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Disclaimer

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Executive Summary

The FP6 FutuRe project, funded by Europe's Rail Joint Undertaking, addresses the urgent need to modernize regional rail transportation and expand its operation into markets which would be marginally viable using conventional vehicles. With a focus on sustainability, efficiency, and inclusivity, the project aims to develop innovative rolling stock concepts that cater to the diverse needs of passengers, including those with reduced mobility. This deliverable, D10.1, outlines the preliminary rolling stock concept model, emphasizing mechanical design, crashworthiness, and accessibility features.

The development of the new vehicle concept began with a comprehensive analysis of existing technologies and market conditions and a derivation of the operational and functional requirements, ensuring compliance with relevant regulations and standards relevant vehicle requirements and specifications, as described in part in D5.1. Based on these results, the work described in this deliverable develops many of the mechanical, electrical and operational systems and technologies required for the vehicle.

The mechanical design development examines two possible structural design types applicable to the vehicle's body, a steel-differential design and a sandwich composite design. For the steel-differential design, topological optimization and automatic design derivation approaches were applied in the course of the design of a lightweight, cost-effective steel-differential design for the car body structure. This design focuses on optimizing force flow and minimizing weight while maintaining structural integrity.

For the sandwich composite design, the use of composite materials to further reduce weight and enhance durability is explored and an examination of the interdependencies of the various material candidates for the sandwich structures carried out. Finally, a possible vehicle structural design consisting of a hybridization of the above two designs is discussed, along with the possible joining technology appropriate for the different design types.

An innovative, lightweight regional rail vehicle places unique demands on its running gear, the development of which is described in the next section. As with the vehicle's structural design, numerous running gear concepts were evaluated and ultimately two variants selected for further development described below. The wheelset running gear is designed to be a simple, lightweight running gear with a conventional, fixed wheelset, single motor-gearbox traction system and two stage suspension. Active suspension systems, including vertical actuators and wheelset steering actuators, were integrated to improve ride comfort and curving performance.

The independently rotating wheel (IRW) running gear follows a more unconventional approach, with a running gear frame developed using topology optimization, resulting in a lightweight and robust design. The IRW concept enables the implementation of a mechatronic guidance and control system, which promises lower wear and noise emissions, especially on tracks with small-radius curves.

As an absolutely essential system in the design of the vehicle, the propulsion and energy architecture is examined and design aspects described in detail according to its different subsystems as well as the use cases and performance under given scenarios. Key results include the evaluation of battery-only and fuel cell hybrid powertrain configurations, with a diesel combustion powertrain for reference. Each configuration is assessed based on costs, emissions, and range relative to relevant tracks and conditions. The battery-only configuration uses either Lithium Iron Phosphate (LFP) or Lithium Titanate Oxide (LTO) chemistries, while the fuel cell hybrid uses an LTO battery to manage power balance. The study also examines hybrid battery

configurations, particularly those combining NMC/LTO or LFP/LTO chemistries, and finds that they offer enhanced cost-effectiveness and overall system lifetime. Additionally, the chapter highlights the importance of selecting the most suitable powertrain configuration to optimize performance while lowering costs. The economic model developed for this chapter provides a framework for sensitivity analyses, helping to determine the influence of different energy prices and discount rates on the overall results.

As the proposed vehicle is designed to work on Group 1 (G1) and Group 2 (G2) regional rail lines, as defined in the MAWP, the deliverable discusses the proposition that the current European regulatory framework (especially the Technical Specification for Interoperability (TSI LOC&PAS) and related standards such as EN 13749, EN 12663 and EN 15227) is overly complex and geared toward heavy main-line rolling stock, which makes the design, certification and cost of small, low-cost regional trains prohibitive. Simplified, Europe-wide guidelines for G1/G2 line vehicles, revisions to the EN 13749 annexes to accommodate IRW bogies, and a recalibration of the TSI's load-case, passive-safety and traction-performance requirements (e.g., lower coupler forces, explicit hybrid-vehicle categories and clearer power-loss limits) would allow the development and certification of lightweight, modular and digitally integrated regional vehicles, lower manufacturing costs, and seamless operation across borders, directly supporting the development of a new generation of light regional rail vehicles.

The FutuRe vehicle's braking system prioritizes weight reduction without compromising safety and performance. The text discusses the choice of compressed air brakes for the current vehicle concept, but also the potential for future airless technologies. The system comprises full TSI-compliant braking for G1 vehicles (main & branch lines) with an 830m stopping distance from 120km/h and gradient capability, along with BoStrab-standard deceleration for G2 vehicles (dedicated small lines). Both vehicle types utilize a blend of electrodynamic (ED), friction, and magnetic track brakes for emergency and service braking, with automated holding and parking brakes managed by a central control device. The bogie brake equipment features friction brakes (tread or disc) for adhesion-dependent braking and magnetic track brakes for independent braking.

In conclusion, the FP6 FutuRe project represents a significant leap forward in regional rail transportation, offering a sustainable, efficient, and inclusive solution for the future of mobility. By continuing to innovate and collaborate, the project aims to set new benchmarks in the industry, paving the way for a greener and more accessible railway network across Europe.

List of abbreviations, acronyms and definitions

Abbreviation / Acronym	Definition
ADM	Automatic Driving Module
APM	Automatic Processing Module
ATO	Automatic Train Operation
ATP	Automatic Train Protection
BEMU	Battery-Electric-Multiple-Unit
BoStrab	Verordnung über den Bau und Betrieb der Straßenbahnen (German, "Ordinance on the Construction and Operation of Street Railways" / light railway regulations)
CAD	Computer-Aided Design
CapEx	Capital Expenditure
CCS	Command, Control and Signalling
COP	Coefficient of Performance
COTS	Commercial Off-The-Shelf
CSM-RA	Common Safety Method for Risk Evaluation and Acceptance
DAC	Digital Automatic Coupler
DMI	Driver-Machine Interface
DMU	Diesel-Multiple-Unit
EA	Energy Absorption
ED	Electrodynamic
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
FCHPP	Fuel Cell Hybrid Power Pack
FFFIS	Functional and Physical Interface Specification
FRMCS	Future Railway Mobile Communication System
GHG	Greenhouse Gas
GoA	Grade of Automation
HEMU	Hydrogen-Electric-Multiple-Unit
HVAC	Heating, Ventilation and Air-Conditioning
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IM	Infrastructure Manager
IoT	Internet of Things
IRW	Independently Rotating Wheel
KPI	Key-Performance-Indicator
LCA	Life-Cycle Assessment
LFP	Lithium Iron Phosphate
LT PEM	Low-Temperature Proton-Exchange-Membrane
LTO	Lithium Titanate
MAWP	Multi-Annual Work Plan

MCG	Mobile Communication Gateway
NMC	Nickel Manganese Cobalt
OpEx	Operating Expenditure
PRM	Persons with Reduced Mobility
RBE	Rigid Body Elements
RME	Rapeseed Methyl Ester
RSM	RailSystemModel
RU	Railway Undertaking
SIL	Safety Integrity Level
SPC	Single Point Constraints
TCBM	Thermal Vehicle Body Model
TCMS	Train Control and Management System
TCN	Train Communication Network
TIMS	Train Integrity Monitoring Systems
TMS	Traffic Management System
TPT	Trajectory Planning Tool
TRL	Technology Readiness Level
TSI	Technical Specifications for Interoperability
UIC	Union Internationale des Chemins du Fer (French, International Union of Railways)
VTCS	Virtual Coupling Trainset
WSP	Wheel-Slide-Protection

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1. Introduction

Deliverable 10.1 builds on the work described in Deliverable 5.1 and describes in detail the work carried out toward the definition and analysis of the preliminary rolling stock concept of the FutuRe regional rail vehicle.

The work towards the development of the FutuRe vehicle is motivated by escalating environmental concerns and the imperative to decarbonize transportation. The FP6 FutuRe project was initiated as part of an endeavour aimed at modernizing regional rail transportation and expanding its reach into marginal markets. This undertaking seeks to address the urgent need for sustainable, efficient, and inclusive regional rail solutions that cater to diverse passenger needs, including those with reduced mobility. With a strong focus on sustainability, efficiency, and inclusivity, the project aims to revolutionize the regional rail landscape by introducing lightweight, modular, and digitally integrated vehicles that are not only greener but also more affordable and accessible.

This deliverable, D10.1, serves as a preliminary blueprint for the rolling stock concept model, laying the groundwork for the mechanical design (chapter 2), crashworthiness (section 2.1.8), and accessibility features (section 4.2) of the innovative regional rail vehicle. Drawing from a comprehensive analysis of existing technologies and market conditions, the project has derived operational and functional requirements that ensure compliance with relevant regulations and standards. Building upon these results, the work described in this deliverable explores and integrates many of the mechanical, electrical, and operational systems and technologies required for the vehicle's optimal performance.

The project introduces novel conceptual observations and important new ideas in several areas. One such area is the mechanical design, where two structural design types - steel-differential and sandwich composite - are examined, along with optimizations using advanced techniques such as topological optimization and automatic design derivation approaches (section 2.1). Furthermore, the deliverable explores the potential of hybridization in vehicle structural design and the appropriate joining technologies for different design types.

Another key aspect is the development of the vehicle's running gear (section 2.2), with evaluations of various concepts leading to the selection of two variants: the traditional wheelset running gear with integrated active suspension systems, and the more unconventional independently rotating wheel (IRW) running gear featuring a topology-optimized frame and a mechatronic guidance and control system.

Chapter 3 gives an overview discussion of the conceptual considerations relating to the propulsion and energy architecture, assessing battery-only, fuel cell hybrid, and diesel combustion powertrain configurations, along with hybrid battery configurations, to determine the most cost-effective and sustainable options. The economic model developed provides a framework for sensitivity analyses, enabling the assessment of different energy prices and discount rates on the overall results.

The deliverable also addresses the current European regulatory framework, proposing simplified guidelines for lightweight, modular regional vehicles to facilitate their design, certification, and operation across borders. Additionally, the deliverable explores braking technologies both on the basis of cost, technological maturity and market availability, but also discusses the potential of new technologies to further reduce vehicle weight and open new freedom in vehicle packaging.

In conclusion, the FP6 FutuRe project signifies a significant stride towards transforming regional rail transportation in Europe. By fostering innovation and collaboration, the project seeks to establish new benchmarks in the industry, paving the way for a greener, more accessible, and sustainable railway network that serves the diverse needs of passengers across the continent.

2. Development of vehicle concept

In WP5, the basic requirements and preliminary concept for a small, light, regional rail vehicle were derived, as described in D5.1. This included a preliminary assessment of the state-of-the-art, applicable regulations, and market conditions, with a specific focus on the unique requirements of regional railway lines concerning regulatory compliance and customer service.

The analysis of existing technologies and commercial outcomes from prior projects identified the technical and business factors that contributed to past successes and failures. This knowledge was incorporated into the current development effort.

Based on these findings, appropriate operational and functional requirements were defined, and established as a basis for the development of the detailed specifications of a regional rail vehicle.

As WP5 was divided into the tasks surveying the state of the art and the development of specifications for the vehicle's mechanical architecture, the propulsion and energy architecture and the other relevant systems, WP10 is divided into the following subtasks (targeting TRL3) [1]:

1. Subtask 10.1.1: Development of mechanical design of rolling stock concept
2. Subtask 10.1.2 Development of traction/propulsion and energy architecture of rolling stock
3. Subtask 10.1.3 Development of other concept relevant system elements
4. Subtask 10.1.4 Development of train control system architecture

In the following, the work and selected results of the listed tasks will be described.

2.1. Development of mechanical design of rolling stock concept

The mechanical design of the FutuRe regional rail vehicle's body was carried out according to requirements defined in D5.1 [2] and the standards deemed relevant given the design and use-case of the vehicle. The standards which have the greatest influence on the general design concept of the vehicle are those which define the greatest loads upon it. These are EN 12663 [3], which defines structural loads on the vehicle, and EN 15227 [4], which defines crash scenarios and required vehicle behaviour during a crash.

Crashworthiness considerations

EN 15227 defines the requirements for the crashworthiness of the vehicle based on certain categorizations. The crash scenarios are defined depending on the vehicle use case (e.g. border crossing trams-trains or light weight vehicle on capillary lines) and determine which crash load cases the vehicle must be designed for. Depending on the use-case of the vehicle in question, crash scenarios can exert highly differing loads; if the vehicle is designed more for use on national and international mainlines, higher collision energies must be managed than if the vehicle is restricted to regional and urban lines with lower speeds and lighter collision opponents.

Vehicle body strength considerations

EN 12663 defines the strength of the vehicle's body using static loads and accelerations. Different vehicle categories are considered in the standard. As in EN 15227, vehicle categories are defined but the categories are differently defined and grouped. Categories defined in the TSI must also be considered here. The categories and corresponding load cases are already in the standard, but in the TSI the category is explicitly defined as P-I or P-II which excludes the categories P-III and P-IV, which are necessary here. For this reason, it is necessary to apply the standard and the TSI to their intended effect, even if this extends beyond the scope defined in the TSI. In particular, the ability to consider other categories, partially defined in the standard under consideration of the vehicle use case (e.g. border crossing tram-trains or light weight vehicles on capillary lines, category P-III or parts of it) is necessary.

In the development of the vehicle's body structure, two types of structural design were considered, researched and compared. One design is based on a steel differential structure, with the main structure of the vehicle made up of welded steel sheets and profiles, while the other design is based on large-scale fibre-reinforced-plastic sandwich panels. Both are described in the following.

2.1.1. Conceptual mechanical steel-differential design of the vehicle body structure

The steel-differential design and the process followed to arrive at it are based on design optimization techniques developed and validated in simulation and in real world testing [5] [6]. The work builds on results from WP5, described in D5.1, and follows an established method examining the vehicle requirements, employing optimization tools like topology optimization to investigate various geometric variants, and deriving a concept design based the optimized structural results.

2.1.1.1. Vehicle body geometry analysis

In deliverable D5.1, topology optimizations were conducted to analyse the influence on the vehicle body structural weight of different longitudinal forces and placement of heavy equipment. The results show that the loads from the different categories tested (P-II, P-III and P-IV) do not have a significant influence on the structural mass of the vehicle body. The same is true for different locations of heavy equipment such as batteries on the train.

On this basis, further analyses were conducted to evaluate the influence on vehicle body weight of different geometric changes. The aim is to decrease structural mass of the vehicle body as much as possible. This could on one hand decrease track wear and energy consumption during operation. On the other hand, if the total vehicle weight is kept constant, the payload fraction increases, which enhances transport capacities and as a result economic efficiency.

2.1.1.2. Vehicle concept

The subject of this study is the bigger version of the vehicle body with a length of 16.5 m and a maximum weight of 32 t as this version will show the biggest changes in weight. Preliminary mass estimations calculated the payload capacity at 11 t, which would lead to a payload fraction of 34 %. The weight of the vehicle body structure is estimated at 4.2 t. The vehicle body of this vehicle consists of different modules as shown in Figure 1.

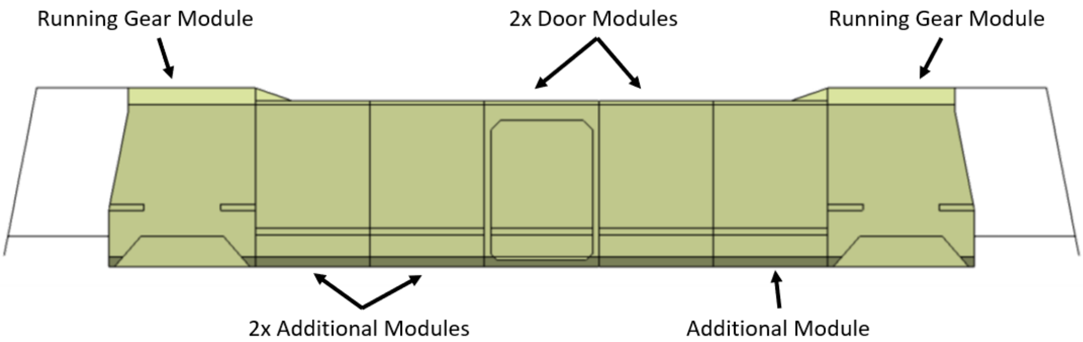


Figure 1: Optimization Model Modules

At each end, there is a running gear module with the vehicle heads attached. This module connects the running gear to the vehicle and houses the crash absorption systems. In the middle, the vehicle features two door modules. Each module has a door on one side. Two door modules put together but installed in opposite orientations creates an entry area with offset opposing doors. Up to three additional modules can be added to increase usable space and payload. This longer version has all three additional modules included.

2.1.1.3. Topology Optimization

The mass calculation methodology uses topology optimizations to estimate the minimal mass of a structure. For this, a purposely over dimensioned vehicle body model is used to represent the maximum possible design space. The optimization method uses a finite element method to carry out linear static simulations of that maximum design space model, which is loaded with its expected relevant maximum static forces and masses in various load cases. In regions where the material stress is low, the optimizer then lowers the density of the elements, whereas the density of elements in highly loaded areas is correspondingly increased. In an iterative process, this method is repeated until the optimizer cannot remove any more material without violation of previously defined boundary conditions. The result is a model of the vehicle body with an optimal material distribution perfectly tailored to its load cases. [7]

2.1.1.4. Model

The maximum design space model for the optimization is a simplified geometry of the vehicle body represented as a mesh of approximately 430 000 tria- and quad-elements shown in Figure 2. These elements are two-dimensional elements and have a virtual, parametric wall thickness that specifies their three-dimensional properties. The starting wall thickness is chosen to be very high, resulting in a very heavy and overdesigned model which the optimizer then thins out. The starting weight of this model using steel and aluminium as representative materials is in the hundreds of tonnes. Due to the use of linear crash absorber elements, the vehicle front itself is not included in the optimization. Its weight is loaded onto the anchor points of the four crash absorbers. Also, all normatively prescribed longitudinal compression forces are loaded onto these anchor points. The weights of the insulation and non-structural cladding elements are represented as a congruent layer of duplicate elements with very low stiffness and wall thickness and a respective density. Forces on the vehicle fronts are introduced using type three rigid body elements (RBE3), single point constraints (SPCs) are introduced with RBE2 elements and forces on surfaces are introduced element-wise.

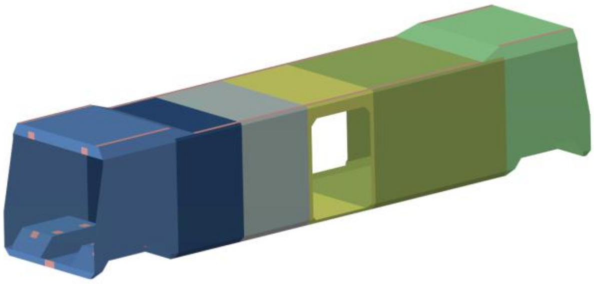


Figure 2: Optimization Model

2.1.1.5. Load Cases

The load cases are derived from the EN 12663 [3]. This norm defines the following load cases to be considered:

- Different longitudinal forces introduced into the buffers, couplings and crash relevant areas of the vehicle body front
- Lifting of the vehicle body in case of derailment or maintenance
- Acceleration forces on the running gear and other equipment, e.g. on the roof
- Maximum occupancy
- Blended load cases

The number and magnitude of forces depend on the specific type of vehicle. The norm specifies different categories of vehicles and scales the forces accordingly. This optimization uses the PII category for main-line multiple units.

2.1.1.6. Optimization Goals

A series of optimizations is carried out with the aim of determining the changes in mass for different vehicle body geometries. The vehicle body structure weights for the following geometry derivatives are analysed:

- Different starting wall thicknesses

- Different non-design setups
- Different abutting faces to the running gear module
- Different door placements
- Different roof setups
- Different wheel well designs

Within these comparisons, the parameters not being directly examined are held constant. Between the comparisons, the design with the least weight was used to continue with the next comparison.

