Graph 15. Interior lighting

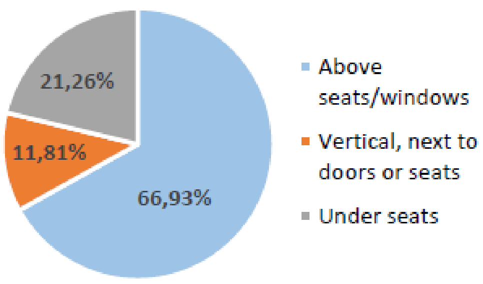


Graph 16. Visibility of internal information displays

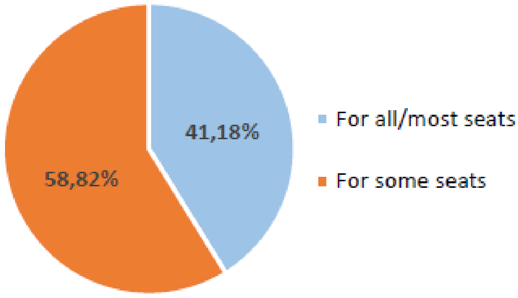
D – Facilities for travelers

The survey also attempted to determine travellers' preferences regarding the presence, location and type of additional vehicle equipment or separate spaces, such as luggage racks, tables, toilets, places for bicycles and prams, or places for caregivers with children or pets. As Graph 17 shows, 2/3 of travellers (67%) prefer luggage racks above seats. About 21% of respondents indicated the wish to leave luggage under the seat, and "only" less than 12% of passengers prefer to leave luggage on vertical racks next to doors or seats.

In the next point of the survey, respondents were asked for their opinion on the availability of tables. As we can see in Graph 18, for most travellers (59%) tables do not have to be within reach of all/most seats, as indicated by 41% of respondents.



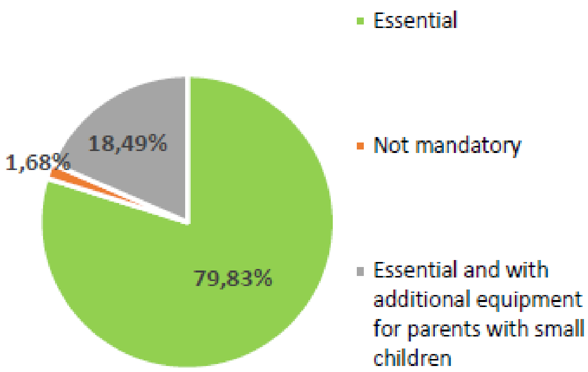
Graph 17. Luggage racks (multiple answer)



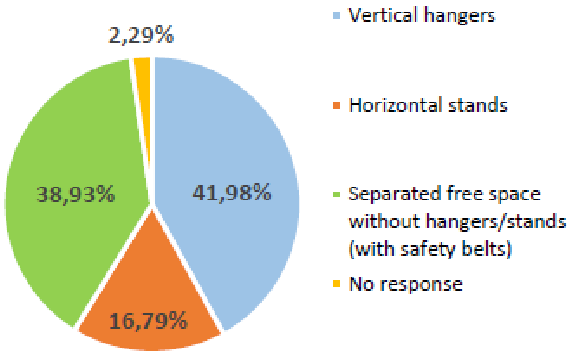
Graph 18. Availability of tables

Almost all passengers (99%) indicated that a toilet on-board is necessary (Graph 19). Some of these people (less than 19%) also pointed to the need to equip toilets with a changing table for small children.

Assuming that newly designed passenger vehicles should provide space for transporting bicycles, based on one of the survey questions, we wanted to obtain an answer regarding equipping this space with preferred elements for holding bicycles (Graph 20). Almost 42% of respondents answered that these should be vertical hangers for vertically suspending a bicycle, almost the same number of respondents (39%) think that it should be a free space without retaining elements (the most of persons who marked this answer were women for whom hanging a bicycle is not comfortable solution), while 17% of respondents think that horizontal stands should be the right elements.

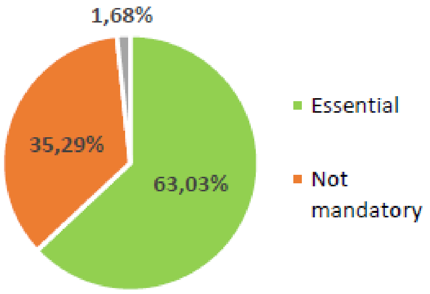


Graph 19. Toilet

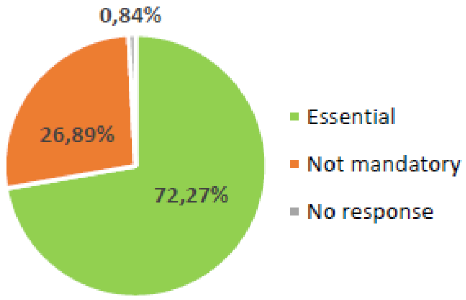


Graph 20. Equipment of bicycles spaces

Based on two subsequent Graphs (Graph 21 and Graph 22), we note that for all respondents, not only with specific expectations, person travelling with a child and a pram should have access to a dedicated seat and a separate parking space for the pram - over 63% and 72% of indications as necessary equipment, respectively.

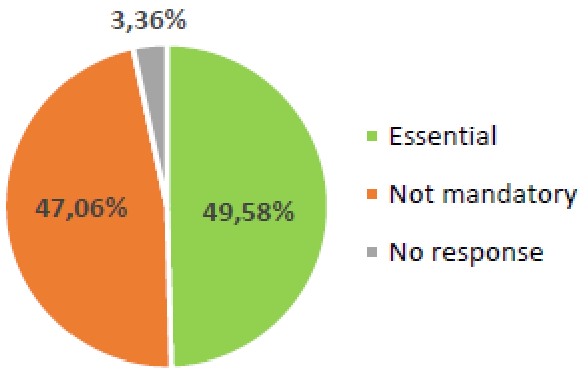


Graph 21. Dedicated place for person with small children



Graph 22. Separate place for a pram

Simultaneously, the next question shows (Graph 23) that travellers do not clearly indicate (less than 50% of the votes) nor do they notice any particular need (about 47% of the votes) to allocate space in the vehicle for persons travelling with pets.



Graph 23. Separate places and space for person travelling with pets

E – Additional equipment

The survey also included the option of multiple selection of preferred elements of additional vehicle equipment, from a list of six elements such as a 230V socket, a USB port, a mobile signal amplifier, a ticket vending machine, Internet/ WiFi access and vehicle interior supervision via a monitoring system (Figure 30).

The largest number of respondents indicated the need to use a 230V socket during the journey (almost 74%) and the Internet (approximately 57%). It also seems to be important for passengers to be able to buy a ticket from an on-board device, as indicated by about 55% of respondents.

The remaining proposed elements of vehicle equipment, i.e., a USB port, a mobile signal amplifier and monitoring, should be built into the vehicle in the opinion of approximately 42-43% of passengers.

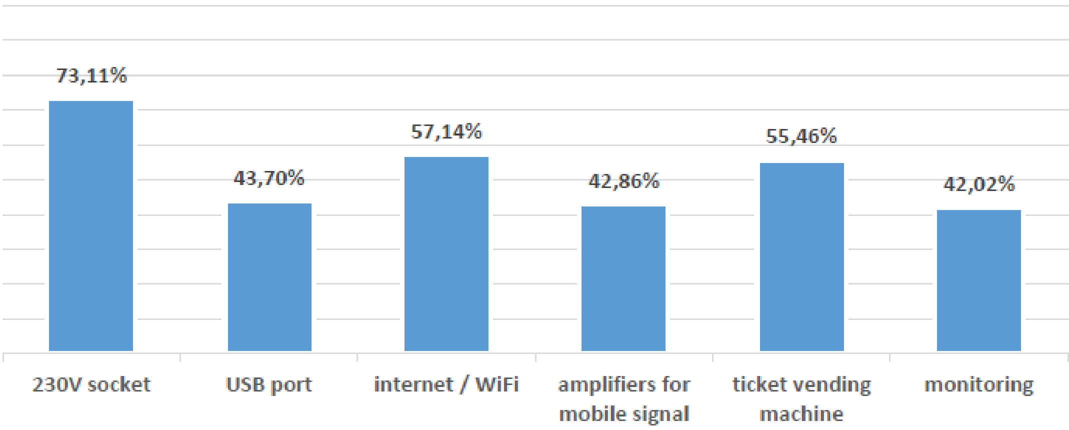


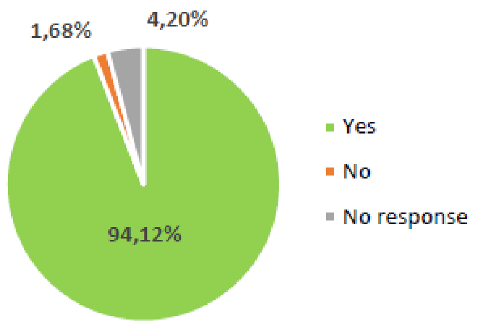
Figure 30 : Additional onboard equipment

1.2.2.4.3 General assessment of current regional train journeys

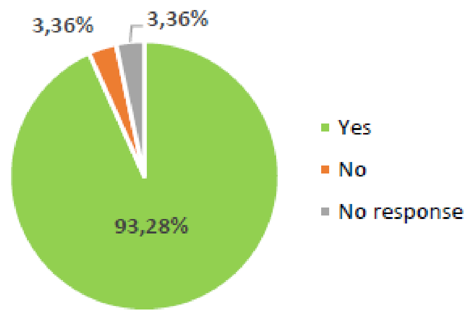
Assuming that the above detailed questions were intended to show respondents' expectations for future journeys, the final part of the survey included three supplementary questions that assessed the current feelings of comfort and safety when travelling by regional train.

Most of travelers (94%) think that they can use current trains easily and efficiently (Graph 25). In some cases, there were additional, positive comments confirming the above statement, including: adapting trains to the needs of disabled people, punctuality, high level of services provided.

In the opinion of 93% of respondents, vehicles currently in service are perceived as functional and comfortable (Graph 26). It was also noted that this is often new, good quality rolling stock, characterized by comfortable seats with adequate legroom and an air-conditioned interior.

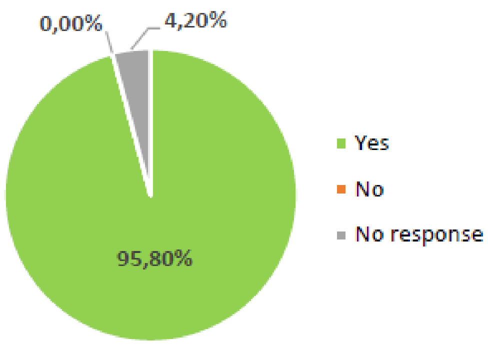


Graph 25. Do you think that the current trains can be used easily and efficiently?



Graph 26. Do you think that the current trains are functional and comfortable?

Passengers were also asked about the feeling of safety on the train (Graph 27), to which over 95% of respondents responded positively, while at the same time no answer was negative. Additional comments show that trains equipped with cameras and constant presence of the conductor gives passengers a further sense of peace.



Graph 27. Do you feel safe on the train?

1.2.2.5 Summary of survey results

As data on the structure of the survey sample show, during three surveys it was possible to obtain opinions from passengers who could represent a large majority of the population, because the respondents use railways both regularly (45%) and occasionally (55%), the gender breakdown was similar and it was 45 to 55%, the age range included teenagers, young people, middle-aged people and seniors and some of them belonged to the group of passengers with specific expectations - they were people with disabilities, with small children/prams or traveling with bicycles.

To summarize received passengers' opinions, the design of a small, light rail vehicle intended for use in regional traffic should consider:

- double-leaf entrance door, open by pushbutton, with permissible overcoming of the step,
- seats arranged mostly in one direction, but some of them also face-to-face, mostly equipped with armrests on both sides,
- luggage racks located above the seat,
- tables available for more than half of the seats,
- general lighting, with some seats equipped with additional, individual lights,
- visibility of information displays from all seats and standing places,
- toilet, that must be accessible to a wheelchair user,
- 230V power socket, Internet / WiFi and a ticket vending machine,
- dedicated seats and space for a person with a child and a pram,
- bicycle spaces equipped with vertical hangers or without retaining elements.

When analysing the answers to the final questions, it was noticed that respondents observed many positive changes. Trains are generally rated as comfortable and safe. During the interviews, there were also cases of dissatisfaction, mainly because of insufficient number of connections between individual towns and overcrowded trains during peak hours.

1.2.3 Integrated discussion and conclusion

Taken together, the findings from the FGDs shed light on the user experience of riding regional trains in Germany, particularly focusing on the interior design of regional train carriages. Those results were enhanced by the surveys among regional railway passengers regarding their expectations in the scope of the interior equipment and construction solutions of the rolling stock dedicated to serving regional traffic in Poland.

The overarching observation from the FGDs study in Germany is a predominantly negative sentiment expressed by participants regarding several aspects of regional train services. The analysis of responses to valanced questions revealed a noticeable negative connotation in most of the feedback, with only a few instances of positive remarks. Safety concerns, seating arrangements, hygiene, and limited information services were among the key areas of discontent. The study highlighted specific user groups, including women, the elderly, individuals with physical incapacities, caregivers with strollers, and children, facing challenges in utilizing regional train services to their fullest potential. The results underscore the need for substantial improvements in the design of regional trains to address the identified shortcomings and enhance the overall user experience.

More specific the survey results indicate that it is important for passengers of regional trains that the design and equipment of the vehicle include wide doors open by pushbutton, properly distributed general lighting, separate places for people with children and for prams, uni-directional seats with armrests on both sides and luggage racks above, visibility information from all areas in the vehicle and the presence of a toilet and power sockets for electronic equipment.

Lastly, the contrasting results obtained from the FGDs in Germany and the quantitative surveys in Poland concerning the general evaluation of regional lines provide an intriguing perspective on the user experience. The predominantly negative sentiment expressed by participants in the German FGDs, highlighting concerns about safety, seating arrangements, hygiene, and information services, presents a stark contrast to the overwhelmingly positive assessments from the Polish surveys. The dichotomy in feedback suggests a potential divergence in user expectations and satisfaction levels between the two regions. The German study emphasized specific challenges faced by various user groups, including women, the elderly, individuals with physical incapacities, caregivers with strollers, and children. These findings underscore the pressing need for substantial improvements in the design of regional trains in Germany to better cater to the diverse needs of passengers and enhance overall satisfaction.

In contrast, the positive evaluations from the Polish surveys indicate a higher level of contentment with the comfort and functionality of the rolling stock currently in service. This contrast of the survey responses in relation to discussions in focus groups may result from the fact that in recent years modern vehicles have been introduced in a given research region that complying with technical requirements that significantly increase the comfort and safety of travelers (TSI regulations), and which replaced obsolete vehicles with low travel comfort. Reported individual cases of passenger dissatisfaction resulted mainly from reasons attributable to the organization of transport, such as an insufficient number of connections, unfriendly timetable or overcrowding of vehicles during peak hours.

This follows, when improving regional line services based on user feedback, users will be more satisfied with regional line services. Considering FutuRe's goal to bring about meaningful change in the field, the insights gained serve as a valuable resource for informing both qualitative and quantitative advancements in the design of regional trains, not only in EU but potentially on a global scale.

1.2.4 Design implications for future regional trains

Based on the findings of the FGDs as well as the survey, design implications were derived for future regional train design. Those design implications concern different aspects of regional trains, such as doors, luggage storage and more.

It is important to stress that these proposals are based on the expectations of the passengers surveyed and may differ from the specifications adopted for the train designs (in particular because of cost constraints and especially on the subject of toilets).

These results are shared for information purposes.

Boarding & alighting: Participants indicated specific preferences for how boarding and alighting could be improved.

These are:

• Level boarding for entry and exit

• Automatic ramps if someone wants to enter with a pram or wheelchair or is mobility impaired

• Better a small gap than steps between train and platform

• System that indicates: let passengers alight first e.g. a traffic light

• Warning button to indicate that you want to alight (“stop on request” pushbutton)

• Doors:

o Double doors

o Wide doors

o Door opening by pushbuttons or automatic door opening

o Separate doors for entry and exit

o Longer opening time

o Door in signal/contrasting colour

o Easy to find: e.g. by an easy-to-understand guiding system

Seats: Participants indicated specific recommendations on how seats could become e.g. more comfortable. Those recommendations are:

• Mix of different arrangements of seats and standing options ○ four-seater/ with tables

o double seats

o (transverse) folding seats

o more seats than standing options

o less four-seater then two-seater

o standing places with backrest/ leaning options

• More comfortable seats, e.g. headrests/ backrest

• Armrests on both sides of each seat: no fighting for the middle-armrest/ touching strangers

• Seats in the direction of travel

• Privacy: passengers prefer to sit alone or in a two-seater/ not facing strangers

• More legroom

• Adjustable seats, e.g. direction of travel, height, length, width

• More free space between folding seats

• Adjustable armrests

Handles: Where and how participants can hold onto during the ride is of great importance as it should ensure passengers' safety. Participants indicated some ideas for improvements, which are:

• More handles/ handrails to hold onto

• Handles on seats

• Lower Handlebars

Interior design: The general appearance and design of regional trains could be improved, for example by:

• More space in general

• Accessibility throughout the whole carriage

• Focus on comfort, more than functionality

• Functioning air-conditioner/ heating system with a comfortable warmth

• More storage space (not only for luggage)

• Secure fastening options for e.g. bicycle, wheelchairs, prams

• Separate bike and passenger area

• Different/ prettier/ calming color design

• Prefer double-decker trains: better view, better distribution

• Higher ceiling

• Modern interior design

• Brightness and good lightning

• Some additional individual lights at seats

• More workstations/ workplaces configurations

  o More power sockets

  o USB ports

  o Internet/ WiFi

  o Amplifiers for mobile signal

• Dedicated space for parents with small children

• Dedicated space for bikes/ prams/ wheelchairs or other equipment

Information systems display: For passengers' sufficient information is very important to be able to foresee their trip. The participants recommended the following potential improvements:

• Larger, more informative, more often available, clearer information displays

• Touchscreen: the ability to search for things

• Should indicate where staff, assistance can be found

• Should be visible from all standing and sitting positions

General hygiene: Providing clean regional lines is of great interest to passengers. Therefore, the participants wish for the following improvements:

• General hygiene must improve

• Buttons and handles must appear/ be more hygienic

• Cushions/ coverings must appear/ be more hygienic

• Disinfectant/ wipe dispensers should be provided for passengers

• Preferred: leather covering/ wipeable surfaces

Toilets: The provision of toilets is a sensitive topic, linked to passenger's satisfaction. Passengers would like the following improvements of toilets:

• Cleaner

• Larger

• Should always be provided

• Disinfectant should be available

• Functioning toilets – faster repair of broken toilets

• Additional equipment for parents with small children/ babies should be available

Luggage storage: Passengers value the option to store luggage safely, but also e.g. easy reachable storing options. Accordingly, participants wish for the following improvements:

• More spaces for luggage storage

• Different luggage storage options

  o Lower luggage storage space

  o Lockable luggage storage space

  o Over-head storage space

  o Space under the seats

  o Vertical racks next to seats

Safety: Generally speaking, passengers should feel safe and secure on regional lines. To enhance this feeling, passengers wish for the following improvements:

• More security personnel/ contact persons

• Emergency button to the driver

• Less slippery/ uneven floor

• Less distance between train and station

• More compartments

• A continuous/open train for better visibility

• In a two- or four-seater: it is difficult to escape when sitting on the inside seat next to the window

1.3. Legal framework analysis and recommendations

Technical Specifications for Interoperability

The TSIs are set out in European Directive 2016/7971 adopted by the European Parliament and the Council of the European Union on the interoperability of the European rail system.

This directive divides the rail system into 8 subsystems:

- Infrastructure
- Traction energy
- Control-command and signalling on track
- Control command and signalling onboard
- Rolling stock
- Traffic operation and management
- Maintenance
- Telematic applications for passenger and freight services.

Each subsystem is addressed by one or more TSIs which set out the essential requirements applying to the systems and subsystems. They do not cover all the regulatory requirements, but when they do for the fields they cover, they take precedence over national texts.

The role of the TSIs can therefore be summarised as follows, for each subsystem:

- Specify the essential requirements (of which safety is one),
- Set the basic parameters,
- Determine the necessary technical specifications, for constituents and interfaces,
- Specify:
    - The conditions for assessing conformity with the TSI,
    - The implementation arrangements and any conditions for non-application of the TSIs (open points, specific cases, national rules).

The rail system operating on a core network line and governed by Safety Decree no. 2019-525 (DSI) must comply with the TSIs.

After the TSIs are updated in 2023, the list of TSIs is as follows:

- CCS, Control Command Signalling,
- TAF, Telematic Applications for Freight,
- Noise
- SRT, Safety in railway tunnels,

- Loc&Pas, Locomotives and passenger equipment,
- ENE, Energy,
- PMR, Accessibility, disabled people and PRMs,
- WAG, Freight wagons,
- OPE, Exploitation Gestion du Traffic,
- TAP, Telematics Applications for Passengers,
- INF, Infrastructure.

Within the framework of a project (Rolling Stock or Infrastructure), the subsystems must comply with the TSIs and national rules in force at the time of the application for authorisation to place in service. The possibilities for derogation are limited (Directive 2016/797, art. 7):
- Project where deployment is at an advanced stage (Case 1),
- Emergency (accident or natural disaster, etc.) (Case 2),
- The economic viability of the project is at risk (Case 3),
- Vehicles from countries with a different gauge (Case 4),
- Landlocked network or separated by the sea (Case 5).

And difficult to obtain:
- Cases 1, 3, 4 and 5: the Member State submits the application to the Commission, with documentation,
- Cases 3 and 4: Examination by the RISC committee and opinions from the other Member States.

This takes between 4 and 11 months.

Another possibility is to request changes to the TSI on the grounds of innovation. This is permitted under Article 10 of each TSI:

Article 10
1. In order to keep pace with technological progress, innovative solutions may prove necessary which do not comply with the specifications defined in the annex and/or to which the assessment methods described in the annex cannot be applied. In such cases, new specifications and/or new assessment methods associated with these innovative solutions are developed.
2. Innovative solutions may relate to the rolling stock subsystem, its parts and its interoperability constituents.
3. When an innovative solution is proposed, the manufacturer or his authorised representative established within the territory of the Union shall declare how it derogates from or supplements the corresponding provisions of this TSI and submit them to the Commission for analysis. The Commission may ask the European Railway Agency (hereinafter referred to as the Agency) for its opinion on the proposed innovative solution.
4. The Commission shall give an opinion on the proposed innovative solution. If the opinion is favourable, the appropriate functional and interface specifications and the assessment method to

be incorporated in the TSI to enable the use of this innovative solution shall be developed and then incorporated in the TSI during the review process in accordance with Article 5 of Directive (EU) 2016/797. If the opinion is unfavourable, the proposed innovative solution may not be applied.
5. Pending the revision of the TSI, the favourable opinion issued by the Commission shall be considered as an acceptable means of compliance with the essential requirements of Directive (EU) 2016/797 and may therefore be used for the assessment of the subsystem.

One of the aims of Task 5, and of the FP6 FutuRe project in general, is to assess the relevance of TSI to the technical and economic issues specific to regional lines and to provide inputs for eventual evolution of those regulation texts.

The elements presented are the result of analysis carried out by the WP5 contributors to identify any incompatibilities between the requirements of the TSIs and the specific needs.

In the following tables, extract from TSI will be inserted (left column) and the comment, suggestion or need for additional studies will be added (*right column*).

1.3.1 TSI Loc&Pas

Power and traction

4.2.8.1 Traction Performance	*There is no categorization of hybrid vehicles defined in the TSI.* ***Power Supply (4.2.8.2.1 - 4.2.8.2.8):*** *- Explore advancements in power supply technologies, such as the integration of renewable energy sources, energy storage systems, or advanced power electronics.* ***Electric Motor (not explicitly mentioned):*** *- Evaluate the need to include requirements or recommendations for electric motor combinations and their integration with the overall electric unit system.* *- Consider emerging technologies like hybrid or all-electric propulsion systems and their impact on the standard.*

	***To update the standard and include the possibility and standard of using the ground-based electric road system, it may consider adding a new section or modifying the existing sections related to power supply and pantographs. (Article 10 Innovative solutions)*
4.2.8.2 Power Supply 4.2.8.1.2 (10) A failure of a power supply device affecting the propulsion power shall not cause the unit concerned to lose more than 50 % of its propulsion power.	*4.2.8.1.2 (9) -The text doesn't explain the safety or performance implications of these limits. Consider adding a sentence on how maintaining appropriate adhesion contributes to operational safety and efficiency.* *4.2.8.1.2 (10) - The text mentions a limit on traction force loss in case of a power equipment failure, but it doesn't elaborate on the reasoning behind the 50% limit.*
4.2.8.2.1 4.2.8.2.1 General (1) The requirements described in this clause apply to rolling stock and interface with the energy subsystem. This clause 4.2.8.2 therefore applies to electrical units. (2) The CR ENE TSI defines the following power supply systems: AC 25 kV 50 Hz system, AC 15 kV 16,7 Hz system, DC 3 kV system and 1,5 kV system. Therefore, the requirements defined below apply only to these four systems and references to standards also apply only to these four systems.	*4.2.8.2.1 (1) - However, it might be beneficial to highlight any potential future considerations or developments that could impact these systems to ensure the text remains relevant in the long term. This would add a forward-looking perspective to the text.* *4.2.8.2.1 (2) - How to identify the requirements for other systems? For example, 1 kV system*
4.2.8.2.2 Operation within range of voltages and frequencies	*4.2.8.2.2 (2) - It might be helpful to clarify whether this information is for monitoring purposes or if there are operational adjustments that can be made based on this data.*
4.2.8.4 Protection against electrical hazards	*4.2.8.4. - As technology evolves, it is essential to consider the longevity and adaptability of the specified provisions.*

4.2.8.2.5 Maximum current consumption at standstill for DC systems (1) For DC systems, the maximum current consumption at standstill per pantograph shall be calculated and verified by measurements. (2) Limit values are defined in clause 4.2.5 of the ENE TSI. (3) The measured value and the measurement conditions related to the contact wire material shall be recorded in the technical documentation referred to in clause 4.2.12.2 of this TSI.	*Additional studies need to be done on the article regarding the project.*
4.2.8.2.9.5 Pantograph static contact force (interoperability constituent level) (1) The static contact force is the vertical force transmitted upwards from the pantograph head to the contact wire and exerted by the traction unit when the pantograph is raised and the vehicle is stationary. (2) The static contact force exerted by the pantograph on the contact wire as defined above shall be adjustable at least within the following ranges (depending on the application of the pantograph): - 60 N to 90 N for AC systems, - 90 N to 120 N for 3 kV DC systems and - 70 N to 140 N for 1,5 kV DC systems.	*Additional studies need to be done on the article regarding the project.*
4.2.8.2.9.10. Pantograph lowering (on-board) (1) Electric units shall be designed to lower pantographs to the dynamic insulation distance in a time period complying with the requirements of clause 4.7 (3 seconds) of the specification referenced in Appendix J-1, index 51, and in accordance with the specification referenced in Appendix J-1, index 52, where the lowering is triggered either by the driver or as a result of a train control function (including control-command and signalling functions)	*Automatic loading not included in the TSI. Charging needs to be initiated by the train driver.*

Braking

4.2.4.2.2. Safety requirements	*Additional studies need to be done on the article regarding the project and limited space on a smaller train.*
4.2.4.7 Dynamic brake — Braking system linked to traction system Where the braking performance of the dynamic brake or of braking system linked to the traction system is included in the performance of the emergency braking in normal mode defined in clause 4.2.4.5.2, the dynamic brake or the braking system linked to traction: (1)Shall be commanded by the main brake system control line (see clause 4.2.4.2.1). (2)Shall be subject to a safety analysis covering the hazard 'after activation of an emergency command, complete loss of the dynamic brake force'. This safety analysis shall be considered in the safety analysis required by the safety requirement N° 3 set out in clause 4.2.4.2.2 for the emergency brake function. For electric units, in case the presence on-board the unit of the voltage delivered by the external power supply is a condition for the dynamic brake application, the safety analysis shall cover failures leading to absence on-board the unit of that voltage. In case the hazard above is not controlled at the level of the rolling stock (failure of the external power supply system), the braking performance of the dynamic brake or of braking system linked to the traction system shall not be included in the performance of the emergency braking in normal mode defined in clause 4.2.4.5.2.	*Additional studies need to be done on the article regarding the project and limited space on a smaller train.*

4.2.4.8. Braking system independent of adhesion conditions	*Additional studies need to be done on the article regarding the project and limited space on a smaller train.*

Running Gear

4.2.3.5.1. Structural design of bogie frame (1)For units which include a bogie frame, the integrity of the structure of the bogie frame, axle box housing and all attached equipment shall be demonstrated based on methods as set out in the specification referenced in Appendix J-1, index 20. (2)The body to bogie connection shall comply with the requirements of the specification referenced in Appendix J-1, index 21. (3)The hypothesis taken to evaluate the loads due to bogie running (formulas and coefficients) in line with the specification referenced in Appendix J-1, index 20 shall be justified and documented in the technical documentation described in clause 4.2.12 of this TSI.	*The requirement relates to the concept of a bogie chassis, but ispartial adaptable to the concept of a suspension system with independent wheels. A consideration of the of independently-rotating-wheel bogie or a single axle bogie in the standard EN 13749 would be necessary.*
6.2.3.7. Mechanical and geometric characteristics of wheelsets (clause 4.2.3.5.2.1) Wheelset: (1)The demonstration of compliance for the assembly shall be based on the specification referenced in Appendix J-1, index 87, which defines limit values for the axial force, and the associated verification tests. Axles: (2)The demonstration of compliance for mechanical resistance and fatigue characteristics of the axle shall be in accordance with the specification referenced in Appendix J-1, index 88, clauses 4, 5 and 6 for non-powered axles, or the specification	*Points 1, 2 and 3 may not be applicable to one of the WP5 solution. Provision should be made for the use of other standards (see point 7) and it should be ensured that the proposed solution can be validated by an existing public standard, or this point should be dealt with in relation to article 10 of the TSI.*

referenced in Appendix J-1, index 89, clauses 4, 5 and 6 for powered axles. The decision criteria for the permissible stress is specified in the specification referenced in Appendix J-1, index 88, clause 7 for non-powered axles, or the specification referenced in Appendix J-1, index 89, clause 7 for powered axles. (3)The assumption of the load conditions for the calculations shall be explicitly stated in the technical documentation as set out in clause 4.2.12 of this TSI. Verification of the axles: (4)A verification procedure shall exist to ensure at the production phase that no defects may detrimentally affect safety due to any change in the mechanical characteristics of the axles. (5)The tensile strength of the material in the axle, the resistance to impact, the surface integrity, the material characteristics and the material cleanliness shall be verified. The verification procedure shall specify the batch sampling used for each characteristic to be verified. Axle boxes/bearings: (6)The demonstration of compliance for mechanical resistance and fatigue characteristics of the rolling bearing shall be in accordance with the specification referenced in Appendix J-1, index 90. (7)Other conformity assessment method applicable to wheelsets, axles, and wheels where the EN standards do not cover the proposed technical solution: It is permitted to use other standards where the EN standards do not cover the proposed technical solution; in that case the notified body shall verify that the alternative standards form part of a technically consistent set of standards applicable to the design, construction and testing of the wheelsets, containing specific requirements for wheelset, wheels, axles, and axle bearings covering:	

— wheelset assembly, — mechanical resistance, — fatigue characteristics, — permissible stress limits, — thermomechanical characteristics. Only standards that are publicly available can be referred to in the demonstration required above. (8)Particular case of wheelsets, axles and axle boxes/bearings manufactured according to an existing design: In the case of products manufactured according to a design developed and already used to place products on the market before the entry into force of relevant TSIs applicable to those products, the applicant is allowed to deviate from the conformity assessment procedure above, and to demonstrate conformity with the requirements of this TSI by referring to design review and type examination performed for previous applications under comparable conditions; this demonstration shall be documented, and is considered as providing the same level of proof as module SB or design examination according to module SH1.	

Other systems

4.2.5.5. Exterior doors: passenger access to and egress from Rolling Stock	
4.2.9.1.8. Internal lighting	*Modern methods of controlling lights are now based on communication networks, predominantly Ethernet. This offers advantages such as easy customization of control at the software level within the TCMS, simplified cabling, and easier access to diagnostics.*

4.2.7. External lights & visible and audible warning devices
 	
• 4.2.7.1. External lights
  ○ 4.2.7.1.1. Head lights
  ○ 4.2.7.1.2. Marker lights
  ○ 4.2.7.1.3. Tail lights
  ○ 4.2.7.1.4. Lamp controls	

4.2.9.1.3.2. Rear and side view	*Related to CCTV*
4.1.4. Categorisation of the rolling stock for fire safety 4.2.10. Fire safety and evacuation	*Related to fire safety systems*

1.3.2 TSI CCS

The TSI CCS (Technical Specifications for Interoperability for Control-Command and Signalling) are crucial for ensuring the interoperability of the railway system in Europe. They enable trains to safely and efficiently cross borders between individual EU member states without the need for adjustments to technical parameters. In the implementation of ERTMS (European Rail Traffic Management System) on lines that will be equipped with signals in the future, transitional mechanisms are being addressed to allow the introduction of ETCS (European Train Control System) even without stationary equipment. Additionally, for secondary lines, a more affordable version of the stationary system is available, known as ETCS Level 1 STOP, which provides basic coverage at low cost.

The fundamental requirements of the TSI CCS are:

- Safety
- Reliability and Availability
- Health Protection
- Environmental Protection
- Technical Compatibility
- Accessibility

Current information on the TSI CCS (Control-Command and Signalling Technical Specifications for Interoperability) is essential. Here are key points that can help in better understanding the topic:

- Control Command and Signalling TSI - European Union Agency for Railways

- TSI CCS relates to the control, command, and signalling of onboard and trackside subsystems of the European Union railway network.
- The specifications apply to vehicles that are currently in operation or that will be certified for operation, as well as to trackside subsystems of the signalling and control system.
- Different baselines of ERTMS (European Rail Traffic Management System) can be integrated and coexist both in vehicles and in trackside equipment.
- Backward compatibility is also ensured between vehicles equipped with ETCS Baseline 3 and trackside equipment equipped with ETCS Baseline 2, which allows for a more efficient transition between generations of these systems and ensures interoperability.

CCS TSI Appendix A – Mandatory specifications

- Appendix A to the TSI CCS contains mandatory specifications that apply to control-command and signalling subsystems.
- The mandatory specifications include:
  - ETCS Baseline 4, Release 1: Specifications for the ETCS system that define the latest requirements and technical standards for the European Train Control System.
  - GSM-R (Global System for Mobile Communications – Railway): A communication standard designed for the operation and control of railway transport.
  - FRMCS (Future Railway Mobile Communication System): A future communication system for railways that will replace GSM-R and provide higher efficiency and better connectivity.
  - ATO (Automatic Train Operation) Baseline 1: Specifications for automatic train operation, which ensures a higher level of automation in railway transport.

The relationship between TSI LOC&PAS 1302/2014 and systems like **TCMS**, **ATO**, and **ETCS** is as follows:

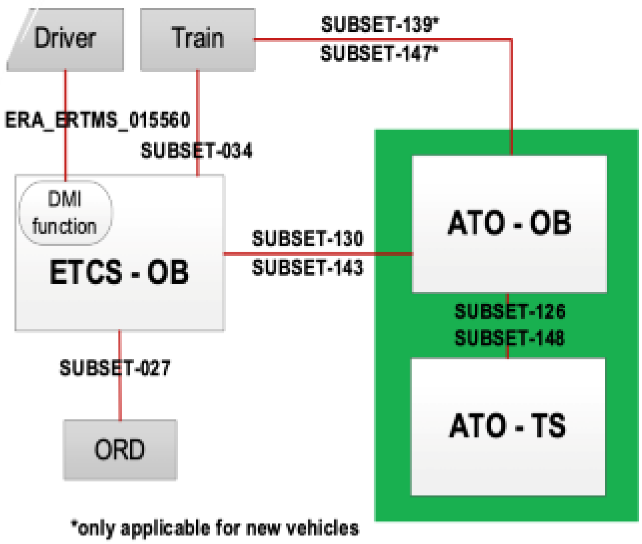
- **TCMS (Train Control and Monitoring System)**
  - TSI LOC&PAS establishes requirements for vehicles concerning control and monitoring architecture. TCMS is the main system that enables the control and coordination of all vehicle subsystems, such as traction, braking, safety functions, and comfort elements.
  - TCMS plays a role in fulfilling TSI LOC&PAS requirements for automation and coordination of subsystems, which includes both mechanical and electrical components of vehicles. TCMS must comply with interoperability standards set in the TSI to ensure that all vehicle components can work together effectively and that vehicles can be operated on tracks across Europe.

- Interoperability specifications include requirements for reliability, availability, and safety. TCMS must meet these requirements to ensure smooth and safe vehicle operation in various national railway networks.

- **ATO (Automatic Train Operation)**
  - ATO is a system for automating train operation and is an extension over ETCS, enabling partial to full automation of train driving.
  - TSI LOC&PAS includes requirements for automated systems, which encompass systems like ATO that must meet the relevant interoperability specifications. TSI LOC&PAS supports different levels of automation, from GoA 2 (which includes automation under driver supervision) to higher levels GoA 3 and GoA 4 (partial or fully autonomous operation).
  - The operation of trains equipped with ATO must comply with safety and interoperability requirements to safely integrate ATO into the European railway network. TSI LOC&PAS defines basic requirements for safety, compatibility, and connectivity to other systems, including ETCS, with which ATO must closely cooperate.
- **ETCS (European Train Control System)**
  - ETCS is the European standard for train control and protection. TSI LOC&PAS mandates that vehicles be equipped with the appropriate version of ETCS, ensuring interoperability between the individual railway networks of member states.
  - TSI LOC&PAS 1302/2014 specifies that all new locomotives and passenger vehicles to be operated within the European railway network must be equipped with the ERTMS/ETCS system to ensure they can function on lines that use this system.
  - ETCS works in conjunction with TCMS to ensure safe and efficient train control. TSI LOC&PAS includes requirements for compatibility between onboard systems and ETCS trackside equipment, enabling trains equipped with ETCS to safely operate on foreign tracks equipped with the same or compatible versions of ETCS.

Subsets used for related systems

SUBSET 026-2 v400	2.5.2.4 ERTMS/ATO on-board equipment 2.5.2.4.1 The ERTMS/ATO on-board equipment is a computer-based system that can substitute the driver for acting on the traction/braking of the train, on the basis of information exchanged with the ERTMS/ETCS on-board

	equipment, with the ERTMS/ATO trackside subsystem and with the train (see SUBSET-125 for details).
SUBSET 125	Subset 125 details the technical requirements and protocols for wireless communication between vehicles (trains) and ground control centers. It includes specifications for the data and messages exchanged, as well as requirements for the hardware and software interfaces enabling this communication. The goal is to ensure that train systems from different manufacturers and operators can communicate effectively and safely with each other and with the infrastructure across Europe.  **Figure 1** ERTMS/ATO reference architecture
SUBSET 130 ATO-OB / ETCS-OB FFFIS Application Layer	The scope of this document is the definition of the standardised set of data to transmit between the ATO-OB and the ETCS-OB to support ERTMS/ATO.
SUBSET 143	This document specifies the communication layers used by ATO-OB for communication to several other on-board subsystems.
SUBSET-126: ATO-OB / ATO-TS FFFIS	Application Layer Defines the application layer for communication between ATO on board (OB) and ATO at trackside (TS). *This is probably not important for now.*

SUBSET-148: ATO-OB / ATO-TS FFFIS	Transport and Security Layers Specifies the transport and security layers for communication between ATO on board (OB) and ATO at trackside (TS).
SUBSET-139: ATO OB / Rolling Stock FFFIS	Application Layer Specifies the application layer for communication between ATO on board and the rolling stock.
SUBSET-147	CCS Consist network communication Layers FFFIS Specifies the communication layers of the CCS network.
SUBSET-151	**ATO-OB / ATO-TS** Test Specifications Contains test specifications for ATO on board (OB) and ATO at trackside (TS).

1.4. Operational and functional requirements for rolling stock

See Appendix 2.

2 Rolling stock architecture

The focus of the project is the connection of rural area and to make these lines economically, socially, and environmentally sustainable which is in direct correlation with the vehicle design and concept which was shown in the previous chapters. The addressed lines are on the one hand Group 1 Regional Lines (G1 Lines) which are lines or networks of lines connected with the mainline railway system. They are characterized by a regular passenger service operated from/to the mainline. On the other hand, there are Group 2 Regional Lines (G2 Lines) which are lines or networks of lines not functionally/operationally connected with the mainline network. Group 2 regional rail is operated by passenger and/or freight services that do not enter mainline infrastructure.

The characteristics of such lines are manifold which is reflected in the requirements for the vehicle. For instance, the necessary vehicle capacity, the propulsion, energy demand and strength as well crashworthiness depend on the group of the lines (G1/G2), the population around the lines, the topography etc.

The vehicle has to be adaptable to the relevant specific requirements to achieve a high attractiveness for all stakeholders, while ensuring high service quality and operational reliability all while being cost-efficient. Thus, different vehicle derivatives are necessary which are adaptable to the respective needs and requirements. To achieve these partially diverging targets, a modular vehicle architecture was defined which allows its adaption to the relevant aspects. Based on the previous analyses, two vehicles were defined which are in different categories with different passenger capacities (length), strength and propulsion systems etc. The modular concept foresees a two-axles-design which needs less weight and space compared to two bogies and still offers the identified necessary passenger capacities and even more by considering the limitation of the maximum axle loads with up to 16 tons, which is the target (infrastructural) here. The defined length for the large derivative for the G1 line is 16.5 m and has a capacity of 40 seats and 60 standing passengers. The maximum speed is 120 km/h for the G1 lines and 80 km/h for the G2 lines. The small derivative has a length of 11.3 m and a seating capacity of 14 with a large multi-use area for standing passengers, bicycles, wheelchairs, etc.

The strength and crashworthiness must be adaptable for each derivative to fulfil the requirements related to the operation on G1 or G2 lines. This needs to be considered in the modularised mechanical design. On the G1 lines, there is mixed operation with every category of existing main line trains possible which has an influence on the strength and collisions requirements. On the G2 lines, mixed operation is excluded and the interaction with usual main-line trains is not foreseen. This has a direct influence on the structural requirements of the vehicle which can be reduced. This promises a positive effect on the weight, structural complexity and cost of the vehicle.

Also, the energy architecture is modularised for a possible adjustment according to the specific needs. As most regional lines are not electrified, alternative emission-free propulsion is necessary. Possible solutions come by battery or hydrogen fuel propulsion, where the optimal choice is depending on distance between charging stations.

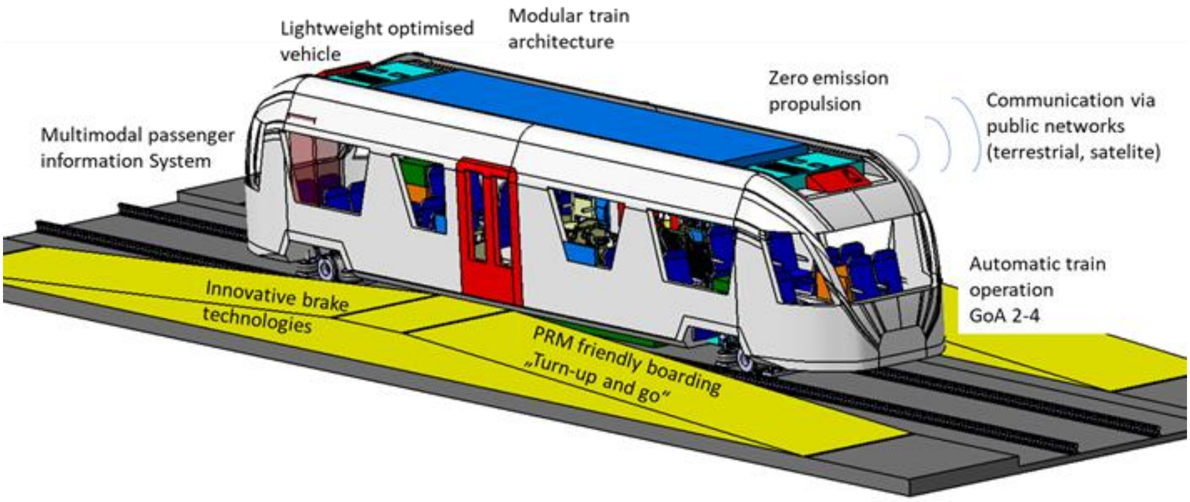


Figure 31 - Vehicle concept

2.1 Mechanical architecture

The mechanical design of a train car body and its running gears play a crucial role in ensuring the safety, efficiency, and sustainability of rail transportation systems. As one of the most visible and essential components of a train, the car body must withstand various environmental conditions, including high and low temperatures, vibrations, impacts, and a structural integrity in the case of operational loads, exceptional loads and crash while also providing a comfortable and secure ride for passengers and crew.

This chapter presents an overview of the key considerations and design principles involved in the mechanical design of the car body and the running gears. A methodical approach is used to develop and evaluate different arrangements and geometries for the car body in order to define the most suitable approach. This will consider different use cases, and a cost-efficient and modular concept of the mechanical architecture for the car body. Furthermore, first running gear concepts and design approaches will be outlined.

2.1.1 Scientific methodical approach: topology optimizations

The mechanical architecture of the car body is first analysed using topology optimizations. Topology optimization is a mathematical and computational method used to determine the optimal material distribution within a given design domain, subject to constraints like structural performance, weight, and functional requirements. The goal is to achieve the best possible design by maximizing desired properties - such as stiffness and/or strength - while minimizing material usage. The process relies on advanced numerical methods (FEA) to iteratively refine the material layout based on specific optimization criteria.

The key principle behind topology optimization is the reduction of inefficient material while maintaining or enhancing the structural performance of a system. The design space is divided into discrete elements, and each element is assigned a material density variable that can vary between 0 (void) and 1 (solid material). Through iterative calculations, the algorithm progressively redistributes material within the design domain, removing elements that contribute minimally to the structure's performance and concentrating material in regions where it is most effective.

An example for the mathematical formulation of a topology optimization problem is to minimize the total volume of material subject to:

- Structural constraints (e.g., displacement, stress, buckling)
- Geometric constraints (e.g., bounds on dimensions, aspect ratio)
- Material properties (e.g., density, Young's modulus)

The following chapters will detail the approach taken to generate car body topology optimizations and interpret the results to generate a structural car body proposal.

Several different analyses were performed on the car body, each with their own goal:

- Structural mass analyses (result = structural mass of car body)
  - Minimum structural mass analyses
    - Determine a virtual, theoretically achievable minimal structural mass
  - Parameter sensitivity analyses
    - Determine the influence of important forces and constraints on the mass
- Structural topology optimization analyses (result = material distribution in car body)
  - Load category analyses
    - Analyse the effect of different load categories from EN 12663-1 on the structure
  - External component arrangement analyses
    - Change the location of key components (like batteries) and determine the effect on the optimal material distributions and load paths in the car body structure

By performing these analyses, it is possible to gain a fundamental understanding of how the normative and assumed loads and boundary conditions influence the car body structure.

2.1.2 Applicable norms

The European normative system provides a multitude of norms defining loads and boundary conditions on a car body. The relevant norms used in the topological analyses are listed in

Table 3.

Table 3 : European norms for mechanical car body design

Norm	Content
EN 12663-1	"Structural Requirements of Railway Vehicle Bodies" Definition of loads and load scenarios for different vehicle categories (use cases) Static load cases that simulate the maximum loads the car body will encounter, such as: • Vertical loads due to passenger weight, cargo, or equipment. • Longitudinal loads due to braking, acceleration, or train coupling/decoupling forces. • Lateral loads caused by wind pressure, centrifugal forces during curve navigation, or uneven track conditions. • Dynamic loads such as accelerations from equipment mounted to the car body frame.
EN 13749	"Method of specifying the structural requirements of bogie frames" Definition of loads resulting from the interaction between the bogie and car body
EN 15663	"Vehicle reference masses" Definition of reference masses for passengers and luggage for different vehicle categories
EN 16404	"Re-railing and recovery requirements for railway vehicles" Definition of lifting scenarios

2.1.3 Model setup

2.1.3.1 Modular Geometry

The dimensions of the car body can be seen Figure in 32. The maximum height of the car body is 2895 mm. Structurally, the car body design space is modular, indicated by the colored parts of the car body in Figure 32. This enables the car body length to be altered easily. See chapter 2.1.7 for more details. The car body is symmetrical along the y-axis and partly symmetrical along the x-axis, compare Figure 33.