2.1.1.7. Results

First, the starting wall thickness of the shell elements is varied. The results shown in Table 1 show that the estimated mass of the vehicle body increases with decreasing wall thickness. This is likely due to the thinner elements having less area moment of inertia. The optimization compensates this by adding more mass. To be able to compare these results to other optimizations done by DLR, a standard wall thickness of 100 mm for all following optimizations is chosen.

Table 1 Variation of the starting wall thickness

Material	SWT 50mm	STW 100mm	STW 150mm
Steel	6.44t	2.89t	1.94t
Aluminium	10.12t	2.52t	1.55t

As the shell elements have a parametric rather than a geometric wall thickness, the actual geometric area moment of inertia is zero. Therefore, the 2D sidewalls are not as stiff in case of cross loads as the 3D walls used in reality. As the roof of the vehicle body is loaded with cross loads coming from the lateral acceleration of the roof equipment, the walls see significant bending forces. This leads to high material densities in the walls. As the front walls or bulkheads of the vehicle body are parallel to the loads introduced by lateral accelerations, they are in a much better position to support these loads and can play an important role in the structure of the vehicle under those load cases. To examine this, the geometry of the front wall was varied across three alternatives shown in Figure 3:

- Completely open front wall (left)
- Front wall extending inward 500 mm (middle)
- Front wall completely closed (right)

As none of these front wall designs corresponds to an actual realistic design, this variation is aimed at understanding the behaviour of a tube-like shell meshed with 2D elements. The results shown in Table 2 confirm the suspicion that the front walls (or indeed any lateral bulkheads) can contribute significantly to the stiffness of the vehicle body cross section under shear forces. Indeed, in this analysis, the 500 mm partial front wall approximately halves the vehicle body weight. As the partial vehicle body fronts approximate a real vehicle body behaviour the closest, all following optimizations have these included.

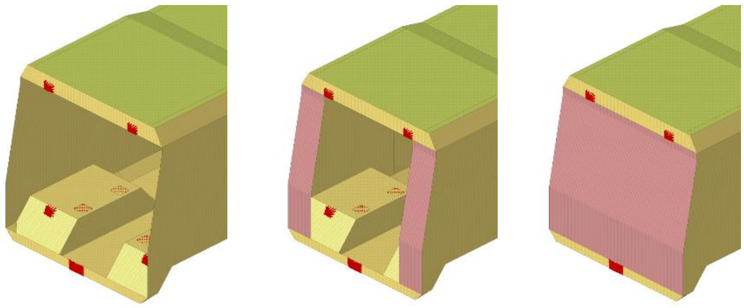


Figure 3: Vehicle body with open front, partial front and closed front (f.l.t.r.)

Table 2 Influence of front wall on vehicle body structural mass

Material	Open front wall	Partially closed front wall	Closed front wall
Steel	3.06t	1.51t	1.32t
Aluminium	2.36t	1.35t	1.04t

The next optimization looks at the influence of the door positions on the vehicle body weight. The current design includes two door modules, each with a door on one side. Both modules put together with their doors oriented in opposite directions add up to a combined door module with offset doors. As there are three additional add on modules, one of the doors is in the Y-Z-symmetry plane of the train, while the door on the opposite side of the train is shifted to the side. The door setup is shown in Figure 4. In comparison with a setup with both doors opposite to each other in the same module in the Y-Z-symmetry plane of the train, the opposite doors do not increase the weight much. The optimization shows a weight increase with opposite doors of 1.7% and 1.9% for steel and aluminium respectively.

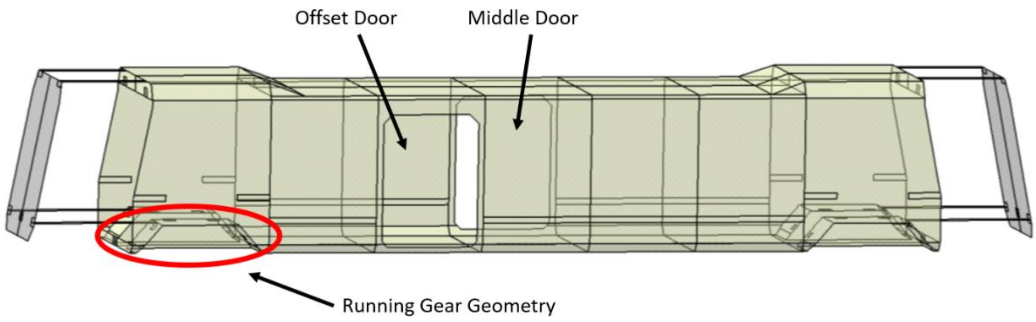


Figure 4: Optimization Model Offset Doors and Running Gear Geometry

The same holds true for the different roof setups. The current design incorporates a roof that is lowered between the running gear modules by 200 mm. A comparison with a total flat roof shows a weight increase of 1.8% and 0.9% with steel and aluminium respectively.

At last, different wheel well options are considered. The geometry changed is shown in Figure 4 circled in red. Depending on the running gear and traction system design, different wheel well options are possible as shown in Figure 5.

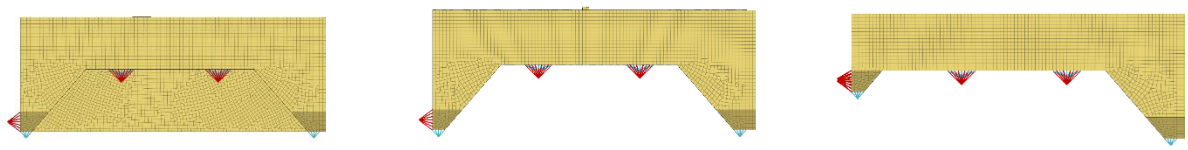


Figure 5: Wheel well options: low floor, high floor, platform (f.l.t.r)

The leftmost option is a design for a low floor running gear. The floor is lowered between the wheels to the main floor height in between the running gear modules. The middle option is a design for a wheelset running gear. The wheel well has the same height throughout the whole vehicle width. The right option is also tailored to a wheelset running gear, but the chin-like structure reaching down on the left of the wheel well is removed as it is not needed. The anchor points for the crash absorbers and the coupler are moved to the top just below the floor. The results for this comparison are shown in Table 3.

Table 3 Weight comparison of wheel well options for different materials

Material	Low floor	Wheelset	Platform
Steel	1.51t	1.37t	1.43t
Aluminium	1.35t	1.23t	1.52t

The optimization shows, that removing the low floor part in between the wheels does come with a weight reduction. The low floor portion has a complex geometry with a higher number of edges and therefore the load paths are less straight which increases weight. The weight reduction for the middle design is higher than for the platform design, approximately 10% vs 5% respectively.

2.1.1.8. Steel-differential design - conclusions

The optimizations show that changes to certain aspects of the vehicle body geometry can have a significant influence on the vehicle body weight. Different wheel-well geometries vary the vehicle body weight by up to 10%, different front walls cut the weight in half, and changing the starting wall thicknesses can decrease the weight of the vehicle body structure by a factor of 6. On the other hand, changes in roof geometry and door positions introduce variations of under 2%. As the results of the topology optimizations are derived from numerical simulations working with idealized structures, the quantitative masses might be not representative of real structure designs. Nevertheless, qualitative predictions are still possible. The implications of these mass variations are shown in Table 4.

Table 4 Influence of payload on predicted structural mass

	Structure mass [t]	Payload [t]	Payload fraction [%]
Preliminary payload	4.2	11	34
Minimum payload	1.23	14	44
Maximum payload	10.1	5.1	16

For the vehicle design this has several implications. First, the wall thickness especially of the side walls of the train have significant influence on the vehicle body weight. The more space we have for beams with larger cross sections, the better their bending rigidity will be, allowing lighter side wall construction with increasing wall thickness. However, to increase usable interior space, the walls should be as thin as possible as the outer vehicle surface is determined by the loading gauge. To solve this, a balance has to be found to find a compromise between a thin but still rigid and light weight wall design.

Furthermore, the design of the wheel wells influences the vehicle body weight. The low floor area between the wheels increases mass relative to a design with a continuous wheel well over the whole width of the train due to a higher geometric complexity and following this more complex load paths. The decision on the preferable running gear concept should therefore include their influence on the vehicle body mass.

2.1.2. Conceptual sandwich composite design of the vehicle body structure

A sandwich composite is a structural configuration consisting of two strong and stiff face sheets bonded to a lightweight, thick core. This arrangement allows the structure to carry bending and shear loads efficiently, with the face sheets primarily resisting in-plane forces and the core providing shear stiffness and stabilizing the faces. Due to their high stiffness and strength-to-weight ratios, sandwich composites are widely used in sectors where weight savings are critical.

In addition to their structural efficiency, sandwich composites offer the opportunity to integrate multiple functions into a single component. This multifunctionality may include mechanical strength and stiffness, fire safety, thermal insulation, acoustic damping, and can also be more lightweight, cost efficient and sustainable. By tailoring the face and core materials it is possible to engineer combinations that meet specific sets of functional requirements.

In the context of rail vehicles, these properties can reduce structural mass, lower energy consumption, and allow for part consolidation. The integration of several required functions into one material system can also simplify assembly and maintenance, making sandwich composites a promising solution for modern lightweight vehicle body design.

2.1.3. Material interdependencies

To support the multi-functional material selection process, a combination of material data tools and structured property dependency analysis was applied. Materials were evaluated based on a range of relevant properties for face-sheet and core applications, such as mechanical properties, thermal conductivity, and acoustic velocity.

A key output from this work is a heatmap visualization (Figure 6) which reveals the sensitivity of structural and functional material properties to imposed performance constraints. For example:

- Thermal conductivity was found to be the most influential constraint for core materials. When the allowed thermal conductivity range was narrowed (to improve insulation), the available materials dramatically reduced, particularly affecting mechanical characteristics such as shear modulus and compressive strength.
- Elastic modulus had the strongest influence on face-sheet materials. Stricter stiffness requirements eliminated lighter and cheaper metals like aluminium, leaving only high-strength steels and fibre-reinforced polymers as viable options.

These trends show that prioritizing one function can significantly narrow down the pool of usable materials and impact other properties indirectly.

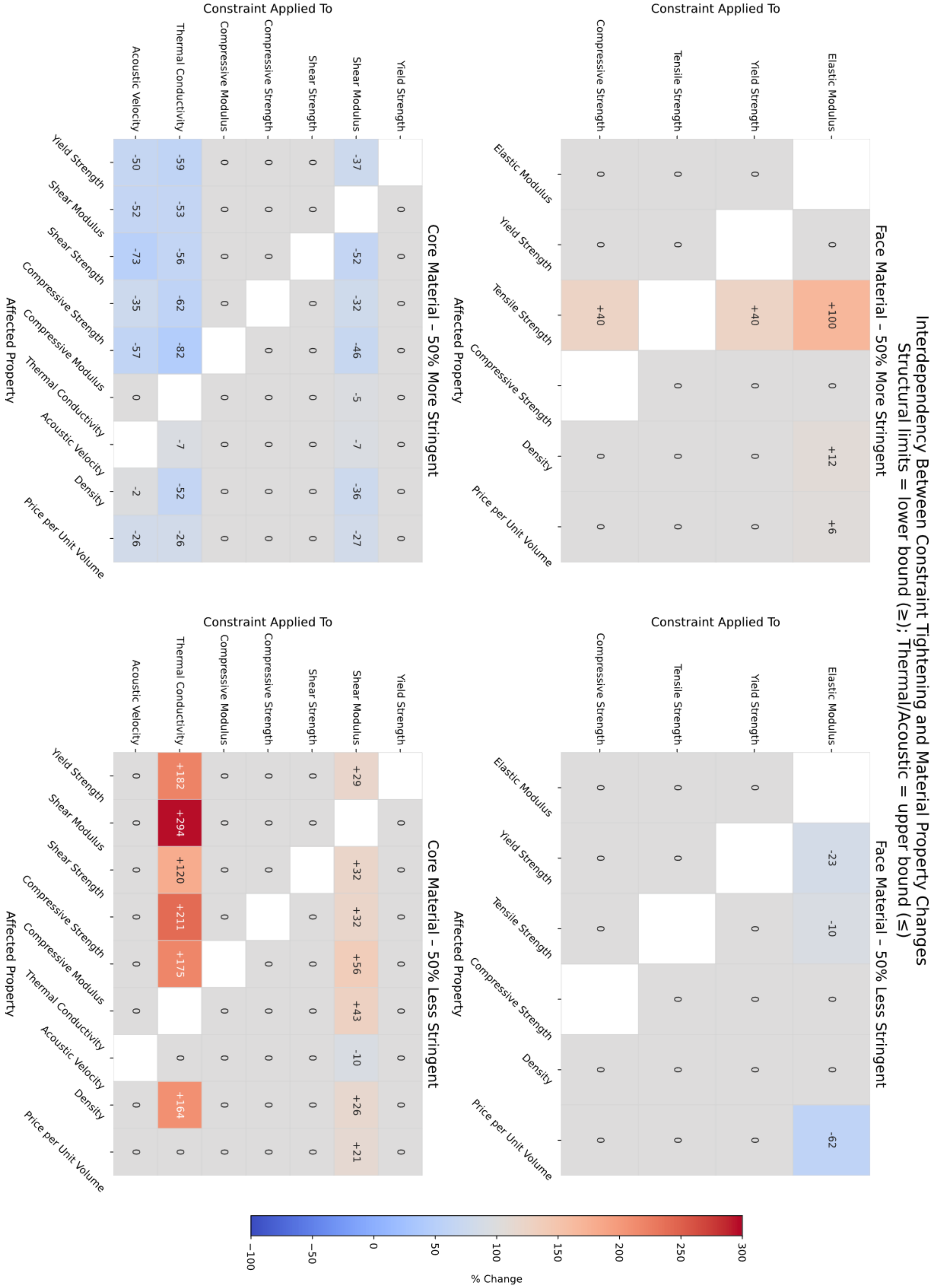


Figure 6: Heatmap visualization of interdependencies between property constraints and resulting material property changes

The results highlight the importance of critical evaluation of which functional targets are essential and where compromise may be acceptable. This work feeds into a broader strategy of constraint-driven screening and optimization, ultimately supporting more informed life cycle and cost modelling for the entire vehicle body.

An important goal of the ongoing research is to enable more informed decision-making through life-cycle assessment (LCA) and cost modelling. These assessments will cover both the sandwich material manufacturing processes and the complete vehicle body design. By quantifying environmental impact and production cost over the full lifecycle, from raw material extraction to end-of-life scenarios, the work aims to identify viable pathways for sustainable implementation of composite sandwich technologies in rail vehicles.

2.1.4. CAD model of the sandwich composite vehicle body

A preliminary CAD model of a rail vehicle body composed of sandwich composite panels has been developed. The design draws on topology optimization results from the project's earlier phase, where a steel reference model was optimized for weight reduction under EN 12663-1 structural load cases (Categories P-II to P-IV) [3].

Window geometries derived from the optimized steel structure, maintaining structural load paths. It is expected that the floor sandwich panels will be thicker due to the structural requirements. This might lead to separate manufacturing of floor, and side walls and roof, with joining the two at assembling phase.

The current CAD model does not yet include local reinforcements required for mounting bogies, couplers, or safety-critical systems. These reinforcements will be integrated following results from structural analysis. Below are sample renderings of the current vehicle body configuration:

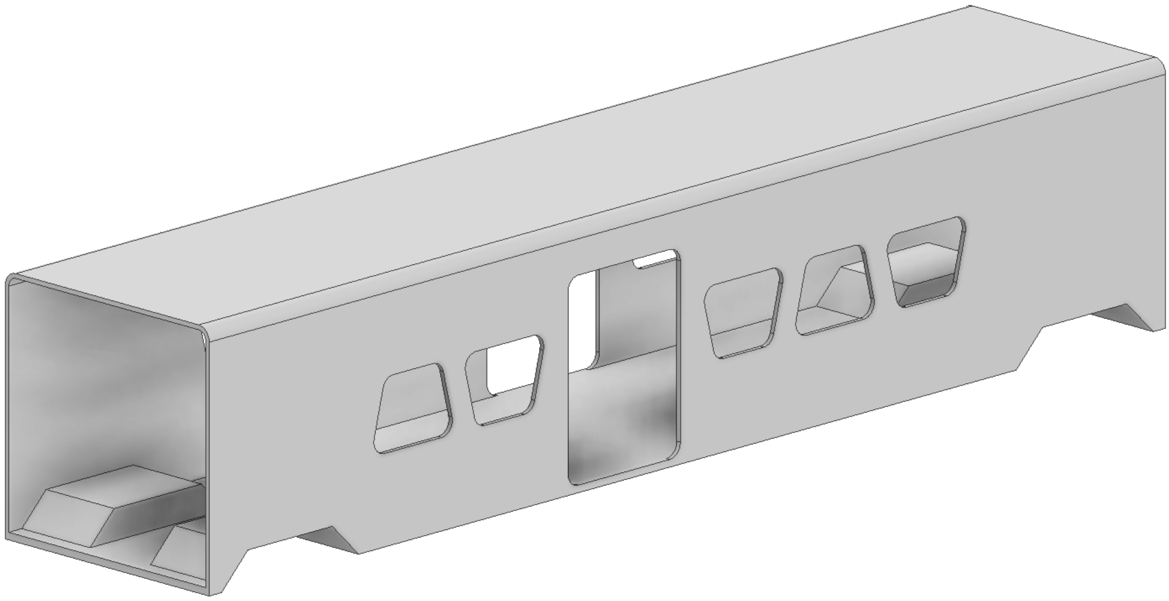


Figure 7: Sandwich composite vehicle body isometric view

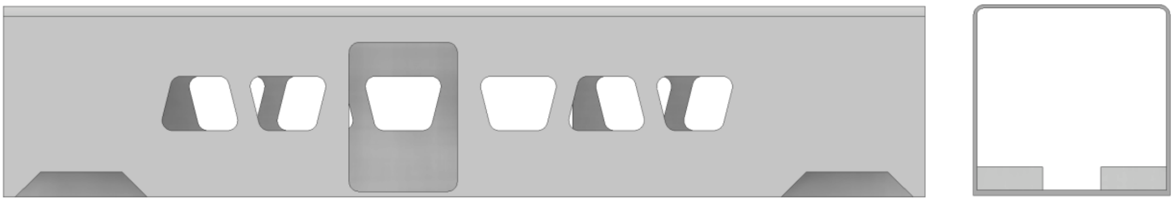


Figure 8: Sandwich composite vehicle body front and side view

2.1.5. Structural simulation

A simplified strength evaluation using finite element analysis is planned for the next stage of development. These simulations will focus on:

- Global and local deflection behaviour under standardized load cases
- Stress concentrations at panel joints and reinforcement interfaces
- Load paths to determine required stiffening elements.

The results will inform the next iteration of the vehicle body design, particularly with respect to the placement and design of local reinforcements, crash structures, and interfaces with mechanical components.

2.1.6. Possible combined building styles

Both structural design types described above have strengths and weaknesses which must be considered in the choice and design of a vehicle body structure. Considering that each design type offers benefits in certain applications and areas, one option would be to combine them in a manner which exploits those benefits while avoiding the potential drawbacks in other areas. For example, while a composite design excels at providing a lightweight structure capable of carrying high loads over large areas, local load introduction into composite structures remains a critical area and presents a challenge for the design of an optimized structure. A metallic structure, on the other hand, is very tolerant of highly localized loads, but can have a higher mass and lower stiffness over large areas. A hybrid design would combine the advantages of both design types, allowing a maximization of lightweight design, robustness and function. However, while such a design represents an optimum of the aforementioned properties, integrating multiple materials, manufacturing methods and design types in one vehicle does introduce additional complexity, meaning that maintaining cost goals could present an increased challenge.

2.1.7. Joining technology

The integration of sandwich composite panels with steel beam framework in the proposed hybrid vehicle body demonstrator requires careful consideration of joining technologies. The objective is to identify viable methods that enable reliable structural performance while supporting lightweight design, manufacturability, regulatory compliance, and long-term durability.

Table 5: Comparative characteristics of bonding methods

Joining method	Relative cost	Weight efficiency	Structural strength / efficiency	Disassembly & repair
Adhesive bonding	Low to moderate	High	High (if shear-dominant)	Low
Mechanical bonding	Moderate	Low–Moderate	Moderate (local stress risk)	High
Hybrid bonding	Moderate to high	Moderate	High (fail-safe)	Moderate
Co-curing / co-bonding	Moderate	High	High	Low
Structured metal interfaces	High	Moderate	High (excellent peel resistance)	Low

2.1.7.1. Mechanical fastening

Mechanical fastening is commonly applied in areas requiring disassembly or point load introduction. However, direct fastening into sandwich panels is unsuitable due to the low out-of-plane strength of the core. To overcome this, various types of inserts are used, including metal sleeves and potted core regions, which redirect loads into the face sheets. This method is widely applied in wind energy, where composite turbine blades are bolted to steel hubs using metallic inserts. In aerospace, it is used for mounting interior panels and equipment, with potted inserts designed to avoid core crushing and delamination. The main limitations of mechanical fastening include the added local weight and stress concentrations near the inserts, which must be accounted for in design.

2.1.7.2. Adhesive bonding

Adhesive bonding is a well-established method for joining sandwich composites to metallic structures, particularly where large surface areas are available. It allows load transfer through in-plane shear over broad areas, thereby minimizing stress concentrations and preserving the integrity of the composite face sheets. Adhesive bonding is also highly weight-efficient, typically adding less than 1 kg/m² to the structure. The performance of an adhesive joint depends on several factors, including the selection of adhesive type (e.g., toughened epoxy), the surface preparation of both adherends, and the design of the joint to avoid peel or cleavage stresses. Sandwich-to-metal adhesive joints are most effective when designed to carry shear loads. For foam or honeycomb sandwich panels, peel stresses must be minimized by joint geometry and by using thickened or filleted bond lines to soften stress concentrations. In aerospace, adhesively bonded honeycomb sandwich panels are common in aircraft floor and wall systems, where lightweight and fatigue resistance are critical.

2.1.7.3. Hybrid bonding (adhesive and mechanical bonding)

Hybrid joints combine the benefits of adhesive bonding with the mechanical redundancy and inspect-ability of fasteners. In this configuration, the adhesive provides continuous load transfer and damping, while mechanical fasteners serve both as reinforcement against peel and as a safety mechanism in the event of adhesive degradation. This approach is particularly suitable for safety-critical applications or when structural disassembly may be required during maintenance. The key to hybrid joint effectiveness lies in balancing the stiffness and load-sharing characteristics of the bonded and mechanical components. Fasteners must be designed to engage only after partial adhesive failure, thereby preventing excessive load concentrations or premature joint degradation. Applications of hybrid joints are common in automotive lightweight body structures, and in naval composite superstructure attachments.

2.1.7.4. Co-curing or co-bonding

A more integrated joining strategy involves the co-curing or co-bonding of steel components directly into the sandwich structure during manufacturing. In this process, steel brackets, inserts, or rails are placed within the layup of the sandwich panel prior to curing. During the consolidation of the composite laminate, the steel component becomes fully embedded and structurally bonded. This technique eliminates the need for secondary bonding or drilling and provides excellent structural continuity at the interface. It also enhances sealing and corrosion resistance, as there is no exposed interface between materials. Co-cured interfaces are commonly used in aerospace, such as in helicopter rotor blades with titanium root fittings, and have been demonstrated in naval composite-to-steel interfaces for hull integration. The primary limitation of co-curing is the requirement for early integration in the design and manufacturing stages, as retrofitting or modifying such joints is difficult. It also demands compatibility of thermal expansion and cure cycles between steel and composite materials.

2.1.7.5. Structured metal interfaces (mechanical interlocks)

Structured metal interface technologies rely on mechanical interlocking features such as etched grooves, protrusions, or undercuts on the steel surface. When the composite resin is cured, it forms a physical bond with the structured surface. This eliminates dependence on chemical adhesion and provides improved resistance to peel and impact.

2.1.8. Crash system dimensioning

The EN 15227 states, that spaces continuously occupied by passengers is not allowed to deform more than 50 mm for every 5 m of length which equals to a deformation of 1 % [4]. Temporarily occupied areas such as door or standing areas without seats are allowed to deform by 30% in longitudinal direction if they are wider than 250 mm. The current vehicle design can therefore be segmented into 3 different zones. A middle zone including all seats and their survivability space which is not allowed to deform more than 1%. Two sections framing the middle section people are allowed to temporarily occupy. These are the aisles people use to reach the seats at the vehicle ends. This area is allowed to be deformed by 30%. As this area is rather short, not much energy can be absorbed here. Outside of these sections, additional energy absorption space is needed to dissipate the energy generated by a crash. This area has to be blocked of for the passengers.

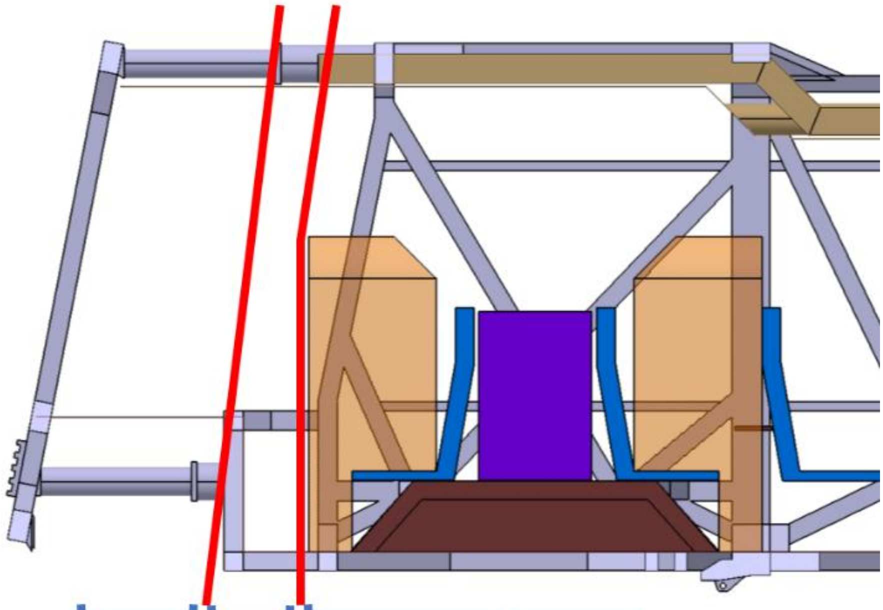


Figure 9: Crash safety zones

The crash absorption zone needs to provide the majority of the deformation space to dissipate the kinetic energy of the crash, as the other zones are not allowed to deform much. To estimate the deformation space required by the FutuRe vehicle to comply with the crashworthiness standards in EN15227 [1], the equations of conservation of momentum (Eq. [1]) and conservation of energy (Eq. [2]) were used to derive the energy absorption (EA) and the corresponding deformation requirements.

$$\sum m_i v_i = \sum m_i v_f \qquad [1]$$

$$\frac{1}{2}m_1 v_1^2 + \frac{1}{2}m_2 v_2^2 = \frac{1}{2}m_1 v_{1f}^2 + \frac{1}{2}m_2 v_{2f}^2 + E_{lost} \qquad [2]$$

In an inelastic collision where the vehicle and obstacle remain coupled after impact, the lost energy can be calculated using Eq. [3.

$$E_{lost} = \frac{m_1 m_2}{m_1 + m_2}\frac{(v_1 - v_2)^2}{2} \qquad [3]$$

EN15227 defines the design collision scenarios (DCS) for four vehicle assessment categories, as shown in Figure 10. The prescribed collision speeds are based on historical accident data and risk analyses. EN15227 also specifies the obstacle geometry and force-deformation characteristics for each scenario.

Crashworthiness design categories (see 5.1)		Design collision scenario (see 5.3) and collision speeds v_C						
		1	2		3			4
		leading end impact between two identical trains	leading end impact with a different type of railway vehicle		leading end impact with a large road vehicle			leading end impact with a low obstacle
Crashworthiness design category (see Table 1)	Detailed requirements	Identical train	80 t freight wagon (see C.1 and C.2)	129 t regional train (see C.3)	15 t deformable obstacle (see C.4)	7,5 t obstacle (see C.6)	3 t rigid obstacle (see C.5)	Obstacle deflectors and lifeguards
C-I	5.4.2	36 km/h [a]	36 km/h [a]	n/a	$= (v_{LC}$ - 50 km/h) ≤ 110 km/h	n/a	n/a	See 6.5 and 6.6 for requirements
C-II	5.4.3	25 km/h	n/a	n/a	n/a	n/a	n/a	n/a
C-III	5.4.4	25 km/h	25 km/h	10 km/h	25 km/h	n/a	n/a	See 6.5 and 6.6 for requirements
C-IV	5.4.5	15 km/h	n/a	n/a	n/a	15 km/h	25 km/h	n/a
NOTE: n/a = not applicable								
[a] for C-I locomotives fitted with heavy duty couplers the collision speed for design collision scenarios 1 and 2 is 20 km/h								

Figure 10: Design collision scenarios for passenger rail vehicles, EN15227 Table 3 [4]

The total energy absorption by the vehicle and the obstacle is given by Eq. [4, where x_{FTR} denotes the deformation of the FutuRe vehicle and $F_{FTR}(x_{FTR})$ is the force-displacement characteristic, while x_{obs} and $F_{obs}(x_{obs})$ describe the obstacle.

$$EA = \int F_{FTR}(x_{FTR})dx_{FTR} + \int F_{obs}(x_{obs})dx_{obs} \qquad [4]$$

For a simplified estimation, the FutuRe vehicle was assumed to have a constant crush force equal to the bumper-level longitudinal compressive resistance specified in EN12663, Section 6.2 [3]. Combining Eq. [3 and Eq. [4 yields Eq. [5, which was evaluated numerically.

$$x_{FTR} = \frac{\frac{m_1 m_2}{m_1 + m_2} \frac{(v_1^2 - v_2^2)^2}{2} - \int F_{obs}(x_{obs})dx_{obs}}{F_{FTR}} \qquad [5]$$

Table 6 summarizes the deformation space required for both the large and small version of the FutuRe vehicle variants, considering collision assessment categories C-I (international, national, regional track use) and C-III (urban, regional track use), and vehicle design categories P-II (passenger coaches and multiple units) and P-III (light railcars, suburban, underground). The highest deformation in each design category is highlighted in red.

Table 6: Required deformation space and energy absorption

Vehicle type	Load category	Crash category	Deformation space required (mm) 1	2a	2b	3	4
Long	P-II	C-I	267	721	715	0	707
	P-II	C-III	129	326	320	0	48
	P-III	C-I	500	1393	1397	0	1482
	P-III	C-III	241	653	658	108	246
Short	P-II	C-I	167	492	486	0	575
	P-II	C-III	80	216	210	0	21
	P-III	C-I	313	964	969	0	1234

P-III	C-III	151	447	451	68	196

(1) 1 = Identical train; 2a = 80t freight side buffers; 2b = 80t freight central coupler; 3 = 129t regional train; 4 = 15t deformable object

Depending on the assessment scenario, the required deformation space ranges from 451 mm to 1482 mm. The largest deformation occurs in collisions with the 15 t deformable obstacle at level crossings, primarily due to the collision speed (56 km/h) and the absence of dedicated energy-absorbing structures.

To comply with C-I collision requirements, the vehicle will require at least 1234–1482 mm of deformation space, with additional allowance necessary due to non-ideal force-deformation behaviour. For C-III scenarios, a minimum of 451-721 mm is required, subject to similar consideration.

These initial results establish a basis for the FutuRe vehicle crash structure design. The preliminary deformation and energy absorption estimates can guide the specification and development of structures to be validated through detailed testing and subsequent design iterations.

2.1.8.1. Implications for the vehicle body

The vehicle body design of the vehicle is directly influenced by the two norms EN 12663 and EN 15227. With increasing crash requirements, the necessary vehicle body strength and also the necessary deformation space in front of the vehicle increases, which potentially increases vehicle length and weight. On the other hand, lower crash requirements could make the vehicle lighter and therefore more efficient but also potentially more unsafe. So, a balance has to be found between lightweight design and acceptable safety risk. As this type of vehicle differs greatly from existing vehicle architectures, the categories in the norms do not reflect the current vehicle very well. So, an adaptation of the norms is necessary.

For the current development state, a low-risk approach is chosen. Although the norms do not reflect the FutuRe vehicle adequately, the TSI states that they are mandatory for certification. So the best suited categories are chosen knowing that they do not comply very well.

The bigger vehicle running on G1 lines conforms to the vehicle body strength category PII, which is used for multiple units and passenger cars. The crash category is CI tailored to vehicles operating on international mainlines. This combines a higher energy in case of a crash with a higher vehicle body strength, decreasing the necessary deformation space at the front. The topology optimizations conducted in D5.1 show that the weight increase of the vehicle body due to the higher longitudinal forces is nominal. So, the decrease in vehicle length is preferable.

The smaller version for the G2 lines will be designed according to PIII, which describes light rail vehicles like trams and commuter trains. Its crash category will be CIII without the crash scenarios with different trains, as the small version is not allowed to operate on lines with different vehicle types. This combination could possibly lead to a lighter less demanding crash system decreasing weight and cost for the small vehicle.

2.1.8.2. Preliminary steel-differential building style

To include the crash considerations into the steel vehicle body design, the vehicle body front is adapted. To build a border between the deformable crash front and the less deformable passenger spaces, a balcony was added to the front of the vehicle (Figure 11). The forces from the buffers and couplings and also the crash absorbers are loaded to the front face of this balcony. The balcony is built in a way, that it leads incoming forces away from the passengers into the vehicle body walls and floor without deforming itself more than 1%.

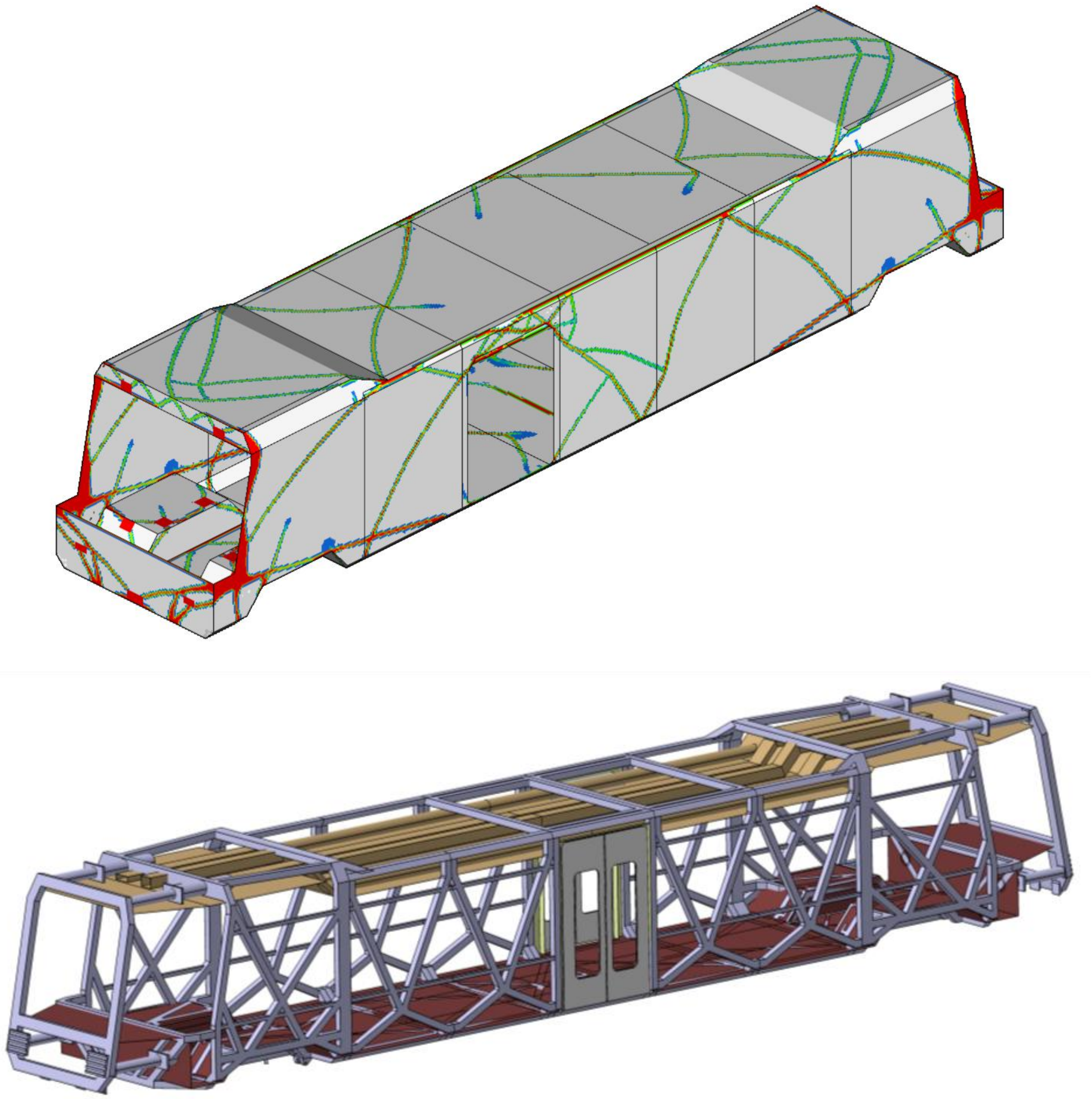


Figure 11: Topology optimization result (top) and preliminary steel differential design (bottom) for vehicle body

2.2. Conceptual mechanical design of the running gear

Development of the conceptual mechanical design as well as the pre-dimensioning of the mechanical part of the running gear based on the work of D4; and in order to meet the requirements of the FutuRe regional rail vehicle.

In order to find an optimal solution, two different designs of running gear were developed. One type is based on a conventional wheelset with a single-stage suspension and active steering, while the other follows a low-floor layout with a portal-axle, direct drive motors and independently rotating wheels (IRW).

2.2.1. Wheelset running gear

The first running gear concept features a conventional solid wheelset. The principle of this running gear concept is to have a very simple, lightweight running gear while maintaining a safety and comfort level similar to current generation rail vehicles. With regard to FP6 FutuRe's interest in a two-axle vehicle, the design consideration is extended to also achieve good stability, curving performance, and wear characteristics, which have historically been a drawback for two-axle rail vehicles.

The starting point of this running gear design is to include only the essential components, selecting the simplest possible versions of each. This yields a setup which consists of a solid wheelset, a single motor-gearbox traction system, a tread brake system and suspension elements for a single-step longitudinal and vertical suspension system, as shown in Figure 12.