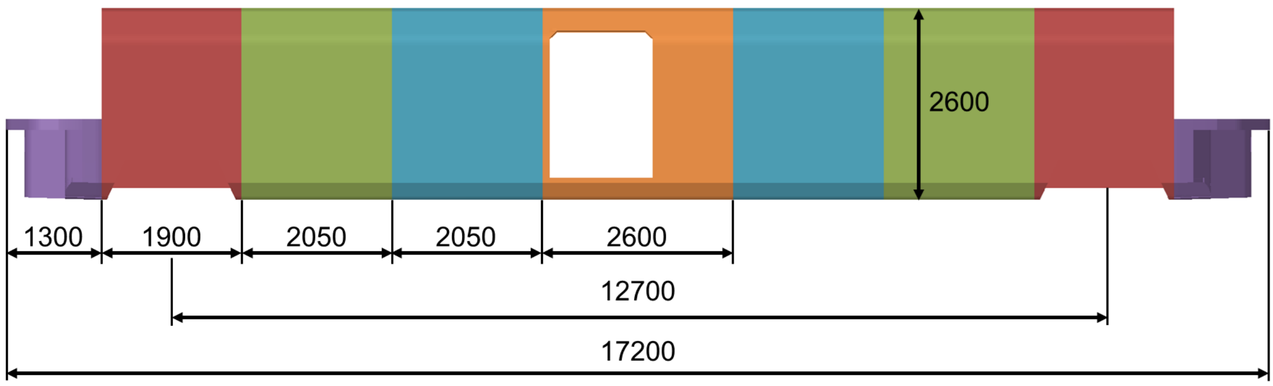


Figure 31 : Car body design space and module dimensions

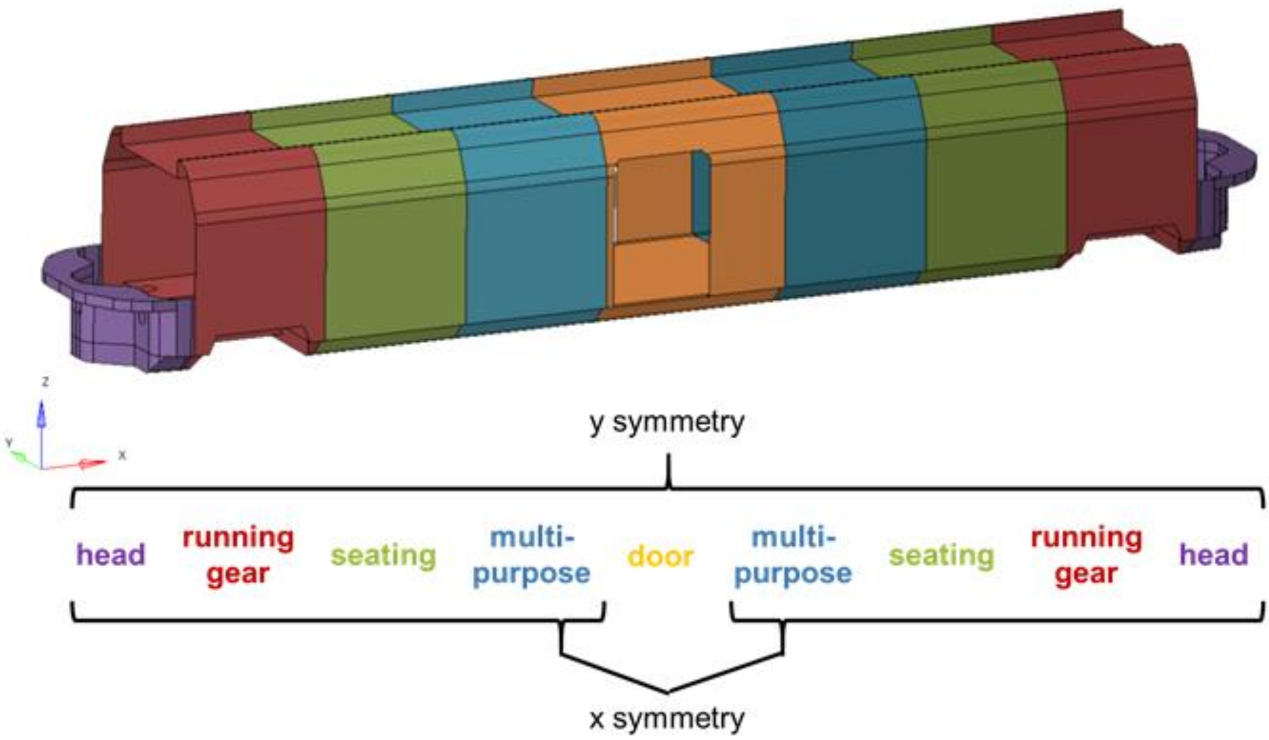


Figure 32 : Car body design space with modular sections and symmetries

The boundary conditions, load setup as well as different equipment configurations can be seen in Figure 33. The configurations will be discussed in more detail in later chapters. The batteries are always attached to the structural design space on their corners. The material for the car body design space is steel.

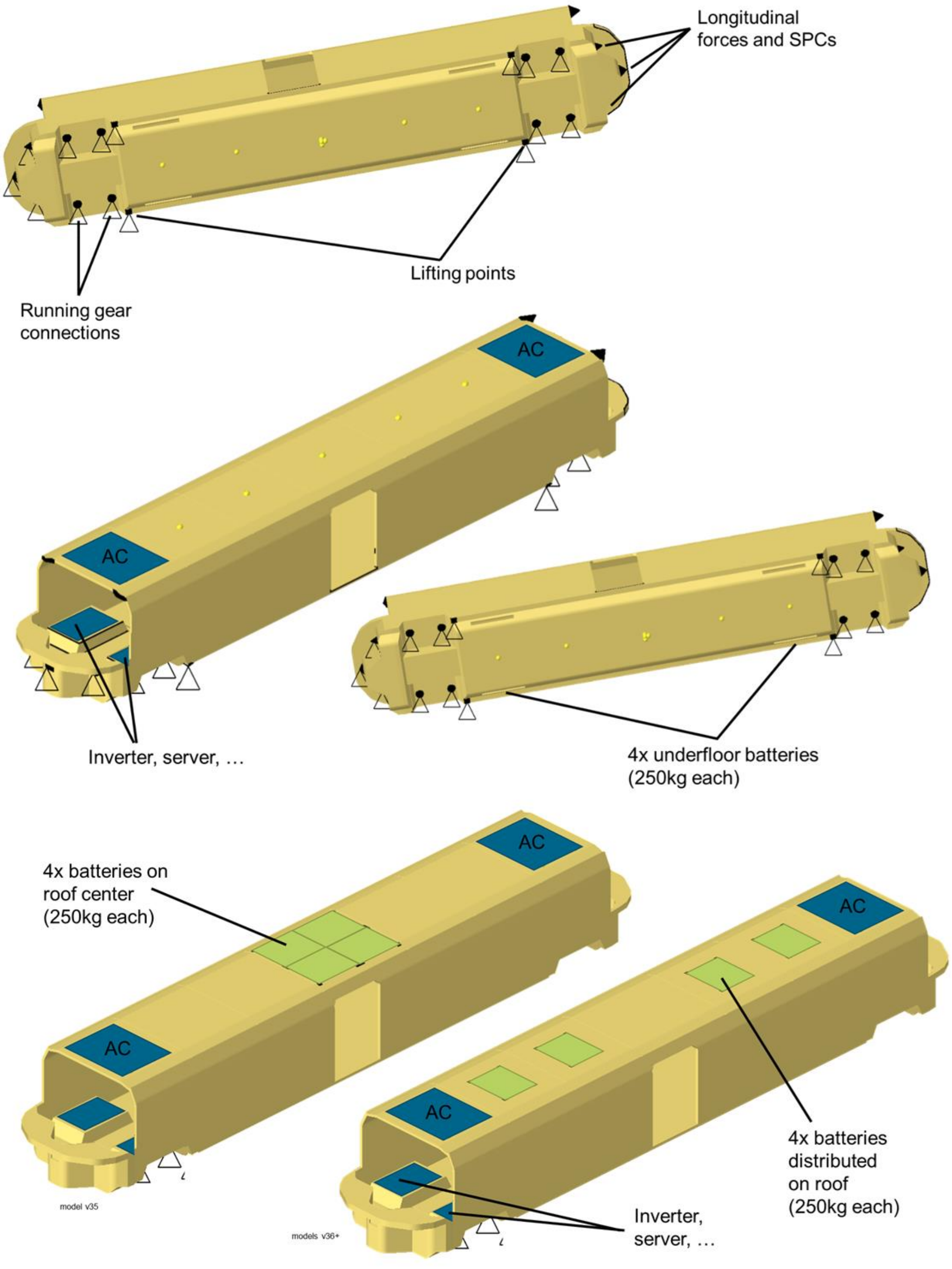


Figure 33 : Car body design space with boundary conditions and different equipment configurations

2.1.3.2 Loads and masses / load cases

The car body is subject to various loads, including passenger weight, track irregularities, and dynamic loads during operation. For the topology optimizations, Table 4 shows the loads and load cases which were applied on the car body. The use case of the vehicle (on which track type the vehicle will run and which other vehicle types it shares the tracks with) defines the applicable load category. Considered are categories P-II (locomotives and multiple units), P-III (underground, suburban and light rail) and P-IV (tram and light rail).

Table 4 : Loads and load cases of the topology optimizations

Load / Load case	**Norm**	**EN 12663-1 load category**		
		P-II	**P-III**	**P-IV**
Exceptional load (350kg/m² standing passengers + seated passengers)	EN 12663-1 EN 15663	11130 kg		
Equipment (batteries, AC, electricals, …)	-	3233 kg		
Distributed masses (cladding, HVAC, seats, …)	-	7483 kg		
Lift 1 side at 2 points	EN 12663-1 EN 15663	-	-	-
Lift at all four points		-	-	-
Lift 3 points, 4th free		-	-	-
Lift 4 points, 1 point offset by -10 mm in z		-	-	-
Lift 4 points with lateral forces		-	-	-
P-category force on window sill	EN 12663-1	300 kN	150 kN	None
P-category force on upper corners	EN 12663-1	300 kN	300 kN	None
P-category force on buffers push/pull	EN 12663-1	1500/ 1000 kN	800/ 600 kN	400/ 300 kN
Accelerations equipment in y	EN 12663-1	1*g		
Running gear x/y acceleration + max. extraordinary load	EN 12663-1 EN 13749	3*g	3*g	2*g
Emergency towing	-	196 kN		

2.1.3.3 Constraints

Topology optimizations need boundary conditions and constraints to ensure that the result performs according to the specifications. The boundary conditions used here are of a structural nature, see Table 5. They define maximum deformations on strategic points in the model. Some of these constraints are normatively mandatory, others are chosen based on common engineering experience.

Table 5 : Constraints for topology optimization

Constrained area	Max value [mm]	Axis
Undercarriage deflection	-13 (1‰)	z
Lifting point	-100	z
Roof deflection	-30	z
Interior floor deflection	+/- 20	z
Buffer deflection	+/- 50	x

2.1.4 Structural mass analyses

The objective of the analysis is to determine how light the car body structure can become under the specified load conditions. The objective of the topology optimization therefore is to find the mass minimum of the design space. For these analyses, all symmetry constraints are removed. The result for each analysis is a mass value in tons. This value represents the virtually possible structural mass (i.e. the net mass of the vehicle structure without any additions, cladding, equipment, seats, etc.). It can be used to compare different configurations with each other, e.g. car body geometries or component arrangements.

2.1.4.1 Minimum structural mass results

The analysis for the virtually possible minimum structural mass was performed on three battery configurations (compare to Figure 33):

- batteries located in the undercarriage of the car body
  - two batteries in slots on each side in each “seating” module
- batteries located on the roof above the door
  - four batteries on the enter of the “door” module
- batteries distributed on the entire roof
  - one battery on the centre of each “seating” and “multipurpose” module

All configurations were set up the same way with P-III longitudinal loads and all other loads listed in Table 4.

The following Table 6 contains the virtual mass results. The results show that the location of the batteries does influence the virtual mass, however, it is not significant.

Table 6 : Virtual mass results for different battery locations and materials

Battery location	Material	Category	Mass
Underfloor	steel	P-III	2,16 t
Above door	steel	P-III	2,19 t
Distributed on roof	steel	P-III	2,18 t
	aluminium	P-III	1,57 t

Furthermore, one simulation was performed with aluminium instead of steel as a material. The virtual mass decreased by 28%, showing that switching the material to aluminium might lead to significant mass savings in the car body structure. However, it must be noted that the decreased Young's modulus of aluminium will likely lead to more massive topologies and might bring further downsides which are out of scope of this analysis.

For these minimum mass configurations, structural topology optimizations were performed as well. The results are presented in the following chapters.

2.1.4.2 Parameter sensitivity analyses results

The parameter sensitivity analyses were performed on an exemplary configuration where the batteries are distributed on the roof of the car body, compare Figure 1. All constraint values presented in the setup chapter were tested for their influence on the car body minimum structural mass. The results can be seen in Table 7.

In Table 8, it can also be seen that the different P-categories seem to only have minimal impact on the virtual structural mass. This effect was studied further by varying the push/pull loads by bigger amounts than indicated in EN 12663-1. The results can be seen in the following table.

Table 7 : Results of parameter sensitivity analysis for topology optimization constraints

constraint	base value	mod. value	cat.	virtual mass	Notes / Conclusion
-	-	-	P-III	2,18 t	batteries distributed on roof / baseline
undercarriage z	-13mm (1‰)	-26mm (2‰)	P-II	1,79 t	undercarriage deflection has drastic influence on mass
			P-III	1,75 t	
			P-IV	1,74 t	
roof z	-30mm	-50mm	P-II	2,23 t	no observable influence of dcon on mass in given setup
			P-III	2,18 t	
			P-IV	2,17 t	
interior floor z	-20mm	-40mm	P-II	2,23 t	no observable influence of dcon on mass in given setup
			P-III	2,18 t	
			P-IV	2,17 t	
buffer x	+/-50mm	+/-100mm	P-II	2,23 t	no observable influence of dcon on mass in given setup
			P-III	2,18 t	
			P-IV	2,17 t	

Table 8

Table 8 : Results of force sensitivity analysis for topology optimization loads

force	base value	modified value	cat.	virtual mass	Notes / Conclusion
-	-	-	P-III	2,18 t	batteries distributed on roof / baseline
buffer push force	400 kN	4000 kN	-	3,85 t	drastic force increase has influence -> force application ok
no longitudinal forces	-	0	-	2,16 t	no longitudinal forces from EN 12663
no vertical loads except structural mass	+/-50mm	+/-100mm	P-II	1,77 t	no accessories (AC, batteries, seats) or passengers
			P-III	1,71 t	
			P-IV	1,67 t	

Increasing the longitudinal buffer push force by a factor of 10 leads to a significant increase in the virtual mass. From this, it can be concluded that the application of the force in the FEM model is correct, and everything is working as expected. Completely removing the buffer force leads to the unexpected result that the mass does not decrease much compared to the baseline model with the usual EN 12663-1 longitudinal loads. Performing another calculation with EN 12663-1 P-category loads but omitting all vertical loads (no passengers or equipment) leads to a decrease in the virtual mass. It can be concluded that the P-category longitudinal loads have minimal impact on the car body structural mass and the vertical are dominant.

2.1.5 Structural topology optimization analyses

Following the minimal structural mass analyses, the following chapters will present the approach and results for the structural analyses. Their goal is to get proposals for the structural design of the car body regarding different load configurations.

2.1.5.1 Load category analysis results

The load category analyses are performed in an analogous manner to the minimum structural mass analyses in chapter 2.1.4.1. The purpose is to study the effect of different load categories from EN 12663-1 on the structure itself. As with the minimum structural mass analyses, an exemplary battery configuration was chosen (distributed on entire roof). Figure 34, Figure 35, and Figure 36 show the topology results. Blue elements received a low material density during the optimization, meaning they are less important for the structure, whereas red elements received a high material density, meaning they are very important for the structure.

Figure 34 also contains noteworthy observations concerning special features of the structure. It can be noted that all P-categories seem to not necessitate a continuous longitudinal beam along the car body. This further underlines the findings in chapter 2.1.4.2 that the longitudinal loads do not have a significant impact on the car body structure.

Overall, the three P-categories lead to similar structural results. For category P-IV – where there are no loads on the upper belt or the windowsill – the structure features even less longitudinal elements as for P-II or P-III.

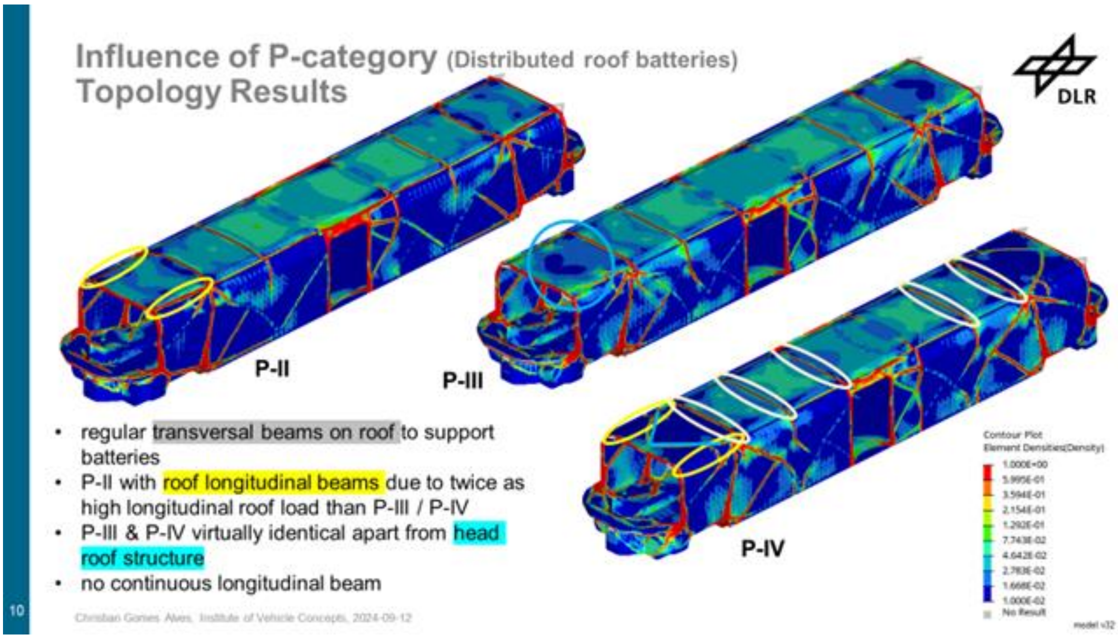


Figure 34 : Results of topology optimizations for different P-category loads - overview

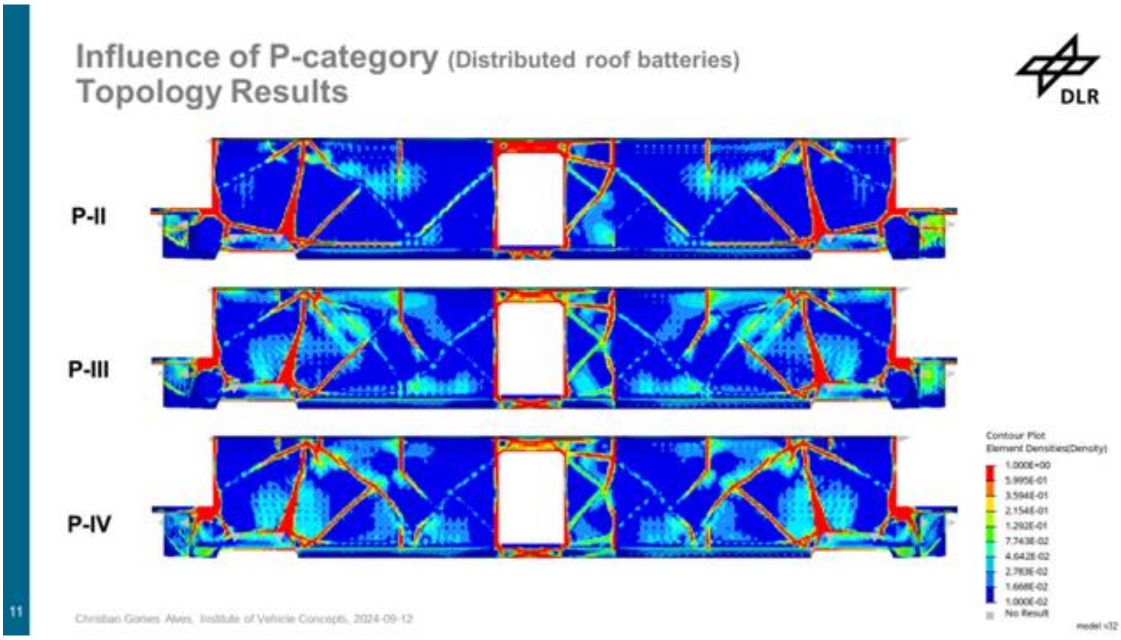


Figure 35 : Results of topology optimizations for different P-category loads – side view

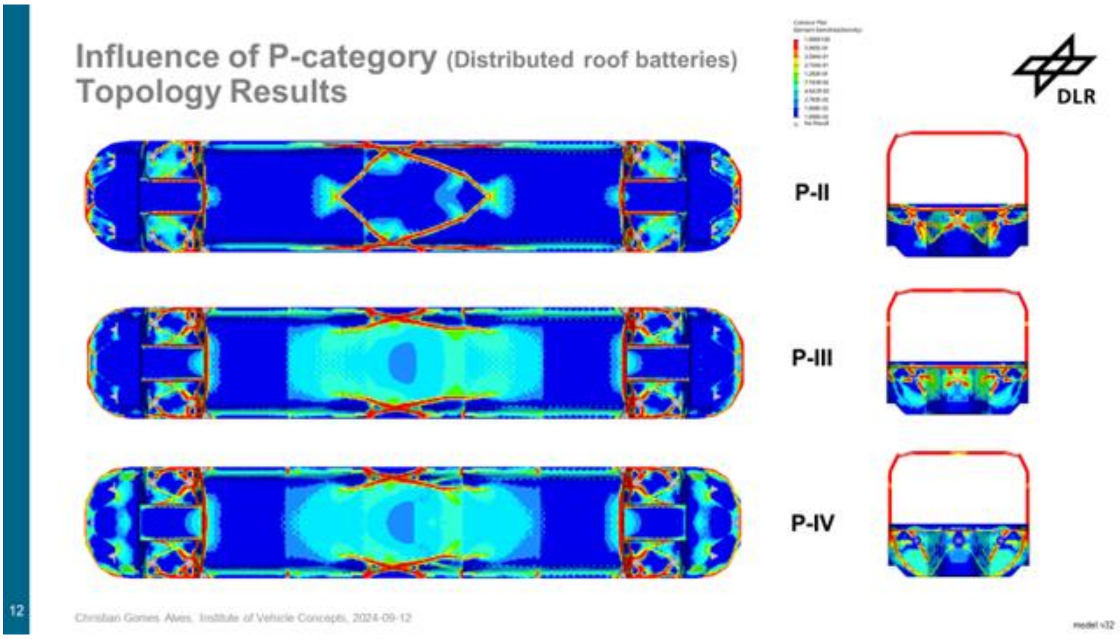


Figure 36 : Results of topology optimizations for different P-category loads – bottom and front view

2.1.5.2 External component arrangement results

As shown in the geometric setup in chapter 2.1.3 and analogously to the virtual mass results in chapter 2.1.4.1, structural topology optimizations were also performed for different battery locations. All configurations feature the same P-III load category and all other loads are equal as well. The only changed parameter is the battery locations. The results can be seen in Figure 37, Figure 38, Figure 39 and Figure 40.

Most noteworthy, the configuration with underfloor batteries does not feature a distinct roof structure. In an attempted to force a more pronounced roof structure, the allowed roof deflection constraint was lowered. However, no distinct roof structure was able to be provoked for this configuration. The AC load above the running gears is not enough to prompt the formation of a structure in the roof. Instead, the roof mainly has to withstand torsional loads from the lifting load cases, meaning a semi-stiff shear plane is enough to distribute these loads into the surrounding structure. The other two battery configurations with the batteries mounted on the roof, however, feature a very distinct roof structure with clear X-beams leading through the battery fixation locations.

Due to the absence of continuous longitudinal beams, all models formed pronounced arches above the running gears with vertical spans to the running gear load introduction points.

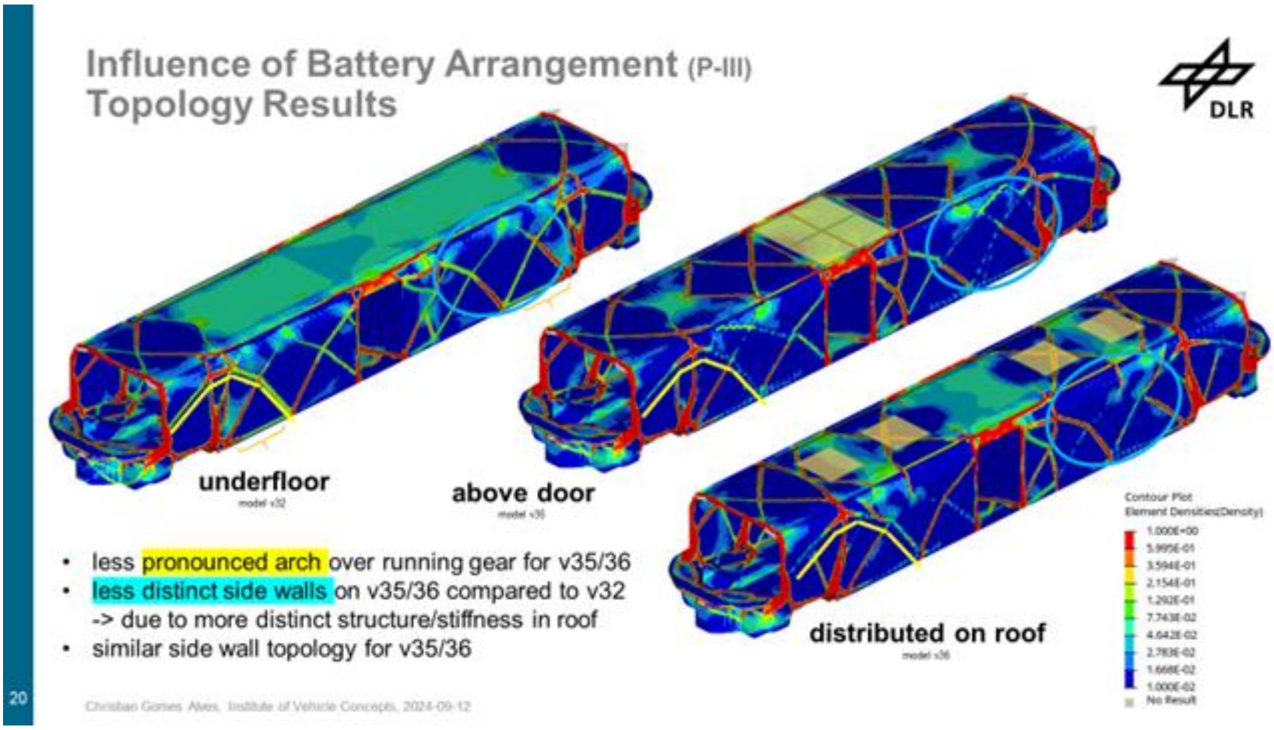


Figure 37 : Results of topology optimizations for different battery configurations – overview

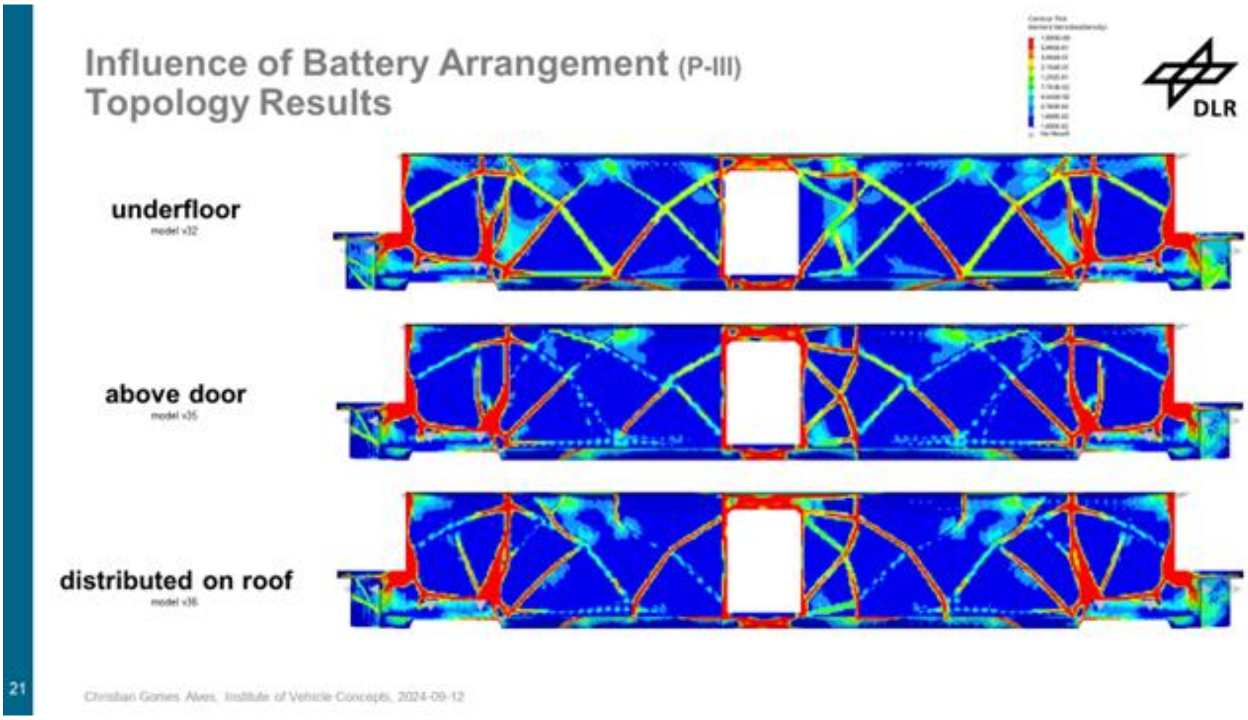


Figure 38 : Results of topology optimizations for different battery configurations – side view

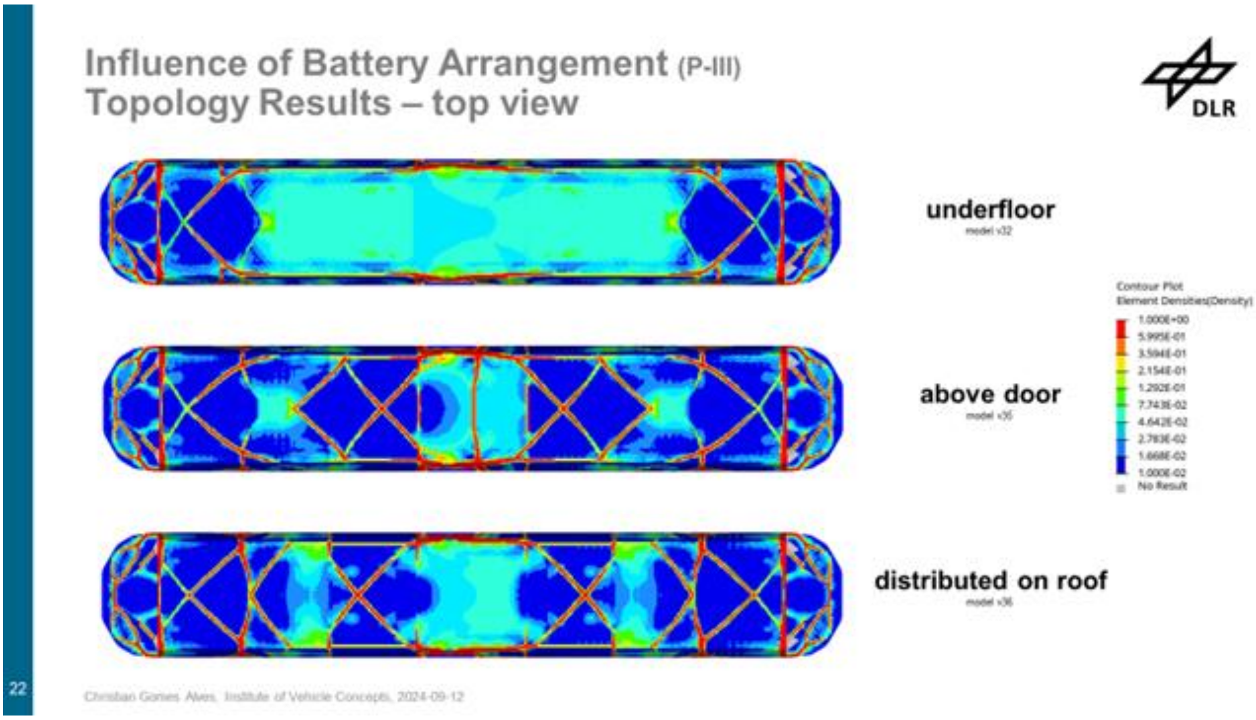


Figure 39 : Results of topology optimizations for different battery configurations – top view

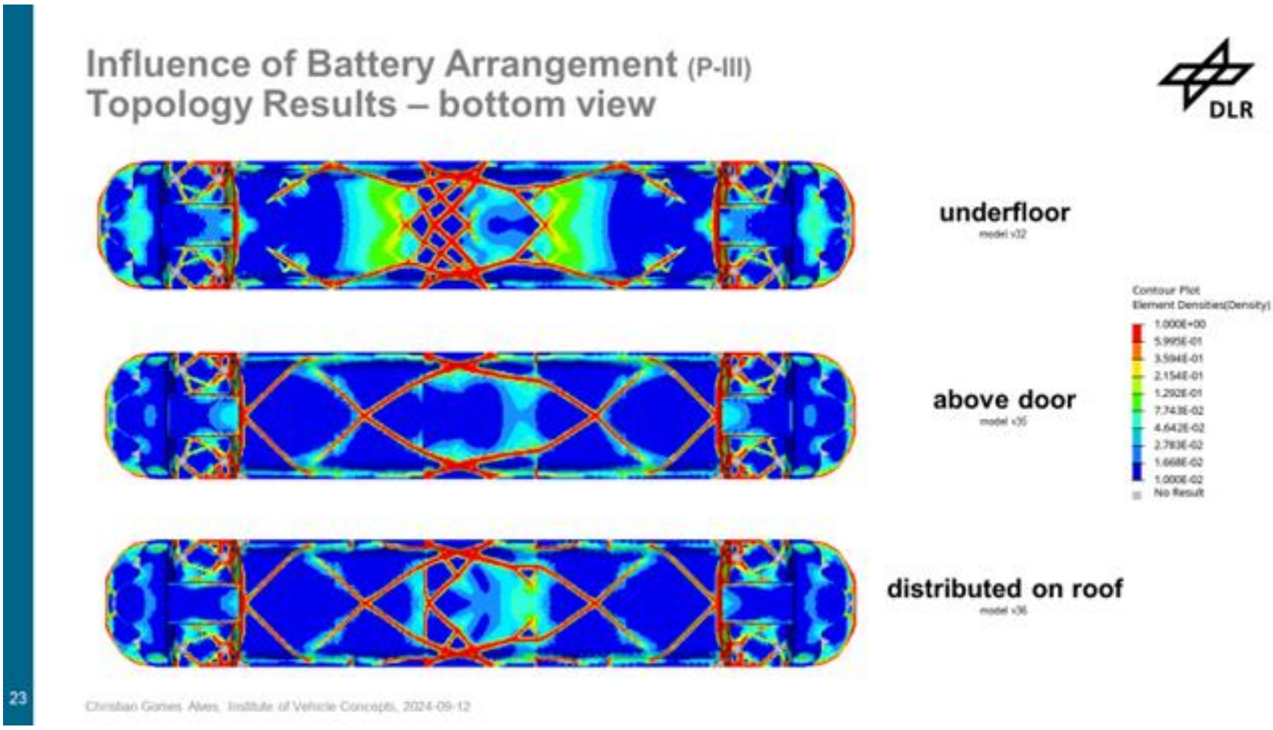


Figure 40 : Results of topology optimizations for different battery configurations – bottom view

2.1.5.3 Influence of forced longitudinal structures in topology optimizations

The absence of a clear longitudinal beam prompted the idea to introduce forced longitudinal beams (see arrows in Figure 41) to lead the topology towards using these beams in dispersing the loads. However, this was not successful, and the topology result for different forced structures is very similar to the topology result with no forced structures. This further proves the previous findings that the longitudinal P-category loads do not have a significant impact on the car body structure and the vertical forces are dominant.

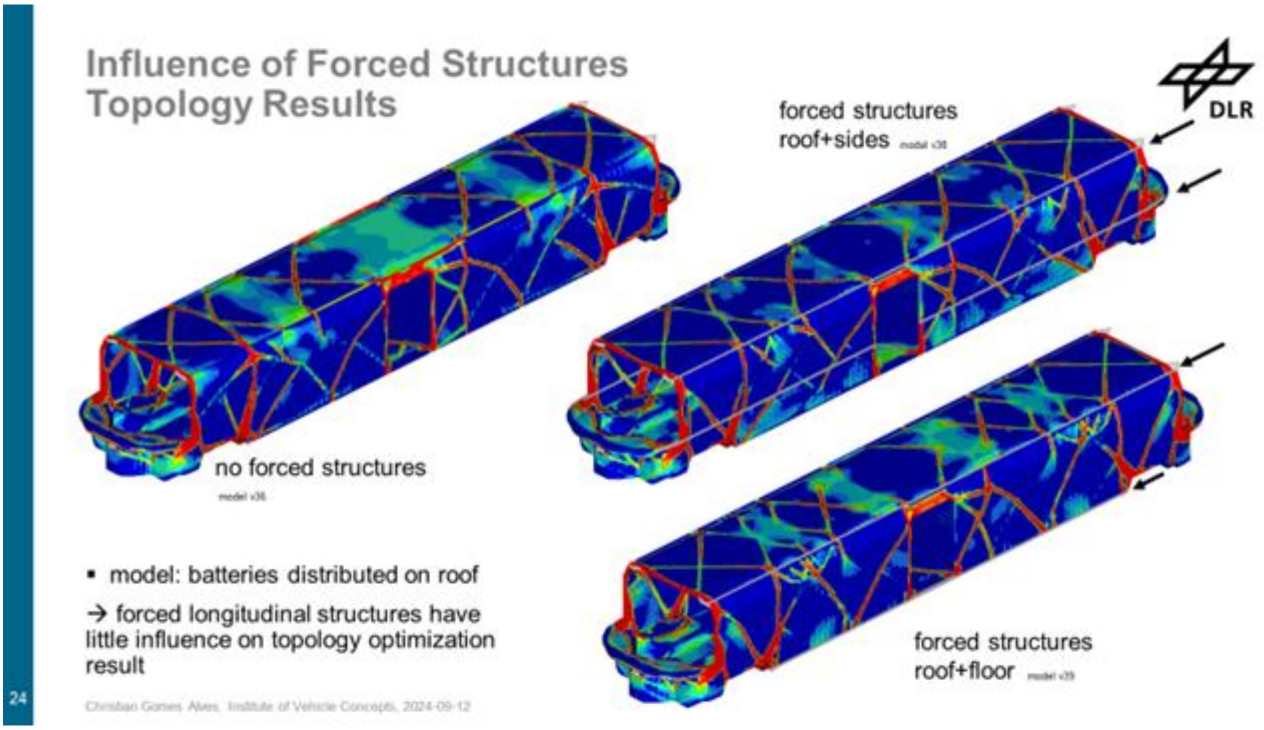


Figure 41 : Results of topology optimizations for different forced longitudinal structures

2.1.6 Conclusion and recommendations for mechanical car body structure

2.1.6.1 Conclusion for Minimum Mass Results

The analyses result for the virtual theoretically minimum achievable structural mass show that there is only a negligible mass saving potential for lighter load categories (P-IV over P-II or P-III).

Regarding component arrangements, the location (underfloor/above doors/distributed on roof) of heavier components like four batteries with 250kg mass each also has a negligible impact on the structural mass.

Based on the assumed base conditions there is no significant weight difference between P-categories from EN 12663-1. This finding, however, should be confirmed by performing FEM analyses on the future mechanical design of the car body.

2.1.6.2 Conclusion for Topology Results

The analyses of the structural impact of different use cases (P-categories) leads to the assumption that P-III and P-IV are overall very similar regarding their weight and their structure. P-III features more structure in the head area and has more beams which longitudinally divert forces into the car body. This is mainly because the lighter load category P-IV does not have any window/roof height loads. P-II, on the other hand, has more distinct head areas with larger and more pronounced longitudinal beams which can be attributed to much larger forces from EN 12663-1.

The analyses comparing different configurations (battery arrangements) show that the roof is mainly loaded with a shear load if no other significant loads are acting directly on the roof. Moving batteries onto the roof will lead to more distinct roof structures.

Overall, the topologies show similar load paths for different derivatives of P-category loads. There are repeating major structures over length with only local variations, see Figure 42 where three different topology results are overlayed.

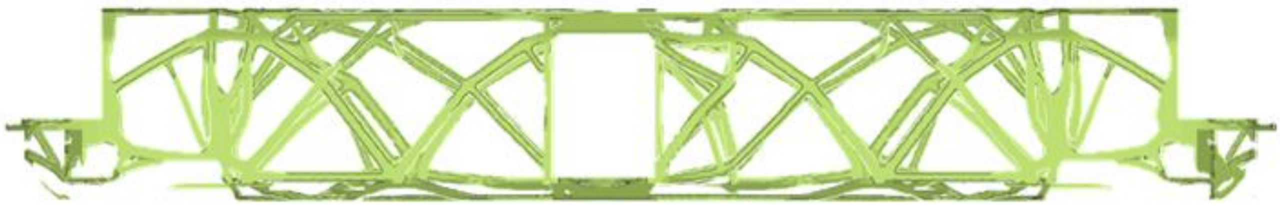


Figure 42 : Overlapping structural topology results for all three different battery configurations

This finding paves the way for the development of a **modular mechanical design** that incorporates **repeating components**. By utilizing a modular approach, it becomes possible to achieve a higher level of efficiency in both design and manufacturing, as the repeated use of identical parts simplifies the production process and reduces the complexity of assembly. Additionally, modularity allows for greater flexibility in maintenance and repairs, as individual components can be easily replaced or upgraded without disrupting the entire system. This design strategy not only enhances the overall structural integrity by ensuring uniform load distribution across similar parts but also promotes scalability and adaptability, making it easier to tailor the design to different applications or operational requirements. Ultimately, the use of repeating parts in major load-bearing structures can lead to significant cost savings, streamlined production timelines, and improved long-term performance. It is therefore proposed to combine two design approaches in the car body's mechanical design:

- load bearing panelling with locally reinforced beams (shell design)
- frame structure with load-bearing structural panelling (frame structure design)

2.1.7 Building styles

There are several different building styles available to design and manufacture a car body, including:

- Differential structures out of steel (or aluminium),
- Integral structures out of aluminium extruded profiles and
- Hybrid structures.

These building styles come with different properties, materials, bonding techniques, advantages and disadvantages. The following tables 9 to 11 give a quick overview:

Table 9 : Materials (Selection)

Materials:	**Advantages:**	**Disadvantages:**
Steel	Experience, high strength / stiffness, cost effective manufacturing	Rust, warpage while welding, fatigue problems
Stainless steel	Non rust, no coating, good welding behaviour	Costly, SO^2-emissions
Aluminium	Non rust, easy to manufacture, high strength, low density	Costly, hard to weld, warpage, fatigue problems
Glass fibre	High specific strength / stiffness, high surface quality, non-rust, fatigue resistant, fast and easy manufacturing	Little experience, costly, fire hazard, damage detection, hard to repair
Carbon fibre	High specific strength / stiffness, high surface quality, non-rust, fatigue resistant, fast and easy manufacturing	Little experience, costly, fire hazard, damage detection, hard to repair
Wood	Cost effective, ecofriendly, integration of different functions	Natural decay, humidity problems, fire hazard
Honeycomb Core Sandwich Structures	Lightweight yet stiff, high strength-to-weight ratio, good thermal and acoustic insulation, corrosion resistant	Expensive, core is prone to impact damage, difficult to repair, certain constituent materials can be fire hazards.
Foam Core Sandwich Structures	Lightweight yet stiff, excellent thermal and acoustic insulation, corrosion resistant	Lower mechanical strength compared to honeycomb, core can deform under heavy loads, difficult to repair, certain constituent materials can be fire hazards.
Hybrid Core Sandwich Structures	Lightweight yet stiff, high strength-to-weight ratio, excellent thermal and acoustic insulation, corrosion resistant	More complex and costly to manufacture, difficult to repair, limited large-scale rail experience.
Plastics	*Not a structure material, to little strength*	

Table 10 : Bonding techniques (Selection)

Bonding techniques	**Advantages:**	**Disadvantages:**
Welding	Space efficient, lots of experience, light weight	Heat entry, warpage, fatigue problems
Screws / bolts	Able to be disassembled, independent of materials, lots of experience	Only axial loadable, can loosen, rust, not tight, lots of parts
Adhesives	Compensation of tolerances / heat expansion, detachable (sometimes), water and airtight	Properties dependent on assembly conditions, hard to repair
Rivets	Fatigue resistant, able to be disassembled, independent of materials	rust, not tight, lots of parts, costly manufacturing
Adhesive bonding (composites)	Lightweight, distributes load evenly, good for hybrid material bonding (metal-composite), eliminates drilling and rivets, smooth surface finish.	Lightweight, distributes load evenly, good for hybrid material bonding (metal-composite), eliminates drilling and rivets, smooth surface finish.
Hybrid bonding	Combines best properties of adhesives and fasteners, provides redundancy	Added wight, more complex design and assembly, increased costs and manufacturing time

Table 11 : General building styles

General building style:	**Advantages:**	**Disadvantages:**
Differential	Simple, pre-product, easy to optimize locally, easy to repair	Lots of welding, warpage, sound insulation
Integral	Easy and fast assembly, high surface quality, no warpage, integration of different functions	Hard to repair, minimum thickness, overdesigned areas, cross-section constant
Hybrid framework	Light weight potential, integration of different functions, easy and fast manufacturing of complex components, fewer components	Little experience, hard to calculate / simulate, fire hazard
Hybrid shells	Light weight potential, integration of different functions, easy and fast manufacturing of complex components, fewer components	Little experience, hard to calculate / simulate, fire hazard
Modular Composite Structures	Easy to replace or repair damaged modules, lighter and simpler assembly, good noise and vibration damping.	Complexity in integrating various modules, higher initial design and tooling costs.

2.1.8 Differential welded steel car body proposal

In a first step, we propose a geometrical car body design concept consisting mostly of welded steel semi-finished products and in some places sandwich shear panels which are adhesive bonded or welded to the steel frame. This proposal for the differential steel welding is based on the following reasoning:

- Material steel: high strength and lightweight construction, easy to manufacture, lots of experience
- Bonding technique welding: space efficient, light weight
- Building style differential: simple, easy to repair, easy to optimize, easy to use on demonstrator

For the shear panels the following reasoning is concluded:

- Material sandwich: High moment of inertia of area, lightweight, integration of function (e.g. insulation)
- Bonding technique adhesives: Good shear bearing capacity

The idea behind this partly hybrid building style is the multi-material approach (suitable material at the suitable position) and to find an optimum between ecological manufacturing and lightweight design. The welded steel frame promises easy and affordable manufacturing due to its widespread use in many different vehicles. The addition of shear panels promises a high degree of function integration, lightweight design, and ease of integration. Areas in which these panels can outperform a pure welding frame are ceilings, load bearing floors, and wall sections. Following the topology optimizations, a car body could look like shown in Figure 44 and Figure 45.