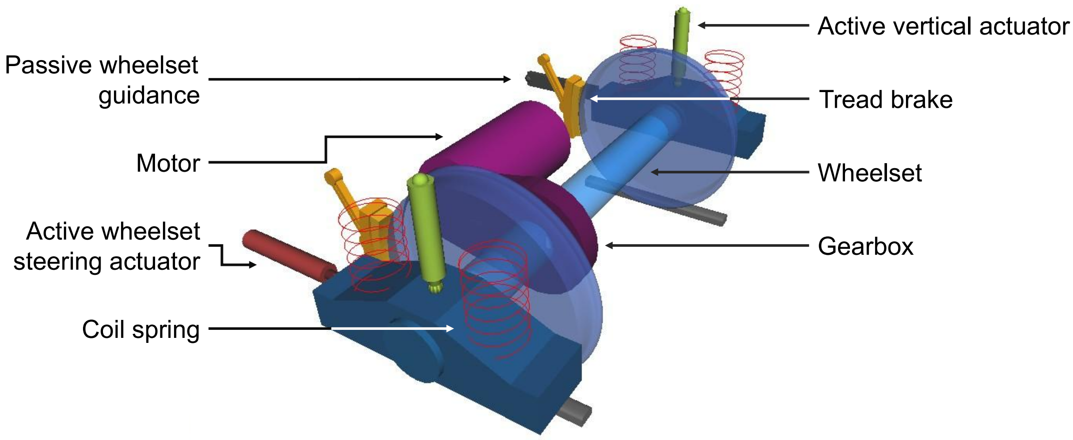
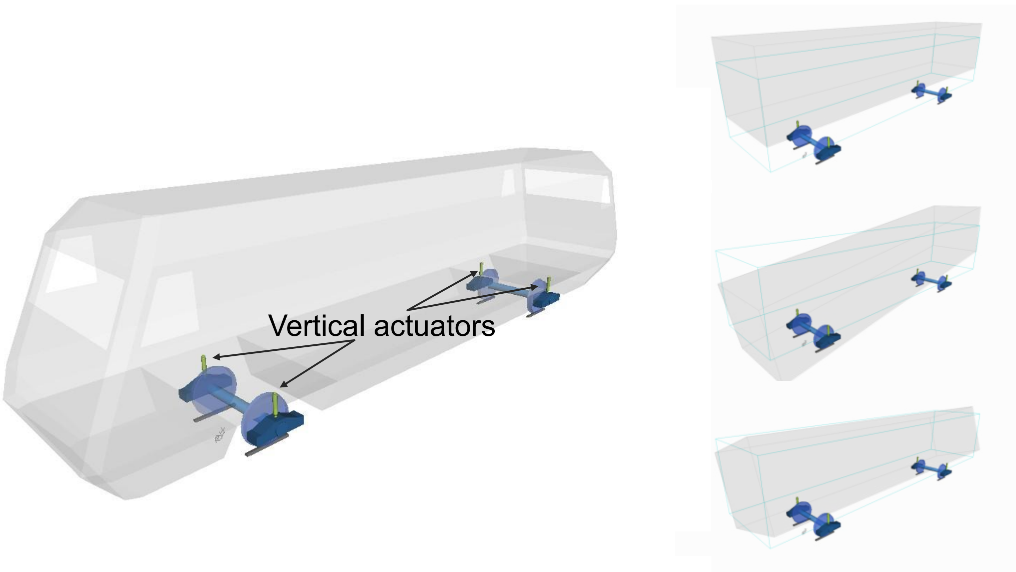


Figure 12 Wheelset running gear concept

The main component of the suspension system is chosen to be a set of coil springs, to adhere to FP4 Rail4Earth's objective of a compressed-air-free vehicle design. The coil spring should have a fairly high spring rate to limit displacements due to load and vehicle dynamics. The suspension will be soft enough to ensure safe running but, without countermeasures, this would lead to deficiencies when it comes to ride comfort and curving performance.

To achieve satisfactory ride comfort and curving performance, a set of active suspension elements will be used. The active suspension elements include active vertical actuators and wheelset steering actuators. This setup shares some similarities with the running gear concept studied and reported in D6.2 of the project PIVOT2 for a two-axle metro vehicle concept [8]. However, the configuration has been further simplified by omitting the running gear frame and active lateral suspension found in the previous concept. This modification brings an advantage of further weight saving on top of the already significant weight saving of around 5.8 tonnes achieved in the previous project by moving from a four-axle vehicle to two-axle vehicle configuration. Reduced weight will lead to a lower energy consumption of the vehicle [9]. Alternatively, the weight saving could be used to increase passenger capacity for the same axle load.

An active vertical suspension system is included in the running gear concept to improve the ride comfort of the two-axle vehicle. It comprises four electrodynamic actuators, one at each axlebox. The actuators will be controlled using a centralized control system, also called modal control. Instead of local control action at each axlebox, a modal control scheme considers the entire vehicle body as the controlled system. This provides a better opportunity to target specific vibration modes of the vehicle body, namely the bounce, pitch, and roll motion, see Figure 13. This is especially important considering the proposed running gear concept lacks anti-roll bars, whose functionality was previously covered by the running gear frame. The relatively stiff coil spring compensates for the absence of an anti-roll bar by controlling body roll, while the active suspension offsets the stiffness of the vertical suspension to maintain ride comfort. Detailed explanation on the active vertical suspension is available in D14.2 of the FP4 Rail4Earth project [10].

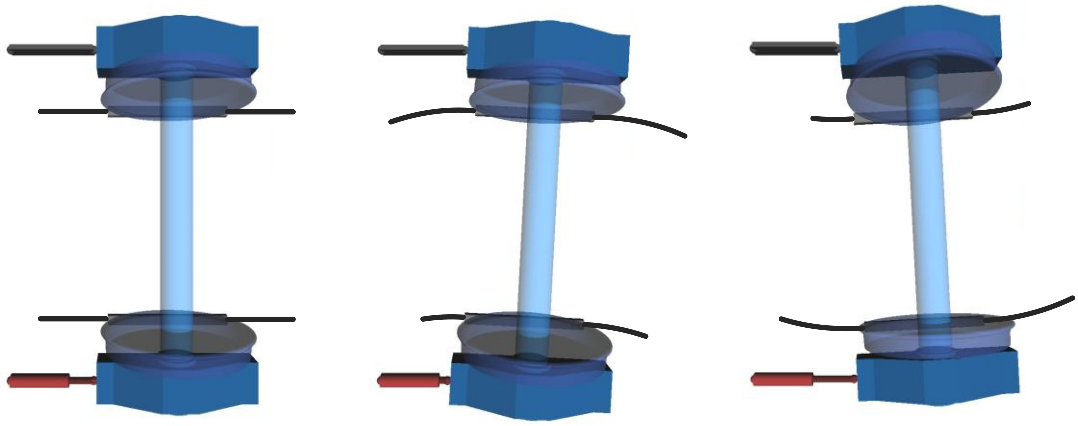


(a) (b)

Figure 13 Active vertical suspension, (a) actuator setup, (b) controllable vibration mode

The other active suspension system is the active wheelset steering, designed to achieve proper curving performance for the two-axle vehicle. Contrary to usual practice, the proposition in this project is to use only one actuator is for each wheelset. The actuator is set up in series with the bushings on one side of the wheelset, while the other side retains the full passive longitudinal guidance. The serial configuration of the actuator makes it safety critical for the vehicle, but will also bring a benefit of lowered force requirements for the actuator compared to a parallel configuration. Therefore, an electrodynamic actuator is a suitable choice here. Electrodynamic actuators have the advantage of having a lower force-to-space ratio than hydraulic actuators while also having the capability to work at higher frequencies. This adds the possibility of using the wheelset steering actuator also for high frequency dynamic control.

The active wheelset steering system works by using the actuator to compensate the passive longitudinal suspension force acting on the wheelset. This results in a principally free wheelset. In practice, freeing the wheelset involves adjusting the actuator length which in turn moves the wheelset towards a near-radial position, as shown in Figure 14. From there, the curving action will be taken care of by the wheelset's self-steering capability. Preliminary results showed a reduction of more than 90% in terms of wear number compared to the passive vehicle, as reported in D17.1 of FP4 Rail4Earth project [11].



(a) (b) (c)

Figure 14 Active wheelset steering, (a) Straight track, (b) Right hand curve, (c) Left hand curve

In its entirety, the proposed running gear concept presents a possibility of significant weight saving and energy efficiency compared to current generation bogie vehicles, while maintaining good safety and ride comfort and introducing a large improvement in wear characteristics. A multibody model of a vehicle with this running gear setup has been created and is being used for the work in this project. The work covers two aspects: Optimization of the passive vehicle suspension and design and implementation of the active suspension systems. The work concerning passive suspension will show the highest possible gain potential with only lightweighting and simplification of the running gear configuration without any active elements. Meanwhile, the work concerning active suspension will show maximised improvements possible with the use of active suspension elements.

2.2.2. Independently rotating wheel running gear

2.2.2.1. Running gear frame

For the IRW running gear concept, a running gear bogy frame was designed. First, a topology optimization was conducted using the EN 13749 as baseline for loads and load cases [12]. The resulting frame is shown in Figure 15 and has a weight of 150kg.

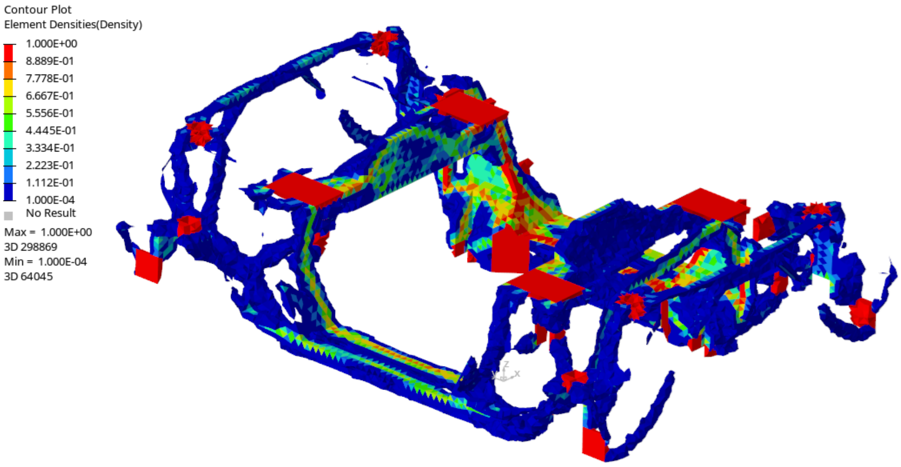


Figure 15: Topology optimization result for running gear frame

As the topology optimization generates organic and intricate structures, manufacturing the result directly is complex and expensive. Therefore, the model has to be redesigned with manufacturing efficiency in mind utilizing an easy to realize building style. The topology optimization results can be used as guidelines to find optimal load paths, whereas the detailed shaping follows the implications of material, pre-product and joining technologies. To aid this transition process, a semi-automatic engineering and design tool based that described in [13] is used to skeletonize and simplify the topology optimization results. It generates a wire frame model that can be used to simplify the load paths and inform design decisions for a well-adapted and lightweight concept design. A wire frame generated by this tool is shown in Figure 16.

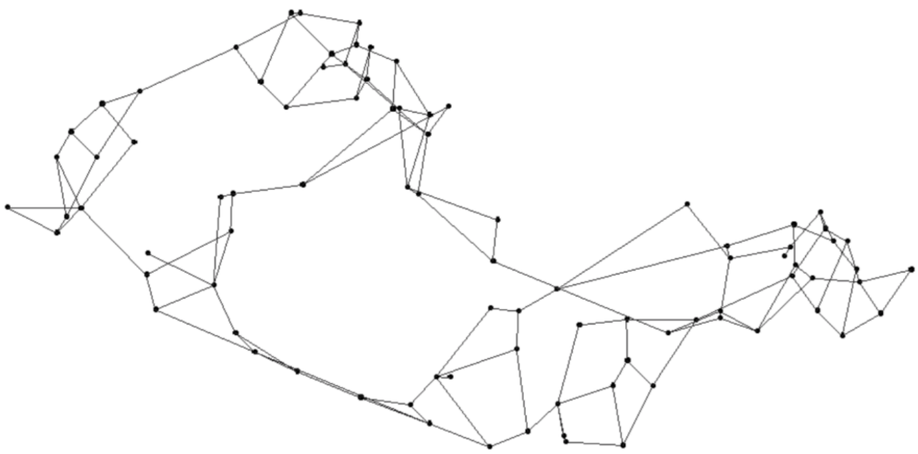


Figure 16 Wireframe of the topology-optimized running gear structure

A concept design consisting of 2d-surfaces and derived from the design tool is shown in Figure 17. This model is composed of 2-dimensional surfaces as centre planes for metal sheets, whose wall thickness is yet to be determined. To do this, a wall thickness optimization is planned.

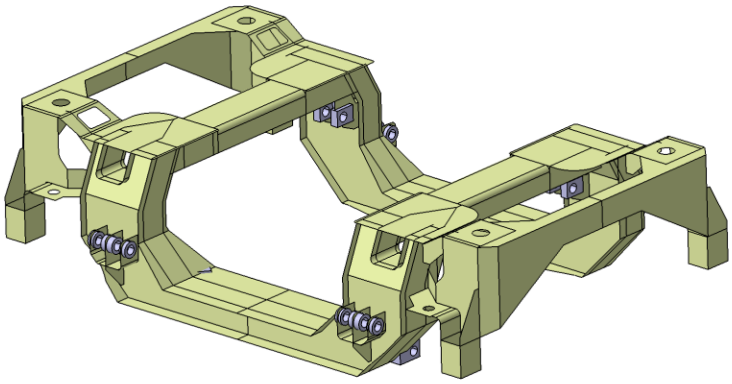


Figure 17 Preliminary design for running gear based on topology optimizations

2.2.2.2. Direct drive axle

Additionally, a new direct drive axle is in development. Previously, the motors were suspended in the running gear frame partially suspending the motors with the primary suspension. The motors were connected to the wheels using a continuous-velocity shaft to compensating relative movement between the motors and the wheels over the primary suspension and the steering angle. However, due to the necessary spaces needed for this relative movement, building space for the motors themselves was limited and therefore the provided motor torque and power was insufficient.

To solve this issue and increase traction power, a new axle design was developed using motors directly connected to the wheel hub. The outrunner rotor of the motor is directly connected to the wheel, while the stator is mounted to the non-rotating axle reaching through the wheel hub. This allows an increase in length of the motor of approximately 38 % with respect to the previous design, which leads to an equal power increase. As the motor is now directly mounted to the wheel, it is no longer suspended by the primary suspension. As a consequence, the high accelerations occurring in the wheel-to-rail contact are able to reach the motor. To still have some cushioning, resilient wheels are used, meaning the wheels are rubber-sprung to have some dampening effect on high shock loads. Also, the primary suspension was changed to Chevron-springs, which have better performance than the previous springs originally design for the lower axle loads of trams. The new axle including the motor and braking units, primary suspension and necessary levers is shown in Figure 18.

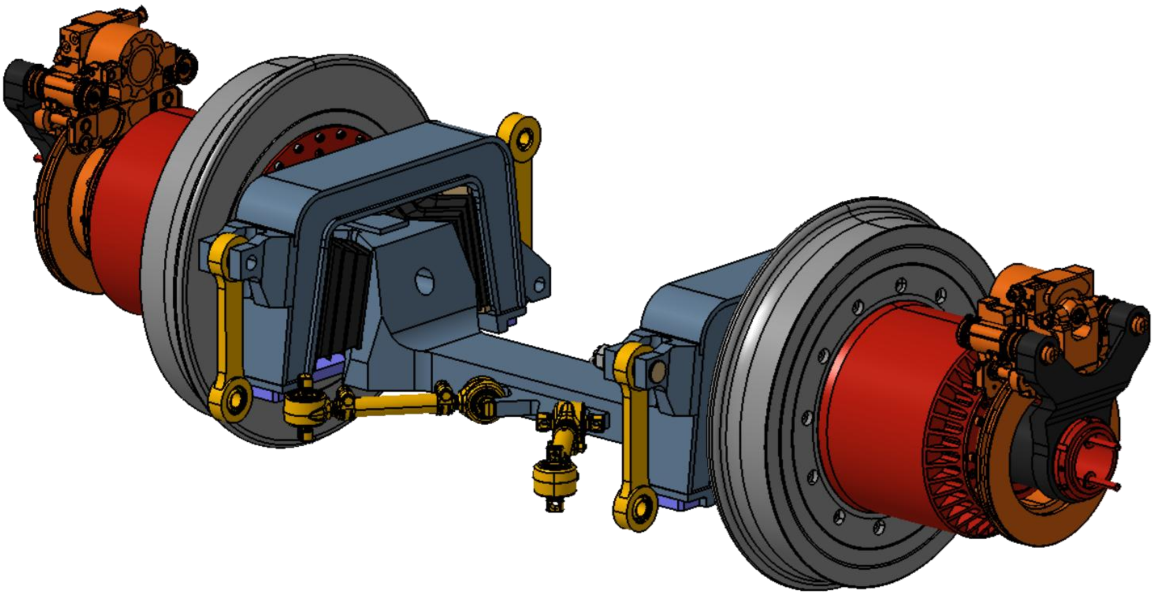


Figure 18: integrated running gear concept

Taken all together, the improved running gear design is equipped with more powerful motors and springs, improving performance especially for the bigger version of the vehicle on demanding tracks with higher gradients. The new integrated running gear concept is shown in Figure 19.

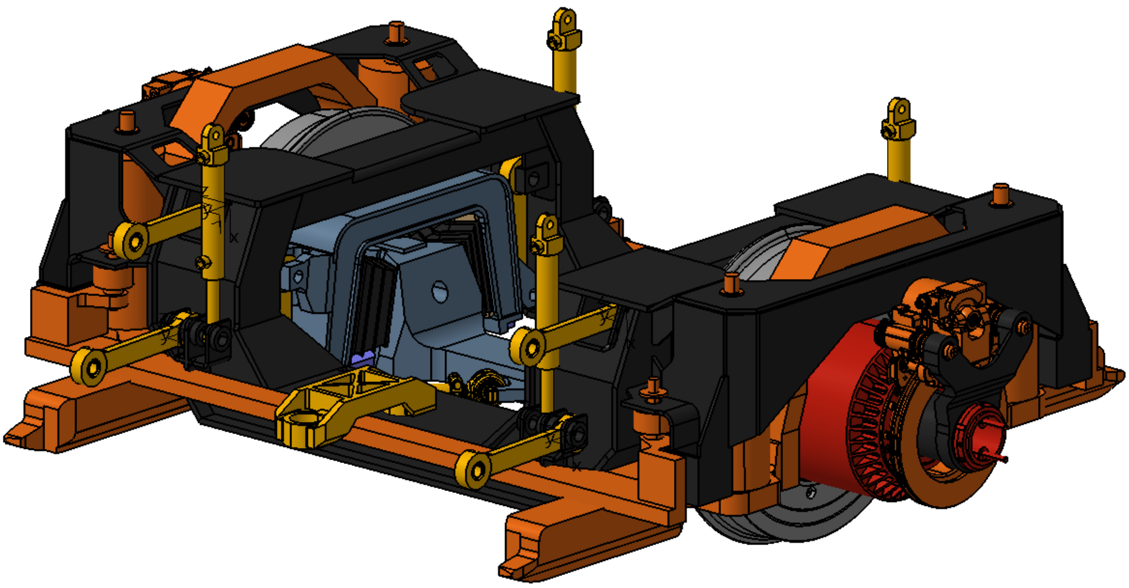


Figure 19: Fully assembled integrated running gear

2.2.3. Comparison of running gear types

With regard to the lightweight design, CapEx and OpEx KPIs set out in the MAWP, the two types of running gear developed thus far follow divergent strategies. The wheelset running gear focuses on maximum simplicity, with a consistent reduction of the parts and mechanics used in it to the greatest extent possible. The components which are used are largely of a conventional nature: conventional coil springs, conventional wheelset and a conventional motor-gearbox drivetrain. While a quantitative analysis of the costs involved in building and operating this running gear design has not been carried out, the use of these well-understood components and designs promises to result in a comparatively low-cost capital expenditure for its manufacturing. As stated above, however, the simplicity inherent to the design of this running gear will tend to compromise the suspension comfort which it can provide. To compensate for this tendency, one area in which advanced technology is used in the design of this running gear is in the active control of its vertical and yaw movements using active electrically driven actuators. In particular, the vertical actuators are intended to improve the ride quality for passengers, despite the relatively stiff suspension necessitated by the lack of an anti-roll-bar. One longitudinal actuator per running gear is used in order to support and stabilize the curving behaviour of the wheelset, ensuring radial steering and low wheel wear.

In contrast, the IRW bogie uses many component designs which are specifically tailored to the FutuRe vehicle's needs and an overall architecture which is unconventional in some aspects. Inverted portal axles may be state-of-the-art for low-floor streetcars, but are unusual in a regional rail vehicle such as this. In comparison to the wheelset running gear, the portal axle design is likely more expensive, but allows a low-floor vehicle design with better accessibility. The outrunner direct-drive motors used to power the IRWs are a completely new design and also represent a higher capital expenditure for the two more advanced motors necessary per bogie versus one simpler one, but eliminate the need for a gearbox. The two-and-a-half stage suspension (primary and secondary suspensions plus resilient wheels) is undoubtedly more complex than the wheelset design, but employs this complexity to compensate for the inherently compromised comfort of a single-axle design using a spring-mass-damper system that can be tuned to filter out undesirable excitations and the track irregularities to be expected on older, minimally maintained rural rail lines.

Ultimately the two designs proposed here offer two paths to the same goal, but further analysis would be needed in order to determine which would be the best choice. Would the IRW bogie's high efficiency and the control authority enabled by the direct drive motors reduce wear and energy consumption enough to compensate for a higher capital expenditure in manufacturing? Can the simplicity and low cost of the wheelset bogie produce acceptable ride quality? Potentially a combination of aspects from each could be incorporated into a new design, enabling an optimum to be found.

3. Traction/propulsion and energy architecture

Per the grant agreement, the goals of subtask 10.1.2 are:

• Selecting the most suitable powertrain configuration (e.g., fuel-cell-hybrid-catenary, battery-catenary);

• Development of a concept of a powertrain configuration, incl. an individual performance management (operation strategy) between components in different use cases;

• Development of an energy architecture to reduce the total energy demand of the vehicle by an optimal operating strategy of the components and thus to increase the range and flexibility of the vehicle,

• Experimental verification of the performance of the most promising powertrain/energy source combinations as well as identification and exploration of areas of improvements for regional lines (efficiency, technical boundaries, etc);

• Monitoring OpEx and CapEx of different technologies for energy storage systems and the propulsion systems selected for this proof.

The FutuRe vehicle is intended to employ electric traction motors for propulsion, with the immediate power needs supplied by a battery. The traction layout is outlined elsewhere in the report. To supply the necessary power to run the vehicle, three different configurations are under consideration:

1. Battery only – Relevant chemistries such as LFP and LTO are considered
2. Fuel cell hybrid – A proton exchange membrane fuel cell provides energy while an LTO battery maintains the power balance of the vehicle
3. Engine hybrid – an internal combustion engine generator set provides energy while an LTO battery maintains the power balance of the vehicle

3.1. Energy and Propulsion System Modelling with Economic Evaluation

The aim of this chapter is the economic evaluation of different technologies for energy systems and the propulsion systems selected for this proof. For this purpose, the CapEx and OpEx of train journeys are considered. The following figure shows the decision support process:

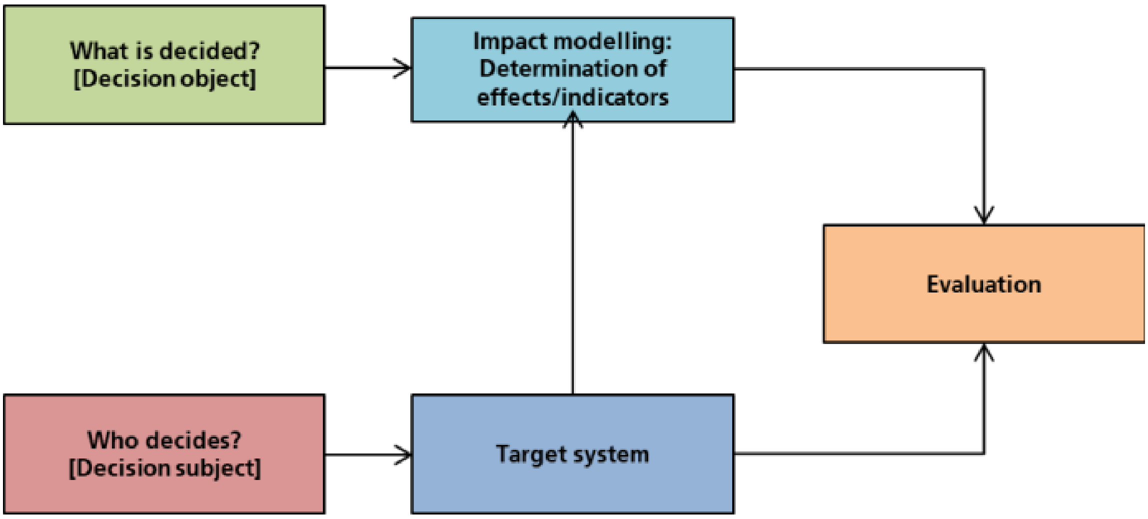


Figure 20 Decision support process

The decision object is the power train configuration for regional trains. There are two alternative configurations plus the reference case:

- Reference Case: Diesel-Multiple-Unit (DMU)
- Alternative 1: Battery-Electric-Multiple-Unit (BEMU)
- Alternative 2: Hydrogen-Electric-Multiple-Unit (HEMU)

The decision-making process is explained from the perspective of the Railway Undertaking (RU) and the Infrastructure Manager (IM). The RU aims to achieve the following targets associated with train operation:

- Lowest possible energy consumption to avoid OpEx
- Minimize greenhouse gas emissions as much as possible to avoid the purchase of certificates or corresponding taxes (OpEx)
- The power train configuration should be inexpensive to purchase (CapEx) and operate (OpEx e.g. maintenance)
- Lowest possible costs for refueling, charging and energy storage infrastructure and their use (OpEx)

The IM is responsible for purchasing and operating the refueling and charging infrastructure. In this evaluation case, the CapEx and OpEx are considered for RU in order not to have to take into account the cash flow between IM and RU.

In order to determine the energy requirements, power train simulations are carried out for the three cases.

The resulting costs are determined using a life cycle cost analysis. This is a monocriterion-based, monetized evaluation method. The evaluation is a technology innovation decision from the perspective of an entrepreneurial decision-maker.

3.1.1. Use Case description

The use case for testing preliminary power and energy consumption, as well as dimensioning strategies, involves a demanding route in Germany from Erfurt Main Station to Rennsteig. To recharge the traction battery, it is assumed that a charging station with 600 kW (minus system losses) will be available at each of the terminal stops (Erfurt and Rennsteig) via a third rail, inverse pantograph or other conductive charging solution. Initially, charging will only be possible when the vehicle is stationary. The distance and elevation profile of this route are illustrated in Figure 21.

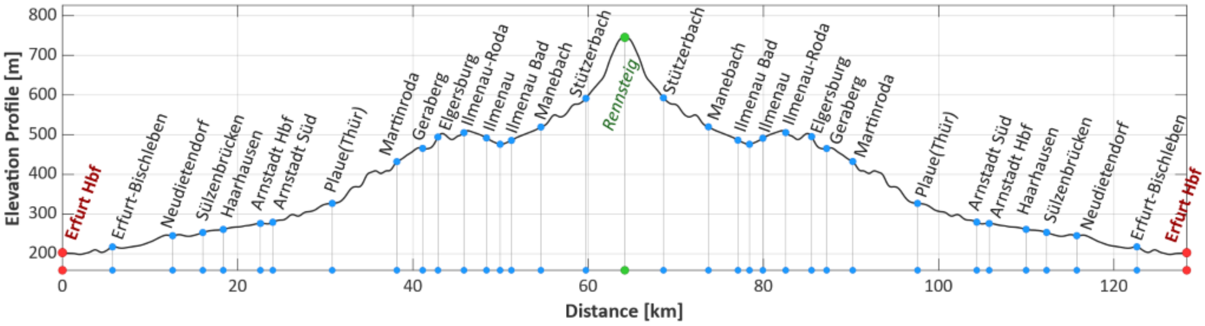


Figure 21 Elevation profile of the demanding use case roundtrip scenario "Erfurt Hauptbahnhof to Rennsteig"

A one-way trip covers a distance of 64 km and overcomes an elevation difference of approximately 500 meters. The maximum gradient reaches 60 ‰ [14]. The round trip consists of 17 stations, with a total duration of approximately 180 minutes. This duration accounts for the current timetable and includes a dwell time of 10 minutes at Rennsteig station. [15]

Table 7

Outward trip	[min]	91
Turnaround Rennsteig	[min]	34
Return trip	[min]	94
Turnaround Erfurt	[min]	21
SUM	**[min]**	**240**
frequency	[min]	60
Number of vehicles without reserve	[-]	4
Number of vehicles in reserve	[-]	1
Number of vehicles needed	**[-]**	**5**
Trips per day	[-]	40
Trips per year	**[-]**	**14 600**
Distance Erfurt - Ilmenau	[km]	50
Distance Erfurt - Rennsteig	[km]	64.4

(A) last stretch from Ilmenau-Rennsteig only on weekends but every trip
(B) last stretch from Ilmenau-Rennsteig 4 times each Saturday and Sunday (as per 2025 train timetable)
(C) every trip full distance to Rennsteig

Table 8 Options Operating Programme

Trips per vehicle per year (5 vehicles)	A	B	C
Erfurt - Ilmenau	2920	2920	2920
Ilmenau - Rennsteig	834	417	2920
SUM	**3754**	**3337**	**5840**
Kilometer per vehicle per year (5 vehicles)	**A**	**B**	**C**
Erfurt - Ilmenau	146 000	146 000	146 000
Ilmenau - Rennsteig	12 014	6007	42 048
SUM	**158 014**	**152 007**	**188 048**

3.1.2. Vehicle and System description

For the drivetrain configuration of the FutuRe vehicle, the performance of existing rail vehicles for regional service will be used as a benchmark. Figure 22 shows the specific power output (kW/t) of single- and double-unit rail vehicles for regional service and rail buses over time.

The figure shows that the specific power of the different vehicles varies a lot, although the trendline indication of about 10 kW/t has been relatively steady over the last few decades. The analysis only includes vehicles that can operate without overhead lines. Besides the new battery- or hydrogen-powered vehicles from recent years, these are mainly diesel-powered vehicles.

The boundary conditions considered within the preliminary calculation including the resistance formula of the vehicle are shown in Table 9.

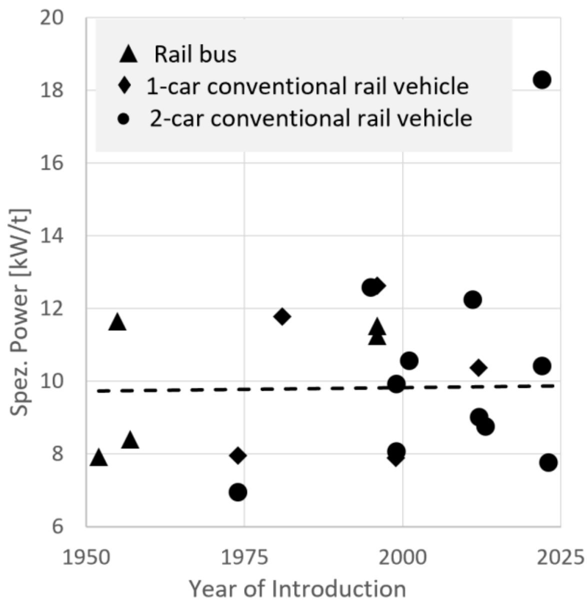


Figure 22 Specific power of different rail vehicles (power and weight of vehicles can vary depending on vehicle configuration) [16]

Table 9 FutuRe vehicle specifications and boundary conditions

Parameter	Unit	Value
Vehicle length	m	~ 15
Seats		~ 40
Max. wheelset load	t	< 16
Number of Wheelsets		2
Max. Speed	km/h	120
Power Supply		battery electric and/or H_2-fuel cell
Maximum Speed	km/h	120
Maximum specific power	kW/t	13
Charging Power (Static / DC)	kW	600

Derived from project boundary conditions, the following tractive resistance coefficients were calculated:

$$A = 400, B = 2, C = 0.2$$

The resulting resistance curve [Formel] is shown in Figure 23, where it is compared with a range of existing one- and two-car multiple units, equipped with either diesel or electric propulsion. [16]

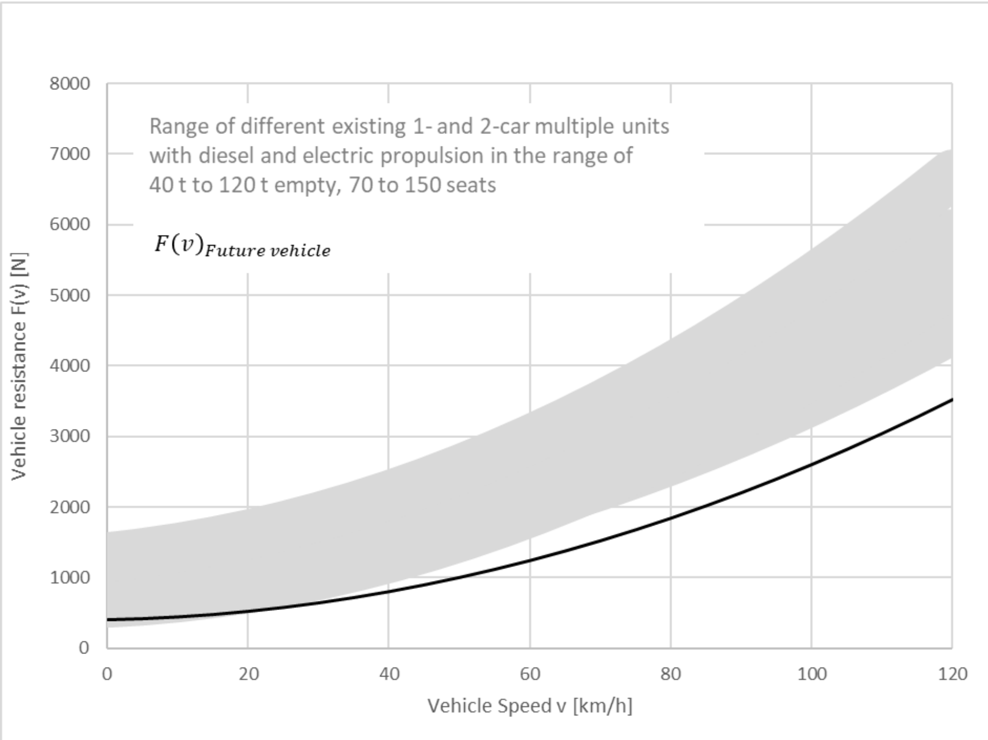


Figure 23 Resistance curve F(v) for the FutuRe lightweight rail vehicle (black) in comparison to approximated resistance curves of conventional market available vehicles [16]

These reference vehicles weigh approximately 40 to 120 tonnes and offer seating capacities ranging from 70 to 150 passengers. The resistance of the calculated lightweight rail vehicle lies slightly below the reference values, which is consistent with expectations for a lightweight new vehicle design.

3.2. Modular Powertrain/ Energy architecture

The main powertrain system is composed of one DC/DC converter, a traction battery, and two traction units. Each traction unit is equipped with a three-phase inverter to supply the asynchronous traction motors, which also operate in generator mode during regenerative braking. The secondary powertrain (optional) consists of two further traction units, fuel cell power pack and a second battery power pack. This can be considered as an evolvement of a Fuel Cell Hybrid Power Pack (FCHPP), which additionally takes into account hybrid batteries and fuel cell hybrid powertrains [17]. The modular approach enables the easy adaptation of different battery chemistries or powertrain components based on use-case-specific requirements. For the transmission of charging energy, it is assumed to have a DC recharging technology. This results in fewer heavy on-board components such as a transformer, which is in line with the lightweight design concept of the vehicle.

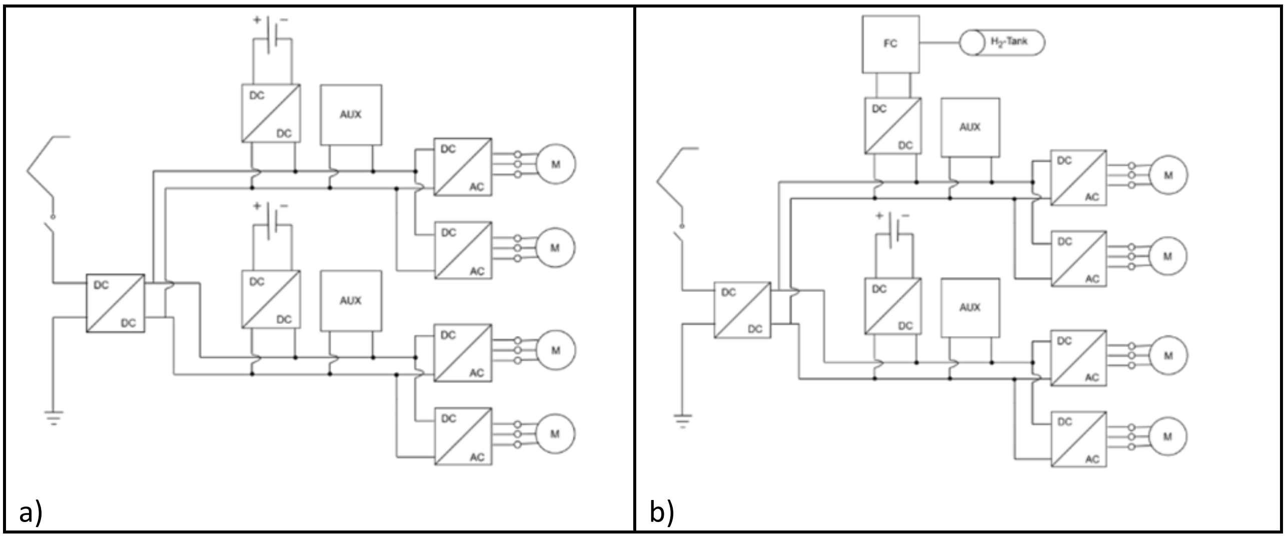


Figure 24 a) battery only powertrain b) fuel cell- hydrogen hybrid powertrain

3.2.1. Hybrid battery technology

Lithium Ion Battery (LIB) technology as primary energy carrier and power supplier is relatively new in the rail industry. Among the battery technologies currently available for rolling stock, Lithium Titanate Oxide (LTO) is commonly used due to its high cycle stability and long expected lifetime. However, advancements in battery cell chemistry are introducing competitive alternatives that offer significantly lower costs. In particular, Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC) chemistries are emerging as strong contenders for rolling stock applications, despite their established use in other mobility sectors. Since each battery chemistry has its own advantages and disadvantages, cost, space, and power performance are expected to be very challenging. Theoretical tests and simulations on hybrid batteries will therefore be considered for this vehicle concept. The expectation for such hybrid batteries is to improve performance, higher degree of modularity, while lowering costs by utilizing multiple battery cell chemistries within a single battery system. These are summarized in Figure 25.