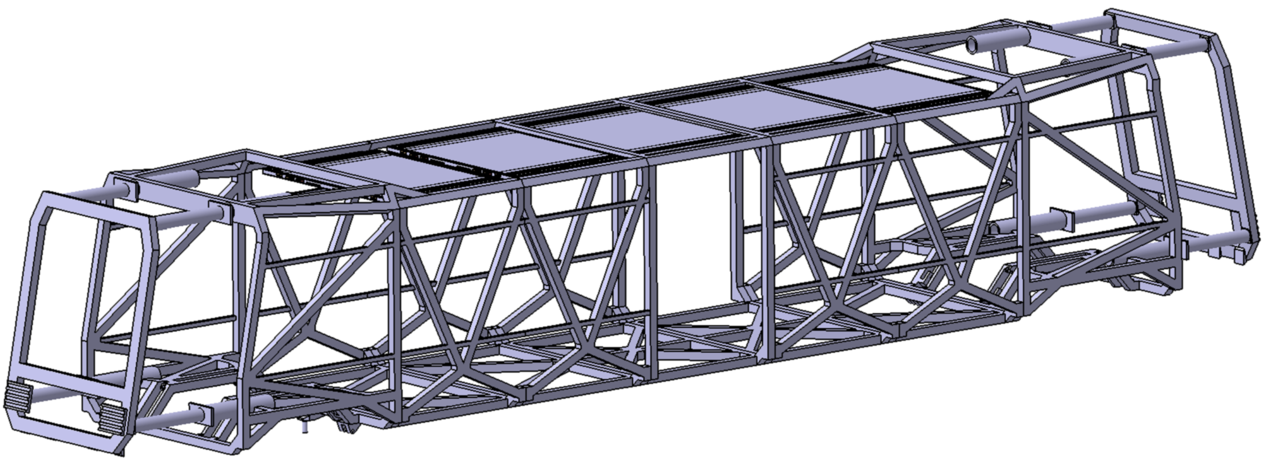


Figure 43 : Car body long version

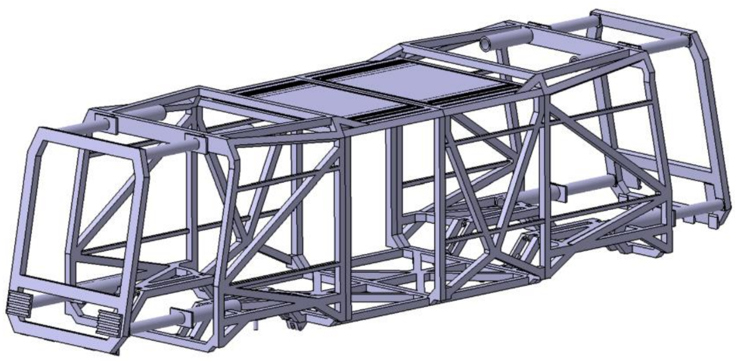


Figure 44 : Car body short version

These frame structures were in part derived from the topology optimization results from the previous chapters using an automatic design tool from DLR[34]. However, during the optimization analyses, different changes were made to the car body geometry. The lengths of the door and passenger modules were adjusted to a 1.8m grid tailored to two rows of seats. Also the door module was redesigned to accomodate the offset doors and a bigger multi use area. The car body height was raised to compensate for a possible wheel set running gear and the car head was changed to incorporate a crash system using energy absorbers. To ensure comparability between the different optimization runs, the topology optimization model remained unchanged, while the engineering model was adapted manually to reflect the new design decisions.

The modules in the engineering model have the following properties:

- Door modules with length 1,8m, providing doors
- Running gear modules with length 2,3m, providing running gear interface
- Head modules with length 1,5m, providing vehicle end and crash absorbers
- Passenger modules with length: 1,8m

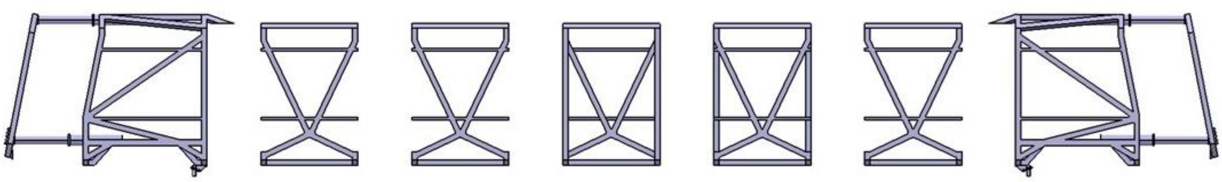


Figure 45 : Car body modules

[34] Gomes Alves, Christian und Barthel, Yannick und Halsner, Matthias (2022) *Automated Derivation of CAD Designs from Topology Optimization Results.* In: World Congress on Railway Research (WCRR) 2022. 2022-06-06, Birmingham, UK. URL: https://elib.dlr.de/148477/

These modules can be arranged into different versions of the vehicle. The smallest possible vehicle consists of two door modules, two running gear modules and two head modules. This sums up to a total vehicle length of 11.1m. A maximum of three passenger modules can be added to increase the vehicle length to 16.5m. This vehicle with its separated modules is shown in Figure 46 The distance between the axels is 5.9m for the small vehicle and 11.3m for the large vehicle. The car body is 2.96m wide using the maximum possible width of the clearance G1-gauge. Referring the proposed floor hight and the specified inner height of the vehicle, the total height of the train over top of rail is 3.3m. A further at least partial hight reduction could be possible by using a low-floor area without steps over the complete car body length, inclusive the running gear areas which has a direct impact on the basic running gear design and would limit the possible running gear concepts.

The door modules have a door on just one side. By using two door modules per train build in mirrored on the XZ-plane, the train has doors on both sides with a longitudinal offset which could offer new aspects for a user centric interior

The running gear modules integrate the running gear at the bottom. It has a higher inner ceiling to accommodate different running gear setups. It can be adapted to use a low floor running gear with a level floor without steps throughout the whole vehicle. It can also be adapted to support a wheelset running gear.

The head modules are partially integrated into the running gear module as there is no need to place a passenger module between a head and a running gear module. The head module contains the crash absorbers and the actual car end.

The passenger modules are designed to offer more seating space and more space under the floor and on top of the roof/ceiling for equipment like batteries, LH2 tanks, fuel cells, HVAC units etc.

The load paths of the different modules were shaped using the results of the topology optimizations shown earlier.

2.1.9 Life cycle aspects and sandwich composite structure

A significant part of the costs is defined by the concept which has to be considered from the beginning on. The approach here foresees a modular approach not only for the complete vehicle architecture but also for the car body and the car body design. The mechanical structure of the car body uses repeating modules existing of repeating components across the derivatives. The base is the identification of key-structure parts of the car body across the variants. These are used for a modular construction kit for the car body structures of the derivatives. Thus, the number of identical parts increases significantly in the production which offers cost efficient manufacturing.

The life cycle properties of structures are significant if the goal to design a lightweight, low-cost vehicle is to be achieved. This encompasses aspects beyond manufacturing, use, and end-of-life considerations, extending also to cost implications. While some cost models exist, ongoing work aims to refine these models specifically for the unique context of rail vehicle component design, including those made of composite materials.

When appropriately utilized, composite materials can provide superior mechanical properties with reduced weight, thereby boosting vehicle performance. This applies to rail vehicles as well, where research indicates that composites can lead to notable weight reductions and other advantageous effects. Such benefits include the ability to integrate functions through customizing the material for specific needs like stiffness, sound insulation, or thermal management.

Life-Cycle Cost Analysis (LCA) is a systematic approach to assessing the total cost associated with a product or system over its entire life span. In the context of rail vehicles, this includes the costs incurred during design, manufacturing, operation, maintenance, and eventual disposal or recycling. The purpose of LCA is to provide a comprehensive understanding of both direct and indirect costs, enabling stakeholders to make informed decisions about materials, design choices, and long-term sustainability. LCA can help to optimize cost efficiency, improve sustainability, and minimize environmental impact. The analysis typically follows the stages of:

1. Initial Investment Costs: Design, development, and manufacturing expenses.
2. Operational Costs: Energy consumption, wear and tear, and maintenance over the vehicle's operational life.
3. End-of-Life Costs: Disposal, recycling, or remanufacturing costs when the vehicle reaches the end of its service life.

By understanding these cost components, manufacturers and operators can select materials and technologies that not only reduce upfront costs but also offer long-term savings.

For rail vehicles, particularly car body structures, implementing LCA provides valuable insights into material selection, design optimization, and operational efficiency. The car body represents a significant portion of the vehicle's weight, which directly influences energy consumption during operation. Therefore, reducing weight through innovative materials while maintaining structural integrity can have profound effects on both life-cycle costs and environmental impact.

As discussed in the previous chapter the most recent building style of car bodies are hybrid structures, where a combination of steel and/or aluminium and/or composites are used to optimize the parts. However, the use of connectors can make the structures heavy and can complicate the assembly process. A natural progression in the building styles would be composite structures, as shown on Figure 46, where the entire car body is made of composite materials. The concept illustrated demonstrates a sandwich composite car body design that would not only maximize lightweighting potential but also simplify the assembly process.

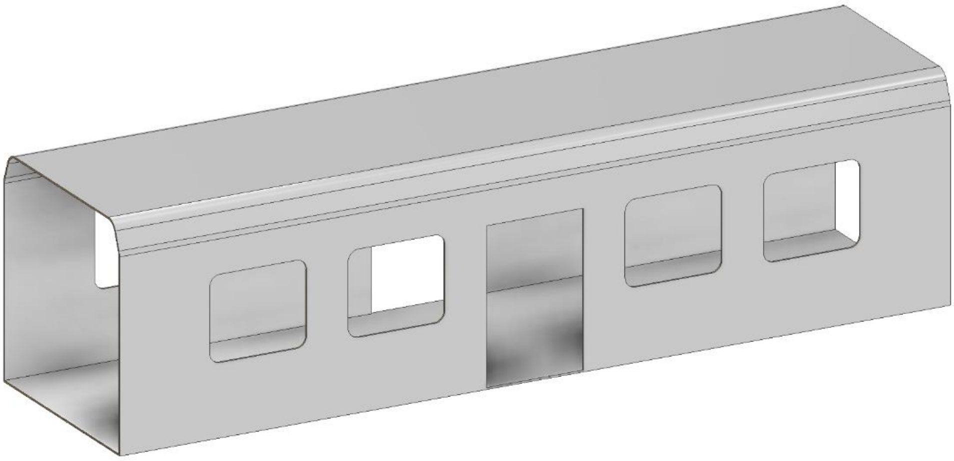


Figure 46 : Conceptual design of an all-sandwich composite car body structure

Sandwich composites are advanced materials composed of two outer layers, typically made from high-strength materials like aluminium, carbon fibre, glass fibre reinforced composites, enclosing a lightweight core, often made of aluminium honeycomb or foam. This configuration provides exceptional structural integrity while significantly reducing weight compared to traditional solid materials.

The primary advantage of sandwich composites lies in their high strength-to-weight ratio, which allows for considerable weight savings in rail vehicle designs. By replacing heavier materials with lighter sandwich composites, manufacturers can enhance the overall efficiency of the vehicle, resulting in lower energy consumption during operation.

In addition to weight reduction, sandwich composites offer the potential for function integration. The inherent design of these composites allows for the incorporation of various functions, such as thermal and acoustic insulation, within the material itself. This means that separate insulating materials are often unnecessary, leading to further weight savings and simplifying the manufacturing process. By integrating insulation properties directly into the sandwich structure, rail vehicles can maintain passenger comfort while minimizing the complexity and weight associated with traditional insulation methods.

The life cycle properties are increasingly important to consider when assessing different concepts and essential if the benefits of e.g. all composite car bodies are to be exploited. While certain aspects are established, there is a need for further investigations into others, such as the modelling of cost for rail vehicle structures made from composite materials.

2.1.10 Mechanical architecture running gear

For the running gear concept, the following specifications are to be followed:

- Two-axle vehicle
- All wheel drive / braking

- Low floor, if possible, for maximum interior space
- High riding comfort on degraded tracks
- Affordable
- Low maintenance
- Low wear and tear
- Minimal unsprung mass
- Light weight

Due to the two-axle vehicle concept and under consideration of the defined frame conditions with a longer distance between the axle than in bogies the running gears must allow a limited rotation around the z-axis.

Two running gear concepts are concepted parallel to each other. In a later stage they are to be compared, and the better suited setup will be used for the vehicle.

The running gear concept has been extensively consulted with FP4, despite significant differences in the operational framework (FP4 targeting services with much higher frequency than FP6 and thus resulting basically in two axles bogie approach).

2.1.10.1 Single wheel running gear concept

The first proposed concept is a single axle – single wheel running gear shown in Figures 48 and 49. It is based on a low-floor, non-rotating, commercial off-the-shelf axle with independently rotating wheels. This axle setup maximizes interior space and enables the vehicle to be low floor throughout its entire length. As this axle is used in existing trams, engineering, manufacturing, and homologation costs are reduced, and its acquisition is simple.

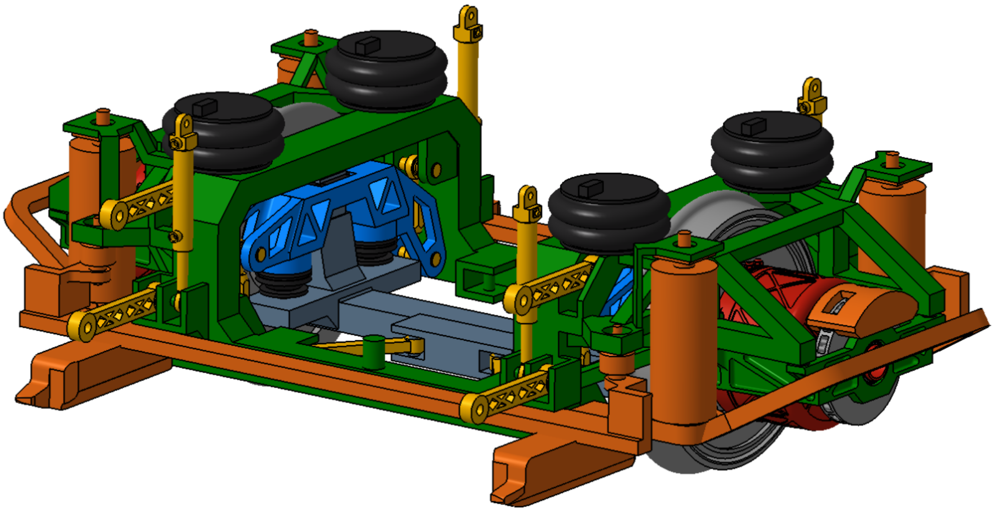


Figure 47 : Running gear proposal ISO

The axle is suspended using rubber springs, which are mounted to Watt's linkages on both sides for low steering resistance. Two additional, diagonal linkages are used to create a virtual pivot point between the axle and the running gear frame enabling steering motion (limited rotatory degree of freedom around z-axis). The running gear frame itself is connected to the Watt's linkages and carries further components like the magnetic track brake. It itself is suspended using air springs and dampers.

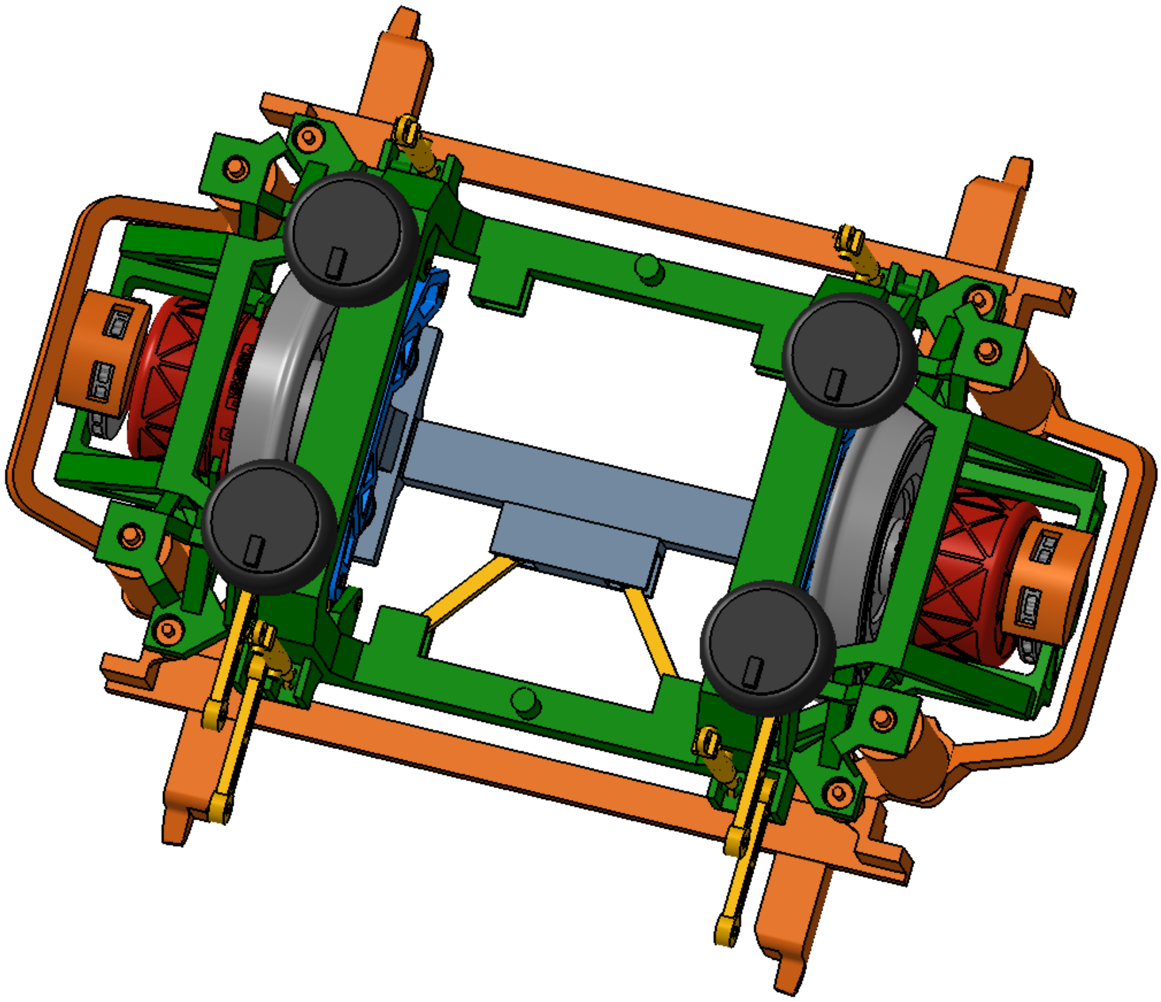


Figure 48 : Running gear proposal top

Every wheel is independently rotating and directly driven by a high-performance outrunner Permanent Magnet Synchronous Motor (PMSM). As the motor is providing high torque density, no gear box is necessary, which leads to a compact, simple, light and easy to maintain driving system. It also enables active mechatronic guidance. Using sensor equipment and independently controlled motor torque and rotation speed on every single wheel, the axle can be steered automatically and in high resolution, which negotiates curves and compensates track irregularities. A high ride quality even on degraded tracks and a reduction of noise emissions and wear is expected. Furthermore, the sensor data could be used to monitor wheels and track behaviour, which enables predictive maintenance of the vehicle and the track.

2.1.10.2 Wheel set running gear

The second proposed running gear concept is a single-axle conventional wheelset running gear. The starting point for the design is a wheelset paired with single step coil spring design with high spring rates to limit displacements due to load and vehicle dynamics. The suspension will be soft enough to ensure safe running but with deficiencies when it comes to ride comfort and curving performance. These deficiencies are set to be overcome by two types of active suspension elements. The general setup for the running gear is similar to what was studied in PIVOT2 for a metro vehicle. However, it has been simplified further by omitting the running gear frame, which was used as anti-roll bar (ARB) for the metro vehicle, as well as the active lateral suspension. In the present work for FP6 FutuRe, the active suspension elements include active vertical actuators and wheelset steering actuators. The work is made in cooperation with FP4 WP14 and WP16 and can contribute to the air free train.

A low force active vertical suspension based on electro-dynamic principle is placed in parallel with two coil springs for each axle box. The four vertical actuators in one vehicle will be able to dynamically control the bounce, pitch and roll motions of the car body. Static or quasi-static active forces are not foreseen. Without the ARB, the vertical stiffness must be increased to limit the roll motion. The increased stiffness leads to challenges for the active vertical suspension, as the passive suspension will transfer more vibrations to the car body that must be eliminated by the active system. However, proper choice of actuator would be able to address this issue. In PIVOT2, there were two actuators for each wheelset located in parallel to the passive wheelset guidance. For FutuRe only one actuator is foreseen, and this actuator is located series with the passive wheelset guidance. This location change will influence the requirement for the actuator from a high force slow acting one to a low force quick acting. Meanwhile, the lateral active control for the vehicle is proposed to be incorporated in the active wheelset guidance. This setup results in a very simple vehicle that is inexpensive to manufacture and maintain, driving down the lifecycle cost of the regional vehicle, while upholding a similar safety and ride comfort level as is customary with current-generation vehicles.

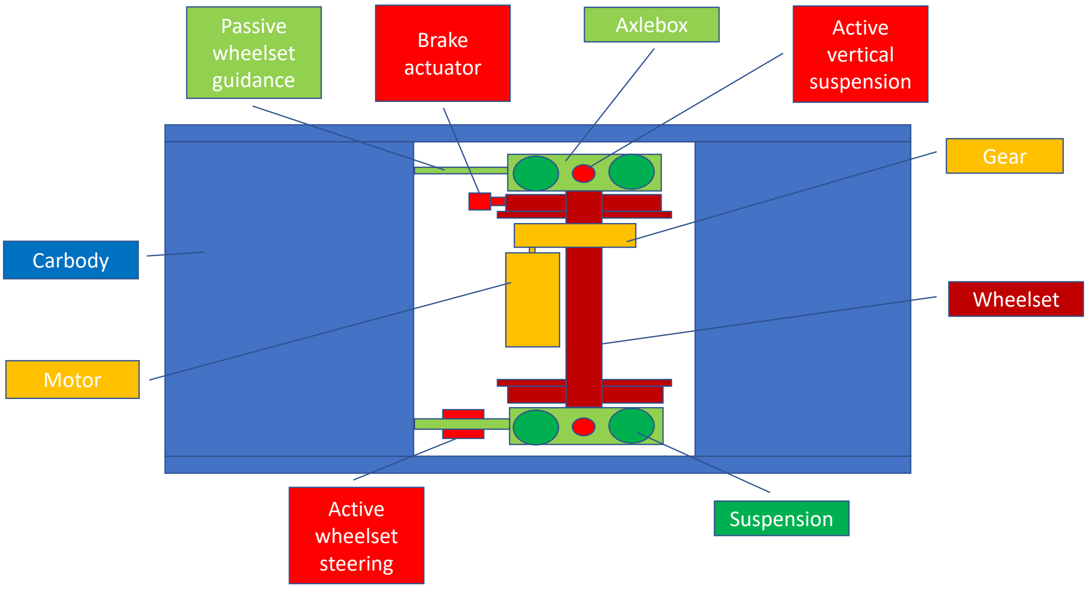


Figure 49 : Possible running gear setup with conventional wheelset (top view)

Development, as well as analysis of the performance and feasibility, of the active vertical and active wheelset steering control will initially be performed using computational simulation approach. In this process, a fully passive vehicle model will serve as the baseline for benchmarking all subsequent iterations of active suspension designs. To establish this baseline, a multibody model of the proposed regional vehicle equipped with fully passive suspension has been developed. The regional vehicle model is subjected to a simulation of running characteristics acceptance tests as defined in EN 14363 to ensure acceptable safety with a fully passive suspension configuration. Optimisation of the passive vehicle suspension parameters is currently ongoing, to determine the extent of possible improvement without using any active suspension elements. This passive vehicle model allows us to capture the dynamics of the vehicle under conventional conditions, providing insights and a baseline for benchmarking subsequent integrations of the active vertical suspension and wheelset steering system.

2.1.11 Multibody simulation of vehicle

Passenger vehicles serving local railway lines in recent years are based on conventional single- or two-section structures, mostly mounted on two-axle bogies.

As part of the design of a vehicle intended for servicing regional lines with low capacity, reduced weight and zero emission drive, an innovative concept of a single-unit, two-axle vehicle was created, with a maximum speed of 80 (G2 lines) or 120 km/h (G1 lines).

The general parameters of the vehicle allowed to propose two versions of single axle running gear: with a conventional wheelset or with two independent wheels. The final version of the running gear will be selected at a later stage of the project, which will also depend on the results of numerical simulations of dynamic behaviour.

Simulations of the designed single-axle vehicle should also take into account a comparison with the existing level of dynamic impact of a vehicle of a similar design. Therefore, in section 2.1.11.6 of this chapter, the simulation results of a vehicle operated on the PKP PLK network with parameters similar to the parameters of the vehicle concept, which could be a reference vehicle for subsequent calculations of the target model selection.

This chapter presents a preliminary specification which parameters are necessary for numerical analysis dynamics of the lightweight rail vehicle dedicate to regional lines.

These parameters of the running gear model may be common to both two-axle bogies and the single-axle system.

The detailed differences between these systems should be defined for the system of vehicle motion equations.

The scope of this part includes the following issues:

1. Specification of running system parameters:
    a. geometric,
    b. mass and inertial,
    c. damping-elastic.
2. Specification of track parameters specific to regional lines.
3. Description of the system of motion equations.
4. Criteria for evaluating simulation results:
    a. Analysis of vehicle driving dynamics, in accordance with EN 14363, safety in relation to derailment.
    b. Assessment of driving comfort - estimation of the N_{MV} and N_{VD} index with reference to EN 12299.
    c. Determination of the critical speed as a function of deterioration of the efficiency of damping elements.

2.1.11.1 General description of the model

The dynamic analysis of the phenomena of the above-mentioned vehicle should be performed using the Multi Body System method (rigid multi-unit element method) considering the geometric parameters of the elements, design data and computer simulation which could be perform by dedicated simulations programs, including MATLAB software.

The mathematical model of the vehicle should be described using a system of second-order ordinary differential equations. Assuming so-called small displacements of individual rigid bodies of the physical model with respect to the adopted inertial frame of reference, i.e. assuming so-called "small vibrations", such a system of equations can be written in matrix form using Formula 1.

$$[\mathbf{M}\ d^2/dt^2 + \mathbf{C}\ d/dt + \mathbf{K}]\cdot\mathbf{q} = \mathbf{F}, \quad (1)$$

where:

q – denotes the generalized coordinate vector of the system

M – is the symmetric inertia matrix,

C – is the damping matrix,

K – denotes the stiffness matrix,

F – is the force vector,

d/dt – is the differential operator.

The exemplary structure diagram of the physical model of the light regional vehicle with 2-axle bogies is shown in Figure 50 where m_{WS} is the mass of the wheel set, $c_{I/II}$ is the stiffness of the I/II suspension stage, $d_{I/II}$ is the damping coefficient of the I/II suspension stage, and M_{CB} is the mass of the body, I_{CB} is the moment of inertia of the body, Φ is the angle of rotation of the body about the transverse axis Y, Θ is the angle of rotation of the body about the longitudinal axis X.

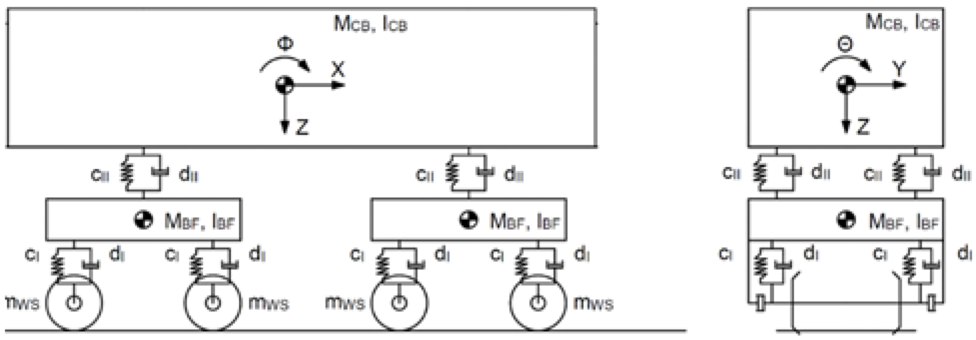


Figure 50 : Exemplary schematic diagram of the structure of the vehicle numerical model

For a single-axle vehicle model, the above parameters are determined accordingly.

The system of rigid bodies interacts with the track through the higher kinematic pairs of wheels and rails profiles which are provided in the form of coordinates measured on real wheel/rail profiles. The model of contact should be based on Kalker's simplified theory and the FASTSIM algorithm.

In order to calculate tangential contact forces the algorithm requires such input data as normal contact forces, coefficient of friction (assumed equal to 0.4 on the basis of EN 14363 requirements described in the annex B and annex T), length of the semi-axes of the contact ellipses (calculated using Hertz theory), and creep values which are given in the form of relative rigid slip (2):

$$\begin{bmatrix} rs_x \\ rs_y \\ rs_z \end{bmatrix} = \frac{1}{vu_x} \begin{bmatrix} sv_x \\ sv_y \\ sv_y \cdot \sin(\alpha) + sv_z \cdot \cos(|\alpha|) \end{bmatrix}, \quad (2)$$

where rs_x , rs_y are creepages (relative rigid slip) in the longitudinal and lateral directions, rs_z is spin; α is contact angle; vu is speed of the moving reference frame (equal to the vehicle speed); and sv is slip velocity. Using formula (3), the slip velocity components in the longitudinal, transverse and vertical directions from the ortho-Cartesian inertial coordinate system Oxyz were determined:

$$\begin{bmatrix} sv_x \\ sv_y \\ sv_z \end{bmatrix} = \begin{bmatrix} vu_x \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ vr_y \\ 0 \end{bmatrix} + \bar{\omega}_w \times \bar{r}, \quad (3)$$

where ω_w is relative angular velocity of the wheelset; r is coordinates of the contact point in the reference frame connected to the wheelset mass centre; and vr is relative velocity of the wheelset mass centre (in the moving reference frame).

2.1.11.2 Track parameters

The track model parameters and its general structure is shown in Figure 51 where: K_{bsz} – lateral stiffness of the rail to sleeper attachment, D_{bsz} – lateral damping of the rail to deck attachment, K_{psz} – vertical stiffness of the rail pad, D_{psz} – vertical damping of the rail pad, K_{bpods} – lateral stiffness of the ballast under the track, D_{bpods} – lateral damping of the ballast under the track, K_{ppods} – vertical stiffness of the ballast, D_{ppods} – vertical damping of the ballast.

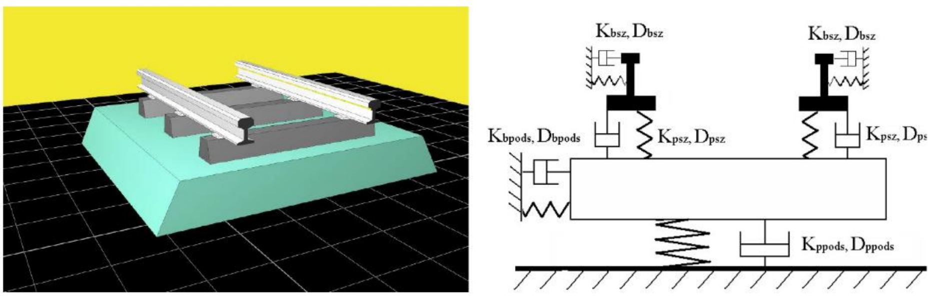


Figure 51 : Structure of the track model considered in the analysis

The track irregularities can be generally defined as the deviations of the track from its design geometry. Thus, the longitudinal level represents the vertical movement of each rail along the track, with respect to its design configuration.

A widely used method to have an analytical representation of the track consists in using the PSD of the measured irregularities in the track. PSD is a function of either the wavelength of the track irregularities or of the wave number, or even the space frequency.

While noting with Ω the wave number and with f the space frequency, these quantities are related to the wavelength λ by the equation

$$\Omega = \frac{2\pi}{\lambda} = 2\pi f \ , \qquad (4)$$

where f = 1/ λ, expressed in cycles/m.

The review literature mentions various forms of the PSD function that mainly take the track quality into account. The European countries use the ‚low level' and ‚high level' spectral density, in accordance with the ORE B 176 report. For the track vertical profile, the ORE B 176 report mentions the following form of PSD

$$S(\Omega) = \frac{A\Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)} \ , \qquad (5)$$

considered as representative for the statistic properties of the European railway system.

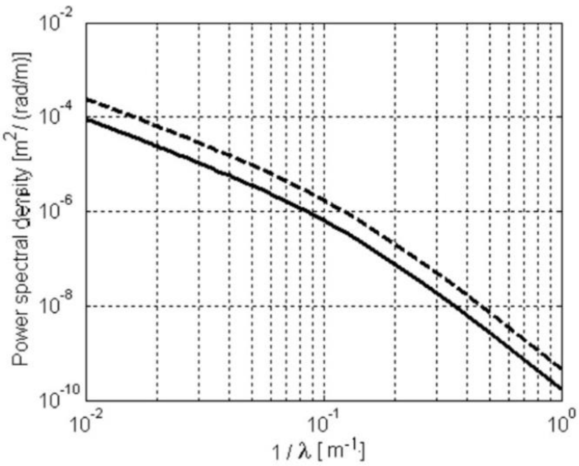


Figure 52 : PSD function of the vertical track irregularity profile. —, A = 4.032·10-7 radm; – –, A = 1.080·10-6 radm.

where:

Ω_c = 0,8246 rad/m,
Ω_r = 0,0206 rad/m,
Ω_s = 0,4380 rad/m,
b = 0,75m,
$A_V = 1{,}08 \cdot 10^{-6}$ m·rad,
$A_A = 6{,}125 \cdot 10^{-7}$ m·rad.

Wavelengths range from 2m to 100m. An example of the vertical and horizontal irregularities of the rail track obtained according to the ORE B 176 High guidelines is shown in the graphs (Figure 53). The vertical axis shows the amplitude of the track unevenness in meters, and the horizontal axis shows the track length expressed in meters.

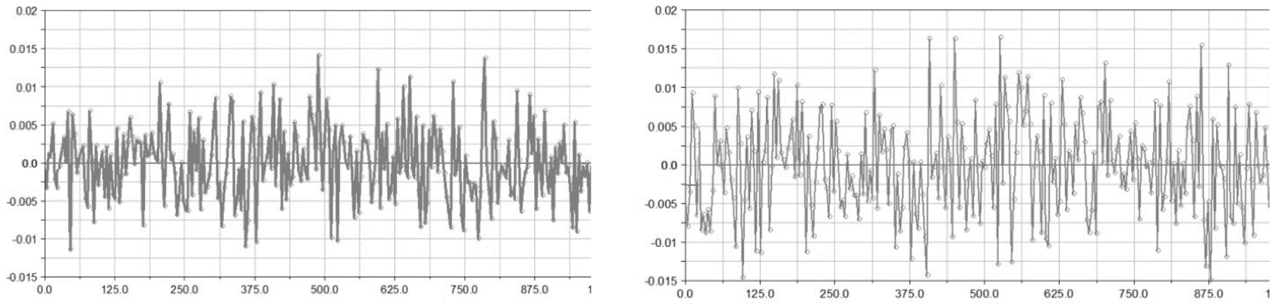


Figure 53 : Vertical and horizontal unevenness of the rail track of the test track according to ORE B 176 High guidelines

2.1.11.3 Vehicle driving dynamics analysis, according to EN 14363

Derailment coefficient Y/Q

This section analyses the driving dynamics of the vehicle model, according to the EN 14363 standard [1]. This standard concerns the tests of driving characteristics and stationary tests of rail vehicles before they are approved for operation. In our case, a numerical analysis of the vehicle model dynamics should be performed, consisting in driving this model on a type S track with two curves of radius R=150 m at a driving speed v below 10 km/h. The track geometry should be selected according to the EN 14363 standard so that the derailment coefficient can be determined at a given track twist dependent on the vehicle geometry.

The track twist limits (according to the EN 14363 standard), on which the vehicle model should move without the risk of derailment, have been determined from the following relations:

1) The limit of track twist based on the pivot spacing g* [‰], in the case of a vehicle whose pivot spacing is within 4 [m] ≤ ≤ 20 [m],

$$g^{*} = \frac{15}{2a^{*}} + 2 \,, \quad (6)$$

where: 2a* - spacing of the pivot pins (the axes of rotation of the bogies) [m],

2) The track twist limit based on the wheelbase in the bogie g+ [‰], in the case of a bogie with a wheelbase < 4 [m],

$$g^{+} = 7 - \frac{5}{2a^{+}} \quad (7)$$

where: 2a+ - wheelbase in the bogie [m].

The values of the twist in ‰ determined from formulas (6) and (7) were converted into the corresponding values of the vertical wheel displacements h [mm]:

$$h^* = g^* \cdot 2a^*; \quad h^+ = 0,5 \cdot \left(g^+ \cdot 2a^+\right) \tag{8}$$

where: g - twist on bases 2a* and 2a+ [m].

The determined values of the required track twist limits for the vehicle calculated according to equations (6) to (8) using real geometric parameters of the vehicle.

The most unfavourable case should be analysed, in which the vehicle is unloaded, without passengers, and has only its own weight. Based on the determined forces in the contact zone, the derailment coefficients Y/Q should be determined as the maximum ratio of the lateral force to the vertical force.

If the value of the Y/Q coefficient does not exceed 1.2, there is no risk of the vehicle derailing. This safety criterion is based on the balance of forces in the inclined plane of contact between the wheel and the rail.

2.1.11.4 Ride comfort assessment with reference to EN 12299

This section considers the issue of assessing the ride comfort of a light regional vehicle model. This assessment consists in determining the N_{MV} index (average comfort, simplified method) and the N_{VD} index (average comfort, full method, standing passenger) according to the EN 12299 standard. The general mathematical notation (6) and (7) from which the above-mentioned indices are determined is presented below. The parameters a with the indices $_{wd}$ and $_{xp95}$, $_{yp95}$, $_{zp95}$, $_{xp50}$, $_{yp50}$, $_{zp50}$ respectively, are the effective value (RMS) of acceleration in 3 directions (x, y, z), recorded in the rail vehicle body. The values of these accelerations are subjected to appropriate filtering and statistical processing before being entered into the relations (9) and (10).

To determine the comfort indicators N_{MV} and N_{VD}, quantiles of the order of 0.95 and 0.5 are necessary, obtained from the values of the cumulative histogram (distribution function) of the effective values (RMS) determined every 5 s.

$$N_{MV} = 6 \cdot \sqrt{(a_{xp95}^{w_d})^2 + (a_{yp95}^{w_d})^2 + (a_{zp95}^{w_d})^2}, \tag{9}$$

$$N_{VD} = 3 \cdot \sqrt{16 \cdot (a_{xp50}^{w_d})^2 + 4 \cdot (a_{yp50}^{w_d})^2 + (a_{zp50}^{w_d})^2} + 5 \cdot (a_{yp95}^{w_d}). \tag{10}$$

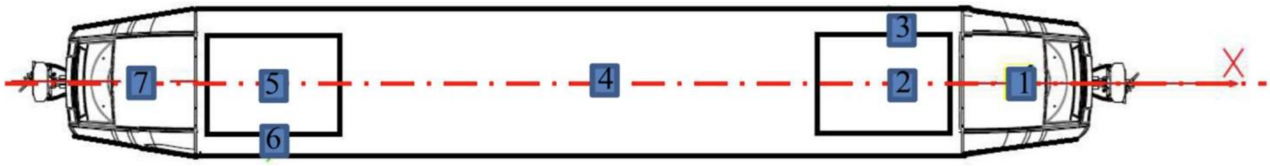


Figure 54 : Location of measurement points of accelerations acting on the driver and passengers in the analysed vehicle.

The listed comfort indicators N_{MV} and N_{VD} should be determined from the accelerations measured at 7 points located on the body of the tested vehicle (Figure 54). The comfort indicators should be determined during travel on 2 sections of track with the parameters of a typical regional railway line, at the maximum speed for the track parameters, not greater than the operating speed of the vehicle.

2.1.11.4 Determination of the critical speed as a function of the deteriorating efficiency of the vehicle model's damping suspension elements

Simulation of stability tests should be performed on a light regional vehicle model. For this purpose, critical speeds of the model should be determined as a function of the deteriorating efficiency of the damping elements, which is 100%, 75% and 50% of the nominal damping of the dampers, respectively. The critical speed of the vehicle model should be determined based on the analysis of the stability of the tested object's motion. The critical speed of the vehicle can be determined based on the definition as the limiting speed value above which its motion is disturbed by an increase in the lateral displacements of the wheel sets and individual vehicle units. Determination of these parameters should consist in simulating the motion of the vehicle model on a straight track with a rail gauge of 1435 mm with a variable travel speed up to maximum operational speed multiply by 2.

2.1.11.5 Simulations results

Example of calculation results for a two-bogie vehicle operated on the PKP PLK regional network:

Table 12 : Basic technical parameters of the vehicle

Parameter	Value
Track gauge	1435 mm
Bogie spacing	15 m
Total length of vehicle	23 m
Operating speed	≤ 120 km/h
Drive bogies	2 x type 26MNa
Diameter new/worn wheels	850 mm / 780 mm
Axle arrangement	Bo’+Bo’

Table 13 : Values of masses and moments of inertia of the vehicle elements adopted for the numerical model.

Empty carbody: $M = 22050.00$ kg $I_{XX} = 76000.0$ kg·m ^{2} $I_{YY} = 103000.92$ kg·m ^{2} $I_{ZZ} = 1035000.00$ kg·m ^{2}	Bogie frame: $M = 2900.00$ kg $I_{XX} = 3400.00$ kg·m ^{2} $I_{YY} = 5238.00$ kg·m ^{2} $I_{ZZ} = 8386.00$kg·m ^{2}
Wheelset: $M = 1230$ kg $I_{XX} = 631.16$ kg·m ^{2} $I_{YY} = 82.09$ kg·m ^{2} $I_{ZZ} = 631.16$ kg·m ^{2}	Axelbox $M = 106.00$ kg $I_{XX} = 7.765$ kg·m ^{2} $I_{YY} = 0.012$ kg·m ^{2} $I_{ZZ} = 13.649$ kg·m ^{2}
Elements transmitting the tractive force - drive bogie ("pivot"): $M = 80.28$ kg $I_{XX} = 1.16$ kg·m ^{2} $I_{YY} = 1.98$ kg·m ^{2} $I_{ZZ} = 1.81$ kg·m ^{2}	Weight of the extreme and intermediate gear of the drive bogie and drive: $M_{skr} = 370$ kg $M_{pos} = 560$ kg 2x $M_{motor} = 4200$ kg

Table 14 : Parameters of the elastic and damping elements of the bogie suspension

Stiffness of the metal-rubber elements of the primary suspension: $K_X = 21000$ [N/m] $K_Y = 3800$ [N/m] $K_Z = 2180$ [N/m]	Secondary suspension spring stiffness: $K_X = 122000$ [N/m] $K_Y = 122000$ [N/m] $K_Y = 92000$ [N/m]
Torsional stiffness of primary suspension: $Kt_X = 261$ Nm/deg $Kt_Y = 2610$ Nm/deg $Kt_z = 261$ Nm/deg	Stiffness of the rubber element of the drive bogie pivot pin bumper: K = 500,00 [kN/m]
Damping of horizontal longitudinal dampers (snaking) of the driving and rolling carriage: $D_Y = 132000$ [Ns/m]	Damping of horizontal transverse dampers: $D_B = 31200$ [Ns/m]

Stiffness of metal-rubber elements at the pivot: K_X = 60000 [kN/m] K_Y = 60000 [kN/m] K_Z = 3300 [kN/m]	Damping of rubber elements of the first stage suspension: D_X = 3000 [Ns/m] D_Y = 6000 [Ns/m] D_Z = 3000 [Ns/m]
Stiffness of the rubber elements of the guide at the drive bogie pivot K_X = 13400 [kN/m] K_Y = 1600 [kN/m] K_Z = 13400 [kN/m]	Torsional stiffness of the rubber elements of the guide at the drive bogie pivot: K_{XX} = 157 [Nm/deg] K_{YY} = 59 [Nm/deg] K_{ZZ} = 157 [Nm/deg]
Secondary suspension vertical damper damping drive bogie: D = 28000 [Ns/m]	

Table 15 : Stiffness and damping values of the track model in the tests

K_{bsz}	D_{bsz}	K_{psz}	D_{psz}	K_{bpods}	D_{bpods}	K_{ppods}	D_{ppods}
0,43 MN/m	0,02 MNs/m	300 MN/m	0,01 MN/m	35 MN/ m	0,03 MNs/m	80 MN/ m	0,1 MNs /m

where: K_{bsz} – lateral stiffness of the rail to sleeper attachment, D_{bsz} – lateral damping of the rail to deck attachment, K_{psz} – vertical stiffness of the rail pad, D_{psz} – vertical damping of the rail pad, K_{bpods} – lateral stiffness of the ballast under the track, D_{bpods} – lateral damping of the ballast under the track, K_{ppods} – vertical stiffness of the ballast, D_{ppods} – vertical damping of the ballast.