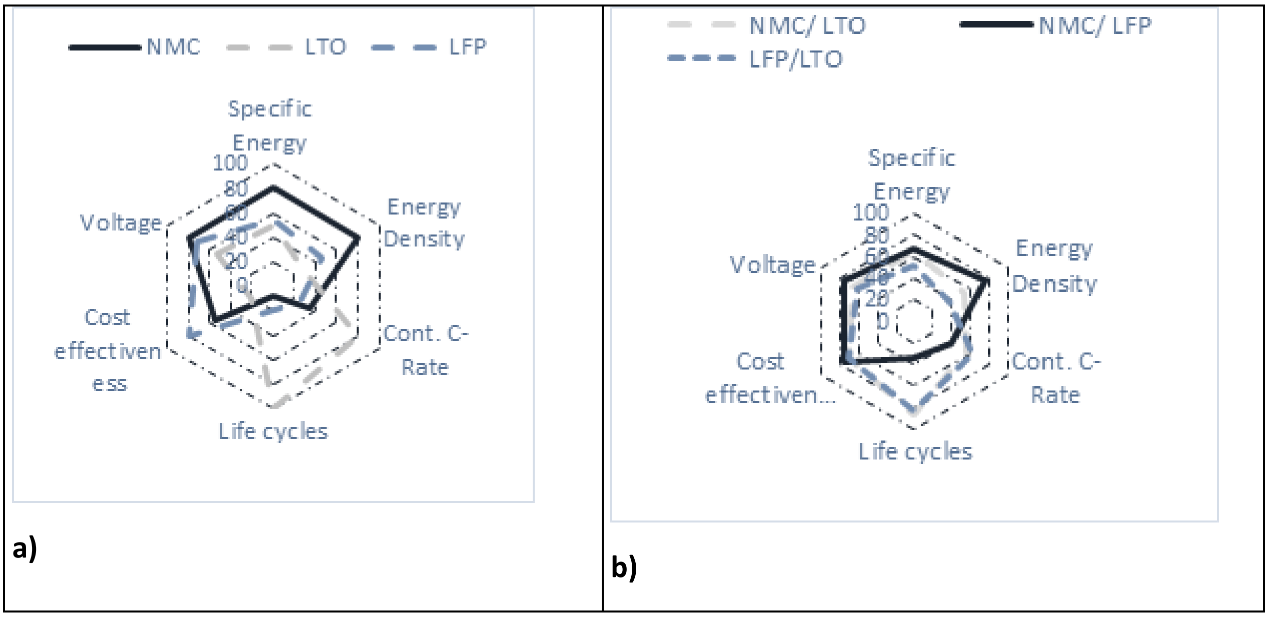


Figure 25 a) Qualitative Comparison of Key Properties of Lithium-Ion Battery Systems b) Projected Qualitative Comparison of Performance Characteristics in Hybrid Lithium-Ion Battery Systems [16]

Figure 25 b) illustrates the expectation that hybrid LIB can enhance both cost-effectiveness and overall system lifetime. Based on their fundamental properties, hybrid configurations combining NMC/LTO or LFP/LTO chemistries are considered particularly promising for rolling stock applications. The improved C-rate capability highly impacts the vehicle design and performance. High C-rate batteries might reduce the need for excessive volume or weight, contributing to compact integration, reduced thermal stress, and extended cycle life under dynamic traction conditions. These combinations aim to extend cycle life while benefiting from the high energy density of NMC or the material advantages and safety of LFP, alongside the robustness and fast-charging / discharging capabilities of LTO.

3.2.2. Fuel Cell Technology in Rolling Stock

Hydrogen has emerged as a promising energy carrier, attracting increasing attention due to its potential for locally emission-free use. Fuel cells can convert chemical energy stored in hydrogen into electrical power, making them a viable energy source for various applications. In particular, several projects are currently investigating the integration of fuel cells into rolling stock, offering an alternative solution for achieving vehicle autonomy [18] [19] [20]. Fuel cell systems are generally integrated into hybrid system layouts, often in combination with a battery system to buffer the generated energy and handle peak power demands during acceleration or regenerative braking. However, this chapter focuses exclusively on the fuel cell system and hydrogen storage tanks.

The current state-of-the-art technology in this field is the low temperature polymer electrolyte membrane fuel cell (LT PEM FC) technology, which operates at temperatures below 100 °C. An overview of the performance specifications and energy densities of commercially available LT PEM fuel cells fulfilling the standards for rolling stock usage is provided in Table 10.

Table 10 LT PEM Fuel Cell and Hydrogen storage energy densities at 350 bar. [21] [22]

Fuel Cell type	Specific power (W/kg)	Power density (W/l)	Air Filter
Ballard FCmove-HD+	380	140	Included
Toyota Vertical type (Type I)	320	210	Not included
Toyota Horizontal type (Type II)	320	240	Not included

The specific power of the fuel cell systems ranges from 320 to 380 W/kg, with a power density between 140 and 240 W/l. The following Table 4 below presents typical hydrogen storage energy densities, which are relevant for applications involving these fuel cell systems.

Table 4:. [Referenzen 11,12]

Table 11 Hydrogen Storages [23] [24]

Tank Type	Specific Energy (Wh/kg)	Energy density (Wh/l)
Luxfer W322H35 (Type 3)	1747	607
Hexagon Purus H2-35-509X2344 (Type 4)	2522	587

The current state of the art in hydrogen storage are type 3 and type 4 storage systems with 35 MPa. These offer energy densities of 1.7 kWh/kg – 2.5 kWh/kg and about 0.59 kWh/l – 0.61 kWh/l.

3.3. ICE hybrid configuration

One of the primary goals of increasing usage of regional rail services is the decrease in emissions that this would bring across the general transportation sector. As passengers make greater use of renewably-powered rail services and correspondingly decrease their use of combustion-engined personal vehicles, carbon emissions will obviously be reduced, but even the switch from an electric personal car to an electric train will bring important improvements in tyre wear particulate emissions and a reduction of overall energy usage.

For many use-cases for which the FutuRe vehicle is envisaged, a pure battery-powered drivetrain with opportunity charging would be sufficient, however, for certain longer routes in colder climates, the use of an internal combustion engine (ICE) generator set as the primary source of energy enables the use of a number of energy carriers not possible otherwise. The utility of this approach is twofold: (i) higher volumetric and gravimetric energy density can enable greater range compared to battery electric and fuel cell vehicles; (ii) pre-existing sustainable fuel value chains can be leveraged for the new vehicle.

In regards to the second point, it is worth noting that in Sweden, hydrotreated vegetable oil (HVO), rapeseed methyl ester (RME) and biogas facilitated nearly 80 % of bus travel within public transit in 2023, and usage of HVO as a drop-in fuel is common for non-electrified rail vehicles [25], [26]. It would thus be possible for these pre-existing value chains to be employed for a new, lightweight vehicle for non-electrified lines.

The fulfilment of these objectives in regards to the investigation of an ICE hybrid vehicle is interpreted as follows:

1. The suitability of an ICE genset drivetrain configuration – with respect to the vehicle design characteristics in terms of allowable weight and size of components, and with respect to route fulfilment – must be investigated. Suitability is taken to involve the following three characteristics:
    a. Fitting inside of the vehicle's design envelope with respect to size and weight
    b. Being capable of fulfilling relevant routes
    c. Being able to operate on sustainable fuels with low GHG emissions
2. A holistic drivetrain concept, including both an ICE genset and a suitable battery configuration, must be defined.
3. A strategy for the interaction between the ICE genset, battery, and traction system must be defined with the goal of suppressing total energy usage.
4. The conclusions should be supported with empirical data.
5. OpEx and CapEx should be investigated in approximate terms so that the ICE genset configuration/-s can be compared with other alternatives

To meet these requirements, this section will begin by outlining the ICE genset drivetrain concept and the control strategy used for the ICE genset. Then, the simulation methodology will be laid out. After this, the suitability of the ICE genset configuration is discussed, using the Erfurt-Rennsteig track as a reference case. Lastly, OpEx and CapEx are discussed. Finally, it should be noted that experimental work in regards to the investigation of novel ICE concepts for high efficiency operation has been undertaken and is awaiting publication.

3.3.1. ICE genset drivetrain configuration

The low-floor design of the vehicle, as shown in Figure 11, is enabled by the use of electric traction motors, with additional drivetrain components placed on the roof. Because of this, using an ICE to drive the axles directly is difficult, and would necessitate major changes to the overall vehicle concept, as well as a higher floor on a section of the vehicle. To avoid this, the ICE genset is used as an energy provider or 'range extender.' A smaller ICE genset, capable of providing for the energy needs of the vehicle but not its momentary power needs, is coupled to a battery. The battery is responsible for supplying traction power, which may momentarily climb above what the genset can provide. The ICE genset is responsible for keeping the battery's state of charge within set margins.

Conceptually, this is identical to how a fuel cell would be used. It enables the secondary power unit – either a fuel cell or an ICE genset – to operate under relatively stable conditions, which is associated with greater fuel conversion efficiency and longer lifespan. This approach also ensures minimal changes to the vehicle design to facilitate the hybrid options.

The key requirements for the ICE genset configuration are:

1. The ICE genset must be able to provide the total energy need of a given route. This means that the maximum power of the ICE genset must be higher than the average power draw of the vehicle.

2. The battery must be capable of providing all momentary traction and auxiliary power needs. Since the traction motors are specified at 390 kW, the battery must be able to supply this amount of power while accounting for traction motor efficiency at maximum load and auxiliary power draw.

A number of fuels are investigated. Fossil fuels – diesel, gasoline, and natural gas – are included as a baseline. The fuels are indicated in Table 12 along with the engine type chosen for that fuel, noting that fuels with diesel-like properties are generally more suited to compression ignition engines while many other fuels are easier to run in a spark ignition engine.

Table 12 Tested fuels by engine configuration

Engine type	Fuels
Compression ignition (CI)	Diesel, HVO, FAME, RME
Spark ignition (SI) – liquid	Gasoline, ethanol, methanol
Spark ignition (SI) - gaseous	Hydrogen, methane (natural gas or biogas)

3.3.2. Specifications

In determining the design envelope of the ICE genset drivetrain configuration, three factors are considered:

1. Available free area on the roof
2. Roof weight restrictions
3. The loading gauge (the limit on the profile of the vehicle, principally a height restriction).

For the loading gauge, the German G1 standard is applied (not to be conflated with the Group 1 or G1 class of rail lines defined in the MAWP). Is it comparatively more stringent than most relevant standards – for example, the Swedish 'Lastprofil A' is wider and taller than the G1 standard, meaning that vehicles designed for the G1 standard fit the 'Lastprofil A' standard.

Preliminary testing indicated that on most tracks, a roughly 100 kW secondary power unit is sufficient to maintain the state of charge. An LTO battery with a capacity of 66 kWh was selected as such a battery could, with sufficient margins, provide all power required by the vehicle. A 110 kW Stadco railway genset [27] and the ABB Max 8C LTO battery [28] were used as references for the component size and weight, with margins for additional components for cooling and power conversion. What remained of the design envelope could then be used for fuel storage. Since liquid fuels are volumetrically dense and the fuel tank layout is flexible, the liquid fuel storage is mainly limited by weight. Gaseous fuel storage – for hydrogen and methane gas – is constrained by the dimensions of the fuel storage tanks. For the dimensions of the fuel storage tanks, Luxfer hydrogen and methane fuel tanks are used as reference [23], [29]. The maximum currently allowed is shown in Table 13. They are subject to change based on the overall vehicle design.

Table 13 Component parameters for the ICE hybrid vehicle configuration with maximum fuel capacity

Component	Capacity
ICE genset	110 kW
Liquid fuel tanks	Up to 1500 l
Methane fuel tanks	Up to 750 m^3
Hydrogen fuel tanks	Up to 70 kg
LTO battery	66 kWh, 8C

3.3.3. Simulation methodology

To investigate the energy consumption of the ICE genset vehicle, a simulation model was developed in Matlab Simulink. The simulation model is outlined in Figure 26. The key distinction is the inclusion of a secondary power unit in the form of an ICE genset which is used to manage the state of charge of the battery.

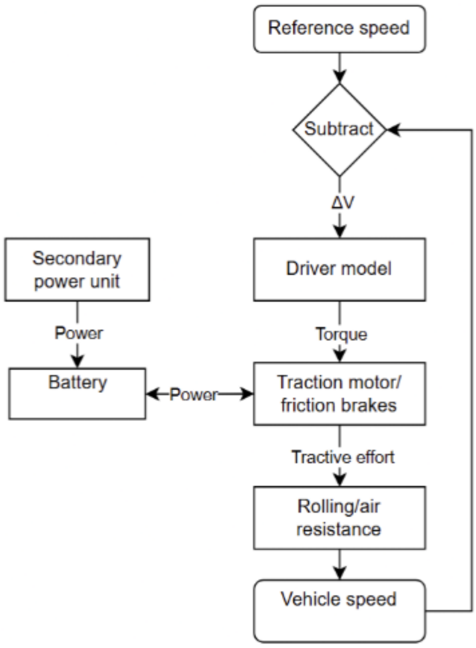


Figure 26 Outline of the simulation model

The ICE in the secondary power unit is simulated using stationary brake efficiency maps, an example of which is shown in Figure 27. The brake efficiency map is only a valid approximation if quasi-stationary operations are assumed. For this reason, the rate at which the ICE is allowed to ramp up or down is limited.

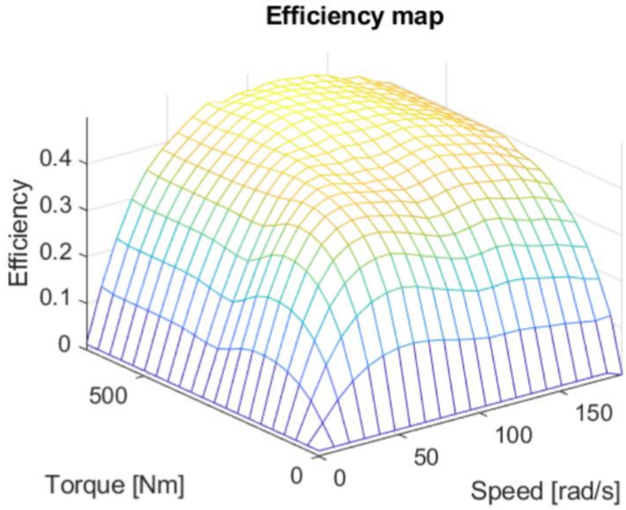


Figure 27 Stationary brake efficiency map for a compression ignition engine

To this is applied the efficiency of the electric motor within the genset, which is obtained from a lookup table for the specific operating point.

The main input to the simulation is a drive cycle, consisting of information on the local track speed limit, the presence of stations or stops along the route, and information on the incline. The Erfurt-Rennsteig track is used as a basis for the drive cycle, and it is described in section 3.1.1. The resistance to the forward motion of the vehicle is calculated based on the equation shown in section 3.1.2.

3.3.4. Suitability of the ICE genset

For the ICE hybrid configuration to be suitable for its task, it must be able to provide enough power to maintain the state of charge to within reasonable bounds. It must also have sufficient range to fulfil the target routes, and the battery must be able to provide all necessary power.

Preliminary testing was done with a synthetic drive cycle with speeds distributed over the range 60-120 km/h and with a mixture of flat and high incline sections, yielding the data shown in Figure 28. The key consideration is the average total power, which is 62 kW. If the secondary power unit was run close to this power level for the entire drive cycle, the overall energy needs of the drive cycle would in theory be met. In practice, if certain sections are very demanding, the battery could be depleted, but based on this data a secondary power unit close to 100 kW is reasonably sized for the vehicle.

The absolute power demand is illustrative of typical operating conditions for the battery and traction motors. In particular, the traction motors need to accomplish two things. First, they must be able to provide the maximum traction power needed to accelerate or decelerate the vehicle. Second, they must be able to maintain cruising speed at good efficiency. Since the efficiency of an electric motor tends to rise as load increases, the use of multiple electric motors operating in such a way that only one motor is active during cruising can be beneficial, as illustrated by the difference in the average traction power in absolute terms and the maximum traction power.

The total power maximum is indicative of battery requirements. If an LTO battery is rated at a charge/discharge rate of 8C, it means that a roughly 51 kWh battery is the minimum, which is met by the 66 kWh LTO battery selected for the vehicle with sufficient margins for capacity degradation over time.

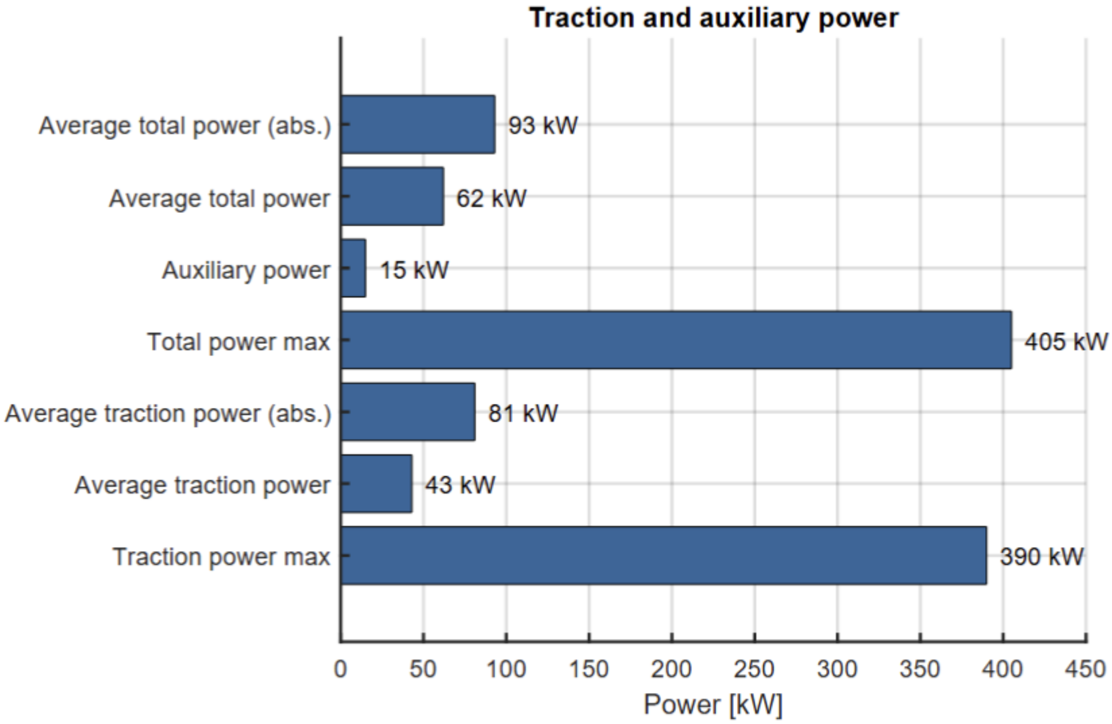


Figure 28 Vehicle power needs

In addition, it is necessary either than the battery only configuration is not capable of fulfilling the route requirements for at least some relevant routes, or that the ICE hybrid provides equivalent or better lifetime emissions than the battery only option. If a battery only option is both capable of fulfilling all relevant routes and has lower emissions, the ICE hybrid option no longer has a reason to exist for the vehicle.

Figure 29 shows CO_2-eq. emissions calculated for the same test cycle as Figure 28. Data is provided for two battery configurations (LTO and LFP batteries), CI and SI engine configurations, a fuel cell, and finally methane and hydrogen SI engine configurations. A number of cases are shown for each, resulting in a wide spread.

For the battery cases, the emissions are based on four EU countries (Sweden, France, Germany, and Poland) as well as an EU average [30]. The same goes for the FC and SI-hydrogen cases, but those also include steam methane reforming of natural gas as a production pathway. For the other fuels, a range of production pathways are included for the well-to-tank emissions [31], to which is added well-to-wheel emissions for fossil fuels [32]. As can be seen, the energy mix of the country makes a large difference to the desirability of a drivetrain and fuel option from a climate perspective. It is particularly noteworthy that net negative emissions can occur with biogas using a liquid manure-based pathway as a result of emission credits, even if the combustion of biogas is still a local source of emissions.