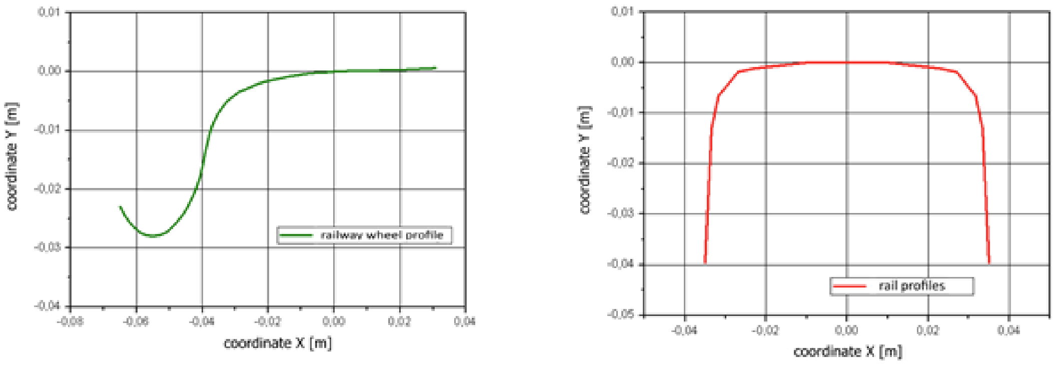


Figure 55 : Profile of a railway wheel (left) and a rail (right)

Table 16 : Values of the required track twist limits

Vehicle type: regional railway vehicle	Designation	Value
Maximum limiting twist (based on the pivot spacing – $2a^* = 15$ m)	g^* [‰]	2,90
Maximum limit twist (based on the wheelbase in the drive bogie – $2a^+ = 2{,}2$ m)	g^+ [‰]	4,70
The value of the vertical displacement of the wheel to obtain g^*	h^* [mm]	46,3
The value of the vertical wheel displacement to obtain g+ in the driving bogie	h^+ [mm]	5,15

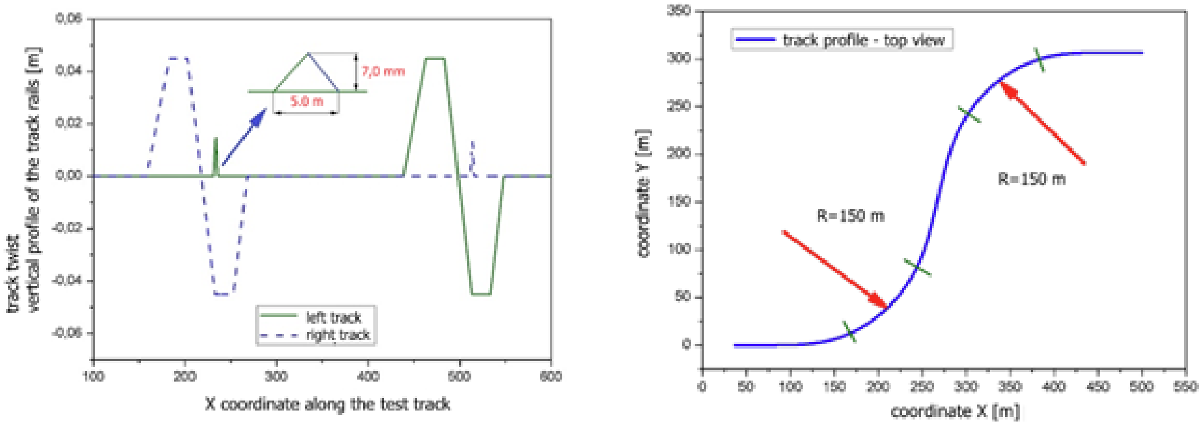


Figure 56 : Vertical and horizontal geometry of the test track according to EN 14363

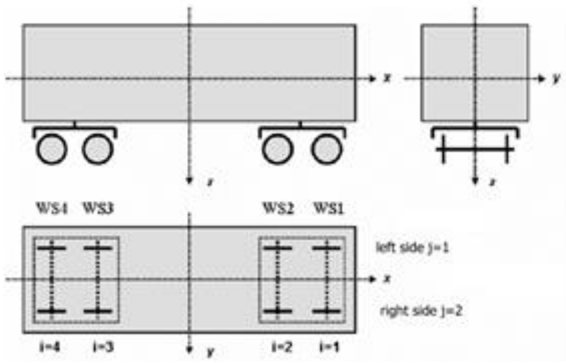


Figure 57 : Coordinate system and wheel designation of the modelled vehicle

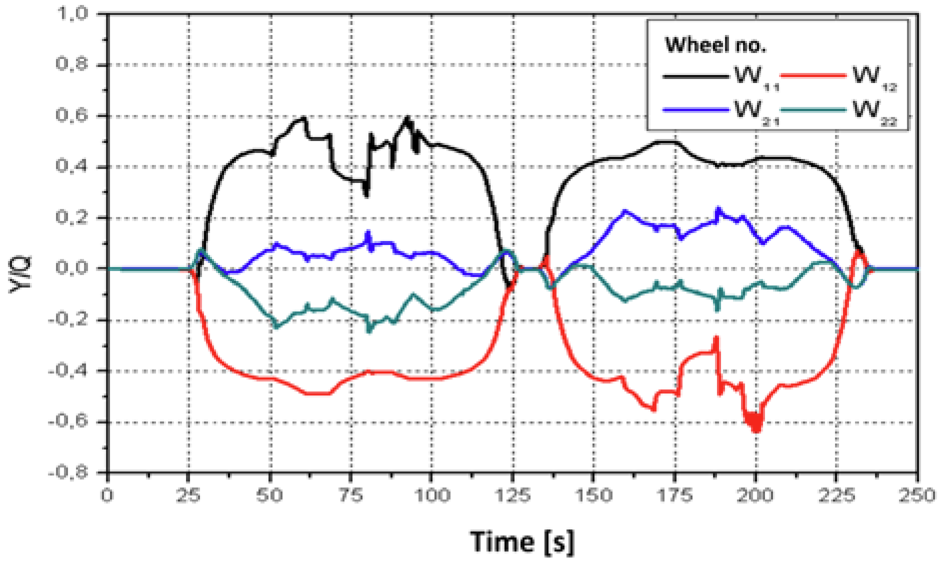


Figure 58 : Changes in the derailment coefficient Y/Q of bogie 1 wheels during the test

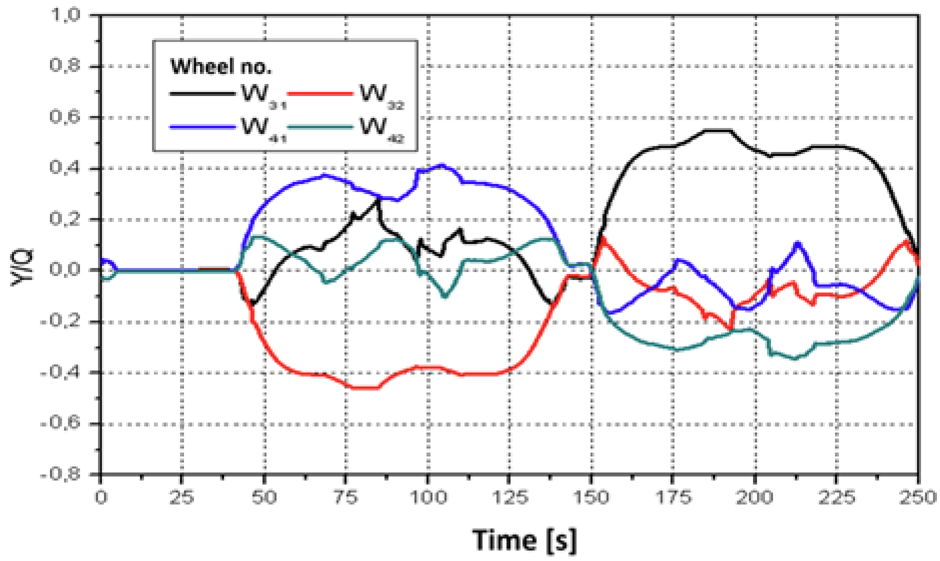


Figure 59 : Changes in the derailment coefficient Y/Q of bogie 2 wheels during the test

Table 17 : Determined maximum values of the Y/Q coefficients

Wheel WSij	*11*	*12*	*21*	*22*	*31*	*32*	*41*	*42*
Y/Q	0.60	0.62	0.28	0.27	0.66	0.62	0.23	0.25

Track 1:

The analyzed railway line (6.8 km long) is characterized by the following track geometry and maximum travel speeds on these sections:

1 Section of track, radius R=1200 m, track inclination 3.9-4.01 ‰, speed v=120 km/h,

2 Section of track, radius R=2500 m, track inclination 4.01-5.9 ‰, v=100÷110 km/h,

3 Section of track, radius R=1500 m, track inclination 2.27-0.65 ‰, speed v=115 km/h.

Table 18 : Average of ride comfort indicators NMV and NVD on the railway line section – Track 1

Measuring point	1	2	3	4	5	6	7
Indicator value N_{MV}	1.13	0.99	0.64	0.72	0.72	0.83	1.00
Indicator value N_{VD}	2.11	2.08	1.96	1.99	1.99	2.02	2.08

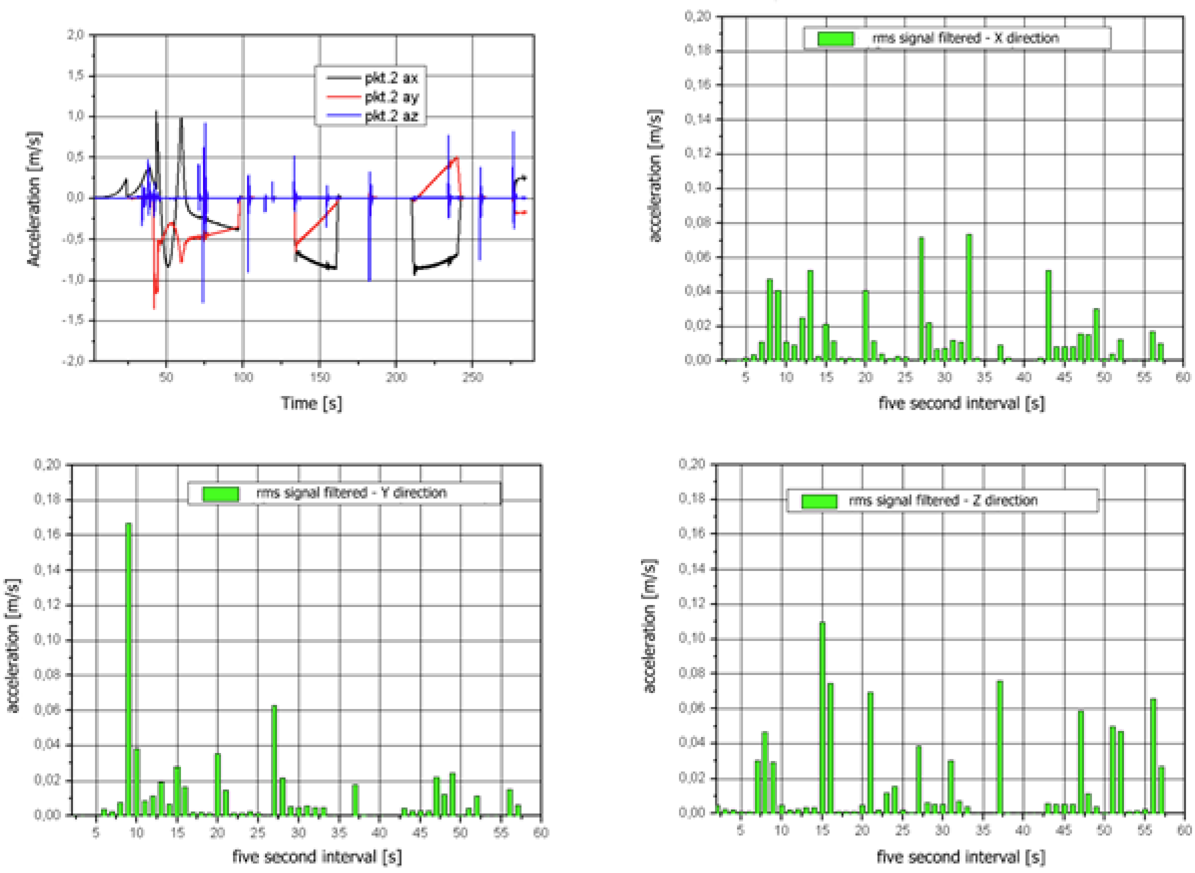


Figure 60 : Acceleration values from point no 2 in vehicle model carbody during ride on track 1 and RMS value from this acceleration in five-second intervals for three directions

Track 2:

The next 8.7 km long railway line, used for ride comfort tests, has the following technical infrastructure parameters:

1 Section of track, curve radius R=1500 m, track inclination 9.9-10.29 ‰, speed v=120 km/h,

2 Section of track, curve radius R=500 m, track inclination 10.2 ‰, speed v=75 km/h,

3 Section of track, curve radius R=300 m, track inclination 10.2 ‰, speed v=75 km/h.

Table 19 : Average of ride comfort indicators NMV and NVD on the railway line section – Track 2

Measuring point	1	2	3	4	5	6	7
Indicator value N_{MV}	0.75	0.66	0.65	0.64	0.66	0.62	0.73
Indicator value N_{VD}	1.95	1.85	1.82	1.82	1.83	1.83	1.87

Track 3:

The last 13.5 km long railway line, on which the ride comfort of the vehicle model was analysed, is characterized by the following railway infrastructure parameters:

1 Section fragment, curve radius R=500 m, track inclination 12.2 ‰, speed v=95 km/h,

2 Section fragment, curve radius R=370-410 m, track inclination 13.45 ‰, speed v=95 km/h,

3 Section fragment, curve radius R=560 m, track inclination 13.45 ‰, speed v=95 km/h,

4 Section fragment, curve radius R=660 m, track inclination 6.28 ‰, speed v=95 km/h,

5 Section fragment, curve radius R=390 m, track inclination 14.5 ‰, speed v=95 km/h,

6 Section fragment, curve radius R=530 m, track inclination 13.3 ‰, speed v=95 km/h,

7 Section fragment, curve radius R=400-670 m, track inclination 16 ‰, speed v=95 km/h,

8 Section fragment, curve radius R=390-590 m, track inclination 26 ‰, speed v=85 km/h,

9 Section fragment, curve radius R=400-500 m, track inclination 21-24 ‰, speed v=85 km/h,

10 Section fragment, curve radius R=400 m, track inclination 25 ‰, speed v=85 km/h.[35]

[35] EN 12299:2009 - Railway applications - Ride comfort for passengers - Measurement and evaluation

EN 14363:2016+A2:2022 Railway applications - Testing and Simulation for the acceptance of running characteristics of railway vehicles - Running Behaviour and stationary tests

Bogies with steered or steering wheelsets, Report No. 1: Specifications and preliminary studies, Vol. 2, Specification for a bogie with improved curving characteristics, ORE B 176, (1989).

Table 20 : Average of ride comfort indicators NMV and NVD on the railway line section – Track 3

Measuring point	1	2	3	4	5	6	7	8	9	10
Indicator value N_{MV}	0.97	0.82	0.70	0.73	0.57	0.80	0.78	0.78	0.82	0.97
Indicator value N_{VD}	2.12	2.02	2.02	2.03	1.97	2.05	2.05	2.05	2.06	2.11

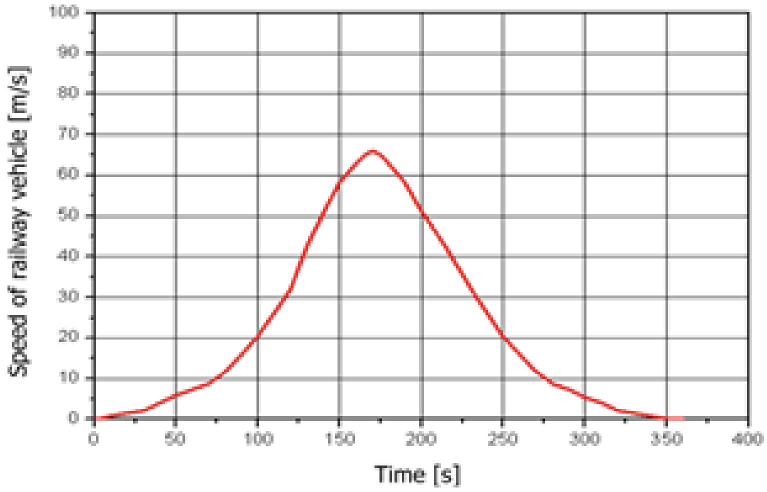


Figure 61 : Speed profile used to determine the critical speed of the vehicle model

Table 21 : Parameters of suspension damping used to determine the critical speed

Dampers of the vehicle model	Efficiency of damping elements		
	100%	75%	50%
vertical damper of secondary suspension	28000 [Ns/m]	21000 [Ns/m]	14000 [Ns/m]
horizontal longitudinal dampers (snaking)	13200 [Ns/m]	99428 [Ns/m]	66285.6 Ns/m]
horizontal transverse dampers	31200[Ns/m]	23400 [Ns/m]	15600 [Ns/m]

Table 22 : Critical vehicle speed values with suspension condition deterioration

	Efficiency of damping elements		
	100%	75%	50%
critical speed	V_{critic} = 190 km/h	V_{critic} = 159 km/h	V_{critic} = 144 km/h

2.2 Traction/Propulsion specifications

2.2.1 Traction/Propulsion Architecture

The objective of subtask 5.2.2 is to research how novel powertrain solutions and sustainable energy carriers can be used to provide functional, cost efficient, clean & sustainable propulsion for the FUTURE lightweight vehicle (LV). This includes technical drive-cycle investigations, cost assessments and life cycle assessments, of battery, electric and hybrid solutions for partially electrified networks, hydrogen combustion engines and fuel cell powertrains, as well as methanol and ammonia (electro fuels) combustion engine powertrains, and their respective energy grids.

The requirements concerning the battery-based propulsion scheme have been also consulted with FP4 to achieve the most economic recommendation for the solution to be chosen.

The final results will provide recommendations for the choice of the optimal propulsion systems for any given track, traffic and infrastructure combination.

Figure 62 provide an overview and status of the subtask, and in this report, we focus primarily on the electrical powertrain simulations and to some extent on hydrogen fuel cell operation:

- Traction system, including traction drive design and optimized control
- Energy system, including battery size and fuel cell size on board and auxiliary loads.
- Charging infrastructure integration, including number of static and/or dynamic charging locations.

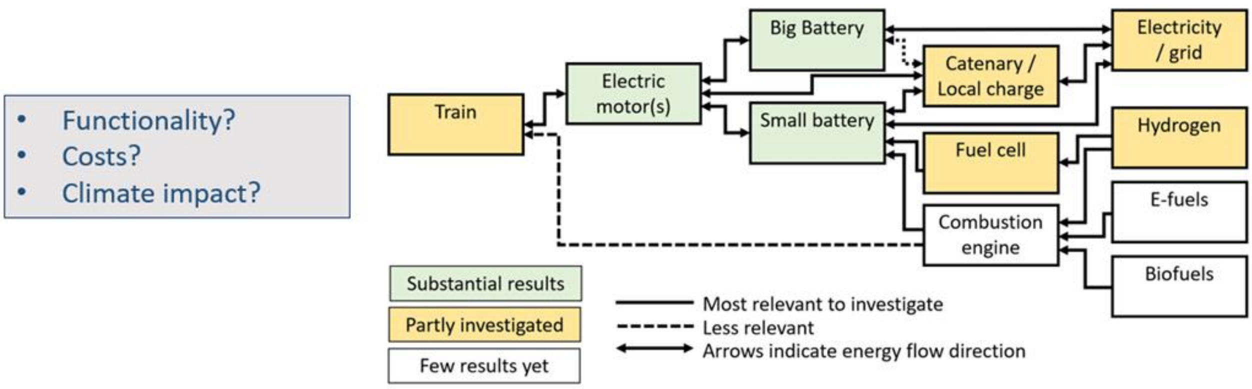


Figure 62 : Overview and status of task 5.2.2

2.2.1.1 Method

Simulations of the propulsion system are conducted using MATLAB/Simulink (see figure 2.2.2), with several drivetrain configurations tested under representative operational conditions. The key elements of the simulation methodology are:

Modelling and Simulation Approach

- Subsystem-Level Modelling: The propulsion system is divided into its key subsystems—drive units, battery management, and auxiliary systems—for detailed analysis.
- Timetable: Operational performance is simulated using data from the German and Sweden routes
  - Key factors included:
    - Speed profiles, acceleration, and stop frequencies.
    - Elevation changes and their impact on energy consumption.
    - Auxiliary power demands across different seasons (e.g., HVAC loads).
    - Energy Flow Optimization:
      - Static and localized dynamic energy supply methods are modelled to optimize power distribution and extend battery life while reducing operational costs
      - Rule based power split to estimate the hydrogen consumption

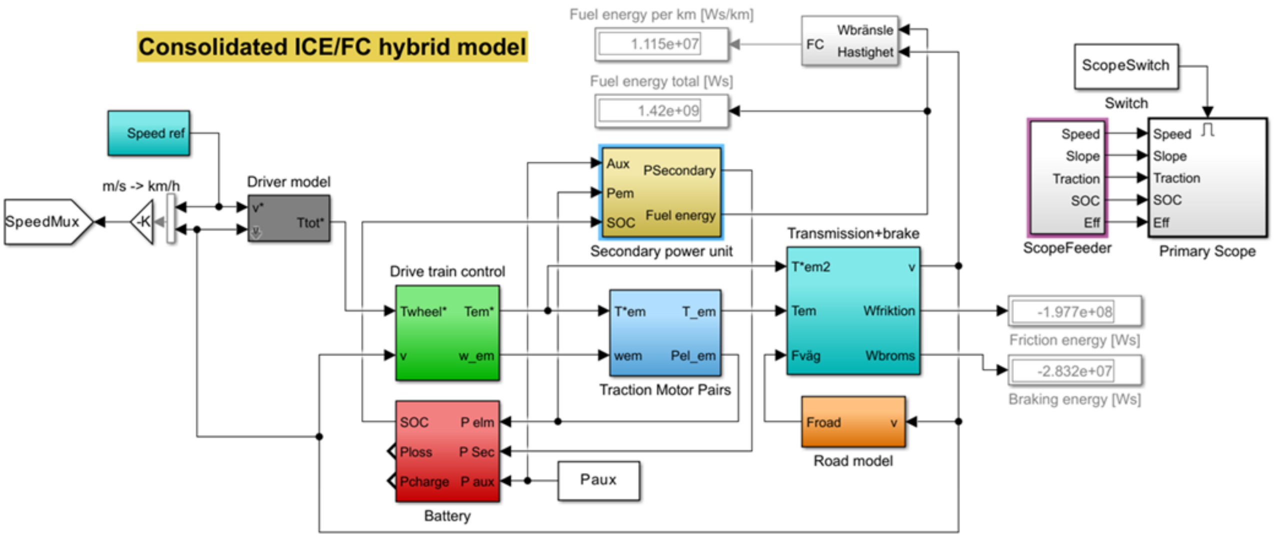


Figure 63 : Example of the model setup in Matlab/Simulink

2.2.1.2 Description of Investigated Drivetrains and Operating Conditions

Key Parameters

The following parameters are used in the analysis:

- Maximum Speed: 120 km/h.

- Vehicle Weight: 30,000 kg (including passengers).
- Maximum Traction Power: 390 kW.
- Fuel cell power: 40-200 kW
- Battery Capacity: Up to the size needed to complete round trip on one charge. As an example, 400 kWh is needed for the round trip for the track Borlänge-Malung in Sweden.
- Number of energy supply stations: From one to maximum one at each stop
- Auxiliary Power: HVAC demand and other auxiliary systems are considered for seasonal variations.
- Timetables (Drive Cycles): Different routes with their timetables and topographies are tested for energy consumption impact.

Operational Flexibility

The system must support a range of operational conditions, including seasonal weather variations and auxiliary power demands. The energy consumption modelling ensures that the propulsion system meets performance standards under different environmental scenarios, ensuring efficient year-round operation.

Powertrain Layout

The current state of traction systems in rolling stock demonstrates that alternative propulsion systems are already in operation. Building on the knowledge gained from various projects, a range of standards has been established to support the practical implementation of new vehicle concepts. One of the key standards is IEC 62864, which defines hybrid powertrain solutions. Using this standard as a basis, the following modified Figure 1 has been adapted for the use case of light rail vehicles.

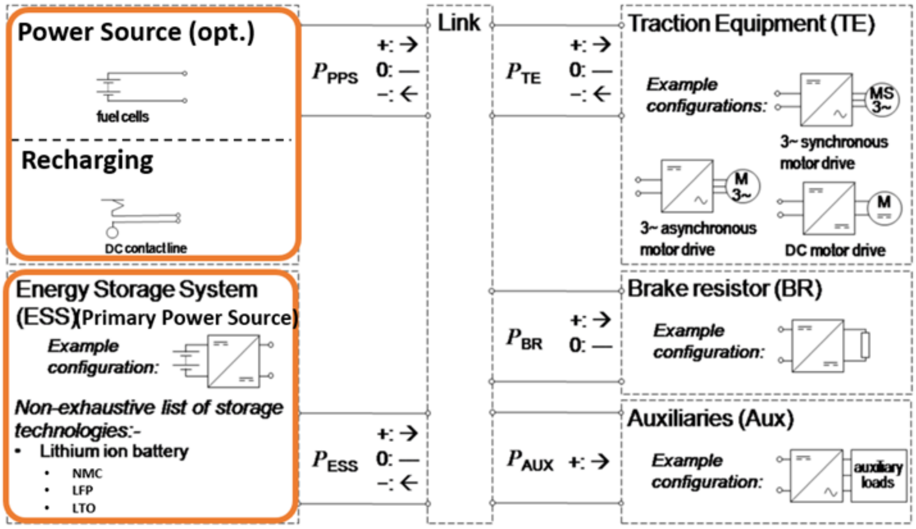


Figure 64 : Source: IEC 62864-1:2016 | IEC Railway applications - Rolling stock - Power supply with onboard energy storage system - Part 1: Series hybrid system adapted to the

The diagram highlights two major power sources connected via the intermediate circuit (DC Link) to the Traction Equipment (TE), the Brake Resistor (BR), and the Auxiliaries (Aux). For LVs, DC charging solutions are recommended to avoid the need for additional power electronics, such as transformers. Additionally, the battery storage system can be considered a primary power source. In cases where multiple power sources are involved, the Energy Management System (EMS) determines the operating strategy and influences the powertrain dimensioning. This affects the interaction between primary and secondary power sources, with a particular focus on the battery, which also functions as an energy storage unit. The behaviour of this energy storage depends on the specific battery cell chemistry used, such as Nickel Manganese Cobalt (NMC), Lithium Iron Phosphate (LFP), or Lithium Titanium Oxide (LTO).

Drivetrain configurations

The efficiency of electric traction motors varies with the load and speed. A large electrical motor will be less efficient at low loads while a small one will not offer sufficient power (load) to fulfil timetable requirements. The purpose of this investigation is therefore to explore the opportunity to use two or more electrical traction motors (ETM) to improve overall efficiency and still meet all power requirements. Dual ETM system allows for better torque distribution, optimizing efficiency during different driving phases, which are also important considerations considering the low friction in rolling stock.

Examples of ETM configurations are provided in figure 2.2.4. Combinations with up to four ETM:s and low floor builds will be considered for further investigations.

- Single Electric Traction Machine:

- Power Output: 390 kW.
- Application: Handles peak power requirements, particularly during acceleration. Performance is less efficient during low-torque phases, such as cruising.
- Advantages: Simple design and control.
- Challenges: Lower efficiency during cruising, requiring larger battery capacities.

· Dual Electric Traction Machines:

- Power Distribution: PETM1-max = [0–390 kW] and PETM2-max = [390 – PETM1_max] kW.
- Application: Distributes power between two ETMs for improved efficiency. Uses a smaller ETM during cruising and engages both machines during acceleration.
- Advantages: Higher overall efficiency, reduced energy consumption, and smaller battery size requirements due to torque-splitting.
- Challenges: Requires a more complex control system.

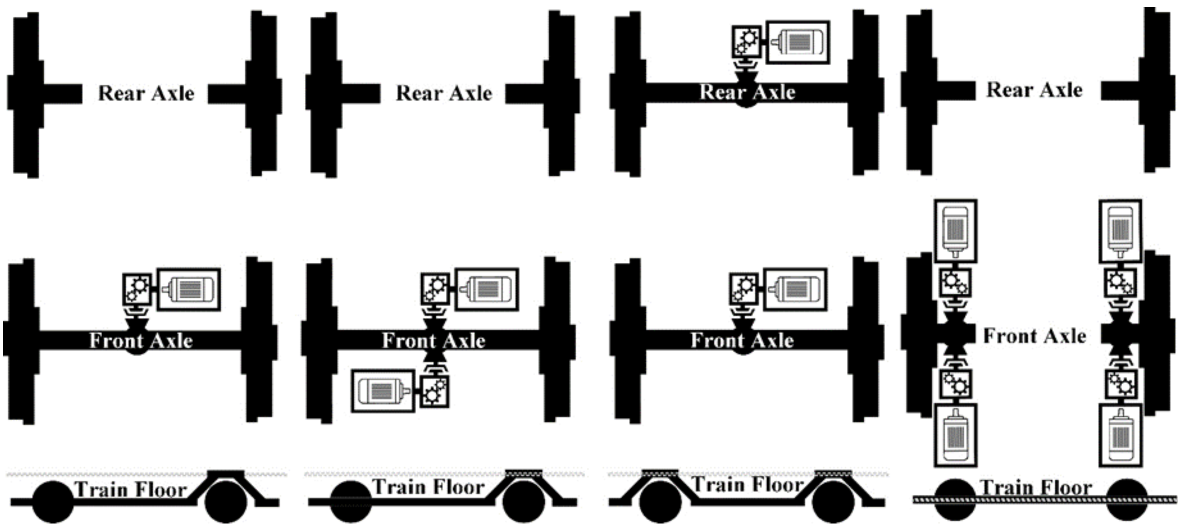


Figure 65 : The three leftmost figures show configurations with one or two axle-mounted electric traction motors (ETM). ETM:s can also be mounted directly to the wheel hubs which offers the possibility for lower floors, as exemplified by the rightmost figure

Operating Conditions

Two real-world routes were used primarily in the simulations.

· Borlänge-Malung track (129 km, 14 stops).

· Delmenhorst-Harpstedt track (21.5 km, 10 stops).

These routes feature some topographical variations, although less than the other investigated routes Erfurt-Rennsteig and Tubingen-Sigmaringen that will be presented in subsequent reports.

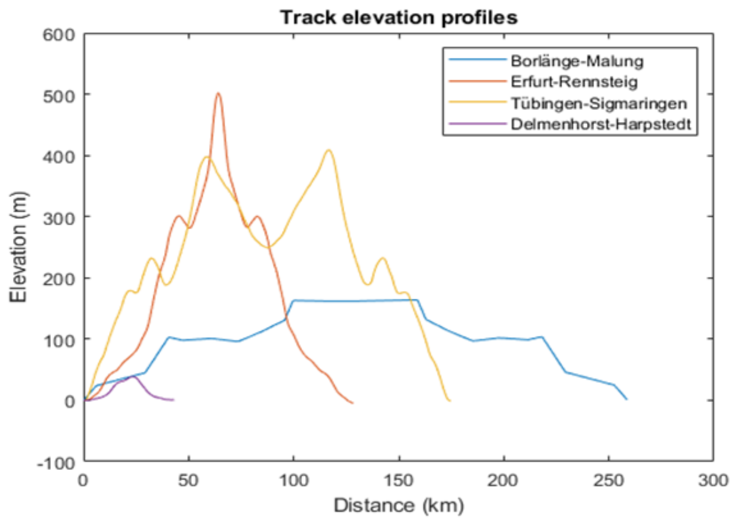


Figure 66 : Topographical profiles of the investigated routes

Energy Supply and Management

- Energy supply: Both static energy supply at and dynamic charging around specific stops or stretches along the route are modelled to explore the relationship with onboard battery size and operational range. The use of a secondary power unit, a hydrogen fuel cell, is modelled in a series configuration with the ETM.
- Energy Recovery: Regenerative braking is modelled to optimize energy recovery during deceleration, reducing overall energy consumption.

Seasonal Auxiliary Loads

Heating and cooling loads are considered in the simulations. Additional studies of this dependence will be presented in subsequent reports.

- Winter: Higher auxiliary power consumption due to HVAC heating demands.
- Summer: Increased power demands for cooling.

Control Strategy

In the dual ETM configuration, torque-split control is applied to optimize energy usage. During periods of low torque demand (e.g., cruising), only the smaller ETM operates. Both ETMs engage when acceleration or higher power output is needed, distributing the load to ensure the system operates at maximum efficiency under all conditions.

2.2.1.3 Overview of Results

Single ETM Configuration vs Dual ETM Configuration

Energy consumption and torque characteristics

By a combination of rated power split (in design) and instantaneous power split (in control) the most energy efficient operation can be accomplished, with the combined machines kept at the rated 390 kW. For the Borlänge-Malung route in Sweden with a battery-powered fully electric train showed that:

Single ETM Configuration: Gives higher energy consumption, particularly during cruising (1.06 kWh/km), due to lower efficiency in low-torque conditions.

Dual ETM Configuration: Reduces the energy consumption to 0.86 kWh/km, which represents a 19% reduction.

Figure 67 illustrates the energy consumption for a single ETM at different power outputs. By instead using a combination of a 70-kW and 320-kW ETM:s, rather than a single 390-kW ETM with same overall power, it is possible to avoid the less efficient power bands for either of the ETM:s.

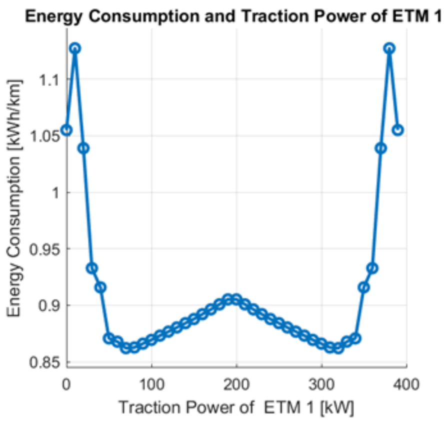
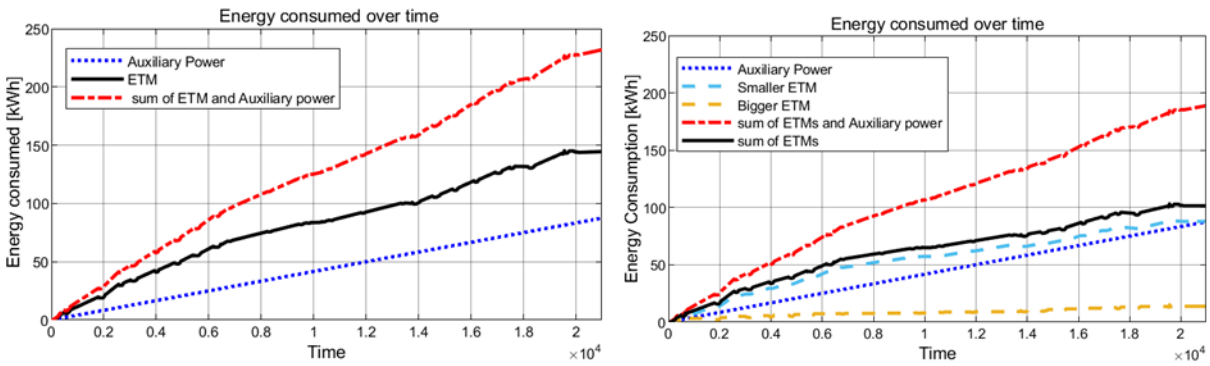


Figure 67 : The relationship between energy consumption (kWh/km) and maximum traction power (kW) of Electric Traction Machine 1

By applying these two configurations on the Borlänge-Malung route in Sweden the accumulated energy consumption over time isbe presented in Figure 68. The figure does not only include the energy consumption needed for the propulsion but also the energy consumption for the auxiliary power (mainly heating) which is a large share of the overall energy consumption in this specific case. The solid line representing the propulsion energy consumption clearly shows the recovered energy at each of the stops, but also the large variation over time between the two configurations. The figure also reveals the proportionate use of the two combined ETM:s with the limited use of the larger of the two. Figure 69 provides greater detail to the toque distribution for the configuration with two ETM:s.



(a) (b)

Figure 68 : a) Energy Consumption with a single 390 kW ETM. (b) Energy Consumption with two ETM:s of 70 kW and 320 kW

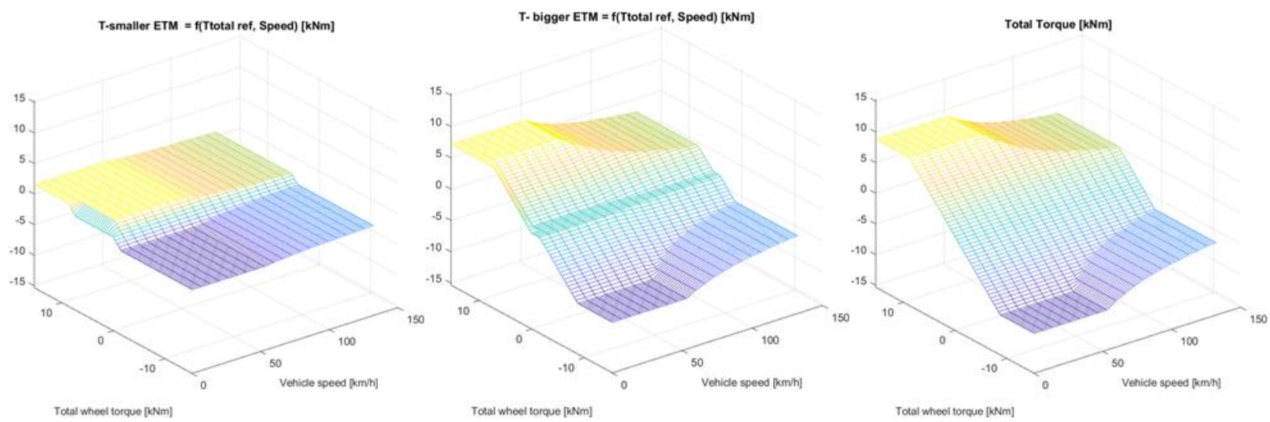


Figure 69 : Torque characteristics as function of vehicle speed and total wheel torque for 70 kW and 320 kW ETM:s

CO_2 impact

While this battery electric LV itself doesn´t emit any CO_2 during operation, we still need to account for the CO_2 emitted during the production of the electricity the LV consumes during operation, but also for the equivalent CO_2 emitted during the production phase of the LV and it´s batteries. The comparative CO_2 emissions between single-ETM and dual-ETM systems are estimated by combining the energy consumptions and battery sizes used in the simulations with data for CO_2 intensity and methods from the literature (Llamas-Orozco, Meng et al. 2023, EEA 2024, Nowtricity 2024) – this does not take the production of the LV into account. Figure 70 clearly shows the direct effect of reducing the energy consumption by almost 20%, with the help of two ETM:s, has on the proportionate reduction of CO_2. We also see that operation has a larger impact than the battery production. Please note that the data for the European case has been reduced by a factor of 10 to fit the diagram. The CO_2 intensity to produce the electricity is much lower than for Europe. To get a clearer picture we will not only do more in-depth analysis of various powertrain and fuel combinations, but also compare with a conventional diesel engine LV as a baseline.

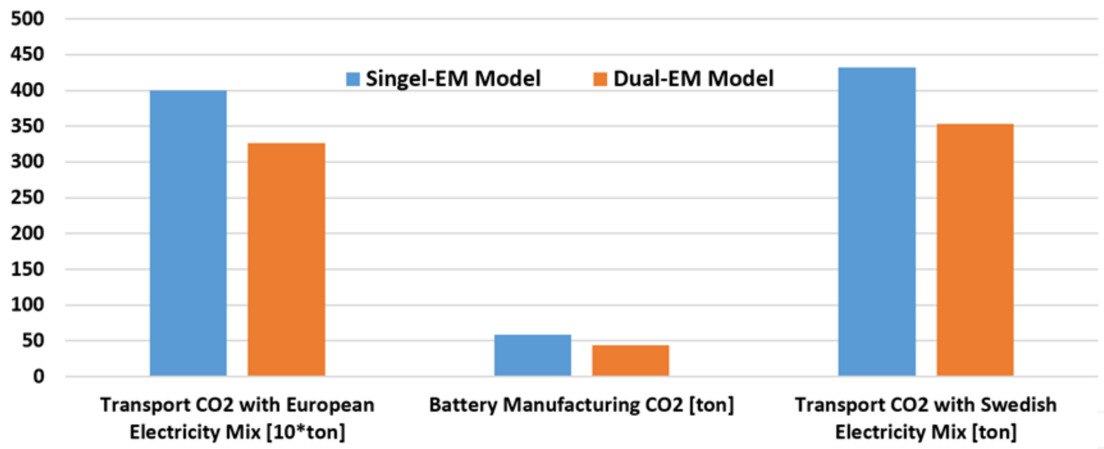


Figure 70 : Comparison of CO_2 emissions for Single-ETM and Dual-ETM Models with European and Swedish electricity mix for the Borlänge-Malung route

Battery energy, life and state-of-charge management

Figure 71 (left) shows the depth of battery discharge (DoD) as a function of battery size, electric road length and number of charging stations. The examples are based on simulations of the Borlänge-Malung route in Sweden with a battery-powered fully electric train. Increasing the number of charging stations reduces the DoD, which decreases the need for larger batteries. Battery life is also extended with the number of charging stations (Figure 71 (right)). The provided information can be used for different strategies to maximize battery life depending on the available number of charging stations, battery size and electric road length. This result incorporates the Rainflow method and the useful life diagram of the battery. It is assumed that the maximum operational life of an LFP battery is 20 years, beyond which battery lifetime estimation is deemed inadequate. For this calculation, the operational scenario assumes continuous train service.

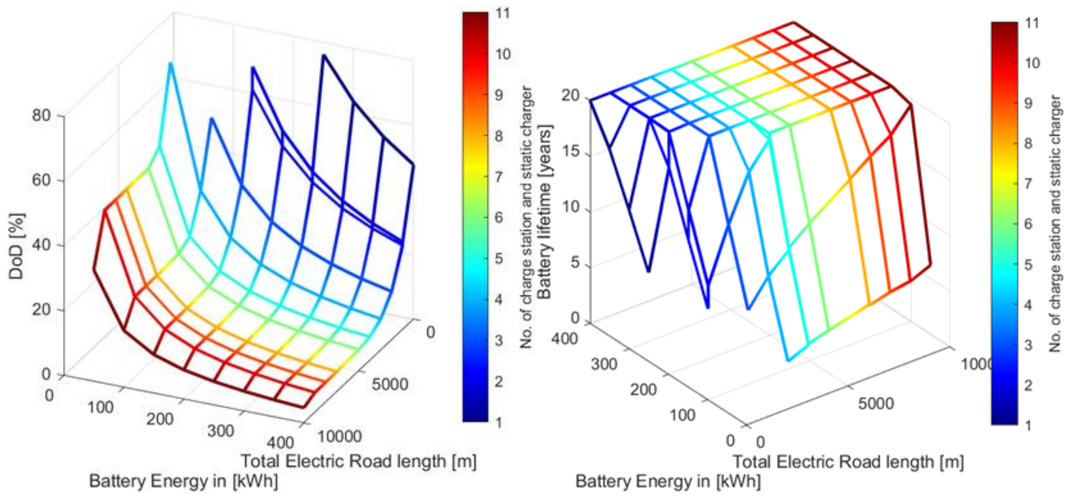


Figure 71 : Left: Relationship between battery energy, charging infrastructure, and DoD. Right: Relationship between battery energy, charging infrastructure, and battery lifetime

Fuel Cell powertrain light vehicle

On routes where electricity is not available or battery installations become overly large or heavy, fuel cell-powered propulsion using sustainable hydrogen offers a zero-emission solution. The rule-based power distribution provides an estimate of the dimensioning of the fuel cell hybrid power pack components hydrogen consumption and defines the operational points for the Delmenhorst-Harpstedt and Borlänge-Malung scenarios. The following picture presents the preliminary dimensioning results for the tracks:

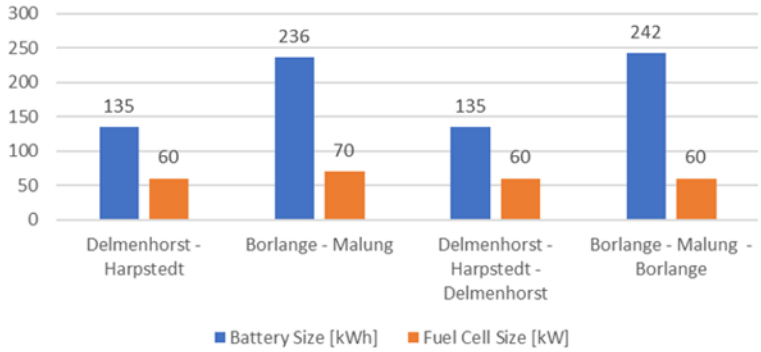


Figure 72 : Fuel Cell hybrid power pack preliminary dimensioning at End of Life [EoL] conditions

The hydrogen consumption for one-way trips ranges from 0.09 kg/km to 0.158 kg/km, corresponding to energy demands varying between 1.3 kWh/km and 2.3 kWh/km. To improve overall efficiency, the fuel cell operates primarily as a range extender, functioning at its most efficient operating points. The fuel cell is relatively small compared to the battery's power output, which handles the peak power demands. For the battery calculation a DoD = 80% is used and the LFP cell chemistry is assumed.

Improving energy efficiency through peak speed optimization

The amount of energy consumed for compartment heating or cooling, for any given temperature difference, essentially scales with time. Thus, if the LV is operated for a shorter time, then the energy needed for heating or cooling can be reduced. To reduce the operational time, speed has to be increased. The question is if the additional energy consumption for faster operation still allows an overall reduction of energy use. For the Borlänge-Malung route in Sweden, with a battery-powered fully electric train, five levels of auxiliary power (heating or cooling) are compared for higher or lower peak speeds. The results in Figure 73 show that if the auxiliary power is above 15 kW, up to 30% increased peak speed maintains or lowers overall energy consumption and travel time for the passengers.

The corresponding results for the Delmenhorst-Harpstedt route are presented in Figure 74. This route has 30% higher peak speeds to start with and optimizing energy consumption is in this context only achieved by reducing the peak speed, to the detriment of travel time.

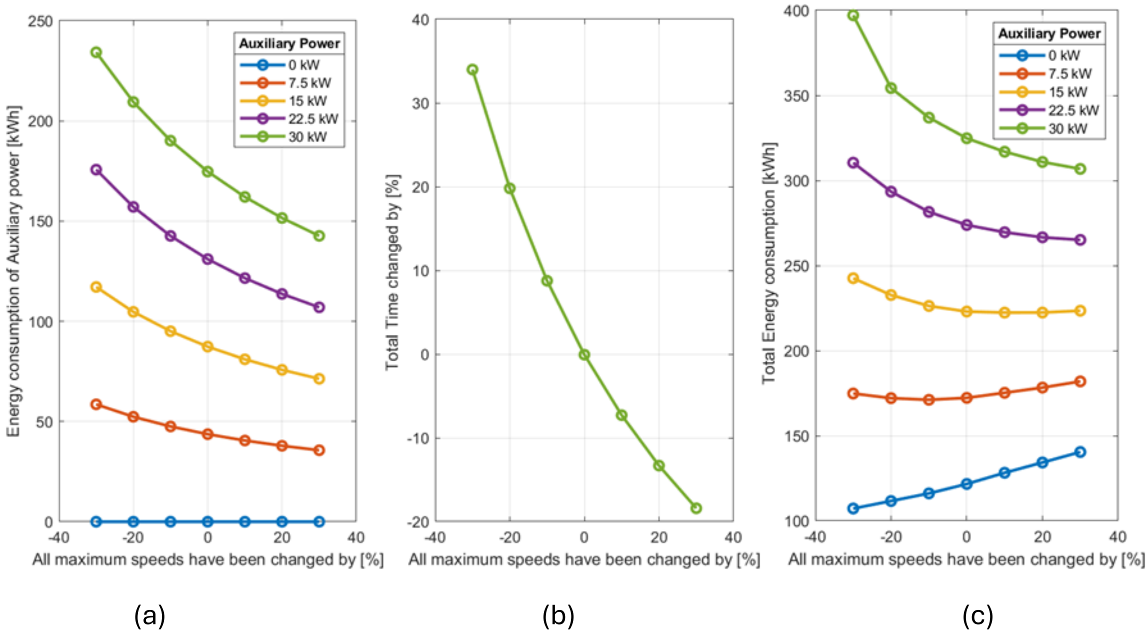


Figure 73 : As a function of changes in maximum speed for the Borlänge-Malung route: a) Auxiliary power consumption b) Travel time c) Total energy consumption

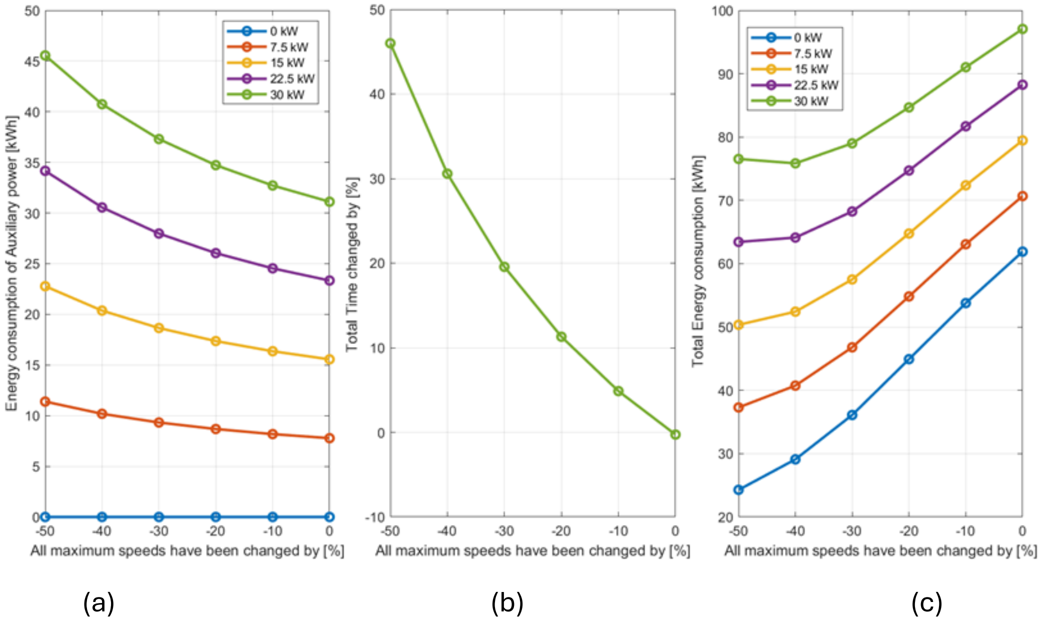


Figure 74 : As a function of changes in maximum speed for the Delmenhorst-Harpstedt route: a) Auxiliary power consumption b) Travel time c) Total energy consumption

Multi-modal fuelling station

The transition to cost efficient and clean LV rail operation also means new ways of providing and distributing energy. Local production of hydrogen at energy-hubs, that also offer high power electric charging, can be used by both rail and road applications, and thus provide more cost-efficient access to sustainable energy. Work is on-going to investigate how such hubs should be arranged, but figure 76 provides one example. Many more results are coming.

Figure 75 : Example of multi-modal fuelling station

2.2.1.4 *Indicative High-Level Powertrain Specifications*

The table below summarizes the key specifications for the powertrain components of the Light Rail Vehicles (LRVs) analyzed in this study. These specifications are based on the modeling and simulation results outlined in the previous sections, specifically optimized for energy efficiency, operational flexibility, and system reliability.[36]

Table 23 : Key specification for powertrain components

Component	Specification	Notes
Maximum Speed	120 km/h	Optimized for typical light rail operation across both urban and intercity routes.

[36] EEA. (2024). "Greenhouse gas emission intensity of electricity generation." from https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-15#tab-chart_7.

Llamas-Orozco, J. A., F. Meng, G. S. Walker, A. F. Abdul-Manan, H. L. MacLean, I. D. Posen and J. McKechnie (2023). "Estimating the environmental impacts of global lithium-ion battery supply chain: A temporal, geographical, and technological perspective." PNAS nexus **2**(11): pgad361.

Nowtricity. (2024). "CURRENT EMISSIONS IN SWEDEN." from https://www.nowtricity.com/country/sweden/.

Vehicle Weight	30,000 kg (including passengers)	Weight reflects maximum capacity scenarios, impacting energy consumption and braking.
Maximum Traction Power	390 kW	Power output is critical for handling acceleration and steep gradients.
Battery Capacity	20-400 kWh, depending on charging and hybrid solution. Many charging stops reduce the battery size needed.	Varies based on route length, auxiliary demands, and availability of charging infrastructure and the powertrain layout such as battery cell chemistry.
Charging Methods	Static and dynamic charging options	Static at station stops Dynamic via conductive track strips to minimize battery size will be investigated
Auxiliary Power Demand	Seasonal variation; peak HVAC load during summer months	High demand during extreme weather conditions for passenger comfort (heating and cooling).
Energy Consumption (Battery Electric Train)	~0.86-2.2 kWh/km	LFP; Other cell chemistries need to be evaluated Dual ETM system is more efficient compared to single ETM configuration
Energy Consumption (Fuel Cell Electric Train)	~1.3-2.4 kWh/km	LT PEM FC, LFP battery According to preliminary simulation results Other cell chemistries (high power demand) need to be evaluated
Hydrogen consumption (One way)	~3.4-11.9 kg	Indication for refuelling time

Torque Distribution	Smart instantaneous torque split between ETMs	Enables improved energy recovery via regenerative braking and optimized cruising efficiency.

2.3 Other system requirements and concepts

Task

The team of Work package 5.2.3 is tasked with the analysis for the concept relevant requirements for other systems, meaning systems not included but closely connected to the mechanical structure and the propulsion and energy systems of the train. This includes the specification and conceptualization of a modular and flexible vehicle interior capable of transporting up to 100 passengers and freight. This interior shall be easily adaptable to different needs of service within regional rail. Systems that are contained in the interior design are among others seating, luggage and bicycles racks, places for prams and wheelchairs and systems to accommodate different kinds of cargo. Furthermore, in this work package requirements and concepts for a novel braking system, signalling, Train Control and Management System (TCMS) and Automatic Train Operation ATO are analysed. Finally, we analysed relevant requirements for the concept for other relevant parts like Heating, Ventilation and Air Conditioning (HVAC) systems, doors, Passenger Information Systems (PIS), doors, lighting etc.

Interior Design

Analysis or the concept relevant requirements:

For the interior design we analysed the differentiating features of passengers. In general, the users can be differentiated by the following aspects:

- Sociodemographic factors, like age, gender, income etc.,
- Diversity, like LGBTQI+, ethnicity, disabilities, etc.
- Geographical factors, like traveling time, degree of urbanization etc.,
- Mobility behaviour, like trip purpose, mode choice, trip distance etc.,
- Psychological factors, like subjective norms, perceived compatibility and safety, etc., and
- General needs, like affordability, reliability, safety, comfort, etc.

Building on these features and the results of the focus group discussion and the survey conducted by IK, the needs of these diverse group of passengers were analysed. In addition, different freight scenarios and types of cargo feasible for transport in the vehicle were analysed. To satisfy the needs of this diverse groups as much as possible, we correlated every differentiating feature with a requirement for a technical solution tailored to fulfil the need of people representing the respective feature. The connections between the different passenger groups, their needs and possible technical solutions with their requirements are shown in a mind map in Figure 77.

As the needs of different passenger groups differ greatly and the technical solutions are not able to be implemented all simultaneously in such a small vehicle, a modular approach was chosen, in which different setups were composed to fulfil the needs of the passenger group which is expected to form the major user group at any given time and location. To change between the setups, the operator shall be able to mount and dismount components like seats, bike and luggage racks, desks, separating walls etc. to build the specific setups or a mixture of them. The passengers themselves shall be able to displace and fold away specific components to tailor the room around them to a certain extend.

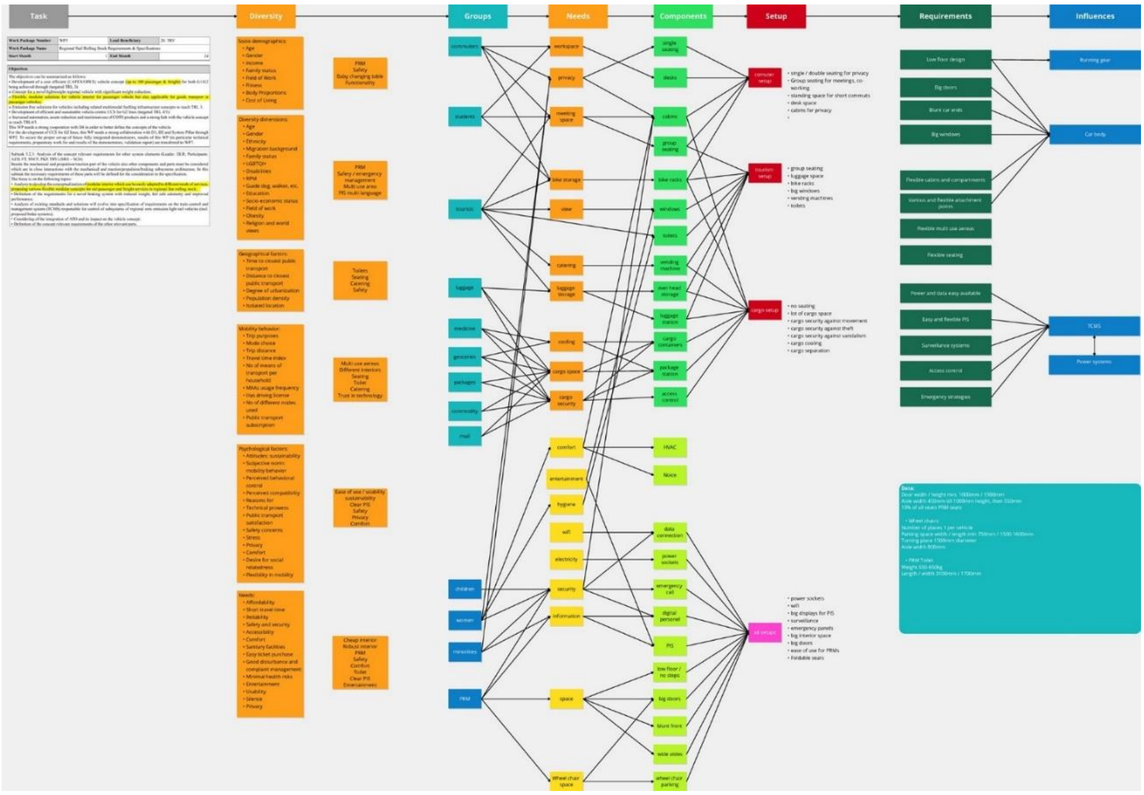


Figure 76 : Interior design requirements mind map

Ultimately, we were able to identify three different use cases for the vehicle interior, for which we build up three different derivatives of the interior:

- **The commute setup:**

This setup is characterized by a passenger group commuting to and from work, school, university and similar. We assume these passenger group to need lots of standing space for short travel distances, space for bikes and privacy for people wanting to work. There is great demand for good connectivity, so plenty of CEE and USB power sockets and stable and powerful WIFI connection are mandatory. We expect this setup to be relevant in the morning and evening of working days.

- **Tourism setup:**

This setup is tailored to a passenger group traveling to, from and during vacation. We assume a need for lots of space for bikes and luggage, longer travel times and a good view outside the vehicle. There is also demand for power sockets to charge electrical bikes. We expect this setup to be most needed on weekends and during vacation seasons.

- **Cargo setup:**

For the cargo setup a lot of empty space is required. Cargo must be secured to the vehicle. This setup could be feasible at night and during low demand.

Requirements:

Building on these three setups and the general needs of all passenger groups, which were identified in the focus group discussion, the survey and in the analysis of the different user groups, we formed the following general requirements for a novel lightweight regional rail vehicle for up to 100 passengers and freight:

- Low Floor Design
- Big doors
- Blunt car ends
- Big windows
- Lots of indirect lighting
- Light coloured wood panels
- Modern design
- Flexible cabins and compartments
- Various flexible attachment points
- Flexible multi use areas
- Flexible seating
- Easy power and data accessibility
- Easy and flexible PIS
- Surveillance systems
- Access control
- Emergency strategies

Building on this and on the general regulations of the TSI PRM, the following detailed requirements are extracted and shown in Table 24.

Table 24 : Interior requirements

Interior Space:	
As big as possible	Low floor, blunt vehicle heads
Compartments	(Re-)movable walls to segment the train, doors included
As flexible as possible	Railing system to mount components to
Doors:	
Width	min 1000mm (TSI PRM), min 1300mm (allowing 1200 mm euro pallet)
Height	min 1900mm
Level boarding	Doors on platform edge height or ramp at platform
Two wing doors	
Push button / automatic activation	
Easy to find using colour and light	
Seating:	
Removable by the operator	Seats on a rail system, seats can be mounted and dismounted
Changeable by the passenger	Changeable backrests, limited longitudinal relocatability, folding seats
Min 10% PRM Seats	More place for bigger seats
Armrests on both sides	Armrests foldable
More two-seater than four-seater	
Dedicated seats for people with children	
Other interior equipment:	
Power connectivity	USB-A / USB-C Sockets, CEE Sockets
Data connectivity	WIFI-Antennas, WLAN, 5G, RJ45-Sockets
Flexible wheelchair spaces	Wheelchair places near the door, obstacles to be folded away
	Width 750mm

	Length 1500-1600mm
	Turning place for wheelchairs diameter 1500mm
Places for people with children / prams	
Removable bike racks	Bike racks on hinges, mounted to the rail system
Removable luggage racks	Luggage racks mounted to the rail system
Removable Desks	Desks on hinges, mounted to the rail system and back rests
Removable handrails, handles	Handles, handrails on hinges, mounted to the rail system
Windows to be opened	
Removable cargo racks	Cargo racks mounted to the rail system
Removable cargo securing points	Cargo securing points on the rail system
Adaptable air ducts	Airducts with valves, different routing options
Adaptable HVAC	HVAC unit swappable, broad temperature range
Adaptable energy storage	Batteries to be added, removed
Toilet:	
Toilet Module	If necessary, mandatory or wished, toilet module
PIS:	
Big screens visible from all positions	Horizontal screens on ceiling, vertical screens near doors
Lots of information	
Clear design	
User interaction using touch	
Passenger Security:	
Remote security personal	Video call station with audio / video interface / connectivity
Security personal on board	Compartment for security personal, working space
Panic / emergency button	Button station with audio interface
Surveillance	Cameras / microphones inside and outside train, live transmission

Design Concept

The interior design concept evolves around the idea of flexibility and modularity. Depending on the time of the day, the time of the year, operator and passenger demands, the operator can adapt or completely swap the interior components to fulfil the needs of the major present user group. It also can be finetuned to the requirements of the track (length, travel time, number of halts, etc.), the operation area (city, rural, mixture, climate, landscape, etc.), the culture of the passengers and more.

Furthermore, the passengers themselves can adapt the interior to a certain degree. Components can be moved or be folded away if not needed. The following chapters dive deeper into each aspect of the modular interior design concept using the bigger vehicle derivate as example:

Floor layout

Figure 78 shows a possible floor layout. As the vehicle interior is highly modular, this is not fixed and can be adjusted.

- Multi use area in door modules
- Seating area on running gear and passenger modules
- Standing area om head module
- Additional walls to build compartments for private office / meeting space

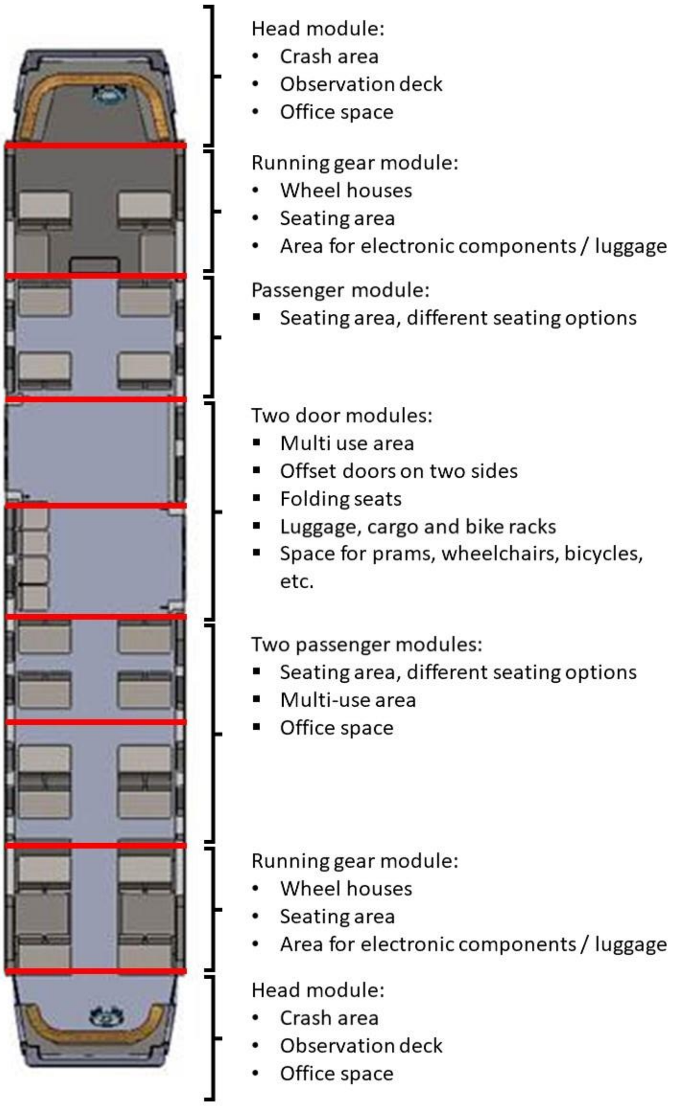


Figure 77 : Floor plan

The floor layout can be further portioned by using separation walls as shown in Figure 79. This could either be done at the vehicle front to build up a lounge for first class travellers, for private office space or for a meeting room. Also, parts of the multi-use or seating areas could be separated to build small, private compartments for single offices.

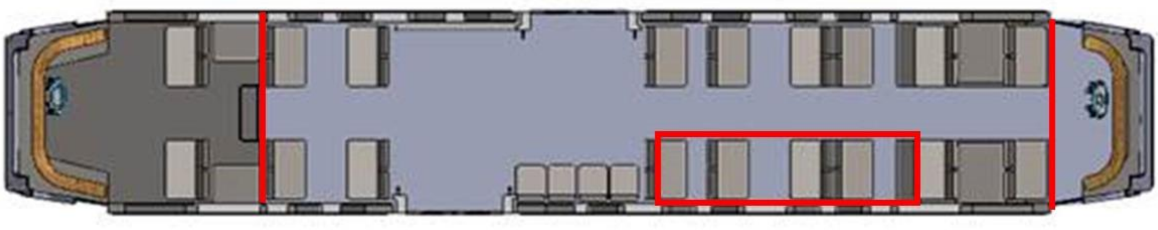


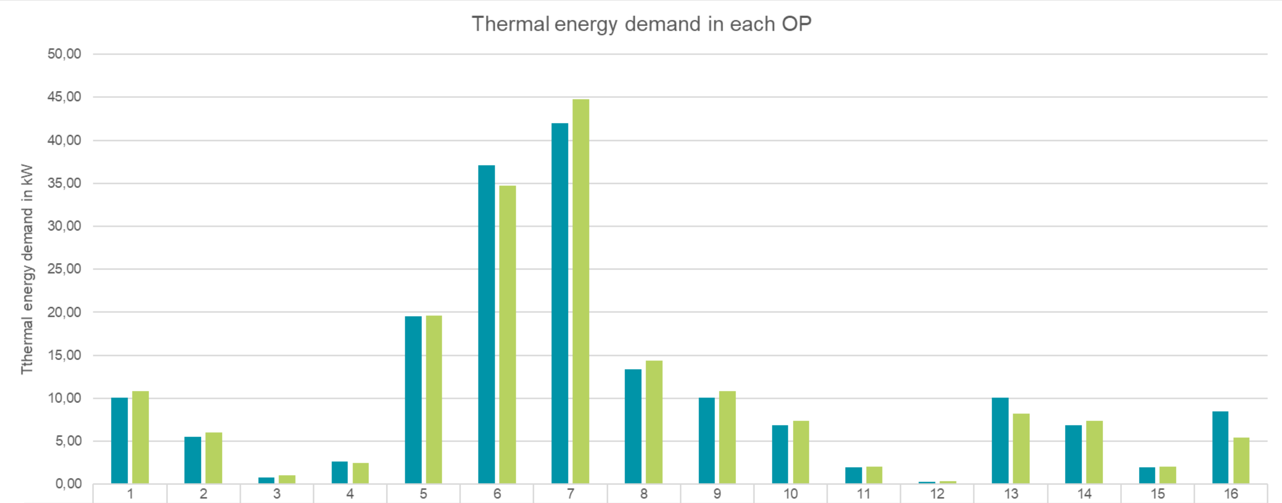
Figure 78 : Possible separation wall positions and compartments

Doors

The doors are placed in a longitudinal offset. Opposite of the door are leaning seats with integrated bike and cargo racks forming the multi-use area, which is accessible in a straight line. So, passengers with bicycles, prams, wheelchairs, or a lot of luggage do not have to travel far or to turn a lot to reach their respective accommodation systems. The doors shall be at least 1,300mm wide to allow two people streams at the same time. Also, euro-palettes which are 1,200mm long can easily be loaded. The doors shall be double winged, to allow some redundancy as the vehicle has only one door per side. The doors should have push buttons and the possibility to be operated automatically. Ramps or steps are optional as it should be easier to install ramps at the halt. As the train has only one door at each side and is driven automatically only one short ramp is needed per halt.

HVAC

The HVAC system plays a crucial role in the overall energy demand, the autonomous range and therefore the feasibility for the use cases. To dimension the HVAC system for the vehicle the thermal power demand was calculated for mid-European climatic demands. The investigation of the HVAC requirements shows that an HVAC needs to provide a different power demand for a variety of ambient conditions. The boundary conditions are chosen due to the standard DIN EN 14750-1 Class A (Railway applications - Air treatment in urban and regional rail vehicles – Part 1: Comfort parameters) and the standard operation points due to DIN EN 50591 (Vehicles - Specification and verification of energy consumption). The results can be seen in Figure 80.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
static	10,12	5,52	0,77	2,67	19,56	37,13	42,01	13,38	10,12	6,85	1,96	0,31	10,12	6,85	1,96	8,48
dynamic	10,86	6,02	1,03	2,50	19,59	34,70	44,77	14,36	10,86	7,36	2,10	0,34	8,23	7,36	2,10	5,46

Figure 79 : Thermal energy demands for HVAC

All operational points were calculated based on a static scenario of the vehicle and a driving-dynamic scenario of the vehicle. The worst-case scenarios are operational points 6 & 7, which represent a passenger volume of 100 % under high ambient temperatures (28°C; 40°C) and a thermal power demand (cooling) of 35 kW - 45 kW. The worst-case conditions for heating can be seen in operational point 8, resulting in thermal power demand of maximum 15 kW. Based on these calculations suitable HVAC systems can be evaluated.

A possible contender for a HVAC system is the Liebherr Modular Air Conditioning System MACS 8.0 shown in Figure 81. This system allows several units on the roof of the vehicle to work together providing the possibility to scale the HVAC system to different use cases. One unit can provide 8kW of heating and cooling capacity, so a maximum of 6 units are necessary to provide 48kW of thermal energy. This would lead to an electrical energy consumption of a maximum of 44kW. In sum, these modules would have a length of 6,000mm and a weight of 900kg.

Figure 80 : Liebherr MACS 8.0 HVAC unit[37]

The HVAC system also includes air duct routing, valves, nozzles, electrical and infra-red heaters. The air duct system shall be as flexible as possible to ensure sufficient air flow and temperature for a big variety of different setups. Different routing options and nozzle positions and directions in addition to a valve system to direct the airflow to be implemented.

Rail System

The vehicle's inner facing is fitted with a rail system on the floor, walls and ceiling to easily mount components. This rail system consists of longitudinal C-rails with T-nuts inserted into them. Possible positions are shown in Figure 82. By opening the connection of the component with the T-nut, the component can easily be removed. The T-nuts can also slide along the C-rails providing longitudinal adjustability. If the components are fitted with quick release leavers and stopping pieces, the passengers themselves could be allowed to move certain components like seats, bike racks or belt attachment points to the position fitted best for their needs. Especially moving seats could benefit an approach to increase flexibility to the floor layout. If more parking space for bikes or wheelchairs is needed, chairs could be moved out of the way. On the other hand, big people with long legs or people with an otherwise increased need for space could move the seat back to increase room between seats. Also, the bike rack could be moved into a position where it is needed instead of moving the bike around potentially disturbing other passengers.

[37] Liebherr MACS 8.0, last checked 18.10.2024, https://www-assets.liebherr.com/media/bu-media/lhbu-aer/transportation/downloads/products/liebherr-macs-8.0-brochure.pdf

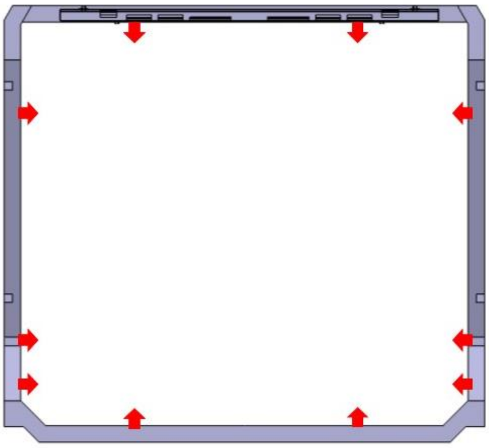


Figure 81 : interior C-rail system

The rail system also makes it very easy to remove all components and clear out all the room inside the vehicle for cleaning, rearranging, upgrading the interior or for making room for cargo. The rail system can also be used as cargo securing points by attaching belt loops or cargo racks to the rails.

Toilets

Both length derivatives of the FutuRe vehicle concept are rather short compared to existing regional trains and have little interior space. To fit a toilet into such a small vehicle proves to be very difficult if not impossible. The small vehicle has between its two-wheel cases approximately 4m length of low floor space. The doors take 1.4m without door frames, handles etc., leaving only 2.6m space left for a toilet. Common PRM toilets have a length of around 3.1m.

For the bigger vehicles a toilet is still difficult to integrate in a flexible and user-friendly interior as it will drastically reduce the number of available seats. From 40 available seats the toilet would replace up to 16 seats.

For especially long tracks it is foreseen to provide a toilet module, which can be installed into the train by the operator.

Seating

Each module of the train can accommodate different types of seats. The seats are mounted to the railing system on the floor and / or the lower sides of the vehicle.

The door modules are fitted with a combination of folding and leaning seats (see for example Ideenzug of the Deutsche Bahn AG in Figure 83. This allows maximum flexibility, quick boarding and alighting and additional space for prams, wheelchairs, bikes, luggage, or cargo.

Figure 82 : Folding seats from DB Ideenzug[38]

The running gear modules can be fitted with benches with changeable back rests (see for example Design + Industry Pty Ltd in Figure 84 to be oriented into the direction of travel. Alternatively, more comfortable seats with integrated armrests and desks can be mounted.

Figure 83 : Seats witch changable back rests[39]

[38] DB Ideenzug Klappsitze Wand, last checked 18.10.2024, https://ideenzug.deutschebahn.com/komponentenkatalog/Klappsitze-Wand-10809956

[39] Millennium 4GT Train Seats, Design + Industry Pty Ltd, last checked 18.10.2024 https://www.design-industry.com.au/sydney-millennium-train-seats

- The head module is a crash zone and cannot accommodate seating.
- The passenger modules could be fitted with any kind of seating as they offer the least spacial constraints and therefore the best flexibility. Two- and four-seater options are feasible. Also, wall facing seats with desks or compartments for private office space can be installed.

Desks

Foldable desks can be fitted to the backrest of some seats and into the armrests or side walls of the very first and last rows of seats in the head modules (see for example a desk setup from Bucher Group in Figure 85.

Figure 84 : Folding desk[40]

Fixed desks could be mounted to the sidewalls of the passenger modules in four-seater groups or on sideways facing seats, also in compartments for private office space (see for example office space from Bucher Group in Figure 86.

[40] Bucher Group, table mechanism, last checked 18.10.2024, https://bucher-group.com/de/produkte/tisch-mechanismus/

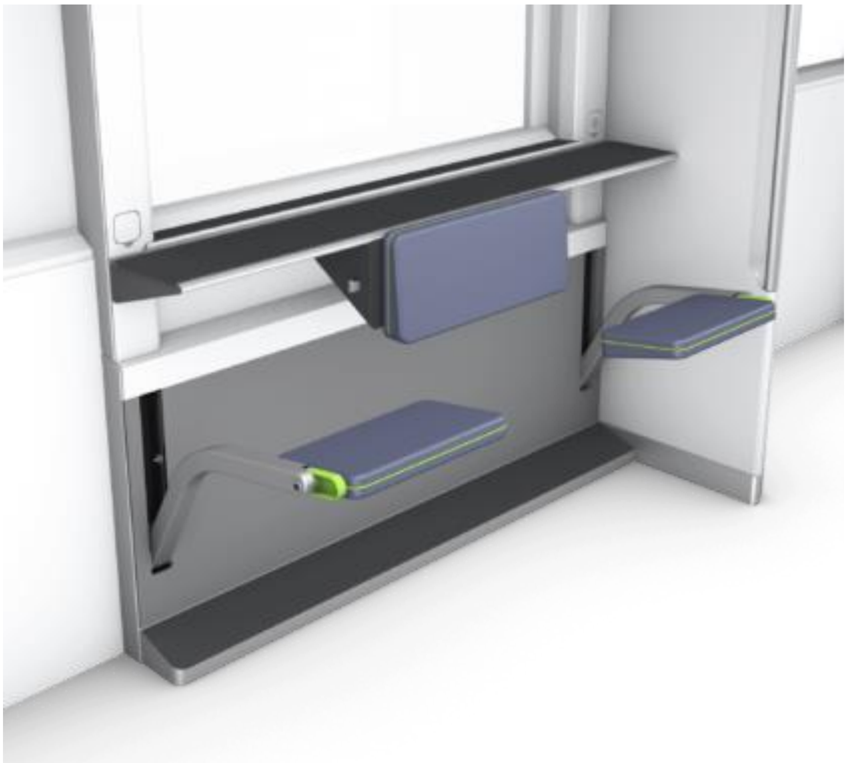


Figure 85 : Open office area[41]

Connectivity

The vehicle interior shall offer a wide variety of connectivity. For power plenty of USB-A, USB-C and CEE sockets are to be reachable from every seat. For the cargo setup, there should also be power sockets available for cooling solutions. Also, a data and internet connection should be available at any time utilizing Wi-Fi and RJ45 sockets.

Bicycles

Bicycles shall be stored in the multiuse area in the door modules. Two storage options are in discussion:

- Bike hangers near ceiling on rail system. They can be folded away if not in use and positioned where needed.
- The folding seats in the multiuse area are also equipped with vertical belts to secure a bike directly to the seats.

[41] Bucher Group, Train Working Area, last checked 18.10.2024, https://bucher-group.com/de/produkte/train-working-area/

Both options can be implemented simultaneously. Depending on the utilization and availability passengers can use what is best suited for the given situation.

Wheelchairs / Prams

The multiuse area with its folding seats offers plenty of space for wheelchairs and prams. Wheelchairs and prams can be placed against the backrests of the adjacent row of seats while parents and attendants can sit nearby on the folding seats. For additional safety, horizontal belts can be used to strap the wheelchair or pram to the folding seats.

Luggage

Above some of the seats, luggage racks can be mounted. Also, the belts in the multiuse area can be used to secure luggage and cargo to the folding seats. Additional luggage racks can be mounted to the railing system if necessary, during holiday seasons and weekends.

Cargo

Due to the attachment of every component of the interior to the railing system, parts of the vehicle or the entire vehicle can be emptied leaving plenty of space suitable for cargo transport. The railing system can be used for cargo security by mounting belt loops on the floor and walls. The vehicle provides room for up to 21 euro-pallets or cage trolleys in the low floor area as shown in Figure 87 Alternatively, cargo racks, pack stations or vending machines could be mounted to the railing system. Also, the CEE sockets and data connections could be used for more complex cargo solutions like cooled cargo containers or access control solutions.

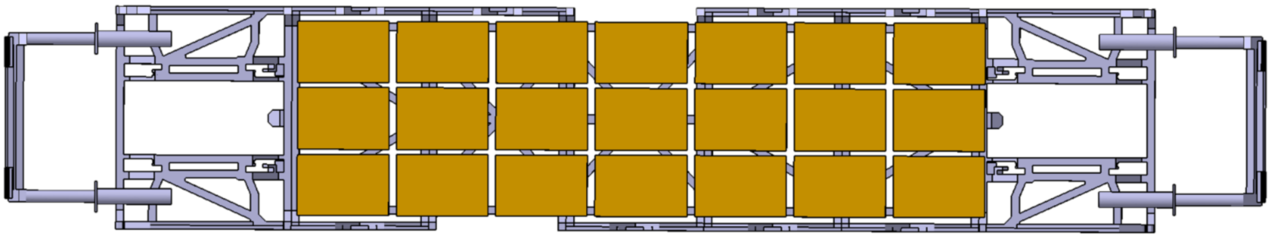


Figure 86 : Euro pallets fit

Handrails

Handrails are placed on most of the seats easily accessible for a wide range of different body types. Additionally, handrails on the ceiling are mounted for taller people as they are not in the way. In the multi-use area vertical handrails are mounted. They could be folded away by the passengers using the railing system if not in use to make room for bicycles, prams and wheelchairs. The locking mechanism for the handrails shall be easy to see and understand, easy to use and shall provide a secure lock.

PIS

The passenger information system consists of different displays and speakers inside and outside of the vehicle. At the exterior of the vehicle a narrow display band revolves around the vehicle just above the windows. At the inside of the vehicle big displays in different orientations are mounted to ensure visibility from every seat and standing position. Near the doors, big vertical screens are mounted to the walls. The windows themselves could be used as screens as well (see for example widow display from Hübner in Figure 88). In the passenger and running gear modules, horizontal screens could be mounted to the ceiling.

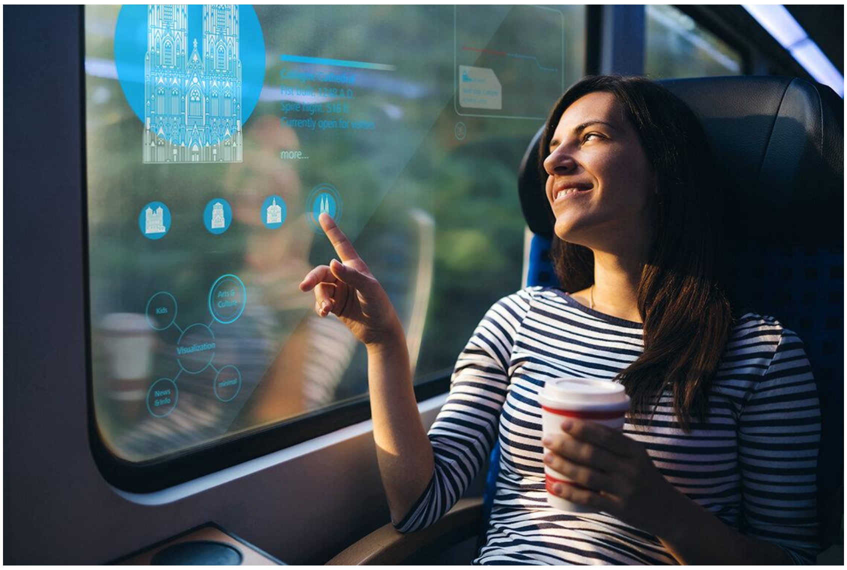


Figure 87 : Window display[42]

The indirect lighting of the train could also be used to transport information. For example, a change of colour at stops, floating lights to indicate direction of travel, different colours to show seat occupancy and bright blinking lights for emergencies.

[42] Claas Michaelis, Nadine Tusche: Holografische Displays in Fenstern eröffnen neue Dimensionen im ÖPNV - Innovation für mehr Fahrgast-Komfort von HÜBNER und ZEISS, 5.9.2024, last checked 18.10.2024, https://www.hubner-group.com/news/pressemeldung/holografische-displays-in-fenstern-eroeffnen-neue-dimensionen-im-oepnv-innovation-fuer-mehr-fahrgast-komfort-von-huebner-und-zeiss/

Security

Safety and security in an autonomously driving public transport vehicle is a delicate topic. It is important to not only ensure safe operation in any circumstance, but to increase the perceived safety of the different passenger groups as much as possible. In the circumstances the vehicle is operation in people prone to feel unsafe. The small size of the vehicle provides no room to evade uncomfortable or dangerous situations by changing seats or wagons. There are also fewer or sometimes no other passengers on board to seek help from and the absence of a driver can create a feeling of isolation. Also, the vehicle is possibly driving through rather dark areas, as the tracks in rural areas are not lit, further increasing the feeling of isolation. Especially people groups with increased safety needs like women, children, ethnic or religious minorities could potentially feel unsafe enough to not use the vehicle at all.

Therefore, a security concept is necessary, that considers not only providing safety but also providing the feeling of safety to create a room of comfort for all passengers.

Surveillance is a key component to be able to detect emergencies and dangerous situations not only inside the vehicle, but also in its direct surroundings. Cameras and microphones are mandatory to be able to detect possibly dangerous situations, react accordingly and save the footage for later evaluation and if necessary, provide proof for legal steps.

The passengers themselves also need a way to communicate an emergency or dangerous situation to the operator and the authorities. Therefore, the vehicle is equipped with panic buttons and a video call system to reach a remote security officer. Such a system is shown in Figure 89. Using the camera of the video call system and the surveillance cameras of the vehicle, the officer can get an immediate picture of the situation at hand. The passenger also sees the officer, which introduces a feeling of being seen and taken seriously. The officer can then talk to the passengers, give advice and if necessary, send police or rescue forces to the next stop.

Figure 88 : Video call system (DLR)

It is also possible to give the security officer the means to intervene with the operation of the train if necessary. The vehicle can be stopped on the track in case of fire or accident and doors can be opened remotely. It also can be stopped at road crossings or other points easily accessible by police and rescue forces in case of medical emergencies or criminal offences.

If a passenger is inflicting danger onto others and is being detected doing so or is reported by other passengers, the security officer could be given means to increase perceived authority. This includes:

- Being visible on all information screens,
- Sudden change of lighting colour and/or intensity,
- Loud broadcasting of the security officers voice or alarm sounds, or
- Sudden short brake or acceleration impulses.

This impulse of a sudden change in the environment could also create a wakeup call for people acting subconscious.

The introduction of a panic room was also discussed. The possibility to section the vehicle provides the opportunity to install a room with a door lockable by the passengers from the inside. This could serve as a safe space for people feeling unsafe. However, this also would create more risk, because of the impossibility of access control. Possible offenders could also enter the room the moment the door is opened. Additionally, being locked in or out could potentially increase stress in both the offender and the victim, further escalating the situation. This is why we advise against panic rooms on trains.

The most effective measure to increase security on the vehicle is to provide security personnel on the vehicle itself, but this would increase operating cost and makes the driverless operation obsolete. A compartment for the security personnel could be installed inside the vehicle. It could be used as an office to do other work in. In the case of emergency, personnel would be reachable but also able to work, which would decrease operator cost of the train as the operator does not have to pay personnel with insufficient workload.

2.4 Braking system

2.4.1 Brake performance

Currently there is no precise requirement in the TSI about the brake performances to be achieved for a vehicle. This is left to each National Safety Authority to specify it in order to ensure the vehicle compatibility with their local infrastructure.

Regarding the FutuRe project, there is not yet an available analysis defining a single set of requirements that would cover the needs applicable for all the EU cases where the FutuRe vehicle could be operated.

As a starting point the requirements listed in the document SAMF005 issued by the EPSF (the French NSA) have been considered:

The following stopping distances must be ensured:

- 830 m when braking from 120km/h (G1 vehicle)
- 300 m when braking from 100km/h (G2 vehicle)

Capacity of running along long gradients is also required:

In addition to the TSI reference case (maintain the speed of 80 km/h on a slope of 21 ‰ constant gradient over a distance of 46 km), and on top of this it is also required the capability of running on 3 gradients (the worst cases in France) and performing an emergency braking at the most critical location. These 3 cases are:

- Modane: 25‰-14km-90km/h + 16‰-11km-100km/h
- Porté-Puymorens / Ax-les thermes: 35‰-25km-60km/h
- Capvern / Tournay: 32‰-10km-100km/h + 23‰-1km-100km/h

Obviously when calculating the brake performances of the vehicle, it shall be verified that the maximum required adhesion levels are not exceeding the TSI requirement: maximum 0,13 for such a short vehicle.

Thermal calculations shall be performed to verify the wheel or disc temperatures do not exceed the material limits both for the long gradients mentioned above and the TSI mandatory requirement of the 2 consecutive emergency applications from the maximum speed.

2.4.2 Bogie brake equipment

The bogie brake equipment is using friction to dissipate the energy and to provide required deceleration. This can be achieved by adhesion dependent brake (Disc brake or Tread brake) or a brake not relying on the adhesion (magnetic track brake).

For the planned short vehicle, independent braking means are necessary to provide a (limited) emergency brake deceleration even in case of a degraded condition (failure of one equipment or degraded adhesion): friction brake equipment per axle + magnetic track brake

For the adhesion dependent braking 2 alternatives can be considered:

- Tread brake unit:

The proposed unit, see Figure 90 create a retarding effort with brake blocks acting on the tread of each wheel.

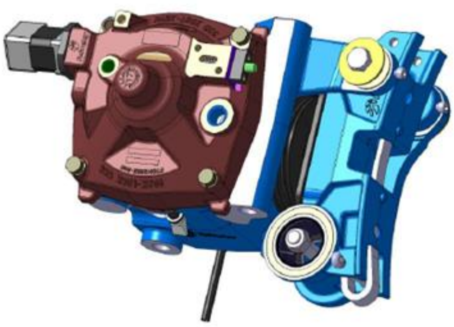


Figure 89 : Compact tread brake unit (without brake block and not showing wheel)

The main advantage of this solution is its low weight and competitive cost. Obviously, the exact sizing shall be validated by calculation in line with expected performances mentioned above.

Another advantage of this solution is in naturally offering an improvement of the "shunting" capacity of the wheels: Electric resistance from one rail to the other through the axle that is used by some signalling systems to detect a train present on a section of track.

- Disc brake

The proposed unit, see Figure 89, creates a retarding effort with brake pads clamped by the actuator on to a disc flanged on the axle.

Figure 90 : Disc brake unit

This solution is frequently easier to install but may have some limitations in our FutuRe project due to the small diameter of the disc. Moreover, depending on the mounting, this system can imply more complex maintenance of the brakes since additional components are added.

Regarding the "shunting" capacity of such solution, required for the proper functioning of the signalling system, this can be performed by additional scrubber units applying small shoes on the treads of the wheels.

- Magnetic track brake

For the adhesion independent brake equipment, it is foreseen to have magnetic track brakes (specially developed for single axle bogies). Their design and installation shall be in accordance with EN16207.

A frame is suspended to the running gear chassis by pneumatic lifting cylinder. It carries 4 sets of magnets + pole shoes. See Figure 92.

When an emergency braking is requested, the frame is pneumatically lowered by the lifting cylinder. When the pole shoes are positioned on to the rail, an electromagnetic attraction force is created by energizing these elements from a 110V on board battery. The friction between these pole shoes and the rails creates a retarding force.

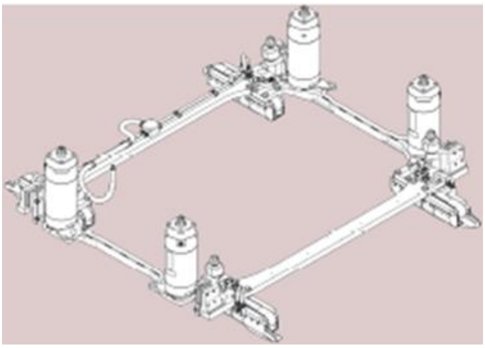


Figure 91 : Overall view of the MTB equipment for one running gear

For this project it is necessary to have one complete set of equipment (magnetic track brake + electric control = pneumatic control + battery) per each axle.

2.4.3 Brake control equipment

The core of the brake control equipment will be the Wabtec Regioflexx device. This modern device includes in a single unit both the pneumatic and electronic (hardware + software) needed to provide the following main functions:

- Service brake control with blending (electrodynamic brake + friction brake) management
- Emergency brake control and monitoring
- Capacity to safely monitor the ED brake when it is also used in emergency application
- WSP (Wheel slide protection) of the latest generation
- Holding brake control and monitoring
- Interfacing with a pneumatic brake for rescue purpose (TSI request) with a distributor emulation function.
- Predictive maintenance

Figure 92 : Overall view of the Regioflexx brake control

This very compact device, light and easy to install, will provide for our FutuRe project a control per car for the service brake and a full independence per axle for the emergency brake application.

In addition to this main device, miscellaneous equipment (auxiliary pneumatic panels, reservoirs, brake indicators, …) will also be included.

2.4.4 Compressed air choice

The choice of compressed air technology for this FutuRe project is due to the other brake technologies (as electromechanical brake) being currently in development in other part of the ERJU research programs. They are not yet mature enough to be integrated into the FutuRe project. However we can switch later to this innovative technology, it will not be so difficult as the overall space envelope of electromechanical brake equipment is not very different than what is foreseen now.

Therefore, an air generation and treatment unit will have to be installed on board. It will include an oil free air compressor.

The sizing of this unit will be determined when all the compressed air consumers on board the train (as air suspension, sanding, flange lubrication, comfort equipment, cab equipment ….) will be finalized.

2.5 TCMS, ATO and signalling

2.5.1 Analysis of Subsystem Concepts

This chapter provides a comprehensive analysis and evaluation of the subsystem concepts and technological units of light rail vehicles. In the introductory section, we will conduct a fundamental analysis of light rail vehicles, providing an overall overview of their structure and functions. This analysis will serve as a starting point for a deeper examination of key systems.

The focus will be on three critical systems that play a pivotal role in modern light rail vehicles:

- **Train Control and Management System (TCMS):** This sophisticated system integrates and coordinates various subsystems of the vehicle, ensures efficient operation, and enables comprehensive monitoring and diagnostics.
- **Automatic Train Operation (ATO):** We will introduce advanced technologies that enable automated train control, enhance driving precision, and optimize energy consumption.
- **Signalling System:** We will discuss the key components and operating principles of signalling systems that ensure operational safety and prevent collisions.

A detailed examination of these systems will allow us to understand their interactions, technological challenges, and potential for future innovations in the field of light rail vehicles. This analysis will include technical specifications, standards, and regulatory requirements, as well as assessments of performance, reliability, and safety of these critical systems.

2.5.2 Identification of the System and Subsystems

Among the main elements, we include:

2.5.2.1 Train Control and Management System (TCMS)

The Train Control and Management System (TCMS) ensures hierarchical control and coordination of all subsystems used in the vehicle, including traction control, braking, safety, and passenger comfort systems. TCMS manages smooth acceleration and braking of the train based on commands from the driver or automated systems (e.g., ATO), thereby ensuring efficient traction management and safe stopping.

TCMS also monitors the functionality of various subsystems such as doors, HVAC, and lighting, and ensures communication with fault diagnostic systems. This enables timely maintenance and minimizes downtime. Safety features include checking the status of doors before departure, monitoring signals from ETCS and ATO systems, and other protective measures to ensure safe operation.

The TCMS has a modular structure, allowing for expansion and implementation of new technologies like autonomous control. Communication between individual subsystems utilizes a combination of industrial buses (e.g., CAN, MVB), which ensure component connectivity and efficient data transfer.

Each car in the trainset can be equipped with its own TCMS, which provides the following functions:

- **Traction and braking control** (e.g., transferring demands for traction or braking force from the control lever to the control units of the propulsion system).
- **Operation monitoring and data logging for maintenance**, including system diagnostics to prevent failures.
- **Integrity checking of individual cars and the entire trainset**.
- **Data distribution to the driver via display**, providing information about the current state of the train.
- **Support for various train operating modes**, including emergency situations.
- **Ensuring availability, reliability, and safety** of train operation through redundancy and isolation of faulty components.
- **Communication** between the train and ground systems for monitoring and control purposes.
- **Support during integration, commissioning, and validation—**for example, implementing service functions that may be required via connection of a service device.
- **Support of TCMS functions in various train configurations**, whether fixed units, coupled trainsets, or a locomotive with wagons.

Most Commonly Used Buses

- **CAN (Controller Area Network):** Used for communication between individual subsystems (e.g., sensors, actuators, and control units), especially where robust and reliable real-time communication is required.
- **MVB (Multifunction Vehicle Bus):** Often utilized for connecting key modules and components throughout the vehicle.
- **WTB Communication - Train Bus:** Employed for linking trainsets or cars (individual logical nodes).
- **Ethernet (TRDP):** Serves for the transmission of larger volumes of data, such as diagnostics, monitoring, and communication with other control systems or external devices.

- The TCMS interface is generally distinguished into two types:
  - **TCMS - TCMS Interface:** The interface between TCMS systems of two cars.
  - **TCMS - Subsystems Interface:** The interface between the TCMS and subsystems within a car.
- The trainset is considered only for the vehicle.
  - How to address the Train Bus? Will the vehicles be coupled? Should it be handled only via Ethernet?
  - Within the car or trainset, using MVB is an option; between cars, WTB is also possible.

Main Components of TCMS

The main component is the Vehicle Control Unit (VCU), which serves as the primary control unit for managing the entire vehicle and auxiliary subsystems.

HMI/DMI Displays

- I/O Modules for connecting devices outside the main TCMS communication network
- Diagnostic Unit
- Communication Network for connecting all subsystems
  - Internal - Vehicle Bus
  - Train-Level - TCG (Train Communication Gateway)
  - Infrastructure - MCG (Mobile Communication Gateway)

2.5.2.2 Traction system

For a light regional vehicle, the use of indirect traction from traction batteries is anticipated, possibly supplemented by an alternative energy source such as hydrogen. The system includes the following components:

- **Traction Batteries:** Modern types such as Li-ion or $LiFePO_4$ batteries are used, providing the necessary energy capacity and reliability.
- **Charging System:** This system serves to charge the traction batteries either at stations or during travel, for example, by utilizing a pantograph.
- **Traction Converters:** Convert direct current from the batteries into alternating current required for the traction motors and allow for power regulation of the motors.
- **Traction Motors:** These are key components of the vehicle's propulsion, providing movement by transmitting torque to the axles.

- **Drive Control System:** This system manages traction, optimizes the use of energy sources, and includes regenerative braking. It regulates how energy is utilized and when it is returned to the batteries during braking.
- **Regenerative Braking:** Allows the energy generated during braking to be returned to the batteries, thereby increasing the overall energy efficiency of the vehicle.

In the case of expanding the system with a hydrogen fuel cell, the following components are added:

- **Hydrogen Tank:** A specially designed high-pressure tank for storing hydrogen, ensuring a sufficient amount of fuel for longer journeys.
- **Fuel Cell:** Converts hydrogen into electrical energy, which is then used to power the traction systems or recharge the batteries.
- **Buffer Batteries to Cover Fuel Cell Response Times:** Serve for quick responses to changes in energy demands that the fuel cell cannot immediately meet, ensuring smooth and stable performance.

In general, battery-powered vehicles are considered for operation over shorter distances, typically up to 100 km depending on specific conditions such as track profile or climatic conditions. By supplementing with a hydrogen fuel cell or another alternative energy system, it is possible to extend the range for longer routes, thereby increasing the flexibility and versatility of these regional vehicles.

2.5.2.3 Brakes

The brake system of a light regional vehicle is designed to ensure safe and efficient stopping of the train in various operational situations. The system includes several types of brakes that complement each other to achieve optimal performance and safety. Below is a detailed description of the individual components of the brake system:

Mechanical brake

The mechanical brake is a key component of the braking system used for direct physical deceleration of the train. It is a friction-based system that acts on the vehicle's wheels through:

- **Disc Brakes:** These brakes operate on the principle of friction between the brake disc, which is mounted on the wheel axle, and the brake calliper that presses against it using brake pads. Disc brakes provide smooth and efficient deceleration and are resistant to changes in temperature and environmental conditions.
- **Drum Brakes:** Used less frequently, these brakes function similarly to disc brakes, where brake shoes press against the inner wall of a drum connected to the wheel. This type is less common but may be used in specific applications requiring certain specifications.