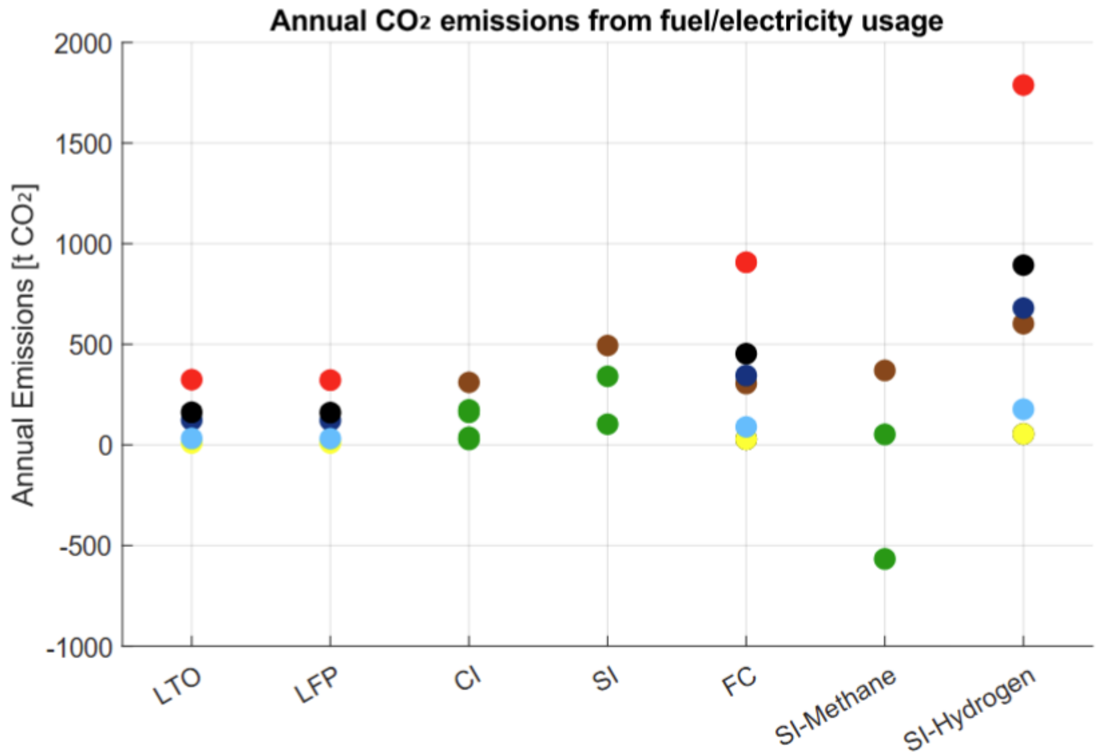


Figure 29 Annual CO_2-eq. emissions for a variety of drivetrain options based on a test cycle. Yellow represents the Swedish mix, light blue the French, dark blue the EU average, black the German, and red the Polish. Brown dots represent energy provided by small modular reactors.

The above data is based on the specific fuel consumption in Figure 30, which is based on the same test cycle as above. The control strategy for the ICE genset configurations can be improved, resulting in a decrease in fuel consumption, especially for the SI case. That being said, the lower efficiency of the ICE genset compared to a lithium-ion battery inevitably results in a higher specific fuel consumption when the system boundary is placed at the grid connection point.

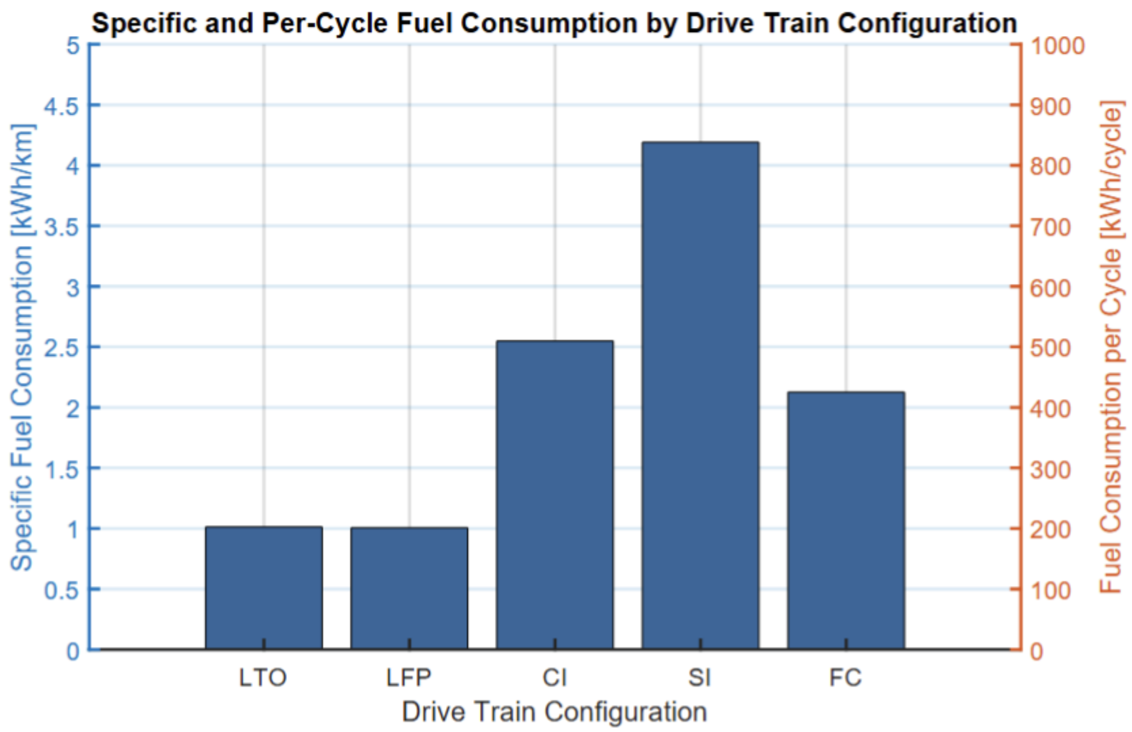


Figure 30 Specific and per-cycle fuel consumption for the test cycle, showing a range of vehicle configurations

Data specific to the Erfurt-Rennsteig track is pending publication.

3.4. Simulation Model

3.4.1. Powertrain Simulation

The simulation framework is structured as a two-step toolchain developed by the German Aerospace Center (DLR).

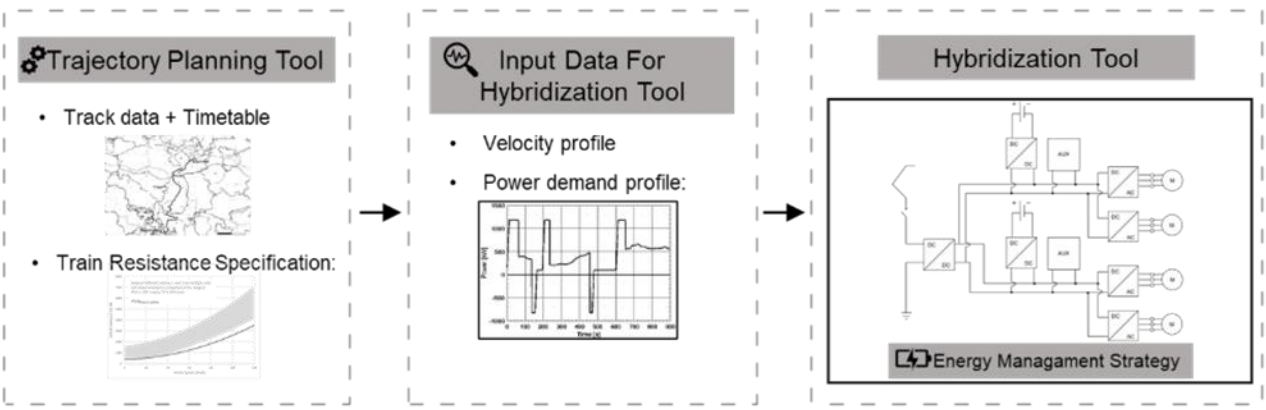


Fig. 6. Simulational Toolchain to determine the powertrain component sizes

In the first step, the Trajectory Planning Tool (TPT) processes input data comprising the track profile, timetable, and longitudinal resistance characteristics of the train [33]. Based on this information, the TPT calculates the required power demand trajectory at the wheel. In the second step, the Energy Management Simulation Tool, referred to as the Hybridization Tool, utilizes the

TPT's output as its input. Within this tool, several energy management strategies can be applied to derive the powertrain component sizing. Depending on the intended propulsion architecture, the algorithm enables either battery-only or combined with fuel cell and battery dimensioning. The dimensioning methodology systematically determines the required dimensions based on operational energy and power demands, ensuring that component specifications are aligned with the system's functional requirements.

3.4.2. CapEx OpEx Model

An LCC-A is often used to compare different technological options for a product in this specific case a comparative analysis of the three alternative power train configurations of a regional train. The methodological basis for this analysis is laid out in the work described in this deliverable, with the results of the analysis to be presented in deliverable 10.2.

As the aim of this analysis is a comparison and not the general decision whether or not to provide a railway service on the line only the costs that differ between the options are relevant, therefore no focus on aspects which are the same for all options like revenues, personnel costs, infrastructure or station charges.

This leaves costs of investment and operation of the power train components, the specific charging infrastructure required and operational costs including:

Rolling stock related costs

- Investment of the vehicle or retrofit of technological components for power supply [€]
- Maintenance of the power train components [€/km]
- Energy costs (amount of energy needed*price) [€/km, €/stop]
- CO_2 and other emission costs [€/km, €/stop] assumption that in the future these will be internalised either directly within the energy price or in some form of certificates

Infrastructure related

- Investment and maintenance of charging infrastructure [€/ year]

Net present value approach

With the Life-Cycle-Cost (LCC-A) approach all these costs occurring over the life cycle of the product are now discounted to a common point in time. The value used for the discount rate has hereby significant influence on the result of the LCC. It is needed to estimate the present value of future costs, helping to compare costs that occur at different points in time. The higher the discounting value, the lower the value of future benefits and costs. [6]

Discount value:

- BVWP: 1.7%
- TAG data book (UK): 3.5%

Figure 31 and Figure 32 visualise a model for the calculation of the LCC of the different power train configurations. This economic model can be used to carry out sensitivity analyses, e. g. to determine the influence of different energy prices or the discount value on the overall result.

	component	unit	life cycle [years]	CapEx [€]	years				NPV [€]
					0	1	2 …	n	
BEMU	power component 1								
	power component n								
	charging infra 1								
	charging infra n								
HEMU	power component 1								
	power component n								
	charging infra 1								
	charging infra n								
Diesel	power component 1								
	power component n								
	charging infra 1								
	charging infra n								

Figure 31 LCC model for power train comparison CapEx

		OpEx [€]									
	unit	maintenance	energy costs [€/km]		co_2 / emissions		years				NPV [€]
		[€/km]	[€/km]	[€/stop]	[€/km]	[€/stop]	0	1	2 …	n	
BEMU											
HEMU											
Diesel											

Figure 32 LCC model for power train comparison OpEx

4. Other concept relevant system elements

Subtask 10.1.3 is tasked to develop the other concept relevant system elements. Based on the defined requirements of WP5 task 5.2 relevant system elements will be considered. The elements in question are:

- A novel, lightweight braking system
- A modular rolling stock interior concept for up to 100 passengers and freight including doors and HVAC
- A concept for integrating ATO into the vehicle concept
- Evaluations of results of vehicle concept development

This deliverable will focus on the interior and braking systems. The ATO integration and concept evaluations will be covered in the deliverable D10.2.

4.1. Braking system concept and technology

The focus of this chapter is on the braking system concept development (in close collaboration with D2), including design of the braking system for reducing the weight of the vehicle.

While compressed air technology is a well-established means of powering and controlling onboard systems such as brakes, alternatives exist in the form of electromechanical or electrohydraulic braking systems offered or in development by various equipment providers in the sector. So-called “airless train” technologies offer potential benefits in terms of packaging, mass and energy efficiency; however, these technologies are currently in development in other part of the EU-Rail research programs and their maturities are at a lower level than the electropneumatic brake and at this stage. For the FutuRe project, the conventional compressed air solution has been preferred due to the possible use of compressed air for different other subsystems (for instance the secondary suspension), however alternative systems are generally designed as drop-in replacements (same size brake actuators) and require the mere deletion of other components (compressor, air tanks etc.), so a change from compressed air to airless would be much easier to implement than the other way around. If all other systems in the vehicle can be implemented using airless technologies, the brakes could follow suit.

4.1.1. Brake performances

4.1.1.1. General consideration

The expected brake performances are key for the design of the brake system of a railway vehicle. Deep analysis has been made in order to refine what could be expected for the 2 types of FutuRe vehicles:

- G1 vehicles which is designed for being able to run both on branch lines and on main lines for connecting to main stations.
- G2 vehicles that are designed to only run in normal service on dedicated small lines with no interference with any other traffic.

4.1.1.2. Brake performances G1 vehicles

The scope of use for this type of vehicles obviously leads to the full compliance to the TSI requirements.

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 G1 vehicle could be operated, however, some investigations have been made into what the requirements are in some targeted countries:

- EN16185-1: appendix A includes a comparison of the brake performances in different countries
- Sweden= The document Krav TRVINFRA-00302 Signalering v7_0 features a table where are listed the needed performances (deceleration function of brake response time) for different speeds allowing to match the signalling stopping distance.
- Germany = A stopping distance of maximum 700m when braking from 100 km/h is required
- France = The needed brake performances are listed in the document SAMF005 issued by the EPSF (the French NSA)

From this analysis it has appeared the requirements are quite close, and the working group, has decided to target the following performances:

- The following stopping distance must be ensured with a high integrity level (emergency brake definition in line with TSI and EN16185-1.):
- 830 m when braking from 120km/h (G1 vehicle) (source SAM F005-France)

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 the capability of running on 3 gradients (the worst cases in France) and performing an emergency braking at the most critical location is also required. 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

When calculating the brake performances of the vehicle, it shall be verified that the maximum required adhesion levels don’t exceed the TSI requirement: maximum μ = 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.

4.1.1.3. Brake performances G2 vehicles

For the G2 vehicles, the TSI are not applicable, and the working group decided to use a standard that is used in Germany (BoStrab) and can be considered as a reference for vehicles running on branch lines and that could sometimes run into cities.

It has been agreed to target the following braking performances (source: BoStrab appendix 2):

- Deceleration: 2.71m/s² from 70km/h in nominal mode (no brake failure)
- Deceleration: 1.07 m/s² from 70km/h in degraded mode (one brake failure)

To be noted these performances have to be achieved in tare condition with the "emergency braking 3" position (definition in EN13452), which means all the brake active: Electrodynamic brake + Friction brake + electromagnetic track brake + sanding + no limitation regarding the required adhesion (WSP not considered).

Regarding the gradient rides, it is only required the vehicle been able to perform a single brake application at its maximum load on the maximum gradient of the considered line.

4.1.2. Braking modes

4.1.2.1. General design

The emergency braking is controlled at train/vehicle level by emergency electric circuit. They are designed in accordance with a "energize to release" principle.

All the actuation devices (driver vigilance device, ATO, passenger alarm, driver emergency actuator, ATP, other emergency devices) are connected to the relevant emergency circuit. The activation of any of the device will result into the cut off of the relevant circuit leading to the application of the relevant emergency brake.

4.1.2.2. Emergency braking - G1 vehicles

For the G1 vehicles, the emergency braking is designed in accordance with the TSI LOC&PAS and EN 16185-1 (the relevant harmonized standard): There is a single emergency circuit which enables the emergency application thanks to any of the above listed initiation devices.

The de-energization of the emergency circuit will provide the following functions: Immediate cut-off of the traction effort, control of the braking by the brake control device, and activation of the magnetic track brake by the magnetic track brake control device.

At this stage it is not fully decided whether the traction control will be able to provide a safe enough control of the ED braking. Therefore, there are 2 alternatives:

- Either the ED brake effort is not used in emergency, and the brake control will manage the emergency brake effort using only friction braking.
- Or ED brake could be used and the blending of it with friction brake is managed by the brake control device

In that case the brake control will demand a load dependent braking effort for each axle to the ED brake control. In return the ED brake control will inform the brake control of the achieved ED brake effort for each axle. The braking control will complement with friction brake effort per axle as necessary in order to get the demanded deceleration.

Through the use of a brake control system with the capacity to ensure a SIL4 monitoring of the ED brake (an example being the Regioflexx® device offered by Wabtec [34]), the use in emergency of the ED brake could be discussed later in the project.

In any case during the emergency brake application the brake control device shall control the requested adhesion in order to keep it within the TSI requirement and will control the WSP (in line with EN 15595 of both the ED brake and the friction brake.

4.1.2.3. Emergency braking - G2 vehicles

For the G2 vehicles, the emergency braking is designed in accordance with the EN 13452 – chapter 6: Several emergency loops will activate the different emergency braking systems in line with EN13452 table 6.

Considering the Bostrab specification, the emergency braking 3 will be the key emergency braking mode. In this braking mode, the ED brake will be used at its maximum capacity, complemented with the magnetic track brake and the friction brake in order to reach the required deceleration (see §2.4.1.3). It is not foreseen to have any blending ED brake/friction brake. And there will not be any adhesion management (WSP not activated).

Other emergency braking modes can be reviewed and implemented on demand at a later stage of the project in order to comply with the operator requirements.

The service braking design is foreseen to be quite the same both for the G1 and G2 vehicles.

The deceleration request is transmitted from the driver or the ATO via the TCMS (data bus). When a deceleration is required the traction equipment (which is connected to the data bus) shall immediately cut-off the traction effort and the control of the braking will be managed by the brake control device.

It will manage the blending between ED brake and friction brake: the brake control will demand a load dependent braking effort for each axle to the ED brake control. In return the ED brake control will inform the brake control of the achieved ED brake effort for each axle. The braking control will complement with friction brake effort per axle as necessary in order to get the demanded deceleration.

4.1.2.4. Holding brake

The holding brake function is managed by the brake control device. Its purpose is to keep the vehicle at standstill during a short stop for instance for the passenger boarding at a station.

It automatically applies further a service brake application when the speed is 0. It automatically releases when a traction effort is requested. These functions are monitored at SIL 4.

It is foreseen to have the same function both for G1 and G2 vehicles.

4.1.2.5. Parking brake

The parking brake function is designed to keep the vehicle at standstill for an indeterminate period of time. Some of the brake actuators shall be equipped with a parking brake function that is based on a spring applied / pressure release principle.

Depending on the required performance (gradient where the parking brake shall keep the vehicle immobilized) the sizing of the parking portion of the actuators shall be chosen and the number of actuators equipped with parking brake function (one / axle, one / wheel) as well.

The control of the parking brake is managed by the brake control device: It will automatically apply when the train is powered down, or on demand by the driver.

4.1.3. Bogie (running gear) brake equipment

The bogie brake equipment uses friction to dissipate kinetic energy and to provide required deceleration. This can be achieved by adhesion-dependent brake (disc brake or tread brake) or an adhesion-independent brake (magnetic track brake).

For the planned short vehicles, 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

At this stage of the project and due to the pending decision regarding the running gear design, for the adhesion dependent braking 2 alternatives can be considered:

4.1.3.1. Tread brake unit:

The proposed unit, see Figure 33, create a retarding effort with brake blocks acting on the tread of each wheel.

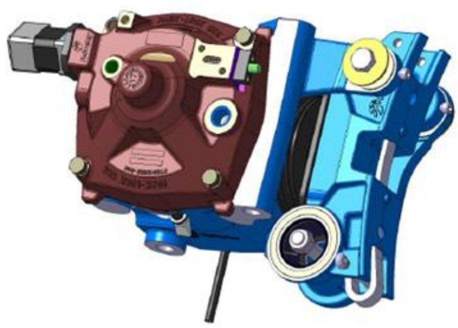


Figure 33 Compact tread brake unit (without brake block and not showing wheel)

The main advantage of this solution is its low weight and competitive cost. 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: The braking action will tend to clean the running surfaces of the wheels, thus reducing the electrical resistance from one rail to the other through the axle, which is used by some signalling systems in order to detect a train present on a section of track.

4.1.3.2. Disc brake

The proposed unit, see Figure 34, creates a retarding effort with brake pads clamped by the actuator on to a disc flanged on the axle.

Figure 34 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.

4.1.3.3. Magnetic track brake

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

A frame is suspended from the bogie frame by pneumatic lifting cylinders. It carries 4 sets of magnets + pole shoes. See Figure 35.