Mechanical brakes are primarily utilized in situations requiring strong braking performance, such as stopping at stations or during emergency braking. The mechanical brake is also necessary when the electrodynamic brake cannot provide sufficient braking effect, for example, at low speeds or when coming to a complete stop.

Electrodynamic brake

The electrodynamic brake is a form of braking where the traction motors operate in generator mode. This means that during braking, mechanical energy is converted into electrical energy, which can be:

- **Recovered:** Returned back to the power supply system or batteries if the train's configuration allows. This mode conserves energy and increases the overall efficiency of the system.
- **Dissipated as Heat:** If it's not possible to return the energy back into the system—for example, due to a lack of energy demand on the route or because the batteries are at full capacity—the energy is dissipated through braking resistors in the form of heat.

Electrodynamic braking is particularly advantageous because it extends the lifespan of mechanical brakes by reducing their load. It is mainly used at higher speeds, where the generated braking forces can be effectively utilized.

Parking brake

The parking brake serves to secure the train in place when it is stopped, preventing unintended movement. The parking brake can be mechanical or hydraulic and acts directly on the wheels or axles.

- **Manual Activation:** The driver can activate the parking brake manually when the train is stopped for an extended period, such as at a terminal station or during maintenance.
- **Automatic Activation:** In some cases, the parking brake activates automatically if the system detects that the train is stationary and traction power is not required. This ensures maximum safety even in the event of a failure of other braking systems.

The parking brake is designed to be strong enough to hold the train on inclined tracks and capable of withstanding long-term loads without the need for frequent maintenance.

Electronic control

Electronic control of the braking system is an important component of modern brake systems, ensuring efficient coordination of all brake parts. Electronic control includes:

- **Central Control Unit (Brake Control Unit, BCU, WSP):** This unit monitors and manages all aspects of braking, including mechanical and electrodynamic brakes, as well as their cooperation with other train systems such as traction and safety systems.

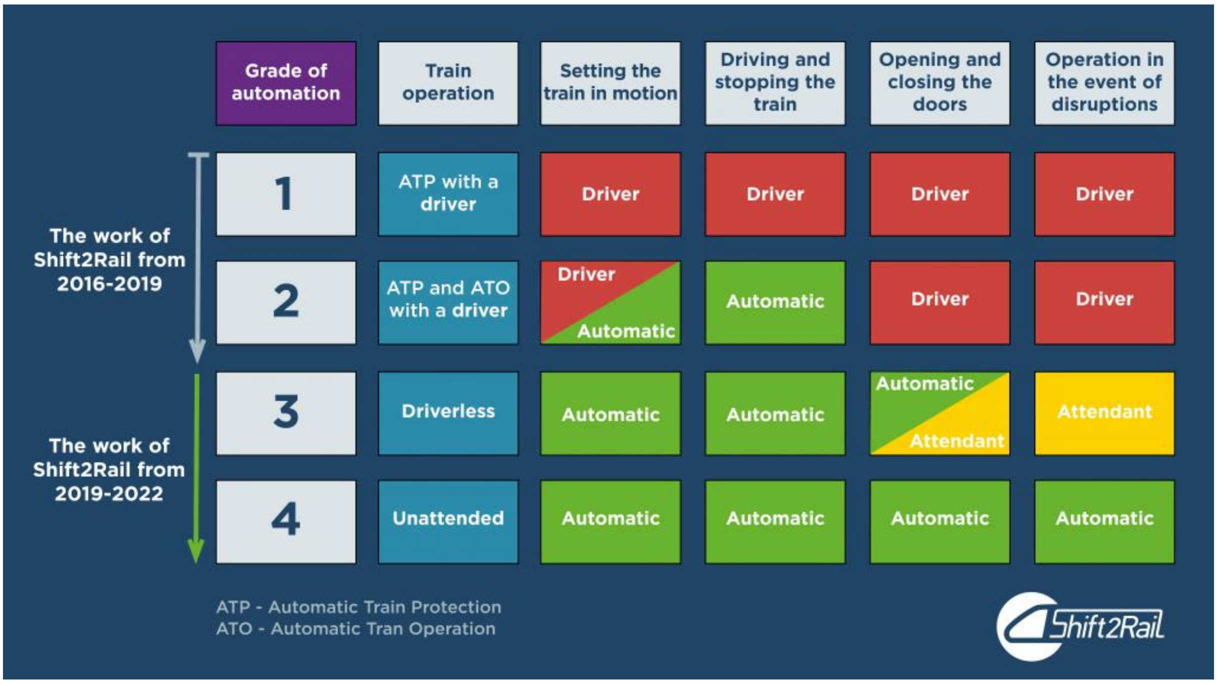
- **Sensors and Actuators:** Sensors monitor the current speed of the train, the condition of brake components (e.g., wear of brake pads), and other operational parameters. Actuators activate braking elements based on commands from the control unit.
- **Interaction with Other Systems:** The electronic control of the braking system is interconnected with other systems like TCMS (Train Control and Monitoring System), ETCS (European Train Control System), and ATO (Automatic Train Operation) to ensure smooth and safe braking during automated or manual operation.
- **Safety Logic:** The electronic control also ensures that in the event of a failure in any part of the braking system, there is an automatic transition to backup solutions or emergency stopping. This system includes a range of redundancies and control mechanisms that enhance the safety of the braking system.

2.5.2.4 ATO (Automatic Train Operation)

ATO is an extension of the TCMS that enables various levels of train operation automation—from partially automated operation to fully autonomous control.

ATO function:

- **Automatic Control of Traction and Braking:** ATO takes over control of acceleration, braking, and train speed, ensuring more efficient energy utilization and smoother operation.
- **Route Optimization:** ATO optimizes departure and arrival times at stations, managing acceleration and braking to minimize delays and enhance passenger comfort.
- **Integration with ETCS:** ATO is typically integrated with the European Train Control System (ETCS), ensuring that the train always operates within the safe limits established by European train control standards.
- **Levels of ATO:** There are several levels of ATO:
  - **GoA1 (Grade of Automation 1):** Manual driving with support from automated functions.
  - **GoA2:** Automated driving under driver supervision, where the ATO system controls speed but the driver oversees the operation.
  - **GoA3 and GoA4:** Higher levels of automation that can include fully autonomous control without the presence of a driver. This is anticipated for future regional vehicles.



Grade of automation	Train operation	Setting the train in motion	Driving and stopping the train	Opening and closing the doors	Operation in the event of disruptions
1	ATP with a driver	Driver	Driver	Driver	Driver
2	ATP and ATO with a driver	Driver / Automatic	Automatic	Driver	Driver
3	Driverless	Automatic	Automatic	Automatic / Attendant	Attendant
4	Unattended	Automatic	Automatic	Automatic	Automatic

Figure 93 : GoA description

Communication between ATO and TCMS

The ATO communicates with the TCMS to obtain data on the vehicle's status, such as current speed, door status, and energy levels. This collaboration enables the systems to jointly manage the efficient operation of the train.

CRV & AVV (AŽD/MSV product)

CRV & AVV is a system designed for the automation of rail vehicle control. Together, CRV and AVV, in the concept of MSV and AŽD, form ATO. This constitutes the current state of ATO operation in the Czech Republic, representing 600 vehicles, track orientation using MIB and GIB.

- **CRV represents the central vehicle regulator, which addresses:**
    - Speed regulation,
    - Traction unit control,
    - Brake management,
    - Coordination of dynamic braking with automatic braking,
    - Multiple vehicle control,

- Aperiodic guidance to the desired speed in the shortest possible time,
- High precision in maintaining speed (± 1 km/h),
- Priority use of dynamic braking, control of automatic air braking,
- Delaying the selection of higher speeds by the specified train length (train exit from speed restriction),
- Keyboard for speed selection,
- Does not require the transmission of information from the track.

- **AVV then serves for:**
  - Targeted braking,
  - Energy optimization of train travel,
  - Compliance with track, set, and signalled speed,
  - Automatic braking to places with reduced speed value and to stopping points,
  - Automatic stopping with high precision at platforms of relevant stations and stops,
  - High time precision and energetically optimal arrival at the destination,
  - Saving traction energy by radio transmission of dispatcher data commands to the train (optional),
  - Requires the transmission of information from the track.

Communication between ATO Components

- **CRV** functions independently of track information, focusing on onboard control systems to manage train operations efficiently.
- **AVV** requires track information transmission to perform functions like target braking and energy optimization effectively.

2.5.2.5 ETCS (European Train Control System)

ETCS is a standardized European system for train control and protection. It is designed to enhance the safety and interoperability of railway transportation across Europe.

A key question arises here: **How to operate vehicles on G1 and G2 lines?** And how to ensure operation on G2 lines without onboard ETCS? Operating vehicles without ETCS outside of G2 lines—is it even possible to run without ETCS?

ETCS is part of the overall safety system **ERTMS (European Rail Traffic Management System)**. It consists of several key components that work together to enable safe and efficient train operations. The main components are:

- **ETCS (European Train Control System):**
  - **Onboard Subsystem:** Includes onboard equipment installed in trains that communicate with trackside systems and monitor the train's position and speed.
  - **Trackside Subsystem:** Comprises equipment located along the track, such as balises and radio communication devices, which transmit information to trains.
  - **RBC (Radio Block Centre):** A central control unit that processes information about train movements and issues movement authorities.
- **GSM-R (Global System for Mobile Communications – Railways):**
  - A specialized wireless communication system designed for railway applications, enabling voice and data communication between trains and trackside systems.
- **FRMCS (Future Railway Mobile Communication System) :**
  - Next generation global standard for European railway communication. Supports the deployment of ETCS Level 2 and beyond.
- **ERTMS Regional:**
  - A variant of ERTMS designed for regional and local lines with lower operational requirements.

ETCS functions

- **Safety Train Control:** ETCS monitors the train's position, speed, and track signals. It ensures that the train does not exceed permitted limits and prevents collisions with other trains.
- **Interoperability:** ETCS is standardized for all railway operators within the EU, allowing trains to transition more easily between different national railway systems.
- **Levels of ETCS:**
  - **ETCS Level 1:** A system that operates based on information obtained from trackside balises. Trains receive information about permitted speeds and other instructions through these balises.

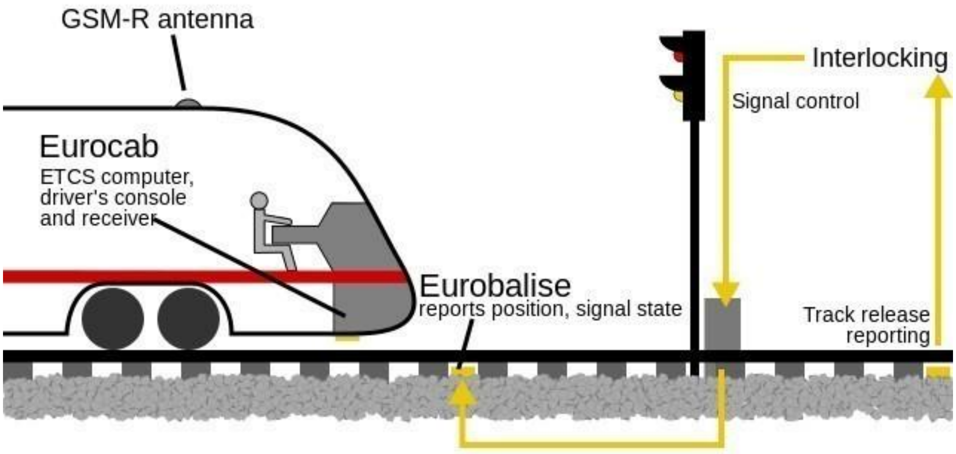


Figure 94 : ETCS L1

- **ETCS Level 2:** Information is transmitted via radio communication (GSM-R). In this mode, the train receives instructions in real time, enabling smoother and safer operation.

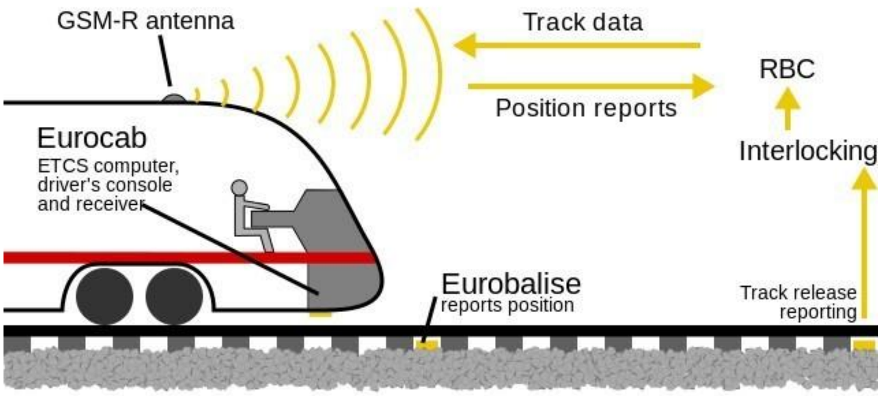


Figure 95 : ETCS L2

- **ETCS Level 3:** A fully digital system where trackside balises are no longer necessary, and communication occurs entirely via radio links.

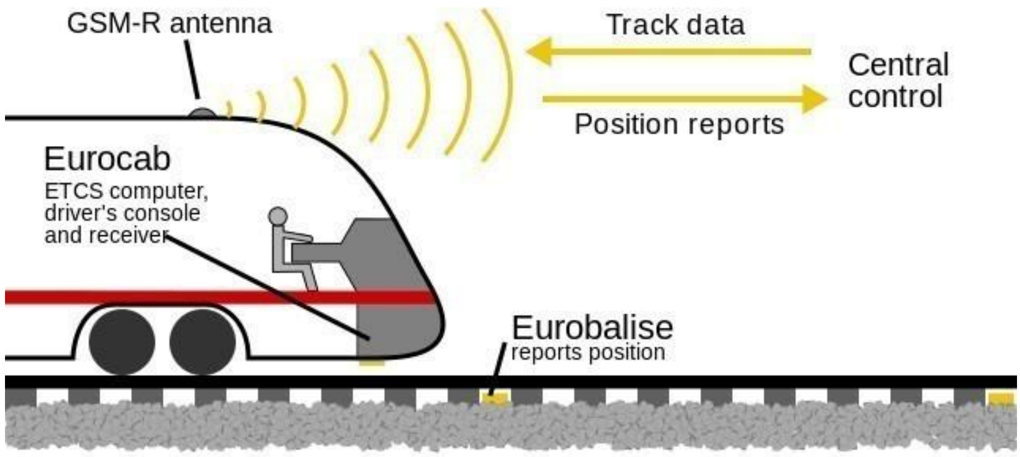


Figure 96 : ETCS L3

Main Components of ETCS

Onboard Components:

- **EVC (European Vital Computer):** The central computer that serves as the main control unit and is connected to all control elements.
- **JRU (Juridical Recording Unit):** A recording unit that logs operational data for legal and safety purposes.
- **DMI (Driver Machine Interface):** The display interface for the driver.
- **BTM (Balise Transmission Module):** A module for transmitting data from trackside balises to the onboard system.
- **STM (Specific Transmission Module):** A device used for train protection where ETCS is not present—for example, the LS06 system.
    - The **STMLS module** creates an interface between the current national train protection system LS and the ETCS system, ensuring a smooth transition between areas equipped only with the national system and those already equipped with ETCS. Deploying the STMLS module on traction vehicles is a fundamental prerequisite of the migration strategy during the implementation of ETCS in the Czech Republic.
- **Basic Technical Description:** The STMLS module is, according to ETCS specifications, a type SN module. On tracks not equipped with the ETCS system, the ETCS core (EVC) hands over supervision of the train's operation to it.

Trackside Components:

- **Eurobalise:** Trackside transponder devices that communicate with the train's onboard equipment.
- **LEU (Lineside Electronic Unit):** Generates telegrams that are transmitted to the onboard ETCS equipment. It is located near the main signal.
- **RBC (Radio Block Centre):** A GSM-R-based central unit that manages radio communication and issues movement authorities in ETCS Level 2 and 3.

Integration of ETCS with TCMS and ATO

- **ETCS and TCMS:** ETCS transmits track and permitted speed information to the central control unit (TCMS), which uses this information to control the traction and braking systems, ensuring safe operation.
- **ETCS and ATO:** The combination of ETCS and ATO enables automatic train operation in compliance with safety regulations. ETCS provides safety limits, while ATO ensures smooth control of the train's movement.

4.2.2 Functions of the Onboard ETCS System. The basic parameter for the functions of the onboard ETCS equipment describes all the functions necessary for the safe operation of the train. The primary function is to ensure the operation of the train protection system and the transmission of information to the driver's cab:

- Setting train parameters (e.g., maximum train speed, braking performance);
- Selection of the supervision mode based on information from the trackside equipment;
- Provision of odometry functions (measurement of speed and distance);
- Localization of the train in a coordinate system based on the location of Eurobalise devices;
- Calculation of the dynamic speed profile for a given journey based on train parameters and information from the trackside equipment;
- Supervision of the dynamic speed profile during the journey;
- Provision of intervention functions.

These functions must be performed in accordance with Annex A 4.2.2 b, and their performance characteristics must comply with Annex A 4.2.2 a.

Open questions

- How to secure tracks on G2 lines without mobile ETCS? Operation outside G2.
- Is there a possibility to operate without ETCS? And how?

- Otherwise, resolve with optical detection of signals from static track signalling.
- How to implement ETCS (low-cost version).
- How to transfer ETCS to areas where tracks will be equipped with track signalling in the future, so that these secondary lines do not have stationary ETCS.
- L1 STOP ETCS - an affordable stationary component (low-cost solution)
- A track map suffices. Typically, there are no variable signals there; otherwise, static ones can be included in the map.
- Approaching automation. GoA 2 is with AVV, but then what about GoA 3 and 4?
- Instead of optical detection, transfer data digitally. Should be an online transmission.
- Sensory (Perception System) PER + CPM - for GoA 3, 4 - X2Rail 4?

2.5.3 ERTMS Regional

ERTMS Regional is a variant of the ERTMS system developed specifically for regional and local railway lines where operational and infrastructure demands are typically lower than on main railway corridors. ERTMS Regional was designed to be cost-effective and flexible for lines with lower traffic frequency and speeds.

Main Characteristics of ERTMS Regional

- **Lower Costs:**

ERTMS Regional was designed to minimize installation and maintenance costs, which is crucial for the economic viability of regional lines.

- **Flexibility:**

The system is flexible and can be adapted to different types of operations and infrastructures, allowing its implementation on various types of regional lines.

- **Safety:**

Despite lower costs and flexibility, ERTMS Regional maintains the high safety standards characteristic of the entire ERTMS system.

2.5.3.1 Structure and Function

ERTMS Regional can include the following components and functions optimized for regional operations:

- Trackside Systems:
  - Less demanding trackside systems and infrastructure adapted to lower speeds and traffic frequency.

    - May include simpler versions of the Radio Block Centre (RBC) and other trackside equipment.
- Communication:
    - Communication between trains and trackside systems can be simpler and less demanding in terms of bandwidth, reflecting lower data transmission requirements.
- Onboard Systems:
    - Onboard systems installed in trains can be simpler and less demanding in computational performance, reflecting lower requirements for functionality and safety.

2.5.3.2 Applications of ERTMS Regional

ERTMS Regional is suitable for application on lines where low costs and flexibility are the main priorities, for example:

- Regional and Local Lines:
    - Lines with lower traffic frequency and speeds.
    - Lines that primarily serve local and regional connections.
- Secondary and Industrial Lines:
    - Lines that serve specific industrial or logistical needs and do not have high capacity or speed requirements.

ERTMS Regional is a key tool for improving the safety and efficiency of regional railway networks in Europe while striving to maintain the cost-effectiveness and flexibility needed for this segment of the railway market.

2.5.3.3 Regional cooperation between ERTMS and ERTMS Regional

Cooperation between standard ERTMS and ERTMS Regional in areas where they connect or intersect is crucial for maintaining safety and smooth railway operations. In these areas, it is important to ensure seamless transition of trains between different systems and levels of ERTMS. Here are some key aspects of this cooperation:

- Seamless Transition: It is important that trains can safely and efficiently transition between areas covered by standard ERTMS and ERTMS Regional. This includes coordination between different ETCS levels and communication between onboard and trackside systems.
- Interoperability: Both systems must be interoperable to allow trains from different countries and with different equipment to operate on lines covered by either standard ERTMS or ERTMS Regional.
- Coordination and Communication: Central control units, such as Radio Block Centres (RBC), must be capable of coordinating train movements and communicating with trains in areas where systems connect or intersect.

- Safety Protocols: Safety protocols and procedures must be firmly established and adhered to in areas where systems intersect to prevent collisions and other safety incidents.
- Infrastructure Adaptation: Infrastructure, such as switches and signals, must be adapted to support seamless transition and cooperation between systems.
- Operational Procedures: Operational procedures and rules must be clearly defined and implemented for controlling trains in areas where systems connect or intersect.
- Testing and Validation: Before commissioning, all aspects of cooperation between systems must be carefully tested and validated to ensure safety and reliability.
- Upgradability: Systems should be designed to be easily updatable and modifiable to meet future requirements and standards.

In practice, cooperation between standard ERTMS and ERTMS Regional should be ensured to maintain a high level of safety and efficiency in train operations in areas where these systems meet.

Routes / Vehicles	G1 route	G2 route
G1 vehicle	YES	YES
G2 vehicle	NO	YES

Figure 97 : Expected matrix resolution

2.5.4 Related Projects

2.5.4.1 Safe4Rail

SAFE4RAIL provides the baseline for a fundamentally simplified embedded computing and networked TCMS platform, for modular integration and certification of all safety-, time- and mission-critical train functions, including distributed hard real-time controls, safety signals and functions up to SIL4.

The generic embedded platform architecture provided by SAFE4RAIL allows mixed-criticality integration and virtualisation to host critical and non-critical functions on reconfigurable computing and networking resources. The project simulation and testing environment is based on the hardware abstraction and domain separation concepts allowing rapid deployment and testing of applications, e.g. by supporting early functional integration testing long before vehicle integration.

The results are demonstrated with a SIL4 brake-by-wire system safety concept. Finally, the project provides recommendations for standardization and certification of next generation TCMS embedded platform.

SAFE4RAIL reduces TCMS system lifecycle and operating costs and minimises time-to-market. It is also expected to encourage interoperability, efficient, safe and secure interconnection of technical solutions among European railway providers, boosting the worldwide competitiveness and preserving the global leadership of the European transport industry.[43]

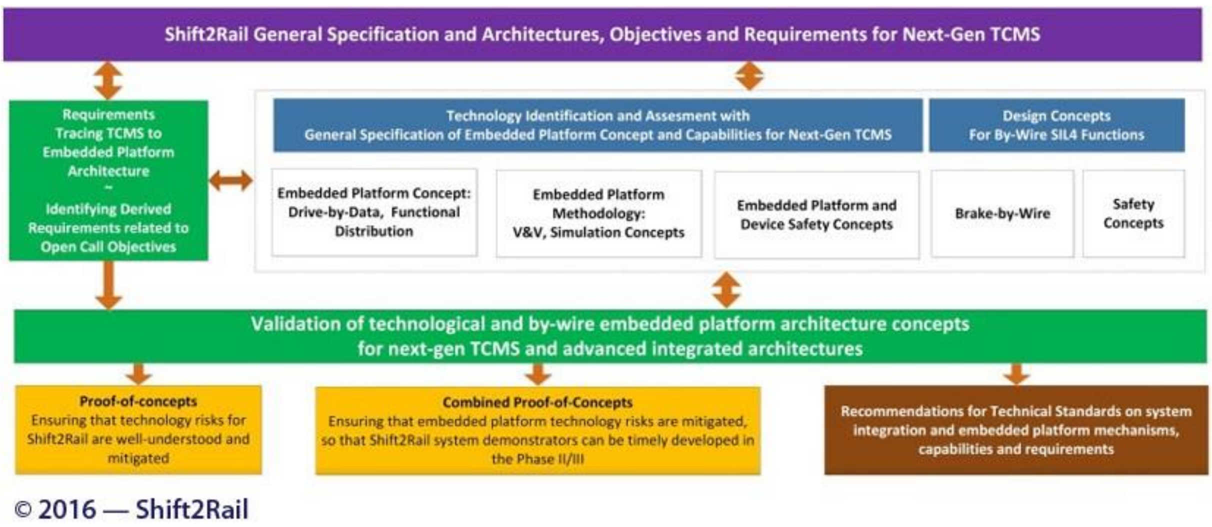


Figure 98 : Shift2Rail project

2.5.4.2 Safe4Rail-2

Safe4RAIL-2 will deliver next-generation network devices (i.e. ETBNs, CSs and EDs) that integrate the Drive-by-Data concept based on Time Sensitive Network (TSN) technology, introducing deterministic communications at backbone and consist levels of the wired train network. Special

[43] https://projects.shift2rail.org/s2r_ip1_n.aspx?p=SAFE4RAIL

attention is paid to the interoperability among the three different equipment manufacturers in the consortium.

In Safe4RAIL-2 an HVAC subsystem (i.e. a non-safety function) will be integrated on top of the FDF implementations of two demonstrators; for this purpose, Safe4RAIL-2 will provide expertise on AUTOSAR (AUTomotive Open System ARchitecture), as a reference middleware for application development and integration, as well as previous understanding of the FDF architecture. In Safe4RAIL-2, the HVAC functionality will be further integrated in the SF for remote Hardware-In-the-Loop tests.

Safe4RAIL-2 will develop and validate LTE devices suitable for WireLess Train Backbone (WLTB) communications, using OAI-based LTE Equipment, supporting UE-to-UE direct communication and fully compliant with 3GPP ProSe LTE Rel. 14 V2X/D2D.

Mosaic5G will provide control and data plane programmability and model-driven network service orchestration for the future Wireless TCMS studies in Safe4RAIL-2.[44]

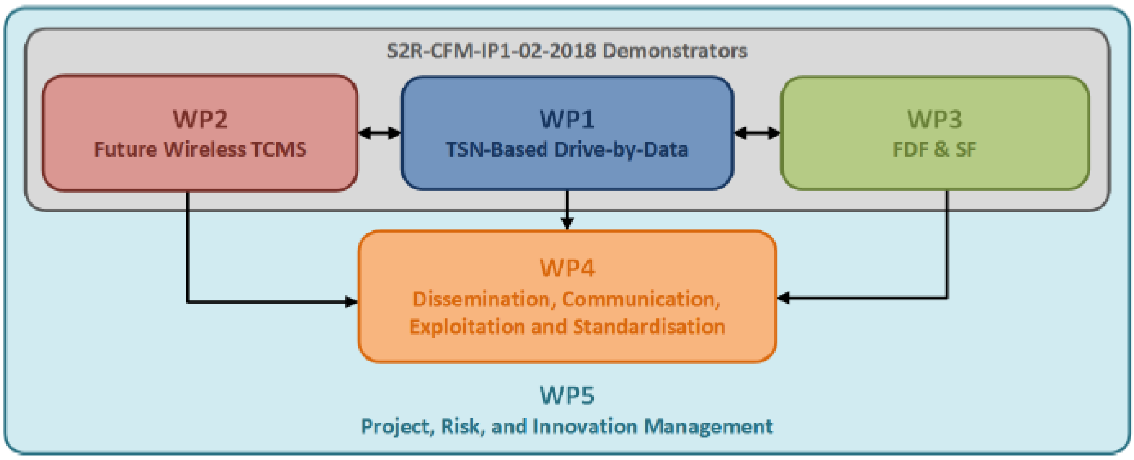


Figure 99 : WP5 Project Risk & Innovations Management

2.5.4.3 CONNECTA

CONNECTA aims at contributing to the Shift2Rail 's next generation of TCMS architectures and components with wireless capabilities as well as to the next generation of electronic braking systems.

The project conducts research into new technological concepts, standard specifications and architectures for train control and monitoring, with specific applications in train-to-ground communications and high safety electronic control of brakes.

[44] https://projects.shift2rail.org/s2r_ip1_n.aspx?p=SAFE4RAIL-2

The project is developed in four phases of work which are reinforcing and extending the early work done in the TCMS part of Roll2Rail as well as start the specific activities of the MAAP of Shift2Rail. The major streams are described below.

1. Define General Specifications for TCMS technologies and high-level architectures to shape the future system with less cabling, increased availability, enhanced performance, easier integration and commissioning of functions and, above it, reduced life cycle costs.
2. Progress and implement new architectures and technologies, tools, norms and standards for the future generation of TCMS as well as for high safety level electronic brakes.
3. Simulate and test virtually all the communication networks and functions of the new generation TCMS subsystems to help to simplify business processes and enhance the interoperability.
4. Evaluate results, disseminate, communicate, and exploit as much as possible at this TRL3-4 level of achievements.[45]

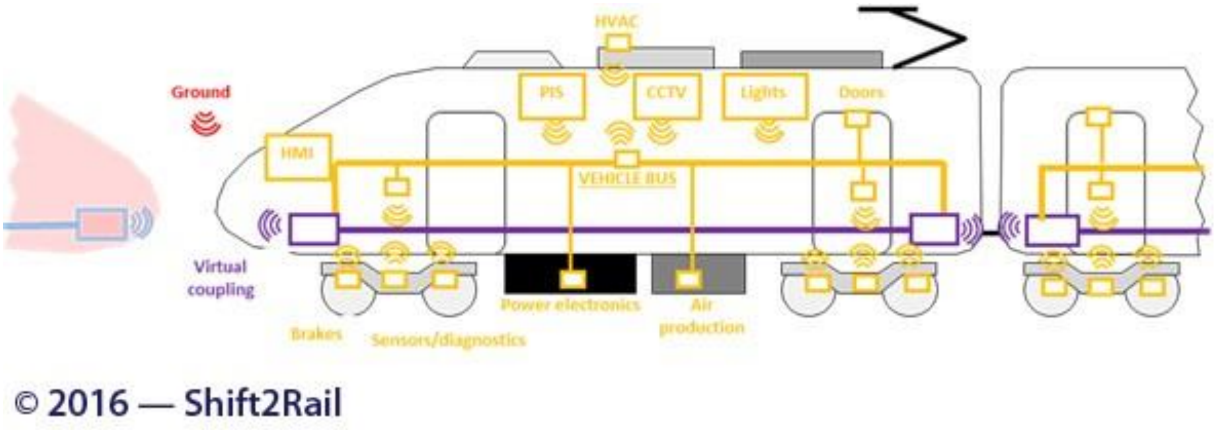


Figure 100 : Shift2Rail project / onboard view

2.5.4.4 CONNECTA-2

CONNECTA-2 aims at contributing to the Shift2Rail's next generation of TCMS architectures and components, combining the new drive-by-data concept for train control together with wireless information transmissions. This project envisions paving the way towards a 50% increase in the availability of trains related to the functioning of train control and monitoring, a 50% reduction in cost, time and effort in certification, commissioning, and maintenance phases, while at the same time

[45] https://projects.shift2rail.org/s2r_ip1_n.aspx?p=CONNECTA

developing the ability to implement SIL4 functions in the TCMS and supporting the development of the “virtual coupling” concept, which can dramatically increase the capacity of lines.

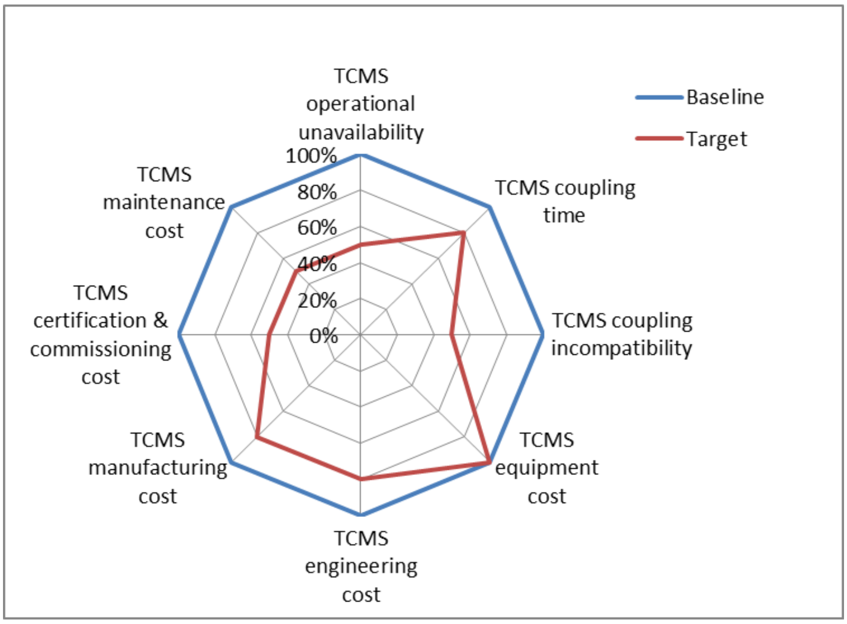


Figure 101 : TCMS objectives

The high-level objective of the work is to continue the activities started in CONNECTA-1 to bring the technologies to TRL5 and deploying them in two laboratory demonstrators. The specific actions to be undertaken within the scope of CONNECTA-2 contributing to the above high-level targets are:

- To continue the development of wireless technologies for the train communication networks, including the wireless ECN, the wireless ETB, the train-to-ground communication, and the train-to-train communication.
- To implement the new train-wide communication network (known as NG-TCN) for full TCMS support including the replacement of train lines, connecting safety functions up to SIL4 and support of “fail-safe” and “fail-tolerant” principles, to provide an optimal train network for TCMS and OMTS (Onboard Multimedia and Telematic Services) as well as communication mean for non-TCMS functions, as defined in CONNECTA-1.
- To continue with the standardisation of functional interfaces of functions (application profiles).
- To implement the Functional Open Coupling (FOC) concept to facilitate the coupling of two or more consists supplied by different manufacturers and which could have different train functions.
- To develop the simulation framework, defined by CONNECTA-1, in which all subsystems of the train can be simulated, allowing remote and distributed testing including hardware in-the-loop through heterogeneous communication networks.

- To implement the Functional Distribution Framework (FDF) to allow the new function-centric approach for the TCMS and the reduction of the number of onboard electronics and of complexity.
- To integrate into the NG-TCN safety critical functions.
- To validate non-railway standards and technologies for use in safety-related railway applications.[46]

2.5.4.5 CONNECTA-3

The Train Control and Monitoring System (TCMS) is the brain and the communications backbone of the train, which has some essential roles on vehicle performance. It integrates and manages all on-board information; it makes train control decisions taking into account the global state of subsystems; it performs communication between equipment, between cars and between vehicles; and it integrates and interacts between different subsystems of the train.

Successful integration of subsystems and the commissioning of TCMS require huge efforts and take an extremely long time due to the lack of standardised application profiles, appropriate architectures and simulation and testing frameworks. The increasing number of new services and applications brings several modifications of the TCMS implemented functions along the train's life, implying re-commissioning the TCMS every time. The current standard in TCMS homologation is largely based on Failure Modes and Effects Analysis (FMEA) based on the TCMS architecture and extensive testing on laboratory setups as well as on the real train. Testing on the train, in particular, requires a great effort and takes lots of time – often delaying the start of service operation for entire fleets significantly. This situation can be significantly improved also by developing a homologation process based on simulation.

Innovation and development of TCMS have been identified as a potential enabler for train weight reduction and increase in reliability1. The integration of functions may reduce weight due to the reduced amount of wires and controllers of each component. A wireless coupling would increase reliability by eliminating electrical system errors. Therefore, a complete new TCMS architecture, mixing wired and wireless communications, enhanced interoperability, and "driven-by-data" concept, is needed. In order to achieve this goal, the future work in TCMS needs to include the definition of new protocols and application profiles, software framework supporting reallocation of functions, the definition and validation of the wireless technology, the definition, design and manufacturing of new devices (routers, repeaters, sensors, end-devices, gateways...) while taking into account safety and security aspects, which may imply the design or use of specific encryption hardware. Both, the virtual coupling together with the functional open coupling concepts, will mean the complete interoperability from the TCMS perspective, while paving the way for a new way of operating trains by creating

[46] https://projects.shift2rail.org/s2r_ip1_n.aspx?p=CONNECTA-2

chains of virtually coupled trains, which can be attached and detached dynamically according to the service needs and available slots.

In that sense, the Shift2Rail project CONNECTA-1 (GA 730539), which started on 1st September 2016 and ended on 30th September 2018, has started to develop the aforementioned technical solutions by producing a comprehensive set of specifications and architectures, and by selecting appropriate technologies. The results and outputs of CONNECTA-1 with a TRL 3/4 were carried on by CONNECTA-2 (826098), which started the 1st of October 2018 and will end the 31st of March 2021, providing prototypes with a TRL 4/5.

The high-level objective of the work is to continue the activities started in CONNECTA-2 to bring the technologies to TRL6/7 and deploying them in relevant laboratory scenarios and real train units.

Such activities aim to:

- Develop the ability to implement SIL4 functions in the TCMS to perform additional safety-critical tasks, removing safe train lines and integrating signalling equipment;
- Increase in the availability of trains related to the functioning of train control and monitoring by 50%;
- Develop the ability to couple any pair of multiple units of different types, which is a feature totally non-existent and can significantly increase line capacity;
- Support technologically the development of the "virtual coupling" concept, which can dramatically increase the capacity of lines, and;
- Reduce cost, time and effort in project engineering, integration and homologation phases by 50%.

2.5.4.6 X2Rail-3

The project aims to continue the research and development of key technologies to foster innovations in the field of railway signalling, telecommunication, testing methodologies and Cyber Security, as part of a longer term Shift2Rail IP2 strategy towards a flexible, real-time, intelligent traffic control management and decision support system. X2Rail-3 will also explore Virtual Coupling, an innovative concept capable of operating trains much closer to one another (inside their absolute or relative braking distance) and dynamically modifying their own composition on the move.

The actions to be undertaken in the scope of X2Rail-3 are related to the following specific objectives:

- To improve line capacity and to achieve a significant reduction of the use of traditional train detection systems by means of the introduction of the Moving Block together with train positioning;
- To overcome the limitations of the existing communication system by adapting radio communication systems which establish the backbone for the next generation advanced rail automation systems;
- To ensure security among all connected signalling and control systems by developing new cyber security systems dedicated to railways;

- To analyse new signalling concepts (Virtual Coupling) that potentially would be able to improve line capacity, reduce LCC and enhance system reliability.
- To improve standardization and integration of the testing methodologies reducing time to market and improving effectiveness in the introduction of new signalling and supervision systems;
- To ensure the evolution and backward compatibility of ERTMS/ETCS technologies, notwithstanding of the required functional enrichment of the future signalling and control systems.

2.5.4.5 TAURO (Technologies for the autonomous rail operation)

D2.1 – Specification of the Remote Driving and Command - Functions suitable for remote command, for regional

The purpose of TAURO's WP2 is to define and propose standardized remote driving and command functionalities for this type of operations in the future.

To achieve it, deliverable D2.1 represents the first required task, whose goal is to prepare a specification to enable the remote driving and command for a number of relevant use cases, carefully selected.

Such use cases are:

- Remote driving under ETCS
- Remote driving in shunting yard
- Remote driving in depots for tramways

The process of defining the specification is divided in three phases. First, a deep analysis of the functions which are suitable for their remote command is performed. This analysis is based on the actual driver tasks based on ERA_ERTMS_0155660 and the EN15380-4 Functional Breakdown Structure. For each function some parameters (including performance and safety concerns) are described.

In a second step, the three use cases are thoroughly defined using SysML, describing the actors, steps and outcome, among other aspects. Finally, a large set of functional and non-functional requirements are identified. This public deliverable means an important input for the next activities in WP2, such as the architecture definition, and other Shift2Rail projects dealing with TCMS and CCS.

3 Multimodal Fuelling Stations

3.1 Introduction and background

This chapter – containing the T5.3 report – explores the emerging field of multimodal hydrogen fuelling stations, focusing on their potential to support the transition towards a hydrogen-powered transportation system. While the development of such stations is still in its early stages, they hold the promise of overcoming existing economic obstacles associated with hydrogen infrastructure by facilitating cost sharing and efficient hydrogen access across various transportation modes. This introduction provides a background on the concept of multimodal hydrogen fuelling, highlighting its significance and the key challenges and considerations involved.

The increasing demand for cleaner transportation solutions has spurred the development of hydrogen fuel cell technology, offering a promising alternative to traditional fossil fuels. However, the widespread adoption of hydrogen-powered vehicles hinges on establishing a robust and accessible refuelling infrastructure. The high cost of hydrogen refuelling stations, both in terms of initial investment and operation, presents a significant barrier to their widespread deployment, particularly in the early stages when utilisation is low.

Multimodal hydrogen stations, capable of serving a diverse range of vehicles, including trains, buses, trucks, and potentially even aircraft, offer a potential solution by enabling economies of scale and more efficient use of infrastructure. Combining multiple mobility ecosystems within the same station could significantly reduce refuelling costs and optimize the hydrogen supply chain. The European Union is actively supporting research and development in this area, recognizing the potential of multimodal hydrogen stations to accelerate the transition towards a hydrogen-based transport system. The Horizon Europe research and innovation programme includes a call for proposals specifically focused on demonstrating and deploying such stations, addressing challenges like high costs, slow approval processes, and the lack of standardized fuelling protocols. This initiative reflects the growing interest and commitment to exploring the viability and benefits of multimodal hydrogen fuelling.

3.2 State-of-the-art of multimodal hydrogen stations

The development of multimodal hydrogen fuel stations that can serve both railway trains and road vehicles, i.e. buses and heavy-duty trucks, is still a fairly unresearched area. Executing implementation projects are even more so under exploited, so far and more information needs to be gathered since finding viable solutions for multimodal hydrogen stations could pose a linchpin in overcoming some currently economic obstacles for invest in and create hydrogen supply infrastructures for both railway and road traffic, as is aimed for by the European Commission.

Challenges and Considerations:

- **Infrastructure Compatibility:** One of the main challenges is ensuring compatibility between the infrastructure required for railway trains and road vehicles. Railway trains typically require higher pressure hydrogen storage and refuelling systems, while road vehicles often use lower pressure systems.
- **Safety Regulations:** Strict safety regulations must be adhered to for both railway and road hydrogen refuelling stations. These regulations can be complex and may vary between different jurisdictions.

- **Cost:** The initial investment in multimodal hydrogen fuel stations can be high, particularly for large-scale facilities.
- **Hydrogen Supply:** A reliable and sustainable supply of hydrogen is essential for the operation of multimodal hydrogen fuel stations.
-

State-of-the-Art Developments:
Despite these challenges, there have been several notable developments in multimodal hydrogen fuel stations:

- **Pilot Projects:** Several pilot projects have been launched around the world to demonstrate the feasibility and benefits of multimodal hydrogen refuelling stations. These projects have helped to identify potential challenges and develop best practices.
- **Technological Advancements:** Advances in hydrogen storage and refuelling technology have made it possible to design more efficient and cost-effective multimodal stations.
- **Integration with Renewable Energy:** Some multimodal hydrogen fuel stations are being integrated with renewable energy sources, such as solar and wind power, to reduce their carbon footprint.

While the development of multimodal hydrogen fuel stations is still in its early stages, mot much knowledge is retrieved on investment and running costs of joint hydrogen supply to railway and heavy-duty road applications. This technology may have the potential to play a significant role in the transition to a hydrogen-powered economy. As the demand for hydrogen increases and the costs associated with its production and storage decline, we can expect to see more of these stations being built around the world.

> *"A key factor for the successful commercialisation of FCH technologies in the heavy-duty truck industry is exploiting potential synergies of FCH applications from other modes of transport, such as cars, buses, taxis, trains, forklifts and maritime (e.g. shared infrastructure, shared component production)."*
>
> Roland Berger, 24 May 2024.

3.2.1 Hydrogen fuelling stations for rail

Hydrogen fuelling presents unique challenges compared to traditional fuels like GNR. While filling with GNR relies on pumps transferring fuel between tanks, hydrogen is generally filled through pressure equalization, which causes heating due to adiabatic compression. The faster the hydrogen is pumped, the greater the heat. For performance reasons, the goal is to fill hydrogen trains like the as quickly as possible, aiming for a full tank in about 20 minutes. However, safety concerns are critical: hydrogen tanks must not exceed 85°C to prevent damage to their thermoplastic liners. Detecting hydrogen leaks during refuelling is also essential, given the pressures involved. Although rail-specific regulations are still in development, heavy-duty road standards offer guidance. To optimize refuelling speed, higher station pressures (500-1000 bars) and pre-cooling hydrogen to 0°C or lower (-20°C to -40°C) are necessary, but these solutions reduce energy efficiency, increase costs, and heighten leakage risks. Thus, effective hydrogen fuelling requires balancing factors like train specifications, station capabilities, operational needs, and safety.

Various approaches have been employed to refuel rail vehicles with hydrogen. The emphasis has been on refuelling systems for 35 MPa compressed gaseous hydrogen (CGH_2) storage systems, as these are most used in rail vehicles (Figure 1).
A verification of the chosen approach has been made with the FP4 to enable a harmonised solution for various types of rail services.

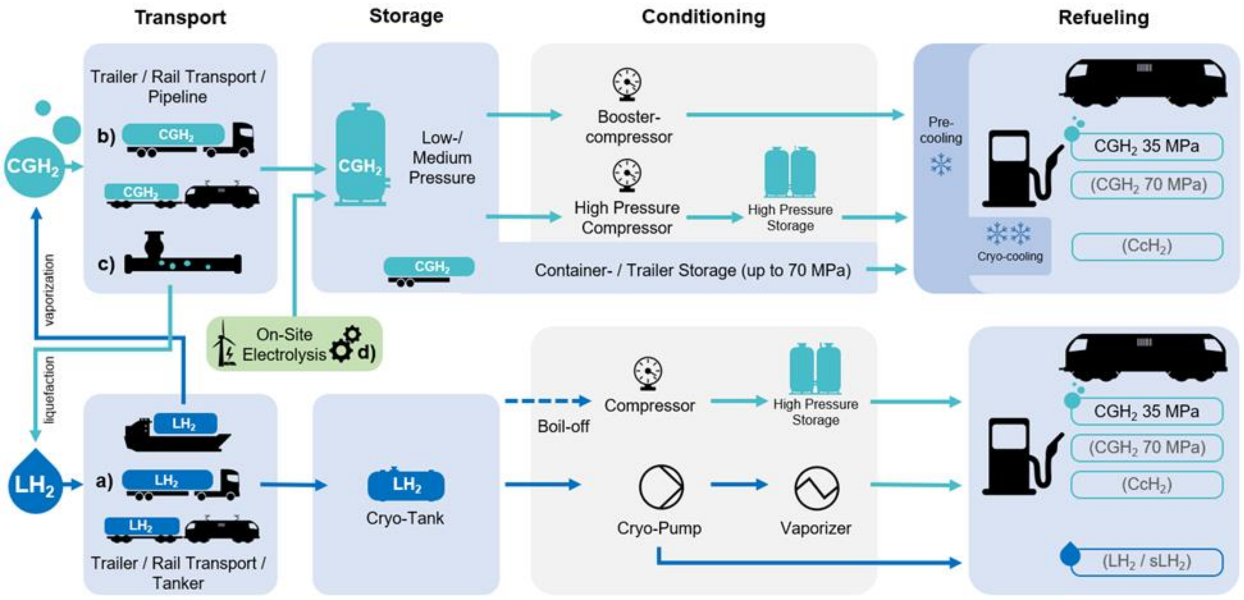


Figure 102 : Hydrogen rail refuelling options (DLR)

Currently, portable hydrogen refuelling stations (HRS) are the most widely utilized solution for vehicle testing and demonstration purposes, where full refuelling is often not necessary. The supply of liquid hydrogen (LH_2) and CGH_2 via road trailers is a common delivery method. Globally, mobile refuelling solutions using containers and trailers are increasingly available, with gas industry manufacturers offering these concepts to a growing number of customers (Table 25).

Table 25 : Hydrogen refuelling for rail, worldwide (based on [1], updated)

Project, country	Project details
Mireo Plus H, Germany	CGH_2-Trailer as overflow solution for Mireo Plus H, Tyczka Hydrogen (Trailer) + Wolftank Group (Dispenser) [2]
FCH2Rail, Spain and Portugal	Transportable, containerized, prototype HRS for converted CIVIA train; 2x storage (45/90 MPa, type I), compressor (Hiperbaric), dispenser; filled with about 2,2 t of H_2 in 20 refuelling operations [3]
iLINT, Europe	Transportable, containerized HRS for Alstom iLINT prototypes, source: LH_2 trailer with > 3t H_2 capacity (Air Products), flexible dispensing unit with two refuelling nozzles [4], [5], used for different locations for trail operation in Europe: e.g., Wien, AUT [6], [7], [8]
iLINT, Europe	CGH_2-Trailer as overflow solution for Alstom iLINT refuelling in Groningen, Netherlands [6], [9], [10]
HydroFlex, UK	HyQube hydrogen refueller from Fuel Cell Systems Ltd and external CGH_2 hydrogen storage (steel cylinders) at 26th United Nations Climate Change conference in Glasgow (COP26) [11], [12]
HydroFlex, UK	Mobile hydrogen refuelling truck from Fuel Cell Systems Ltd with 65 kg H_2 [13], [14]
Hydrogen Pioneer, UK	Exchange of metal hydride or 20 MPa storage cylinders [15]
Vehicle projects, USA	20 MPa tube trailer (Air Products) + temporary compressor for demonstration in [15]
Taiwan	Low-pressure metal hydrogen storage canister recharging station [16]

In the railway industry, the development of hydrogen (H2) fuelling stations is still in its early stages. Road applications have driven the technology forward due to their market demands and financial and safety challenges, resulting in well-established standards for refuelling stations, filling nozzles, communication protocols between vehicles and charging stations, and filling procedures (such as leak tests, pressure, flow rates, and temperature management). Regarding railway, the pioneering work done by Germany relied heavily on existing road standards. In France and other countries, the same approach has been taken, with railway operators often reusing the fittings, filling, and communication protocols originally developed for buses. However, efforts to standardize heavy-duty hydrogen applications, including rail, are currently underway. Standards like ISO 17268, ISO 19880, ISO 19885, and SAE J2601 (-2 or -5 for heavy-duty) and J2799 are currently used and are being updated. Additionally, regarding national regulations hydrogen stations must adhere to specific decrees or law such as, for example in France, ICPE 1416 for distribution (currently being revised at the request of the SNCF to address rail applications) and ICPE 4715 for storage.

For commercial train operation, gas suppliers working closely together with vehicle manufacturers for hydrogen supply and refuelling. Compressed gas storage with a maximum pressure of 50 MPa currently established on the HRS side. In Tübingen, Deutsche Bahn, DB Energy, and Siemens Mobility will test a fast hydrogen refuelling system and develop a communication standard between HRS and trains. As part of the H2goesRail project, the consortium is also investigating pre-cooling for 15 min. train refuelling. [1] The specifications of HRS in the German railway sector currently in operation or under construction are shown in Table 2. The shown hydrogen refuelling stations supply two-car hydrogen multiple units of the type of Alstom iLINT (Bremervörde and Höchst) and Siemens Mireo Plus H (Tübingen and Basdorf).

Table 26 : Hydrogen refuelling stations for 35 MPa rail with 2 dispensers in Germany (based on [1], updated)

HRS	Bremervörde	Höchst	Tübingen	Basdorf
Status	operation from 2022	operation from 2022	operation from 2024	under construction
Refuellings/d	12 x 130 kg	14 (27)	test facility, 180 kg	7, 120-150 kg
Supply	road trailer	chemical by-product + electrolysis	road trailer + mobile refueler	electrolysis + road trailer
Storage	constant pressure tubes, 2,030 kg H_2, 50 MPa	4 x 40 ft. Container with ADR certification 4,400 kg H_2, 50 MPa	30 MPa Trailer, up to 900 kg H_2	50 MPa

The entire hydrogen supply chain for vehicle fuelling must be considered. Initial operational experience indicates that localized bottlenecks in the hydrogen supply can lead to disruptions in train services in Lower Saxony. Due to delivery issues, the supply of the first hydrogen train fleet is currently limited. The operator Eisenbahnen und Verkehrsbetriebe Elbe-Weser (evb) is responding by implementing measures to reduce consumption and deploying diesel railcars to maintain operations on the RB 33. [17] However, there is no long-term experience of refuelling trains with hydrogen for commercial operation to date. At the same time, standardization in this area is still in its early stages.

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3.2.2 Hydrogen refuelling stations for road

The road network of hydrogen fuel stations being developed in the EU may play a linchpin role in supporting the developments of hydrogen fuelling infrastructure for railway bound traffic when it comes to access hydrogen and sharing costs. This is why Task 5.3 entails a focus, not only on hydrogen supply for railway transport, but also for road transport as well as joint solutions i.e. multimodal hydrogen fuelling stations for both railway and road vehicles.

State of the Art Hydrogen Road Refuelling

The state of the art for hydrogen road refuelling is rapidly evolving, driven by increasing demand for cleaner transportation solutions. Currently, there are approximately 550 hydrogen refuelling stations globally, with Europe accounting for about 200 of these. Germany is one of the leading countries in this rollout within EU, with the most extensive network of hydrogen stations for road traffic, many of which are being upgraded to accommodate heavy-duty vehicles like trucks and buses.

The European Union has ambitious plans to further expand its hydrogen refuelling infrastructure, aiming for a station every 150 kilometres along main traffic corridors. This expansion is crucial to support the growing number of hydrogen-powered vehicles, including buses, trucks, and cars. While North America, including Canada, has a smaller number of stations compared to Europe and Asia, the Canadian government's Hydrogen Strategy outlines a vision for a significant increase in hydrogen infrastructure to support the adoption of fuel cell electric vehicles, which can be seen as means for supporting the prominent industry sector budding in Cananda, encompassing the value-chain of solutions from electrolysers to vehicles.

Buses

- **Refuelling time:** The average refuelling time for a fuel cell bus is around 10.28 minutes. About 50% of refuellings occur overnight (between 8 p.m. and 3 a.m.) to ensure capacity and availability. Buses typically refuel every 24 hours and spend an average of 10 hours per day in service. [1]
- **Pressure:** Buses typically refuel at 350 bar.

- **Costs:** Specific costs associated with hydrogen refuelling stations are not easily retrieved. However, the average daily hydrogen consumption for a bus is approximately 14.62 kg. [1]

Heavy Duty Trucks and Lorries

- **Refuelling time:** Heavy-duty trucks can refuel with 30 to 100 kg of hydrogen in 8 to 15 minutes. [1]
- **Pressure:** Currently, most trucks refuel at 350 bar, but it is expected they will transition to 700 bar soon to increase range. [4]
- **Costs:** We have not yet obtained specific costs for truck refuelling stations. However, factors like station capacity and location significantly impact costs. [4, 6] Research suggests that investing in hydrogen refuelling stations in conjunction with the power system, rather than independently, could lead to cost savings. [8]

Light Weight Vehicles Like Cars

- **Refuelling time:** Cars can typically refuel with 5-6 kg of hydrogen in under 5 minutes. [1, 6]
- **Pressure:** Cars currently refuel at 700 bar. [4]
- **Costs:** The cost of hydrogen refuelling for cars varies considerably, and future predictions are not reliable. However, high capital expenditure (CAPEX) and operating expenses (OPEX) are both considered as bottlenecks for wider adoption. [6]

Implementation Status

Existing Stations

- In 2021, approximately 550 hydrogen refuelling stations were operating globally, with about 200 in Europe. [11] The majority of these stations store hydrogen in compressed gas form at pressures up to 700 bar. [8]
- **Germany leads Europe with the most extensive network**. As of spring 2021, there were 92 stations, primarily designed for passenger cars. [13] By the end of 2024, there were at least 50 stations in Germany suitable for trucks and buses.14 Germany has a goal of having 300 hydrogen refuelling stations by 2030. [8]
- In October 2024, a new hydrogen refuelling station for heavy traffic opened at the Port of Gothenburg in Sweden. [16] The station, operated by Hydri, has a daily capacity of 1,500 kg of green hydrogen, enough to refuel approximately 35 trucks. [17]

Planned Stations

- The EU has a target of having a hydrogen refuelling station every 150 km along its main traffic corridors. Discussions are ongoing to potentially set an even more aggressive target. [4] The EU also aims to have a publicly accessible hydrogen station in all urban nodes and every 200 km along the TEN-T network by 2030. [13]
- **The revised Alternative Fuel Infrastructure Directive (AFID) aims for around 300 truck-suitable hydrogen refuelling stations across Europe by 2025, increasing to at least 1,000 by 2030**.15 These stations should have a minimum daily capacity of at least 6 tonnes of hydrogen and at least two refuelling points per station.15 The AFID targets will be reviewed in 2025 and adjusted if necessary. [8]
- **Germany aims to have 85 truck-suitable stations by 2025 and 300 by 2030. [8]**

In general

- **Green Hydrogen:** There's a strong emphasis on utilising green hydrogen produced from renewable sources to fuel these stations. [15]
- **Operational Flexibility:** Research suggests integrating hydrogen refuelling stations with the power system can lead to cost-efficiency. [8] For instance, stations can adapt their hydrogen production (through electrolysis) based on electricity price fluctuations, helping to balance the power grid. [8]
- **Hydrogen Supply:** Stations can receive hydrogen in various ways, including:
  - **Delivery by truck:** Compressed gaseous hydrogen or liquid hydrogen is transported via trailers to the stations. [1, 6, 22]
  - **On-site production:** Some stations have on-site hydrogen production facilities, using either steam methane reforming (SMR) or electrolysis. [22]
  - **Pipeline delivery:** In some locations, hydrogen may be delivered to stations via pipelines. 20
- **Standardisation:** Standardisation is crucial for efficient and safe hydrogen refuelling, particularly for larger vehicles like trucks and buses. [26, 27] Currently, most stations for light-duty vehicles adhere to the SAE J2601 standards or similar protocols, but these are often unsuitable for larger vehicles. Efforts are underway to develop and standardise refuelling protocols for medium- and heavy-duty vehicles, including factors like pressure, temperature, and flow rates. [27]

Hydrogen Refuelling Stations in the EU: Current and Projected Figures

Current Numbers

As of 2021, there were approximately 228 HRS operating in the EU. [41] Germany led the way with 101 stations, followed by France with 41 and the UK with 19. Other European countries with a significant number of HRS included Switzerland (12) and the Netherlands (11). These numbers are expected to have increased since 2021. A more recent figure for Germany, from spring 2021, reported 92 stations in operation, mainly designed for passenger cars.[6] By the end of 2024, at least 50 of these stations had been upgraded to refuel buses and trucks. [17, 11]

Projected Numbers

Ambitious plans to expand the HRS network has been set up in the EU:

- The EU's Alternative Fuels Infrastructure Regulation (AFIR) mandates a publicly accessible HRS in all urban nodes and every 200km along the Trans-European Transport Network (TEN-T) by 2030.5 This regulation is designed to create a dense network to facilitate travel for hydrogen-powered vehicles throughout the EU. [13]
- The revised Alternative Fuel Infrastructure Directive (AFID) sets a target for Europe of around 300 HRS suitable for trucks by 2025, increasing to at least 1,000 by 2030.2 Each station for commercial vehicles (trucks/buses) should have a minimum daily capacity of at least 6 tonnes of hydrogen and at least two refuelling points. [6]
- For Germany, the AFID targets 85 truck-suitable HRS by 2025 and at least 300 by 2030. [6]
- The EU is also considering a more aggressive target of an HRS every 150 km along all main traffic corridors. [4]

These targets aim to remove concerns about range limitations and encourage wider adoption of hydrogen fuel cell vehicles in various categories, including buses, trucks, and passenger cars. [4] The AFID will be reviewed in 2025 and adjusted if necessary. [6]

Hydrogen Refuelling Stations in Germany: Current and Projected Figures

Hydrogen Refuelling Stations in Germany: Current and Projected Numbers. A description of the current number of hydrogen refuelling stations in Germany and the ambitious targets for their expansion.

Current Status

As of spring 2021, Germany had 92 hydrogen refuelling stations in operation [6], primarily designed for passenger cars. This represents the largest hydrogen refuelling network in Europe [17]. However, recognising the need to support the adoption of hydrogen-powered commercial vehicles, efforts have been underway to upgrade existing stations and build new ones suitable for trucks and buses. By the end of 2024, H2 MOBILITY, a key player in the German hydrogen refuelling sector, had successfully converted 32 of its existing locations for use by trucks and buses. Overall, the network offered 53 refuelling points with 350-bar dispensing pressure, suitable for both heavy-duty and light-duty vehicles [17].

Projected Numbers

Germany has set ambitious targets for expanding its hydrogen refuelling infrastructure, aligned with broader EU objectives:

- **AFID Targets:** The revised Alternative Fuel Infrastructure Directive (AFID) sets specific targets for Germany, aiming for 85 truck-suitable hydrogen refuelling stations by 2025 and at least 300 by 20303. These stations should have a minimum daily capacity of 6 tonnes of hydrogen and at least two refuelling points per station.
- **Core Network for Heavy-Duty Vehicles:** The AFID also mandates the establishment of a core network of hydrogen refuelling stations for trucks and buses along the main transport corridors, with a station available every 200 km by 2030 [6].
- **EU-wide Targets:** Germany's targets are part of a broader EU ambition to create a dense and accessible network of hydrogen refuelling stations across the continent. The EU aims for a station every 150 km along main corridors and is even considering a more aggressive target [4].

Factors Driving Expansion

Several factors are driving the rapid expansion of hydrogen refuelling infrastructure in Germany:

- **Policy Support:** Strong governmental support through policies like the AFID and the National Hydrogen Strategy are providing incentives and setting targets for the development of hydrogen refuelling infrastructure [1, 11].
- **Industry Commitment:** Companies like H2 MOBILITY Germany are playing a crucial role in building and expanding the network, investing in new station construction and the upgrade of existing facilities [11, 17].
- **Environmental Goals:** The push towards decarbonising the transport sector and achieving climate neutrality is a significant driving force behind the transition to hydrogen as a fuel source [43].

Future Outlook

Germany is well-positioned to become a leader in hydrogen mobility, with significant progress already made in establishing a nationwide refuelling network. The continued support from policymakers, industry commitment, and the growing demand for clean transportation solutions are likely to accelerate the expansion of hydrogen refuelling stations in the coming years. The review of the AFID in 2025 will provide an opportunity to assess progress and adjust targets based on technological advancements and market developments.

Hydrogen Refuelling Stations in Canada: Current and Projected Figures

Current Status

At the end of 2021, there were **729 hydrogen refuelling stations (HRSs) globally**. Breaking this down by continent, Asia had almost 60%, Europe had 29%, and North America had 10%. [41] While this doesn't give a precise number for Canada, it suggests that North America, as a whole, is lagging behind Asia and Europe in HRS deployment. Linde, a global industrial gas and engineering company, has built Southeast Asia's first H2 fuelling station in Malaysia. [26] This implies that the availability of HRSs in North America, including Canada, might be even lower than in Southeast Asia at that time.

Projected Numbers

We cannot retrieve specific targets for the number of HRSs planned for Canada. However, the "Hydrogen Strategy for Canada" from 2020, provides a glimpse towards future developments. [41] This strategy, while not defining concrete targets for fuel cell electric vehicles (FCEVs), does present a vision for hydrogen in Canada in 2050 that includes "more than five million" FCEVs on the road. [41] Such a substantial fleet of FCEVs would necessitate a significant expansion of hydrogen refuelling infrastructure across the country.

Considerations

- **Limited Information:** Although information is readily available on global trends and specific developments in regions like Europe and Asia there seem to be a lack of detailed information about Canada's HRS network. This suggests the need for further research using sources specifically focused on Canadian hydrogen infrastructure development, since Canada has a strong hydrogen technology industry.
- **Government Strategy:** The "Hydrogen Strategy for Canada" is a crucial document for understanding the country's ambitions regarding hydrogen and fuel cell technology. Consulting this document would provide more insights into the government's plans and targets for HRS deployment.
- **Industry Developments:** Monitoring the activities of companies like Linde, which are involved in building hydrogen infrastructure in various regions, including North America, can offer additional clues about the potential growth of the HRS network in Canada.

3.2.3 Hydrogen Supply

There are several hydrogen supply methods that are currently in use and may continue to play a role in the future, but in what direction is the development tipping towards?

Prevailing Methods

- **Truck Transport:** Currently, one of the main methods for transporting hydrogen to refuelling stations is via trucks or trailers. This method is particularly relevant when hydrogen is produced off-site at a large-scale industrial facility [80, 1]. For instance, in

Whistler, Canada, the challenge of obtaining liquid hydrogen due to the distance from the production facility was overcome by trucking it across the country [26].

- **On-Site Production:** Another method is producing hydrogen directly at the refuelling station [80, 22]. This can be achieved through various technologies, including:
  - **Steam Methane Reforming (SMR):** This widely used method utilizes natural gas as a feedstock to produce hydrogen. While cost-effective, it produces emissions [1].
  - **Water Electrolysis:** This method uses electricity to split water into hydrogen and oxygen, offering a zero-emission pathway when powered by renewable energy sources [80, 13, 26].
  - **Biogas:** South Korea has seen the introduction of hydrogen stations powered by food biogas [26].
- Pipelines: Pipelines, in the context of transporting hydrogen in general, is seen as not competitive compared to on-site electrolysis at refuelling stations [80, 26]. This pretty much excludes hydrogen transport via pipelines due to factors like economies of scale and the low likelihood of natural gas pipeline rededication for hydrogen. Those pipes are, not made to entail such small molecules as hydrogen, not to withstand the increased pressure needed and hydrogen tend to embrittle certain readily used metals [22].

The Future of Hydrogen Supply Solutions

The future of hydrogen supply is closely tied to the global shift towards renewable energy sources and decarbonization efforts. Green hydrogen, produced from renewable energy through electrolysis, is expected to play a pivotal role in meeting the growing demand for clean energy. Advancements in electrolyzer technology and the increasing availability of renewable electricity are driving the transition towards this sustainable fuel source. While gaseous hydrogen is suitable for various applications, liquid hydrogen offers higher energy density and is particularly promising for heavy-duty vehicles. However, developing the necessary infrastructure for liquid hydrogen remains a significant challenge. The optimal approach to hydrogen production, whether centralized or decentralized, will depend on various factors, including demand, transportation costs, and renewable energy availability.

- **Green Hydrogen:** There is a strong emphasis on the transition towards green hydrogen production from renewable energy sources like wind and solar power [80, 1, 6] This aligns with global efforts to decarbonize the transport sector and achieve climate neutrality.
- **Electrolysis:** Electrolysis is expected to become increasingly important for hydrogen production, driven by the growth of renewable energy and advancements in electrolyser technology [80, 13, 6].
- **Liquid Hydrogen:** Liquid hydrogen, with its higher energy density, is seen by several actors as a promising option for larger vehicles like trucks and buses, enabling longer ranges and more efficient storage. However, developing the necessary infrastructure for liquid hydrogen remains a challenge [80, 1, 97, 11].
- **Centralized vs. Decentralized Production:** The optimal approach, whether if centralized production at large-scale facilities or decentralized production at/near refuelling stations, depends on factors like demand, transportation costs, and the availability of renewable energy resources in specific locations [6].

To realize the full potential of hydrogen as a clean energy carrier and make use of the higher energy density compared to BEV batteries [102] several key considerations must be addressed. Governments will need to establish supportive policies, regulations, and incentives to foster the development of the hydrogen economy. Continued research and development efforts are essential to reduce the costs associated with green hydrogen production, transportation, and storage. Expanding the hydrogen refuelling station network, including both gaseous and liquid hydrogen options, will be crucial for supporting the widespread adoption of hydrogen vehicles. Public-private partnerships will be instrumental in driving innovation, sharing risks, and accelerating the deployment of hydrogen infrastructure. By addressing these challenges and leveraging the collective efforts of governments, industry, and research institutions, the future of hydrogen supply holds the promise of a cleaner and more sustainable energy landscape.

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3.3 Hydrogen Safety, Legal requirements, and Standards

This section deals with safety and regulatory requirements as well as standards for hydrogen usage and, importantly, relating them to the specifics of multimodal fuelling stations.

3.3.1 Introduction to Hydrogen Safety legal requirements and standards

Safety is a key priority for all stakeholders in the rail transport industry. For many decades, the industry has safely transported, handled and used liquid fuels based on established procedures and training. This solid foundation will be invaluable to support to the introduction of alternative energy carriers with properties and related hazards different to those of the conventional fuels that the industry handles safely on a daily basis.

This report will focus on compressed gaseous hydrogen (GH2) for use in fuel cell electric or internal combustion engine drivelines, and assuming a nominal working pressure for the multiple-unit / locomotive (rolling stock) hydrogen storage of 35 or 70MPa. To give perspective to the properties and hazards of hydrogen, they are compared with those of diesel fuel.

If hydrogen is used as part of an electric driveline there will be other hazards linked to traction batteries which are considered only at a high level in this report. Further investigation of any additional risks of co-located battery charging and hydrogen refuelling infrastructure should be undertaken in future work.

The use of hydrogen in rail applications is not new, and it is now 5 years since the world's first commercial hydrogen-powered passenger train entered service in Germany [1], which means that there is much to learn in terms of safety and operation from earlier activities.

3.3.2 Hydrogen Properties and Hazards

In this section, the main hazards linked to hydrogen are summarised with emphasis on those most relevant to the rail environment.
Hydrogen is a hazardous and extremely flammable gas. Conventional fuels such as diesel fuel and energy carriers such as Li-ion batteries are also hazardous. The key point is to understand the differences between the properties and related hazards of hydrogen and those of conventional fuels and energy carriers, and to mitigate the risks by developing appropriate technical and organisational solutions.
Hydrogen is a colourless (invisible), odourless and tasteless, non-toxic, non-carcinogenic, non-ecotoxic, non-corrosive, buoyant and extremely flammable gas. Although non-toxic, in sufficient concentration in a poorly ventilated enclosure, hydrogen can displace oxygen and act as a simple asphyxiant.

⚠ As hydrogen is odourless, colourless and tasteless it is undetectable with human senses. Technical solutions such as hydrogen sensors are needed to detect the presence of hydrogen.

⚠ When exposed to hydrogen at high pressure or high temperature (above normal atmospheric pressure or high temperatures), the ductility, toughness and fatigue life of many common metallic alloys is reduced and crack growth rate can increase.

Due to hydrogen's small molecular size and low viscosity, only helium is comparable. Leak pathways may exist through which hydrogen may leak but other gaseous fuels, fuels vapours or leak test gases would not. Hydrogen systems can only be adequately leak tested with hydrogen, helium, or an inert trace gas containing at least 5% of hydrogen. Hydrogen permeates through all materials to a greater or lesser degree, and especially when there is a strong driving pressure, for example, in compressed hydrogen storage systems. Permeation is normally considered to be negligible through metals, but may be significant for polymers.

At ambient temperatures, hydrogen has strong buoyancy and dispersion characteristics which is very positive in open locations such as a railway line through the countryside, but can be negative in enclosures such as rolling stock compartments or train maintenance depots, as a flammable mixture will form more quickly.

Hydrogen is extremely flammable when mixed with air, with very wide limits of flammability and detonation. Flammable hydrogen/air mixtures are easily ignited with the minimum ignition energy being very low.

Pure hydrogen burns with a very pale blue flame which can be very difficult to see in daylight or well-lit enclosures. Impurities in the air such as dust or sea spray may increase the visibility of the flame, but this cannot be relied upon. The combustion product is water. Hydrogen flames radiate much less heat than hydrocarbon flames which reduces the risk of igniting nearby materials and makes the area of a fire more accessible, but this also means that a person can approach much closer to the flames before warning pain is felt. Technical solutions such as thermal imaging should be considered as appropriate.

Hydrogen/ air mixtures are highly reactive from a combustion perspective. Hydrogen combustion hazards include micro- or standing flames, jet fires, deflagrations and under some conditions possibly detonations depending on the sequence of events following a release of hydrogen as well as the nature of the release and the environment. Hydrogen/air mixtures may explode, typically as a deflagration in the open following delayed ignition of a hydrogen release. Some conditions, e.g. a degree of enclosure and congestion in the enclosure, can cause turbulence in the burning mixture which leads to flame acceleration and high overpressures, and potentially detonations. An event which starts as a deflagration can transit to a more severe detonation if the flame front accelerates sufficiently through the burning mixture.

3.3.3 Hydrogen Storage Hazards

Due to the very low density of hydrogen, storage in usable quantities is one of the key challenges to the transition to hydrogen as an energy carrier. While other technologies have been investigated, currently hydrogen has primarily been stored as a compressed gas or a cryogenic liquid. Compressed gaseous hydrogen is considered for this project as it is a relatively mature technology for which significant development has already been undertaken for automotive applications.

Storage of hydrogen as a compressed gas is typically at nominal working pressures of 35 or 70MPa for road vehicles, and higher pressures are needed at the refuelling station. Transient pressures immediately following fast refuelling are also significantly higher on-board the vehicle (+25% for 70MPa systems, i.e. up to 88MPa). While all-metal cylinders are commonly used for transportable industrial gas bottles, they are too heavy for typical land vehicle applications. Hydrogen vehicles would typically use “Type 3” or “Type 4” containers which typically use a full carbon fibre – resin composite structural overwrap to provide the strength around a thin metal or polymer liner for containment (Type 3 and Type 4 respectively). It is this type of construction which would be realistic for railway on-board storage systems in the near term.
This type of technology can also be used for the transport of hydrogen, and storage at refuelling stations (perhaps in combination with all-metal industrial cylinders for low throughput refuelling stations). For road vehicle systems, all containers incorporate on-tank valves to isolate fuel lines in the event of a system leak and a thermally activated (temperature triggered) pressure relief device (TPRD) [2]. The TPRD is a key safety component as it prevents excessive pressure rise due to heat. The temperature rise in the gas during fast refilling has to be managed so that the tank materials are not exposed to excessive temperatures beyond their service conditions of -40 to +85°C [2]. Pre-cooling of the hydrogen to -40°C at the refilling station may be used to optimise the refuelling time.

While high pressure leaks may be audible, the sound of hydrogen leaking can’t be relied upon in a noisy environment such as a rail depot or station where personnel may also be using earing protection. Hydrogen or ultrasound sensors are essential.

High pressure systems may result in jet releases or in the case of immediate ignition a jet fire, while delayed ignition may result in an explosion. Modern pressure vessels are designed and tested to “leak before burst”, but even so such a major release is still a significant hazard with a sudden release of compression energy and the potential for subsequent, delayed ignition leading to a potential explosion. In extreme conditions a rupture could occur, for example, an intense localised fire that increases the gas pressure while reducing the strength of the container. A rupture is the instantaneous and explosive release of compression energy with fragmentation damage and the potential for subsequent ignition.

3.3.4 Hazard Comparison Between Hydrogen and Diesel Fuel

In this section the hazards of hydrogen are compared with those of diesel fuel. The key safety related properties of hydrogen and diesel fuel are given in Annex 1.

Diesel Fuel

Diesel fuel is a complex mixture of hydrocarbons mainly obtained from crude oil.

Physiological Hazards

Diesel fuel is generally not considered highly toxic, although they can have toxicological effects. Nonetheless, these fuels should be handled with care as over-exposure can lead to harmful effects.

The most common health effect associated with chronic or repeated diesel fuel exposure is dermatitis [3], while the main hazard is chemical pneumonia following aspiration. Diesel fuel is suspected of causing cancer depending on duration and level of exposure. It is is irritating to the eyes, skin and respiratory tract, and also if the liquid is swallowed.

In comparison, hydrogen is a non-toxic, non-carcinogenic, non-corrosive gas, however, in sufficient concentration in a poorly ventilated enclosure for example, hydrogen can displace oxygen and act as a simple asphyxiant.

Environmental Hazards

Spillages of diesel fuel can contaminate ground water and are toxic to aquatic life with long lasting effects but are expected to be non-persistent [3].
Hydrogen is non-ecotoxic.

Material Compatibility

Diesel fuel is incompatible with some non-metallic materials such as natural rubber and silicone [4]. For hydrogen there are special material incompatibility issues with several common metal alloys at elevated pressures or elevated temperatures due to hydrogen embrittlement or attack (see Section 2), but many non-metallic materials or polymers are compatible.

Release & Dispersion

Molecular hydrogen (H2) is the smallest molecule and has a low viscosity which means that it has a propensity to leak when other fuel vapours would not. The leak testing of hydrogen systems must follow stringent procedures using specific hydrogen leak test gases, and not, for example nitrogen. In contrast diesel fuel vapours do not leak as easily as hydrogen.

Diesel fuel is a liquid under normal conditions, and its vapours are approximately five times heavier than air. This means that the fuel and the vapours from leaks or spillages of diesel fuel may linger for some time after the release. In contrast, hydrogen under normal conditions is approximately 16 times lighter than air and in the open will rapidly rise and disperse in the atmosphere.

At ambient temperatures, hydrogen is a buoyant gas with strong diffusion characteristics which is a very positive characteristic for releases in the open as the hydrogen will rise and disperse quickly. In an enclosure it may mean that a release would quickly generate a flammable mixture. Dispersion is very much dependant on the particular scenario, the size of the release, degree of enclosure, ventilation and the availability of any ignition sources, etc.

Detection

Diesel fuel spillages are readily detectable due to the colour of the liquid and its characteristic hydrocarbon odour.

Both propane and butane are almost odourless when pure, though LPG typically contains an odorant such as ethyl mercaptan making leaks readily detectable.

Hydrogen is colourless, odourless and tasteless which means that a leak is impossible to detect with human senses. A high-pressure leak may be very loud, but this can't be relied upon and especially not in the noisy environments associated with railways. A wide range of hydrogen detection technologies are available.

Ignition

Flammable hydrogen/air mixtures are easily ignited with the minimum ignition energy being 0.017mJ at the stoichiometric concentration, which is more than an order of magnitude lower than that of diesel fuel and propane or butane all at approximately 0.25 mJ. At the lower flammability limit the minimum ignition energy for hydrogen/air mixtures is closer to that of the hydrocarbon fuels. From a simplistic perspective, a weaker spark is required to ignite hydrogen/air mixtures.

The high autoignition temperature of hydrogen (585°C) is an advantage, as it is significantly higher than LPG (365-470°C) and diesel fuel (approximately 250°C).

Combustion

Diesel fuel is classed as being a flammable liquid, while LPG and hydrogen are classed as being extremely flammable gases [5] [6] [7] [8] [9] [10]. The lower flammability limit (LFL) of diesel fuel (0.5 % by volume in air) is lower than LPG (1.4 – 1.7 %). In contrast hydrogen has a significantly higher LFL of 4% meaning that a higher concentration is needed before it becomes flammable when mixed with air.

Hydrogen has extremely wide limits of flammability in air (4 to 75% by volume in air). Below those limits the mixture is too lean to burn, i.e. insufficient oxygen, and above too rich, i.e. not enough oxygen. In contrast the flammability limits of diesel fuel (0.5 to 5.0% in air) and LPG (propane 1.7 to 10.8%, butane 1.4 to 9.4%) are much narrower. While this means that for a given release a greater quantity of hydrogen may be within the flammability limits this is, however, offset to some degree by the much stronger diffusion and dispersion characteristics of hydrogen in many situations.

In safety data sheets diesel fuel is not considered explosive, however, the data sheets refer multiple times to flammability or explosive risks, e.g. [11]. One of the key indicators of the reactivity of the fuels is the burning velocity which for hydrogen (2.65-3.25m/s) is almost an order of magnitude faster than diesel fuel (approx. 0.35m/s) and LPG (approx. 0.45-0.46 m/s). LPG/air mixtures are considered to be potentially explosive. Hydrogen/ air mixtures can explode as a deflagration which is typical of fuel/air mixtures in the open, and in the presence of certain conditions such as enclosure and congestion faster deflagrations and detonations may potentially occur as well as the transition from a deflagration to a detonation.

Diesel fuel burns with visible flames (yellow/smoky and blue/yellow respectively) and as with other hydrocarbons, the flames radiate significant heat which can trigger secondary fires but also provides a warning to emergency responders. In contrast pure hydrogen burns with an almost invisible, very pale blue flame in daylight or in a well-lit building [12]. Some photographs or videos show a pale-yellow flame, but this is due to impurities in the air burning such as dust. It should be assumed that a hydrogen flame is invisible without thermal imaging equipment. Hydrogen flames also radiate much less heat than hydrocarbon fires, in the order of 10% compared to 27-40% for an equivalent diesel. Depending on the particular situation for hydrogen this may mean fewer secondary fires, but it also means that less warning is provided to emergency responders which is especially hazardous in combination with the very poor flame visibility.

3.3.5 High Voltage Systems

Both battery electric and hydrogen fuel cell electric railway drivelines are based on a high voltage system architecture which results in electrical hazards which must be managed safely. At the rail depot, high power battery charging infrastructure will have electrical hazards that need to be managed safely. Working with high voltage systems is normal for the rail industry, and this topic is not considered further in this report.

3.3.6 Batteries

Li-ion batteries may be used on both battery-electric rail vehicles and hydrogen fuel cell electric rail vehicles. As with hydrogen, significant hazards exist with the use of Li-ion batteries if the related risks are not adequately managed and mitigated. These hazards include fires, explosions, and toxic combustion products. The risks linked to these hazards are mitigated by battery management systems which monitor all cell voltages, currents and temperatures. The mechanical and thermal design of the battery prevents the spread of thermal events.

There are different Li-ion battery chemistries which can behave differently from a safety perspective. The Li-ion batteries used for propulsion consist of several cells. The key hazard of Li-ion battery systems is a thermal runaway which can be initiated from mechanical damage causing an internal short circuit within the cell, thermal failures, over-charging or over-discharging. Any of these events can lead to elevated temperatures that are high enough to induce rapid exothermic decomposition of the cell materials. Thermal runaway is a chain reaction within a battery cell that is initiated when the temperature inside a battery reaches the point that causes a chemical reaction to occur in the cell. This exothermic chemical reaction produces more heat, which drives the temperature higher, causing further chemical reactions that create more heat and becomes self-propagating, eventually affecting adjacent cells. In a thermal runaway, the battery cell temperature rises very quickly.
The heat can damage adjacent cells, such that the thermal runaway propagates throughout a battery pack. In minor cases, a thermal runaway can cause batteries to be damaged beyond repair, while in more serious cases, thermal runaway can cause batteries to explode or burn. When a thermal runaway occurs an excess of gases is created, which must be vented from the cell to avoid an explosion. The outcome of a thermal runaway depends on many factors including the battery chemistry and the gases that are released as a result of the thermal runaway. Typically, a mixture of different gases including hydrogen, carbon monoxide (CO), hydrogen fluoride (HF), hydrogen chloride (HCl) and sulphur dioxide (SO_2) will be released with different flammability properties and levels of toxicity. Hazards associated with batteries are not considered further in this report.

3.3.7 Legal Requirements and Standards

Existing railway legal requirements do not specifically address the special hazards of hydrogen. Furthermore, the lack of rolling stock and infrastructure technical standards and safety requirements have been identified by CER as two of the key barriers to the large-scale introduction of hydrogen powered trains in Europe [13].
A detailed investigation of broader railway specific legal requirements and standards that may apply to rolling stock or infrastructure projects is beyond the scope of this current report. However, CER as with other parts of the rail industry and other rail projects often refer to automotive regulations or standards as being relevant in lieu of similar rail regulations or standards. In part this is to benefit from experience gained in the automotive industry, but also to benefit from economies of scale. An in-depth investigation of directly or indirectly applicable automotive regulations and standards from the UN, EC, ISO, IEC and SAE is beyond the current scope of work.

There are currently three international standards at early or potential stages of development for hydrogen rolling stock:

- IEC / TC9 CD 63341-1 ED1 Railway applications - Hydrogen and fuel cell systems for rolling stock - Part 1: Fuel cell system
- IEC / TC9 CD 63341-2 ED1 Railway applications - Hydrogen and fuel cell systems for rolling stock - Part 2: Hydrogen fuel system
- ISO/PWI 19887-2 (proposed work item) Gaseous Hydrogen — Fuel system components for hydrogen fuelled vehicles — Part 2: Rail vehicles

A full listing of directly or potentially indirectly applicable legal requirements and standards is beyond the current scope of work, however, five selected on-road vehicle documents are discussed below:

- EC Regulations 79/2009 & 406/2010 (withdrawn 2022)

These regulations are no longer valid for the type-approval of on-road vehicles in the European Union as they were withdrawn in July 2022 and superseded by R134 (see below).

- UN ECE WP.29 R134

R134 [14] is derived from GTR 13 (original version) for use in countries implementing the type-approval system including the European Union. The regulation is applicable to compressed gaseous hydrogen storage systems in cars, buses and trucks for on-road use. Work is ongoing to develop R134 Rev.1 from the new requirements contained in GTR13 Amd.1 (see below).

- UN ECE WP.29 GTR 13 Amd.1

Global Technical Regulation GTR13 Amd.1 [15] contains requirements for both compressed and liquid hydrogen storage systems for on-road vehicles (cars, buses and trucks). Amd.1 was adopted in 2023 and represents a significant revision in comparison to the original version. As a GTR, it contains technical requirements but not type-approval procedures. Work is ongoing to transpose the new requirements into a revised version of R134. Of particular note, the GTR contains a detailed rationale explaining the background to the requirements which is also applicable to the requirements in R134.

- EU 2021/535

This Implementing Regulation [16] includes requirements for the type-approval of liquid hydrogen storage systems for on-road vehicles based on requirements extracted from GTR13.

- SAE J2601-5_202402 Technical Information Report (TIR), High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles

The TIR [17] applies to high-flow fuelling protocols for fuelling of compressed gaseous hydrogen vehicles at peak flow rates from 60 to 300 g/s with compressed hydrogen storage system (CHSS) volume capacities between 248.6 and 7500 L which have been qualified to UN GTR 13, i.e. on-road vehicles.

The above documents represent significant technical advances from CNG road vehicle regulations, and a move from prescriptive to performance-based regulation. In addition, they incorporate more than 25 years research considering the different hazards posed by hydrogen.

Before adopting automotive regulations or standards for the rail industry, it should be considered whether the requirements they contain are applicable to rail applications. UN ECE GTR13 and R134, etc. were written for, and legally only apply to, on–road vehicles (cars, buses & trucks). Many relevant ISO standards cover “land vehicles” but were written for on-road vehicles. However, the underlying test regime, methods and criteria may be suitable for adoption by the rail industry subject to review and appropriate changes. Rolling stock has different service and environmental conditions which must be considered in the context of the automotive test philosophy used in the existing on-road vehicle documents, see table below.

Table 27 : Difference between road & rail service conditions

DIFFERENCE BETWEEN ROAD & RAIL SERVICE CONDITIONS		
Service/Environmental Condition	**On-road**	**Rail**
Hydrogen capacity (kg)	Up to 100	Ca50 to 500 or more
Nominal working pressure (MPa)	35 or 70	35, maybe 70
Service life (yrs)	15 or less (R134)	> 30
Temp. Range (°C)	-40 to +85	?
Pressure cycles (to 1.25 x NWP)	11000/22000 inc. high margin	?

Pressure relief devices on a typical system	1-10	>>5
Type 4 tank permeation	Controlled by test	
Refuelling requirement	Up to 100kg in 10-15mins	Min 100kg in 10-15 mins
Other	-	Different vibration spectra Different accident loads

Earlier this year the World Hydrogen Council coordinated a ISO/IEC meeting to discuss how ”Land Vehicle” standards could be adapted to rail, for example, by creating dedicated sections, or new ”parts”.
In addition to any rail specific legal requirements and standards, infrastructure projects must comply with appropriate European, national or potentially local legislation. An investigation is beyond the current scope of work.

3.3.8 Summing Up Hydrogen Safety, Legal Requirements and Standards

Hydrogen has been safely produced and used in large quantities for many decades in several applications including the process and space industries, and this knowledge base can be transferred to the railway environment. The hazards associated with hydrogen are significantly different to those of the diesel fuel which is handled daily by the railway industry. Hydrogen is an extremely flammable and hazardous gas, but diesel fuel is also flammable and hazardous. While some properties of hydrogen make it more hazardous than diesel fuel, other characteristics make it safer.
Because of the ease of ignition of hydrogen/air mixtures, the probability of a fire or explosion is extremely high if the concentration of hydrogen is within the flammability limits. Unprotected flames or sparks should be avoided in the vicinity of hydrogen storage, or handling equipment, etc. Given hydrogen’s propensity to leak, special consideration is needed when leak testing equipment, and in enclosures or other situations where the hydrogen is not able to disperse freely into the atmosphere.
Due to the difficulty in detecting the presence of hydrogen or its flames, those working directly with hydrogen systems, during maintenance or emergency response for example, must be aware of the special properties of hydrogen. Training should cover their inability to detect hydrogen’s presence without detectors, or to see or feel heat radiated from hydrogen flames.

In terms of refuelling, examples of key issues that need to be addressed in future safety studies and risk analyses include:

- Evaluation of fuel transport and fuel transfer operations as historically these have been the most critical steps.
- Definition of safety distance in the context of the rail refuelling environment, i.e. what is its purpose.
- International perspective on safety distances.
- Safety distance around fixed refuelling facilities, e.g. bulk storage.
- Safety distance around the refuelling point, and the interaction of the safety distance with other rolling stock servicing operations should be considered.
- Evaluation of refuelling hydrogen rolling stock while conventional rolling stock is also being refuelled nearby.
- Evaluation of refuelling hydrogen rolling stock while battery electric rolling stock is being recharged nearby.
- Development of emergency procedures and equipment in case of hydrogen hose pull-out.

- Development of leak or fire detection, management and emergency response procedures, based on benchmarking other industries and adaption to the rail environment.
- Evaluation of how extreme weather conditions will affect refuelling.
- Evaluation and development of safe maintenance procedures.
- Indoor maintenance procedures.
- Role based staff training and qualification.

A fundamental requirement for the success of hydrogen-fuelled rail applications is that hydrogen can be handled in a safe, efficient and internationally standardised manner. Existing legal requirements and standards for handling fuel at rail depots are not adapted to the special hazards of hydrogen and how they differ from the hazards of conventional fuels. The key to the successful and safe introduction of hydrogen in the rail environment is that all involved whether designers, system operators or emergency responders understand the differences between the hazards of diesel fuel and hydrogen. These differences need to be considered in relevant legal requirements and standards. Given the very nature of the rail industry in Europe, legal requirements, standards and procedures will need to be harmonised internationally.

From a safety perspective, there are no insurmountable obstacles for hydrogen to be handled safely in the railway industry as shown by existing demonstration projects [1]. However, there are several challenges to overcome to ensure that safety is at least equivalent to diesel fuel, and that the risks associated with the particular properties of hydrogen can be mitigated to safe levels. The railway industry has many advantages over other industries due to the safety critical and well-controlled environment. The challenges associated with the safe use of hydrogen have been successfully tackled by other industries, so the rail industry should learn from existing legal requirements, standards, and procedures, and adapt them to the railway environment.

While the hazards associated with hydrogen are different from those of diesel fuel, the risks associated with those hazards in the railway industry can be managed safely provided that the components and systems are designed, specified, integrated, operated and maintained for hydrogen rather than conventional or similar fuels.
Existing railway legal requirements do not specifically address the special hazards of hydrogen. Furthermore, the lack of rolling stock and infrastructure technical standards and safety requirements have been identified as key barriers to the large-scale introduction of hydrogen powered trains in Europe. Significant work will be required to learn from the legal requirements and standards already developed for the automotive industry, and to adapt them to the special conditions of the rail industry.

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3.4 Analysis of the requirements for multimodal fuelling infrastructure (rail and non-rail)

Figure 103 : Multimodal Hydrogen supply for commuter trains, buses plus lorries

3.4.1 Multimodal Hydrogen Stations: Bridging Road and Rail

A key challenge is the high cost of hydrogen refuelling stations, both in terms of capital expenditure (CAPEX) and operational expenditure (OPEX) [13, 112]. This cost barrier is particularly acute in the early years when utilisation is low [112]. Combining multiple mobility ecosystems (railway, maritime, and airports) within the same HRS could offer a solution by reducing refuelling and supply chain costs [112].

For instance, a multimodal station at an airport could supply hydrogen for:

- **Aviation systems**, including aircraft and ground support equipment
- **Heavy-duty cargo transport vehicles** [112]

Planned Multimodal Station Development

The European Union is funding research and development into multimodal hydrogen stations. **The Horizon Europe research and innovation programme includes a call for proposals for "Demonstration and deployment of multi-purpose Hydrogen Refuelling Stations combining road and airport, railway, and/or harbour applications"** [112]. The programme aims to address several challenges hindering HRS development, including high costs, low reliability, slow approval and construction processes, and the lack of standardised fuelling protocols [112].

This research initiative indicates a strong interest in developing and deploying multimodal hydrogen stations in the future.

Vehicle Compatibility and Hydrogen Pressures

Types of vehicles that could potentially use multimodal stations and the hydrogen pressures involved:

- **Trains:** hydrogen-powered trains like the Coradia iLint6 and the Mireo Plus H7, signifying the potential for trains to be refuelled at multimodal hydrogen stations.
- **Buses:** The use of hydrogen fuel cell buses in various locations, suggesting their compatibility with multimodal refuelling infrastructure [118, 26, 11].
- **Trucks:** Hydrogen have potentials for heavy-duty trucks, particularly in long-haul transportation [13, 6, 4]. For instance, H2 Mobility, a German energy company, is retrofitting existing hydrogen stations to serve both light and heavy commercial vehicles at 700 and 350 bar [13].
- **Cars:** While battery electric vehicles currently dominate the passenger car market, the future role of hydrogen fuel cell cars is not quite obvious [13, 41].

Two primary hydrogen pressures for refuelling:

- **350 bar:** Currently used for most trucks and buses [4, 13].
- **700 bar:** Predominantly used for passenger cars, with an expectation that trucks will also utilize this higher pressure in the future for increased range [4].

Future Developments

Several key trends for the future of multimodal hydrogen stations are identified:

- **Capacity Increase:** Stations will need to scale up to accommodate larger volumes and more frequent refuellings as demand for hydrogen fuel increases [112, 26]. Proposed projects aim to develop stations with a capacity of 1,000 to 3,000 kg/day, with individual fills of over 200 kg expected in under 20 minutes [112].
- **Liquid Hydrogen:** Liquid hydrogen's higher energy density could become more widely used, particularly for heavy-duty vehicles with greater storage needs [112, 102].
- **Renewable Energy Integration:** Integrating multimodal stations with renewable energy sources, such as wind and solar power, for on-site green hydrogen production aligns with decarbonization goals [112, 26].
- **Standardization:** Developing standardized refuelling protocols across various vehicle types and regions would streamline infrastructure development and enhance compatibility [112, 11]. The EU is supporting research into developing a proven protocol for vehicles with larger on-board storage, aiming for inclusion in international standards [27].
- **Network Expansion:** Expanding the hydrogen refuelling network, encompassing both gaseous and liquid hydrogen options, is crucial for broader hydrogen vehicle adoption [97]. Policy initiatives like the EU's AFIR aim to accelerate network development [13, 6].

In General

Good examples of operational multimodal hydrogen refuelling stations is hard to find, but the available information points to their viability and potential benefits. Developing such stations will require meticulous planning, infrastructure investment, and cross-sector collaboration to ensure their success. As the shift towards a hydrogen-based transport system progresses, multimodal stations could play a pivotal role in encouraging the adoption of hydrogen vehicles across diverse transportation modes, contributing to a more sustainable and environmentally friendly future.

3.4.2 References on Analysis of the Requirements for Multimodal Fueling Infrastructure

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Conclusion

This deliverable provides a multi-disciplinary baseline for the design of future regional rolling-stock and will directly feed the work scheduled in WP 10. The main findings can be summarised as follows.

Focus-group and survey work underline that the market now expects clean interiors, universal boarding, secure luggage/bike areas and reliable onboard connectivity; incorporating those elements from day one will help to convert latent demand into sustained ridership growth.

Seat-kilometre cost keep rising with inflation and the extra hardware for batteries, fuel cells, or “smart equipment”. This highlight the pressure for frugal design and shared components, amongst a more industrialized approach for what could be a “mass production” of those trains.

To succeed, future designs must embed :

- a flexible “building-block” architecture for vehicles and interiors;
- battery/H_2 drivetrains compatible with a sparse network of multi-energy depots;
- passenger-centred layouts (hygiene, storage, safety) that directly address the issues surfaced in user research.

Automation remains cautious: after the demise of Taxirail, only the Stadler train for the Rheineck–Walzenhausen rack line is ordered for GoA 4; most other projects aim for GoA 2-3 with retrofit paths to full ATO.

Regarding TSIs, the study shows that compliant with the current regulation is achievable but may create limitations to the development of a new regional rolling stock. For example, new categories of car bodies and crashworthiness could be analysed, all the current clauses regarding running gear are written for axles and bogies and independent wheels are still an exception not properly described, the TSI also lack a category for battery-hybrid or road charging solutions, etc.

This documents also lays the technical cornerstone for a G1 regional train.

In summary, D5.1 articulates a clear and evidence-based vision of a light, modular, zero-emission regional train centred on passenger needs. It provides a foundation for the upcoming design work and supports Europe’s Rail JU goals for decarbonised and more resilient regional mobility.

Appendix 1 – Vehicles prices

Year	Vehicle	Price	Price per vehicle	Price/seat	Cond.	Amount	Cars	Seats	Source
1962	VT 98	121 943 €	121 943 €	2 102 €	new	1	1	58	http://www.privat-bahn.de/LAG_Tettnang.html
1987	ÖBB 5047	196 216 560 €	1 962 166 €	31 648 €	new	100	1	62	https://de.wikipedia.org/w/index.php?title=%C3%96BB_5047&oldid=248371194
1997	LVT/S	13 804 881 €	766 938 €	11 799 €	new	18	1	65	https://shop.vgbahn.info/media/pdf/Vorschau/Vorschau_909802.pdf
2010	RS1	70 000 000 €	2 333 333 €	23 333 €	new	30	1	100	https://www.tagblatt.ch/wirtschaft/tschechische-bahn-bestellt-bei-stadler-ld.193109
2010	RS1	8 850 000 €	1 770 000 €	17 700 €	new	5	1	100	https://de.wikipedia.org/wiki/Rurtalbahn_GmbH
2010	Pesa SA135	183 195 000 €	3 105 000 €	44 357 €	new	59	1	70	https://www.polot.net/en/szt-sa135-pesa-2021-1144
1986	BR 628.2	1 160 633 €	1 160 633 €	8 290 €	new	1	2	140	https://de.wikipedia.org/wiki/DB-Baureihe_628
1995	Regiosprinter DKB	12 925 459 €	807 841 €	9 617 €	new	16	2	84	https://de.wikipedia.org/wiki/RegioSprinter
1996	Regiosprinter Voigtlandbahn	16 565 857 €	920 325 €	11 504 €	new	18	2	80	https://www.baureihe654.de/?page_id=72
2008	Alstom Lint 41	70 000 000 €	2 333 333 €	17 949 €	new	30	2	130	https://www.alstom.com/de/press-releases-news/2008/3/2008-03-27_CL_NRE_de
2008	Bombardier Itino	70 400 000 €	3 200 000 €	26 891 €	new	22	2	119	https://www.fr.de/rhein-main/darmstadt/sauber-odenwald-11688336.html#:~:text=Betreiberin%20der%20Odenwaldbahn%20ist%20die,der%20%C3%96kovariante%203%2C7%20Millionen.
2016	Alstom Lint 41	170 000 000 €	3 269 231 €	25 148 €	new	52	2	130	https://www.alstom.com/de/press-releases-news/2016/4/alstom-liefert-52-coradia-lint-regionalzuge-an-abellio
2016	Alstom Lint 54	12 000 000 €	4 000 000 €	24 242 €	new	3	2	165	https://de.wikipedia.org/wiki/Rurtalbahn_GmbH
2017	Alstom Lint 54	16 000 000 €	4 000 000 €	24 242 €	new	4	2	165	https://www.nahverkehrspraxis.de/vier-neue-fahrzeuge-fuer-die-odenwaldbahn/
2020	Alstom Lint 41	120 000 000 €	4 000 000 €	30 769 €	new	30	2	130	https://www.alstom.com/de/press-releases-news/2020/3/alstom-liefert-30-coradia-lint-regionalzuege-die-hessische-landesbahn
2020	Newag 36WEh Hybirid	30 530 000 €	5 088 333 €	34 852 €	new	6	3	146	https://www.rynek-kolejowy.pl/wiadomosci/dolny-slask-podpisal-umowe-z-newagiem-na-hybrydy-od-razu-powiekszyl-zamowienie-99011.html
2021	Newag 36WEh Hybirid	28 000 000 €	5 600 000 €	35 000 €	new	5	3	160	Informacja prasowa ŁKA, 2021.04.07. Przetarg na hybrydy dla ŁKA rozstrzygnięty
2022	Alstom iLint	93 000 000 €	6 642 857 €	42 582 €	new	14	2	156	https://www.alstom.com/de/press-releases-news/2022/8/weltpremiere-erstes-netz-mit-14-wasserstoffzuegen-nimmt-niedersachsen
2022	Newag 36WEh Hybirid	27 330 000 €	5 466 000 €	36 440 €	new	5	3	150	https://kolejowyportal.pl/pomorze-zachodnie-zamawia-dodatkowe-piec-hybryd/
2023	Siemens Mireo Plus B	77 000 000 €	3 850 000 €	32 083 €	new	20	2	120	https://vm.baden-wuerttemberg.de/de/service/presse/pressemitteilung/pid/land-bestellt-erstmals-batterieelektrische-zuege/
2023	Newag 36WEh Hybirid	23 000 000 €	5 750 000 €	42 593 €	new	4	3	135	https://de.railmarket.com/news/rolling-stock/5256-pomeranian-region-will-get-four-dual-mode-units-from-newag
2011	RS1	8 800 000 €	1 760 000 €	17 600 €	used	5	1	100	https://www.vde.com/resource/blob/2068330/fad0182ad0b4c787712dcdd6618be2d2/vde-study-evaluation-of-climate-neutral-alternatives-to-diesel-multiple-units-data.pdf#page=57&zoom=100,120,122
2019	GTW 2/6 (DB Regio)	7 500 000 €	625 000 €	5 787 €	used	12	2	108	https://eurailpress-archiv.de/SingleView.aspx?show=606443
2023	RS1	13 000 000 €	1 181 818 €	13 742 €	used	11	1	86	https://www.eurailpress.de/nachrichten/fahrzeuge-komponenten/detail/news/tschechien-cd-kauft-11-weitere-stadler-rs1.html
2023	Desiro Classic	9 120 000 €	1 520 000 €	13 818 €	used	6	2	110	https://www.lok-report.de/news/europa/item/42376-tschechien-cd-kauft-sechs-desiro-br-642-bei-der-hlb.html
2024	PESA SA136	4 800 000 €	1 600 000 €	10 191 €	used	3	3	157	https://www.lok-report.de/news/europa/item/47521-polen-polregio-erhaelt-drei-sa136.html
2024	RS1	5 700 000 €	1 425 000 €	14 250 €	used	4	1	100	https://www.zvw.de/rems-murr-kreis/f%C3%BCr-57-millionen-euro-verband-kauft-vier-gebrauchte-regio-shuttle-f%C3%BCrs-wiesel_arid-790012

Appendix 2 – Common European Requirements for Regional Battery and Hydrogens Trains

Nr.	Requirement	Network	Value	Explanations / Comments
A	General requirements			
A.1	General Specification			
A.1.2	Number of coaches per train	Any	1	
A.1.3	Minimum train length	Separate (G2)	10 m	The smallest coach length that gives a proper layout
A.1.4	Maximum train length	Mixed (G1)	15 m	The length of the coach is limited by the allowed axle load
A.1.5	Platform height with level access (no steps)	Any	550 mm	Other heights to be covered by movable ramps
A.1.6	Multiple-unit train control / operation	Any	Yes	No electrical connections between coaches
A.1.6a	Maximum number coaches in multiple operation	Any	2	To be discussed
A.1.7	Emergency towing rod	Any	Yes	Normal multiple operation without mechanical connection
A.1.8	Mechanical automatic coupler	Any	Optional	Replacing requirement A.1.7 (but still without electrical connections)
A.2	Capacity			
A.2.1	Minimum seating capacity	Separate (G2)	20	Maximum number of seats in smallest coach, flexible layout offered
A.2.2	Maximum seating capacity	Any	40	Maximum number of seats in largest coach, flexible layout offered
A.2.3	Operational normal Standing capacity	Any	60	Flexible layout offered, capacity limited by axle load and space
A.2.4	Number of bicycles	Mixed (G1)	0 - 4	Flexible layout including bicycle racks offered
A.2.5	Number of bicycles	Separate (G2)	0 - 4	Flexible layout including bicycle racks offered
A.2.6	Number of PRM spaces	Mixed (G1)	1	Flexible layout including PRM space offered
A.2.7	Number of PRM spaces	Separate (G2)	0 - 1	Flexible layout including PRM space offered
A.2.8	Multipurpose area	Any		Flexible layout including multipurpose area offered
A.2.9	Freight Capacity	Any	8000 kg	Capacity limited by allowed axle load
A.2.10	Variability of the passenger capacity	Any		Two coach lengths offered, and flexible layout that can be changed during life
A.3	Area of operation			

A.3.1	Area of operation	Any		National in Europa, crossing border in exceptional cases; both national and cross-border traffic, across whole Europe.
A.3.2	Blank			
A.3.3	Climate conditions	Any	T1	EN 50125-1
A.3.4	Exceptional climate conditions	Any		Higher class than required by A.3.3 are optional
A.4	Lifespan			
A.4.1	Yearly milage	Mixed (G1)	150.000 km/a	
A.4.2	Yearly milage	Separate (G2)		Probably less than G1
A.4.3	Yearly operational	Mixed (G1)	6000 h/a	
A.4.4	Yearly operational	Separate (G2)		Probably less than G1
A.4.5	Life time	Mixed (G1)	30 years	
A.4.6	Life time	Separate (G2)		Probably less than G1
A.4.7	Min. service life of the traction battery	Any		
A.4.8	Min. service life of the fuel cell (if used)	Any		
A.4.9	Min. service life of other drivetrain components	Any		
A.5	Environmental compatibility			
A.5.1	Locally emission free operation	Any	Yes	Battery with hydrogen or other media as range extender (to charge the batteries)
A.5.2	Noise	Any		TSI Noise applies
A.5.3	Use of sustainable Materials and allowed Materials	Any		Follow REACH regulations
B. Infrastructure Requirements (TSI INF related)				
B.1	Track			
B.1.1	Max. line length	Mixed (G1)	80, 200 km	
B.1.2	Max. line length	Separate (G2)	30 km	
B.1.3	Blank			
B.1.4	Blank			
B.1.5	Blank			
B.1.6	Max. axle load	Mixed (G1)	16 t	EN 15528
B.1.7	Max. axle load	Separate (G2)	16 t	EN 15528
B.1.8	Max. load per meter	Mixed (G1)	5 t/m	EN 15528 (WABTEC 4 t/m)
B.1.9	Max. load per meter	Separate (G2)	5 t/m	EN 15528 (WABTEC 4 t/m)

B.1.10	Max. gradient		40 ‰	To be discussed
B.1.11	Max. gradient for long slopes (up to 3 km)		10 ‰	To be discussed
B.1.12	Max. attitude difference		?	Important for braking dimensioning?
B.1.13	Loading gauge	Any	G1	
B.2	Station			
B.2.1	Operable platform height with step height <= 230mm	Any	380 mm	(ÖBB: current 200/380/550mm; future 380/550mm)
B.2.2	Operable platform height with step height > 230mm		?	
C. Vehicle requirements (TSI LOCPAS related)				
C.1	Vehicle body			
C.1.1	Loading gauge	Any	G1	Determination of load gauge should depend on use-case analysis G1-Loading gauge Profile (Possible in every country except UK?);
C.1.2	Axle load	Mixed (G1)	16t	Maximum axle load based on EN 15663 (exceptional load?) fulfilling EN 15528 category A reduction of the energy consumption, reduction of the carried energy storage, high agility of the vehicle, etc. Low superstructure load for effort reduction on reactivated lines. less damage of the superstructure for reducing the effort for reactivation lines
C.1.2a	Axle load	Separate (G2)	10t	Target maximum axle load based on EN 15663 (exceptional load?) reduction of the energy consumption, reduction of the carried energy storage, high agility of the vehicle, etc. Low superstructure load for effort reduction on reactivated lines. less damage of the superstructure for reducing the effort for reactivation lines
C.1.3	Car body strength	Mixed (G1)	Category P-III	Mixed operation makes a compatibility necessary to existing vehicles. High braking performance allows a reduced strength for the car body according to EN 12663-1. Thus category P-III could be the suitable base for the car body strength, if homologation in this case is possible. Alternative: The standard can be deviated from the same level of safety.

C.1.4	Car body strength	Separate (G2)	Category P-IV	Separate operation offers an adaption of the loads according the occurring scenarios. The loads could be reduced compared to EN 12663-1 category P-III (light commuter train). Reduced loads allow simplified and lighter technical car body designs. Load definitions are possible, base could be crash-scenarios of EN 15227. As alternative the strength of the car body can be based on fatigue loads from operation. In this case, proof of sufficient strength is required.
C.1.5	Crashworthiness	Mixed (G1)	Category C-III	Collisions cannot completely avoided. Thus a crashworthiness is necessary which considers the potential collision partners. For mixed operation the EN 15227 category C-III seems suitable. If homologation is possible.
C.1.6	Crashworthiness	Separate (G2)	Category C-IIIw/o Scenario 2	Separate operation allows a adaption of the crashworthiness due to that some collisions partners of EN 15227 are not possible. Analyses are necessary regarding the potential collision partners. EN 15227 category C-III scenario 1, 3 and 4 could be a base also C-IV could be possible
C.1.7	Collision with animals, max size			Based EN 15227 or adaption necessary? / Moose, reindeer, wild boars... --> Not direct considered in EN 15227
C.1.8	Platform and module concept for cost-efficient production and low-cost vehicles			Extended use of same parts. Same base design of the vehicle for G1 and G2
C.2	Vehicle equipment (windows, floor, panelling , painting, etc.)			
C.2.1	-			
C.3	Vehicle Interior			
C.3.1	Handrails			
	The vehicle should have an adequate amount of handrails	Any		Check TSI and national regulatory
	The vehicle need to have handrails or handles on various heights for different people	Any		Check TSI and national regulatory
	The colour scheme - calming, natural, highlighting important information with bright colours	Any		
C.3.2	Seating			

	The vehicle should have different seating options e.g.. 4 Seater or in row (62% in row)	Any		
	Folding seats	Any		
	Seat lower height accessible without steps	Any		
	Fixed seats easy to reach without steps	Any		
	Seats should be adapted to the use of the vehicle	Any		
	Standing place with backrest	Any		
	Seats easy to clean	Any		
	Benches/seats with switching backrest for x% of the capacity	Any		To change the seats in driving direction
	Adjustable /movable armrests for PRM seats	Any		
	Adjustable /movable armrests for all seats	Any		
	Adequate legroom	Any		
	Providing Tables for X% of the seats	Any		
	Providing workstations (privacy wise)	Any		
	Handles on the seats (help people to get in or out the seat)	Any		
	The seats are supposed to be equipped with armrests	Any		
	The Seats for PRM / elderly need to have armrests	Any		
C.3.3	Toilets			
	Toilets	Separate (G2)	No	
	Toilets	Mixed (G1)	Optional	
	If the vehicle is equipped with a toilet a baby nappy changing facility needs to be installed	Any	Yes	
C.3.4	Luggage and Bikes			
	The vehicle needs to provide space for X% bikes	Any	0 - 4	Flexible layout including bicycle racks offered
	The bike area needs to be able to be switched to a winter sports storage area	Any		Flexible layout including multipurpose area offered
	There needs to be space for heavy and bulky luggage	Any		Flexible layout including multipurpose area offered
	Luggage security has to be taken in to account in the vehicle design	Any		
C.3.5	Technical equipment for user			

	Power sockets	Any	Optional	
	USB Charing Ports	Any	Yes	
	Wi-Fi	Any	Yes	
	Option to equip the vehicle with a vending machine	Any	Optional	
C.4	Running gear			
C.4.1	Vehicle rail interaction	Any	Yes	Fulfilment of safety related requirements in EN14363
C.4.2	Vehicle rail interaction	Any	$T_Y \leq 75$	At curve radius 300 m? To be discussed.
C.4.3	Ride comfort	Mixed (G1)	$N_{MV} \leq 2.5$	Target: according EN 12299 at low track quality according ERRI B176
C.4.4	Ride comfort	Separate (G2)	$N_{MV} \leq 2.5$	Target: according EN 12299 at low track quality according ERRI B177
C.4.5	Curve radius in operation	Any	150 m	
C.4.6	Curve radius in work shop area	Any	80 m	
C.4.7	Structural strength running gear (primary suspended)	Any		Strength for the structural load bearing part of the running gear based on structural requirements of bogie frames (adaption necessary)
C.4.8	Strength of wheelset and running gear (part before primary suspension)	Any		Depending on the running gear concept (single wheels or wheelset)
C.5	Traction System			
C.5.1	Max. speed	Mixed (G1)	120 km/h	
C.5.2	Max. speed	Separate (G2)	80 km/h	
C.5.3	Blank			
C.5.4	Average station distance (slow/ express train)	Any		Use case depending
C.5.6	Min. starting acceleration (m/s^2)	Any	0.8 m/s^2	
C.5.7	Design of the drivetrain so that regenerative braking is as efficient as possible	Any		Fully regenerative service brake charging the battery.
C.5.8	Typical continuous traction power (battery operation)		?	
C.5.9	Maximum traction power	Any	390 kW	
C.5.10	Maximum time for max power			
C.5.11	Typical average power for ref. Speed profile according to EN 50591 profile	Mixed (G1)		
C.5.12	Typical average power for ref. Speed profile according to adapted EN 50591 profile	Separate (G2)		Adapted speed profile
C.5.13	Modular propulsion and energy architecture, scalable depending on use case			

C.5.14	Min. battery reserve capacity for disturbances / standstill time		?	
C.5.15	Redundancy		?	How much performance loss is ok? drivability with failure of 50% of the motors has to be possible;
C.5.16	The vehicle needs to be able to brake regenerative		0.5 m/s^2	At maximum speed
C.5.17	Standardised interfaces for ext. Energy supply			
C.5.18	Standardised interfaces for recharging			
C.5.19	Standardised interfaces for battery and fuel cell stacks			
C.6	Driving Control Systems (Control-command and signalling, ATO)			
C.6.1	-			
C.7	Auxiliary			
C.7.1	-			
C.8	Monitoring and safety equipment			
C.8.1	-			
C.9	Lighting			
C.9.1	The vehicle needs equipped with adequate lights	Any		
C.9.2	The light is changing with daytime / outside light	Any		
C.10	HVAC			
C.10.1	-			
C.11	Ancillary plant (sand, lube, …)			
C.11.1	-			
C.12	Doors and Entrances			
C.12.1	Door width	Any		U.C.R. --> wide door
C.12.2	Door height	Any		
C.12.3	Automatic Door opening	Any		
C.12.4	Level boarding on 550 mm	Any	Yes	
C.12.5	Level boarding on 380 mm	Any	No	
C.12.6	Ramp in general	Any		
C.12.7	Ramp automatic	Any		
C.12.8	Door in signal colour	Any		Stainless steel door plus orange colour stipes ?
C.12.9	Exit sign at the ceiling	Any		Signs at the ceilings pointing towards the exit
C.12.10	Exit buttons/indicator	Any		Vehicle only stops when indicated
C.13	Information systems			
C.13.1	Large screens	Any		

C.13.2	Every seat needs vision to a screen with information about the itery	Any		F1 or 90% need vision?
C.13.3	Well structured and various information on the ride and connections	Any		
C.13.4	Information on the Region	Any		
C.14	Pneumatics and hydraulics	Any		
C.14.1	-			
C.15	Braking System			
C.15.1	Deceleration during service braking	Any	0.5 m/s^2	Regenerative braking only
C.15.2	Deceleration during emergency braking	Any	1.1 m/s^2	Mechanical braking only
C.16	Coupling			
C.16.1	-			
C.17	Support systems, enclosures			
C.17.1	-			
C.18	Electrical cable routing			
C.18.1	-			
D. Electrical Power Supply and Charging (TSI ENE related)				
D.1	Charging			
D.1.1	Energy supply voltage and frequency on electrified line (pantograph)		?	To be investigated if possible
D.1.2	The Vehicle needs to be able to be supplied while stand still		Yes	
D.1.3	Minimum charging power stand still		?	
D.1.4	The Vehicle needs to be able to be supplied while driving		Yes	
D.1.5	Minimum charging power driving		?	
D.1.6	The vehicle needs to be able to high-power charge		Yes	
D.1.7	Minimum power for high-power charging		?	Needs to be defined
D.1.8	Max. turning time at final station			
D.1.9	Max. charging time at the turning station		?	
D.1.10	Average turning/ charging time at final station		?	
D.1.11	Max. ext. power supply for overnight parking		?	depending on climate conditions
D.1.12	Max. non-electrified line segment		?	
D.2	Hydrogen Refuelling			

D.2.1	Required refuelling distance Target value		?	>> 5.2.2
D.2.2	Max. refueling time		?	>> 5.2.3
D.3	Non Driving Energy Demand			
D.3.1	Additional standstill time			The vehicle maybe stopped on the line due to different reasons, like signaling error, collision with animals etc. In this case, the vehicle must be able to keep certain systems (light, ventilation, toilet) running for a while.
D.3.2	Power demand while standstill			
E. -				
F. Signalling and Communication Requirements (TSI CCS related)				
F.1	CCS			
F.1.1	On-board CCS	G1		(WABTEC: ERTMS)
F.1.2	On-board CCS	G2		(WABTEC: G2 CCS)
F.2	ATO			
F.2.1	On-board ATO	G1		(DLR: suggestion ATO Level 3+ or higher / autonomous driving mode; WABTEC: ATO over ERTMS, GoA 2-3)
F.2.2	On-board ATO	G2		(DLR: suggestion ATO Level 3+ or higher / autonomous driving mode; WABTEC: ATO GoA 3-4)
G. User centered requirements / User centred design				User centred vehicle design depends on user requirements. Relevant questions are e.g. Who are the users? Which user groups exist? Which user requirements need to be addressed? Which diversity design aspects need to be considered? Are all users equally able to use the vehicle (e.g. mobility impaired, older/ younger passengers, women, people with strollers, etc.)
G.1	General			
G.2	Hygiene			
G.2.1	Use antibacterial materials on handles an buttons	Any		
G.2.2	Hygiene of the seats has to be taken in to account in the vehicle design	Any		
G.3	Safety / Security			
G.3.1	Security has to be taken in to account in the vehicle design	Any		
G.3.2	Security button	Any		
G.3.3	CCTV / Monitoring	Any		

H. Regulations and Safety

H.1	Regulations		
H.1.1	Standards and Requirements	Mixed (G1)	TSI adapted to the needs or common national requirements (e.g. EBA-Check list "non-TSI conform Vehicles" or Tram Train requirements
H.1.2	Standards and Requirements	Separate (G2)	Common definition of relevant trans-European requirements for the special needs of the vehicles for G2-lines based on the relevant existing TSIs but adapted (approach of a TSI-light for G2 w/o interoperability). Approach: Homologation for G2 lines are accepted in every EU country
H.2	Safety		
H.2.1	-		

Appendix 3 – Uses Cases (Germany and Sweden)

		DLR (Germany)	
Nr.	Section	Value	Comment
X	**Mixed Operation (G1)**		
X.1	Track		
X.1.1	*lines with a physical and/or logical connection with main lines; hence interoperability is required*		full compatibility with common secondary lines
X.1.2	Minimum track length [km]	5 km	Use Case Analyses for tracks to be reactivated
X.1.3	Maximum track length [km]	30 / 70 km	Use Case Analyses for tracks to be reactivated / 80 % of non electrified tracks in Germany [ETR 11/22 p. 69]
X.1.4	Average distance between stops	2,5 - 3 km	Use case analyses for tracks to be reactivated
X.1.5	Loading Gauge	G1	- " -
X.1.6	Maximum Axle Load	16 t	- " -
X.1.7	Maximum load per meter	5 t/m	- " -
X.1.8	Maximum gradient	30 ‰	maximum considerable gradient in Germany is 61,2 ‰ [Steilstrecke Wiki]
X.1.9	Minimum curve radius track	140 m	Use case analyses for tracks to be reactivated
X.1.10	Minimum curve radius maintenance	80 m	- " -
X.1.11	Electrification	no	- " -
X.1.12	Single- or double-track railway	single	- " -
X.1.13	Blank		
X.1.14	Blank		
X.2	Station		
X.2.1	Platform length min.	29 m	Use case analyses for tracks to be reactivated
X.2.2	Platform length max.		
X.2.3	Platform height min.	0 mm	- " -
X.2.4	Platform height max.	550 mm	- " -
X.2.5	Blank		
X.2.6	Blank		
X.3	Carriage		
X.3.1	Minimum required passenger capacity per hour	20	
X.3.2	Maximum required passenger capacity per hour	60	

X.3.3	Max estimated average riding time per trip	25 min	
X.3.4	Blank		
X.3.5	Blank		
X.4	General		
X.4.1	Number of vehicles	>500	first estimation, should be defined by the operators, results from preceding Use Case analysis
X.4.2	Blank		
Y	**Separate Operation (G2)**		
Y.1	Track		
Y.1.1	*lines with no physical and/or logical interaction with the main lines; hence interoperability is not strictly required*		separate infrastructure with homogeneous vehicles with reduced requirements
Y.1.2	Minimum track length [km]	3 km	Use case analyses for tracks to be reactivated
Y.1.3	Maximum track length [km]	20 km	- " -
Y.1.4	Average distance between stops	2 km	- " -
Y.1.5	Loading Gauge	G1	- " -
Y.1.6	Maximum Axle Load	16 t	- " -
Y.1.7	Maximum load per meter	5 t/m	- " -
Y.1.8	Maximum gradient	25 ‰	maximum considerable gradient in Germany is 61,2 ‰ [Steilstrecke Wiki]
Y.1.9	Minimum curve radius track	140 m	- " -
Y.1.10	Minimum curve radius maintenance	80 m	- " -
Y.1.11	Electrification	no	- " -
Y.1.12	Single- or double-track railway	single	- " -
Y.1.13	Blank		
Y.1.14	Blank		
Y.2	Station		
Y.2.1	Platform length min.	29 m	Use case analyses for tracks to be reactivated
Y.2.2	Platform length max.		- " -
Y.2.3	Platform height min.	0 mm	- " -
Y.2.4	Platform height max.	550 mm	- " -
Y.2.5			
Y.2.6			
Y.3	Carriage		
Y.3.1	Minimum required passenger capacity per hour	10	Use case analyses for tracks to be reactivated
Y.3.2	Maximum required passenger capacity per hour	50	- " -
Y.3.3	Max estimated average riding time per trip	20 min	- " -

Y.3.4			
Y.3.5			
Y.4	General		
Y.4.1	Number of vehicles	>600	first estimation, should be defined by the operators, results from preceding Use Case analysis

Nr.	Section	TRV (Sweden) Value	Comment
X	**Mixed Operation (G1)**		
X.1	Track		
X.1.1	*lines with a physical and/or logical connection with main lines; hence interoperability is required*		
X.1.2	Minimum track length [km]	129 km	
X.1.3	Maximum track length [km]	167 km	
X.1.4	Average distance between stops	5 - 10 km	
X.1.5	Loading Gauge	SEa	Compliant to G1
X.1.6	Maximum Axle Load	16 t	
X.1.7	Maximum load per meter	5 t/m	
X.1.8	Maximum gradient	25 ‰	Maximum gradient in Sweden, a few exceptions exists but regional vehicles will not run there
X.1.9	Minimum curve radius track	150 m	Minimum radius in Sweden
X.1.10	Minimum curve radius maintenance	90 m	
X.1.11	Electrification	no	
X.1.12	Single- or double-track railway	single	
X.1.13	Blank		
X.1.14	Blank		
X.2	Station		
X.2.1	Platform length min.	25 m	
X.2.2	Platform length max.		
X.2.3	Platform height min.	350 mm	Approximate heigth, large variability
X.2.4	Platform height max.	580 mm	
X.2.5	Blank		
X.2.6	Blank		
X.3	Carriage		
X.3.1	Minimum required passenger capacity per hour	20	
X.3.2	Maximum required passenger capacity per hour	60	One use case has a larger demand but this is out the scope for FP6
X.3.3	Max estimated average riding time per trip	30 min	
X.3.4	Blank		
X.3.5	Blank		

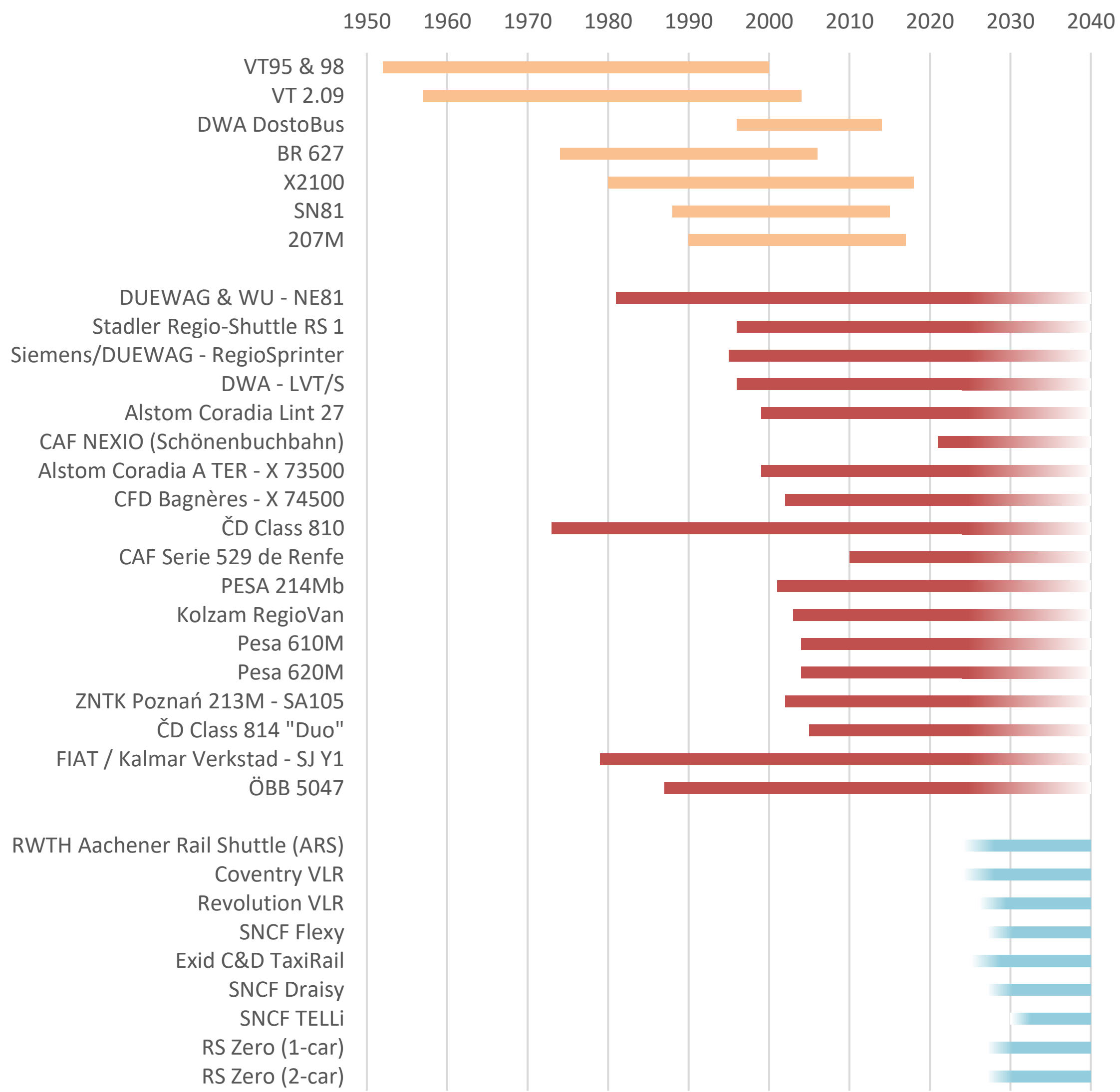
X.4	General	
X.4.1	Number of vehicles	50
X.4.2	Blank	
Y	**Separate Operation (G2)**	
Y.1	Track	
Y.1.1	*lines with no physical and/or logical interaction with the main lines; hence interoperability is not strictly required*	
Y.1.2	Minimum track length [km]	
Y.1.3	Maximum track length [km]	
Y.1.4	Average distance between stops	
Y.1.5	Loading Gauge	
Y.1.6	Maximum Axle Load	
Y.1.7	Maximum load per meter	
Y.1.8	Maximum gradient	
Y.1.9	Minimum curve radius track	
Y.1.10	Minimum curve radius maintenance	
Y.1.11	Electrification	
Y.1.12	Single- or double-track railway	
Y.1.13	Blank	
Y.1.14	Blank	
Y.2	Station	
Y.2.1	Platform length min.	
Y.2.2	Platform length max.	
Y.2.3	Platform height min.	
Y.2.4	Platform height max.	
Y.2.5		
Y.2.6		
Y.3	Carriage	
Y.3.1	Minimum required passenger capacity per hour	
Y.3.2	Maximum required passenger capacity per hour	
Y.3.3	Max estimated average riding time per trip	
Y.3.4		
Y.3.5		
Y.4	General	
Y.4.1	Number of vehicles	

Appendix 4 – Vehicles Table

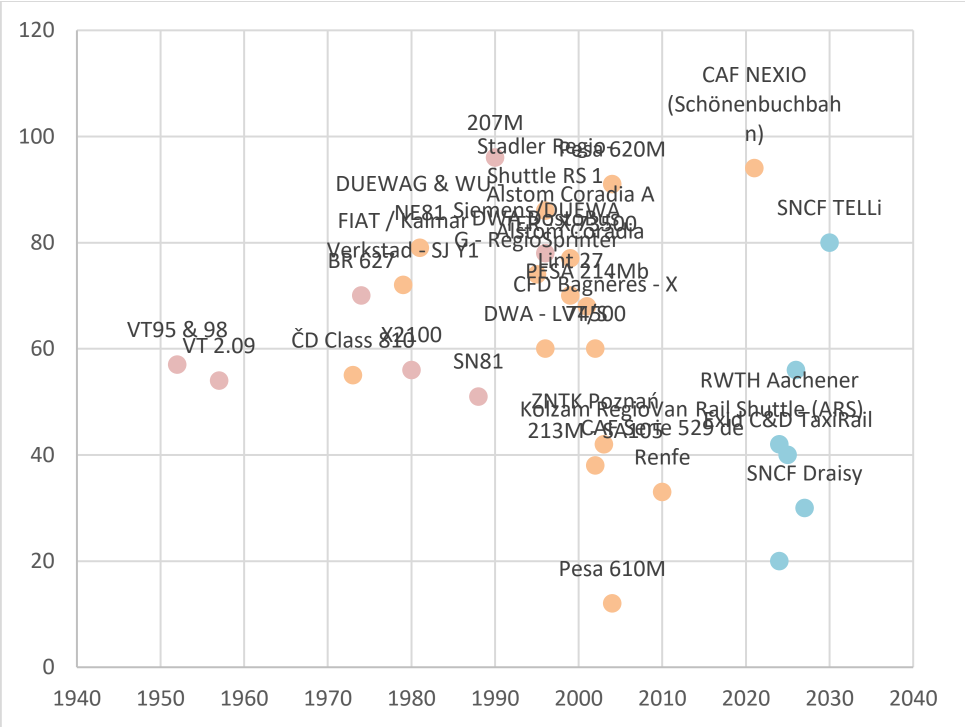
Category	Manufacturer / Vehicle	Series	Displayed Name	Introduction Year	End of Production	End of use	Years in service			Country	Number of units built	Number of seats built	Number of cars
Unit										-			
Decommissioned Vehicles	Wagonfabrik Uerdingen	VT95 & 98	VT95 & 98	1952	1962	2000	48			GER	3306	188,442	1
	VEB Waggonbau	VT 2.09	VT 2.09	1957	1968	2004	47			GDR	159	8,586	1
	DWA DostoBus	BR 670	DWA DostoBus	1996	1996	2014	18			GER	7	546	1
	DUEWAG & MAK	BR 627	BR 627	1974	1981	2006	32			GER	13	910	1
	ANF Industrie	X2100	X2100	1980		2018	38			FR	53	2,968	1
	Kolzam SPA-66	SN81	SN81	1988	1990	2015	27			PL	6	306	2
	ZNTK Poznań 207M	SA101, SA1	207M	1990	1992	2017	27			PL	15	1,440	2
Operating Vehicles	DUEWAG & WU	NE81	DUEWAG & WU - NE81	1981	1995	in service	43	16		GER	26	2,054	1
	Stadler Regio-Shuttle	RS1	Stadler Regio-Shuttle RS 1	1996	2013	in service	28	16		GER	497	42,742	1
	Siemens/DUEWAG RegioSprinter		Siemens/DUEWAG - RegioSprinter	1995	1999	in service	29	16		GER	40	2,960	2.5
	DWA LVT/S	BR 672	DWA - LVT/S	1996	1999	in service	28	16		GER	24	1,440	1
	Alstom Coradia Lint 27	BR 640	Alstom Coradia Lint 27	1999	2012	in service	25	16		GER	47	3,290	1
	CAF NEXIO Schönenbuchba	BR 455	CAF NEXIO (Schönenbuchbahn)	2021	2023	in service	3	16		GER	12	1,128	3
	Alstom Coradia A TER	X 73500	Alstom Coradia A TER - X 73500	1999	2004	in service	25	16		GER/FR	377	29,029	1
	CFD Bagnères	X 74500	CFD Bagnères - X 74500	2002	2002	in service	22	16		FR	5	300	2
	Vagonka Studénka	810	ČD Class 810	1973	1982	in service	51	16		CD, SK	678	37,290	1
	CAF Serie 529 de Renfe	529	CAF Serie 529 de Renfe	2010	2011	in service	14	16		ES	12	396	1
	PESA	214Mb	PESA 214Mb	2001	2016	in service	23	16		PL	50	3,400	1
	Kolzam RegioVan	211M	Kolzam RegioVan	2003	2012	in service	21	16		PL	2	84	1
	Pesa 610M	610M	Pesa 610M	2004	2004	in service	20	16		UA	1	12	1
	Pesa 620M	620M	Pesa 620M	2004	2013	in service	20	16		UA, LT, BY	29	2,639	1
	ZNTK Poznań 213M	SA105	ZNTK Poznań 213M - SA105	2002	2007	in service	22	16		PL	7	266	1
	ČD Class 814 "Duo"		ČD Class 814 "Duo"	2005	2012	in service	19	16		CZ	209	0	2
	FIAT / Kalmar Verkstad	SJ Y1	FIAT / Kalmar Verkstad - SJ Y1	1979	1981	in service	45	16		SWE	100	7,200	1
	ÖBB 5047		ÖBB 5047	1987	1995	in service	37	16		AT	100	6,200	
Future Concepts	RWTH Aachener Rail Shuttle (ARS)		RWTH Aachener Rail Shuttle (ARS)	2024			16		16	GER	0		1
	Coventry VLR		Coventry VLR	2024			16		16	UK	1	20	1
	Revolution VLR		Revolution VLR	2026			14		14	UK	1	56	1
	SNCF Flexy		SNCF Flexy	2027			13		13	FR			
	Exid C&D TaxiRail		Exid C&D TaxiRail	2025			15		15	FR	0		1
	SNCF Draisy		SNCF Draisy	2027			13		13	FR	0		1
	SNCF TELLi		SNCF TELLi	2030			10		10	FR	0		2
	Stadler RS Zero (1)		RS Zero (1-car)	2027			13		13	GER	0		1
	Stadler RS Zero (2)		RS Zero (2-car)	2027			13		13	GER	0		2
	Stadler RhW		RhW	2027			13			CH	0		1
Larger Vehicles	Alstom	X 72500	Alstom X72500	1997						FR	117		2
	Alstom iLint		Alstom iLint	2018						GER			
	Alstom Coradia Akku	BR 1440.4	Alstom Coradia Akku	2025						GER			
	Alstom / Lint 41H	BR 648	Alstom / Lint 41H	2001						NL	50		2
	Alstom / Lint 41H	BR (1)648		2001						DE	429		2
	PESA Link	631		2014						EU	1		1
	Škoda	RegioPante	Škoda Regio Panter BEMU	2026						CZ			2
	Siemens Mireo Plus B/H		Siemens Mireo Plus B/H	2024						GER			
	Stadler Flirt Akku		Stadler Flirt Akku	2023						EU/US			
	Stadler / GTW	GTW 2/6	Stadler GTW 2/6	2005						IT	12		3
Double	ČSD 810			1973						CZ	680		1
	MAN, Duewag	VT627		1974		in service				PL			1
Concept (old)	RB002 BREL-Leyland (Demonstrator)		RB002 BREL-Leyland (Demonstrator)										

		Weight				Specific dimensions			Capacity				Dimensions				Traction			
Number of axels	Number of decks	empty [t]	full [t]	max. axel [t]	Payload ratio	[t/m]	[t/seat]	[kW/t]	Total	Seats	Standees	Freight	Lenght [m]	Width [m]	Height [m]	Loading Gauge	Traction power [kW]	max. speed [km/h]	Energy-storage	Capacity [l]
2	1	13.90	21	9.7	0.51	1.05	0.24	15.83	95	57	38	-	13.27	3.25	3.00	G1	220	90	Diesel	
2	1	17.45	21.5	12.5	0.23	1.29	0.32	9.28	54	54		-	13.55	3.08	3.53	G1	162	90	Diesel	
2	2	22.25	32	16	0.44	1.36	0.29	11.24	110	78	32	-	16.33	3,07	4.63	G1	250	100	Diesel	810
4	1	34.75	40	13	0.15	1.51	0.50	8.46	70	70		-	23.05	2.88	4.16	G1	294	120	Diesel	1000
4	1	43.70	48.6	10.9	0.11	1.95	0.78	10.07	65	56	9	-	22.4	2.87	3.81		440	140	Diesel	480
4	1	23.20	33.7	16.5	0.45	1.41	0.45	4.74	140	51	90	-	16.5	2.6	3.25		110	90	Diesel	
4	1	53.00	61.9		0.17	1.69	0.55	0.00	118	96	140	-	31.28	3	3.6			90	Diesel	
4	1	42.50				1.78	0.54		79	79		-	23.90	2.83	3.90	G1		100	Diesel	
2	1	42.00		14		1.68	0.49		174	86	88	-	25.00	2.90	4.10	G1		120	Diesel	
4	1	49.20				1.98	0.66		174	74	100	-	24.80	2.97	3.45	G1		120	Diesel	
2	1	23.00	32	16		1.39	0.38		60	60		-	16.54	2.93				100	Diesel	
4	1	41.00				1.50	0.59		140	70	70	-	27.26	2.75	4.34	G1		120	Diesel	
8	1	72.50	90	12,9		1.85	0.77		255	94	161	-	39.14	2.90				100	Catenary	
4	1	50.00				1.73	0.65		77	77			28.90	2.90	3.70			140	Diesel	1000
6	1	39.00	45	6.5		1.49	0.65		73	60	13		26.24	2.58	3.5	Metric		85	Diesel	300
2	1	20.00	31.6	16		1.43	0.36		95	55	40	-	13.97	3.003	3.5			80	Diesel	300
4	1	33.78				1.99	1.02		49	33	16	-	17.00	2,56	3,74			100	Diesel	
4	1	48.00				1.96	0.71		120	68	52		24.5					120	Diesel	
2	1	23.30		16		1.59	0.55		90	42	48		15	2,91	3,75		235	100	Diesel	380
4	1	58.00				2.12	4.83		15	12	3	-	27.35	3	4.222			160	Diesel	
4	1	50.00				1.83	0.55		171	91	80	-	27.35	3	4.435			120	Diesel	
2	1	28.00	34	17		1.58	0.74		90	38	52	-	17.7	2.9	3.8			120	Diesel	
8	1																			
4	1	45.00				1.84	0.63		72	72			24.4	2.88	3.7			130	Diesel	600
										62										
2	1	17		12.5		1.42			90	42	48	modul	12.00	3.00	3.35	G1		100	BAT	
4	1	11	16	4	0,45	1,00	0,55	15,91	70	20	50	-	11,00	2,65	3,17		175	65	BAT	
4	1	24,8	32,5	8,1	0,31	1,34	0,44		82	56	26	-	18,50	2,80	3,80			100	BAT or Diesel+Bat	
2	1		8						40	40			8	3				100	BAT	
2	1			10					80	30	50		13					100	BAT	
8	1								120	80	40		30					120	BAT /CAT	
4	1			18						70			27,4	2,82	4,275		600	120	BAT / H_2	80-11(
8	1			18						150			53,14	2,82	4,275		1200	120	BAT / H_2	90-180
	1																		CAT	
8	1	116							150	150			52.9	2.9	4.21			160	Diesel	1200
6	1		65							120			41.89	2.75				120	Diesel	
6	1		65							120			41.89	2.75				120	Diesel	
4	1								67	67			28,65	2,88	4,28			140	Diesel	
8	1								323			-	52,9	2,82	4,26		1360	160	BAT /CAT	-
6	1		66						214	104	110		39.9						Catenary	
2	1								95	55	40	-	13,97					80	Diesel	300 l
4	1	41.00				0.59			70	70			23,25					80	Diesel	

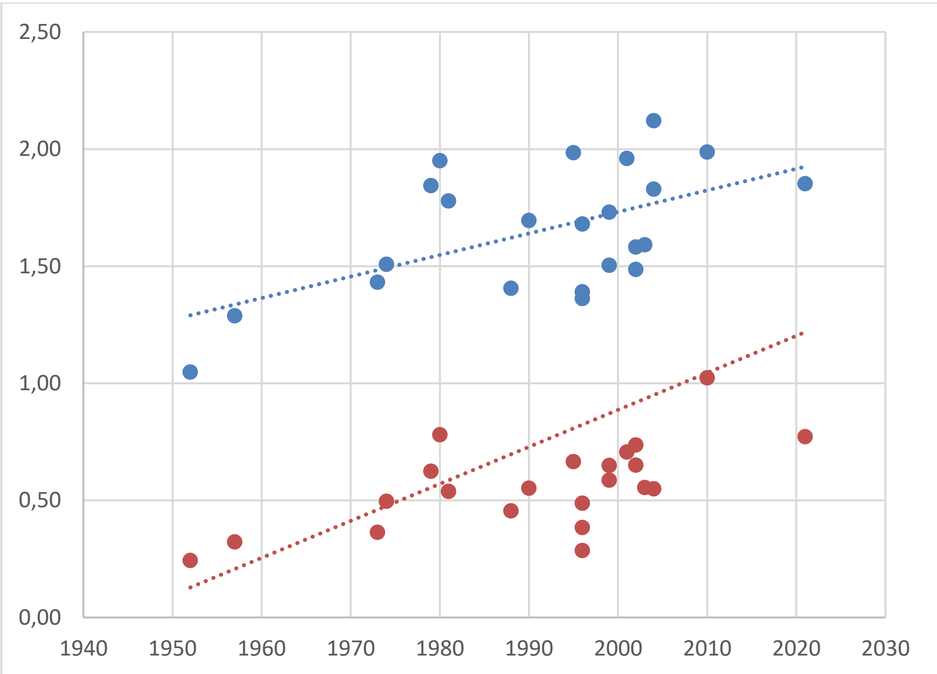
Range [km]	Automation level	Lines of service	Track gauge	Legal Framework	Important features	Floor level	Entrance Steps	Door width	End coupling	Longitudinal compression [kN]	Crash-worthiness	Other milage
	-	all	1435									
	-	all	1435				yes					
	-		1435									
	-	all	1435	EBO				1300				
	-	all	1435						UIC			
	-	all	1435						UIC/EN			
	-	all	1435						UIC/EN			
			1435									
	-	all	1435	EBO						1500		
	-		1435			530						
	-	all	1435									
	-	all	1435	EBO		580				1500		
	-		1435			760	0	1300	Scharfenberg			
	-		1435							1500		
	-		Metric									
	-	all	1435/1520			1100	3	2x 915	UIC/EN			
	-		Metric									
	-	all	1435						UIC/EN			
	-	all	1435			600			UIC/EN		P-3	ca. 200.000
	-		1520		For General Director of UA Railways, inspection vehicle				SA-3			
	-		1520					2x 1300	SA-3			
	-	all	1435						UIC/EN or Sch-rg			
	-											
	-		1435						UIC/EN			
	-											
100	full	All	1435		Modular concept for pax and freight					800	³3 - C3 / LNT	
20	full	Tram			Ultra light weight	Low	---	2x 900				
	---	All	1435		Very Light Rail	High	---	2x 855				
					Rail/Road							
			1435		Very Light Rail							
100			1435		Very Light Rail						P3 - C3	
			1435		Light Rail	Modular			Scharfenberg	1500	C1	
0 / BAT; 700 / H2			1435					1300	Scharfenberg			
/ BAT; 1000 / H2			1435					1300	Scharfenberg			
					Cog train / GOA4							
	-	all							Scharfenberg		C1	
	-	all										
	-	all										
	-	all	1435									
	-	all	1435									
	-	all	1435			600			Automatic		C1	
80	-	all	1435						Scharfenberg			
	-	all										
	-	all										
	-	all	1435									
	-											
	-	all	1435						UIC/EN			
			1435									



Operational Timeline of Light Railcars and Shuttles in Europe (1950–2040)



Seats per trains



Evolution of tons per seat (red) and per meter (blue)