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

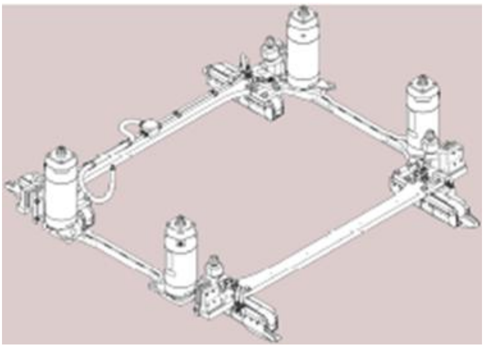


Figure 35 Overall view of the MTB equipment for one running gear

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

4.1.3.4. Brake control equipment

The core of the brake control equipment will be the brake control device [34]. This device includes both the pneumatics and electronics (hardware + software) needed to provide the following main functions in a single unit:

- 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) thanks to an embedded function emulating a traditional pneumatic distributor (this function is mandatory for the G1 vehicle).
- Predictive maintenance

Figure 36 Overall view of the Regioflexx® brake control [34]

An important factor in the choice of device for FutuRe project is its compactness and its capacity to provide a control per car or per axle for the service brake and a full independence per axle for the emergency brake application. These requirements are imposed by the unique design and size of the FutuRe vehicle. One appropriate device would be the aforementioned Regioflexx® [34], which is also fully certified and features a very high TRL with several units already in service.

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

Each Regioflexx® system features two independent fully integrated electronic units driving the electro-pneumatic (EP) equipment:

- A brake control unit (BCU) performing all functions rated up to SIL 2 (i.e., non-safety-critical)
- An independent, SIL 4 safety unit executing and monitoring all safety-related functions

The safety unit also commands the BCU to execute specific safety functions, such as emergency braking (EB). This operation is under permanent supervision by the safety unit, which, in case of misalignment with targets, acts to restore a safe state.

Regioflexx® is designed to be directly connected to the TCMS (wired control and data bus) for exchanging all the necessary information with the train control system and the other train equipment such as traction equipment.

Given the decision to use compressed air for the brakes, 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 ….) are finalized.

4.2. Modular rolling stock interior concept

The interior is the main point of interaction for passengers with the vehicle. Consequently, the user experience hinges significantly on the success of a comfortable, safe and welcoming space which users can trust and are willing to spend time in. As the vehicle is built to increase usage of regional rail services, the vehicle interior has to be as accessible and attractive as possible to people currently favouring other modes of transport. This holds true especially for people with valid reservations against public transport. Some user groups from e.g. political or ethnic minorities, children, women or people with physical or psychological impairments have a higher need for privacy and security and as such, may need special accommodations. The interior space is therefore designed to offer such a space for differed types of users within different use cases. At the same time, the interior setup must be functional, flexible, adaptable, sustainable and economically viable in acquisition and maintenance.

4.2.1. Regulations

To help with increasing accessibility for physically, cognitively, visually or aurally impaired people, the Technical Specifications for Interoperability for Persons with Reduced Mobility (TSI-PRM) [35] summarizes design criteria to improve ease of use of the railway transport system as a whole. It states that train stations shall be built in a way, that people with impaired vision or hearing, people with language barriers or difficulties reading and understanding signs, people relying on walking aids, crutches or wheelchairs can orient themselves easily and independently. Information is conveyed using multiple communication paths like easy-to-understand signs and pictograms, speaker announcements and informative lighting systems. Also, every place in the train station should be accessible without stairs or steep ramps.

Similar design criteria hold true for the vehicle itself. It shall be designed in a way, that impaired people can still use it as easily as possible. For example, the doors shall be easy to find and identify. The boarding of the train shall be easy and without obstacles especially for wheelchairs. The interior shall be laid out to be easily understood, so that everyone can orient themselves quickly and without confusion. Information can also be conveyed inside of the train using different colours, lighting, big and clear displays, announcements and similar. The place should be easily traversable even with impaired mobility. So, the aisles should be wide and there should be enough space in areas with high passenger density like the door- and multi-use-areas.

In this stage of development, the focus of the interior design lies on the general layout. So, the relevant regulations mainly concern the spacing of the different components such as seats, racks, walls and doors. For example, the number and dimensions of wheelchair spaces is regulated by the TSI-PRM. For the given train length, a minimum of two wheelchair spaces is required. Also, the width of the aisle is defined with at least 800 mm, so that a wheelchair or pram is able to go through. [35]

4.2.2. Design concept

The task of WP 10.1.3 includes the design of an interior concept to fulfil those requirements for a vehicle designed to transport up to 100 passengers and / or freight in rural areas. Key design considerations include:

- Passenger comfort
- Passenger safety
- Accessibility for all different kinds of passengers
- Maximum flexibility and adaptivity
- Low acquisition and maintenance cost
- Low weight
- Sustainability

To enable flexibility and adaptivity, the interior is modular. All components such as seats, desks, bike and luggage racks etc. are mounted to a C-rail system, traversing the vehicle on the floor, walls and ceiling. The connection of the components to this rail system is built in a way, that the operator can easily and quickly mount and unmount components, tailoring the interior to specific use cases in a short amount of time. So, the vehicle can be adapted to different use cases on different lines in different areas all over Europe. This increases the number of operational scenarios and therefore the total number of vehicles. As a consequence, development and manufacturing cost for the individual vehicle decreases. In addition, the operator can adapt the interior to changing user demands over time. Depending on whether the vehicle is used during a workday or the weekend, during holiday season or even during day or night, different interior setups can be realized by adding and removing components appropriate for the current use case. This short term adaptivity increases utilization and therefore economic viability. The easily removable interior components enable the vehicle to be completely emptied out in a short amount of time, opening the room for customized setups.

As every component can be individually added and removed, lots of different setups are possible to realize. In the deliverable D5.1 three general setups are chosen to get an overview on the possibilities: a tourism setup, a commuter setup and a cargo setup. Above and beyond that, some additional setups are broached to give an example for the flexibility of this modular interior. As a result of the modularity, each setup can be laid out in various ways.

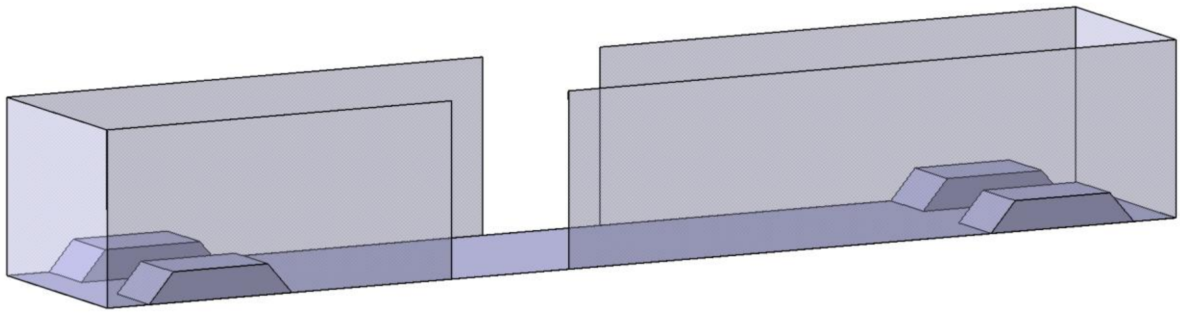


Figure 37: Usable interior space with wheel wells and door cut-outs

In the following, possible layout configurations for each setup are presented. To focus on the interior, the usable interior space is simplified as a box with the inner dimensions of the larger vehicle variant. This box is shown in Figure 37. The doors are positioned in an offset, they are not directly opposite to each other. This allows a multi-use area to be placed directly opposite of the door including folding seats with integrated bike racks and belts to secure wheelchairs and prams to. So, passengers do not have to travel far or around tight corners inside of the vehicle to reach their designated spaces. A short and straight path leads to their designated accommodations. This is especially comfortable for people with prams, wheelchairs, bicycles or heavy cargo or PRMs. The bumps on the floor on each vehicle corner are wheel wells housing components of the IRW running gear concept. For the wheelset running gear, the floor between the bumps can be raised using ramps or stairs. The interior setups in this deliverable are shown with the IRW concept as this features the more challenging geometry. To work around the wheel wells, seats are arranged on either side of it facing away from the wheel well. The space between the backrests of these seats is used for server racks to house the electronics for the train control and management system (TCMS), the Automated Train Operation (ATO) systems, the control, command and signalling (CCS) systems and more. This enables ease of access for operation and maintenance. Further development is necessary to determine the size and numbers of the server racks as the same space could also be used for additional cargo racks or a small vending machine. Also, the exact location and dimensions of the overhead cargo racks, the desks and the handles are still to be determined.

4.2.3. Tourism Setup

The first setup is tailored primarily to tourists traveling to and from vacation, sightseeing, recreational areas and other tourism hotspots during weekends and holiday season. It is distinguished by a large multi-use area to accommodate multiple bicycles and bigger luggage. Also, four-seater groups are installed to encourage social interaction as tourists are more likely to be travelling in groups. Additional luggage space using designated racks and overhead storage can be installed as tourists tend to have more luggage as they possibly stay along over extended periods of time. As the travel time for tourists is expected to be longer, a vending machine is installed to offer snacks and drinks. In the figures, the front of the vending machine is pictured as an indent.

4.2.3.1. Tourism layout 1

The first layout of the tourism setup is shown in Figure 38. This configuration provides a total of 39 seats, with 24 fixed seats and 15 folding seats. It offers three wheelchair spaces that can also be used to secure bikes, prams or luggage. In addition, a vending machine and a cargo rack is installed. The centre of the vehicle is designated as a large multi-use area, equipped with foldable seats, providing the wheelchair spaces. On the left side of the vehicle, left of the folding seats, half-height partitions with folding tray tables for the fixed seats on the opposite side are installed. These partitions create a barrier between the fixed seats and the multi-use area, to prevent loose cargo from hitting the sitting passengers. It is also usable as a rest to lean and secure wheelchairs, prams, bikes and large luggage to. The vending machine is placed to the right of the vehicle. In front of the vending machine, a designated space for customers is created by framing the machine with an opposing partition with handles, so that the vending machine can be used without disturbing other passengers passing by. On the other side of the vending machine is a cargo rack for bigger luggage. Depending on the spacing of the seats, some of them can be equipped with foldable tray tables and armrests.

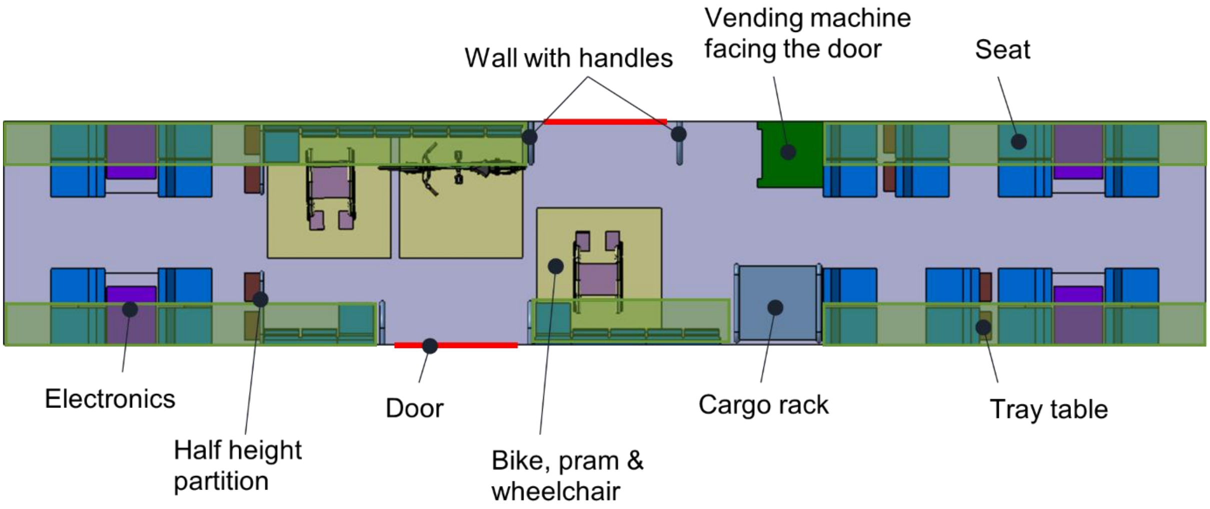


Figure 38: Top-down view of Tourism Setup, Layout 1

4.2.3.2. Tourism layout 2

Another layout is created by relocating the vending machine to the left and rotating it by 90 degrees, so that it faces the aisle. This enables the placement of more seats, but the passenger using the vending machine are now standing in the aisle possibly disturbing other passengers. As the machine is not in the middle of the vehicle anymore, it is less obvious and possibly harder to find and reach. On the other hand, fewer people need to go past it to reach seats, as there are less seats beyond the vending machine. Also, opposite of the vending machine there are now fixed seats, so in front of the vending machine there will be less traffic. In this layout, the free space created by moving the vending machine is used to increase the number of fixed seats to a total of 42 while still providing the minimum number of wheelchair spaces. Of the 42 seats are 30 fixed, 12 are folding seats. This layout is shown in Figure 39.

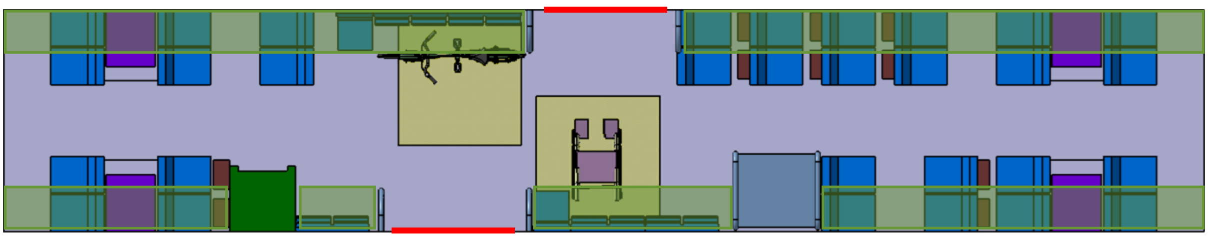


Figure 39: Top-down view of Tourism Setup, Layout 2

4.2.3.3. Tourism layout 3

The free space created by moving the vending machine can also be equipped with additional folding seats if a bigger multi-use area is needed. This layout is shown in Figure 40. It leaves passengers a wider space in front of the cargo rack, improving the accessibility of the luggage rack. Also, it increases the multi-use area, while still ensuring the necessary capacity of two wheelchair spaces. The seat configuration decreases by one seat, supplying 41 seats in total, 26 of them are fixed.

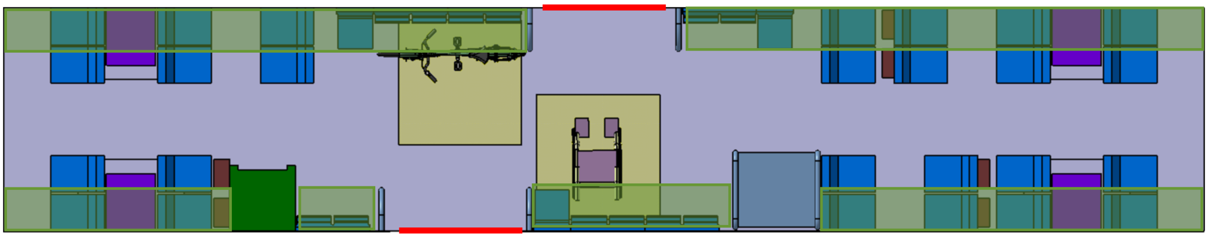


Figure 40: Top-down view of Tourism Setup, Layout 3

4.2.3.4. Tourism layout 4 with restroom

Especially for long travel times, regional vehicles are often equipped with a restroom providing a toilet, a changing table, a sink and in general a private safe space. On one hand, this increases passenger comfort and enables long travel times, on the other hand due to its large footprint a significant number of seats have to be removed for it to fit inside of the train. Figure 41 shows a layout with a PRM-compliant toilet as they are used in common regional trains. The regulations do not specify an exact footprint of the restroom, but its interior has to be big enough to be used independently by person with a wheelchair. Therefore, the interior space of the restroom must be at least 1.5 m x 2.2 m, so that a wheelchair user is able to enter and navigate the space. The entrance door of it must be at least 0.8 m wide. To operate the restroom and especially the toilet, additional systems such as fresh water, waste disposal, electricity and more, are needed, enlarging the footprint even more. To fit a common restroom into the interior design, up to half of the fixed seats have to be removed.

Figure 41 shows a possible layout including a restroom. The vending machine is facing the side to again create a space for the user away from the aisle. This however is again a trade-off between ease of use for the vending machine and reduced number of seats, as a rotated vending machine makes room for additional seats. Ultimately, building in four-seater groups is difficult, due to low space capacity. Nevertheless, this configuration still provides three wheelchair spaces and 36 seats, 16 of which are fixed.

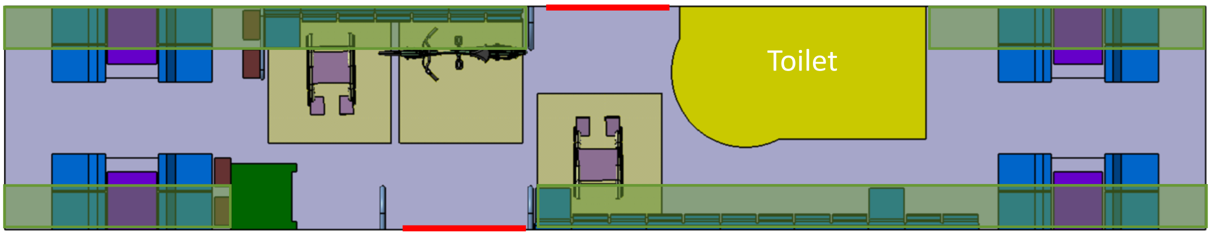


Figure 41: Top-down view of Tourism Setup, Layout 4

4.2.4. Commuter Setup

The second setup is specialized for people commuting to and from work, university, school or similar. Therefore, this setup is more likely to be used during workdays. We expect this setup to see lots of passengers traveling shorter distances, so travel time is shorter. Therefore, a lot of standing space and folding seats are needed as they offer more time efficient change of passengers. Commuters tend to carry less luggage, but the number of bicycles, prams and wheelchairs could be higher as general passenger numbers are higher. Additionally, workplaces with desks and privacy are provided for passengers wanting to use their commute to work. The seats in the private section have to be reserved prior to the commute.

4.2.4.1. Commuter layout 1

The first layout of the commuter setup shows Figure 42. On the left side of the vehicle is a removable wall, which partitions off a separate section on the left end of the vehicle. This section has less but more comfortable seats equipped with desks to create a quiet and more private space to work in. In the middle of the vehicle is a spacious multi-use area, which allows at least four wheelchair users or multiple bicycles to fit in. On the right side of the vehicle are fixed seats with additional folding desks. This configuration counts a total number of 44 seats, of which 20 are fixed.

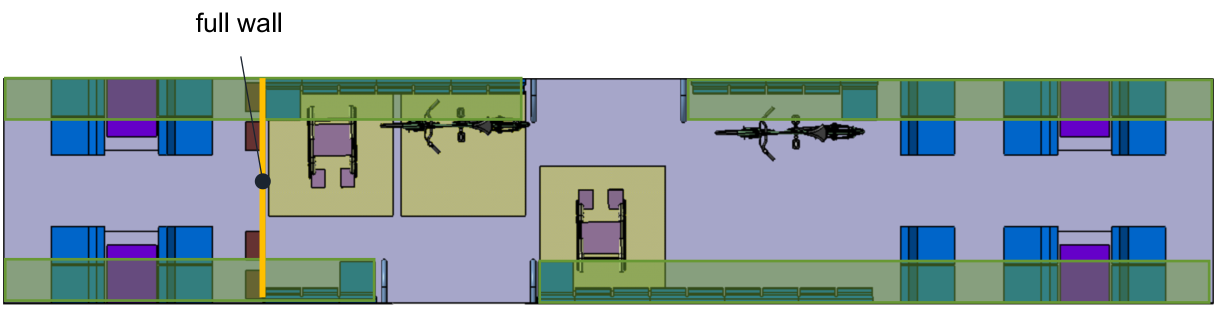


Figure 42: Top-down view of Commuter Setup, Layout 1

4.2.4.2. Commuter layout 2

A portion of the multi-use area on the right side of the train can be substituted for additional fixed seats with desks raising the number of workplaces. Figure 43 shows this increase in workplaces. However, the number of wheelchair spaces remains the same, as well as the total number of seats. Exclusively, the number of fixed seats rises up to 24.

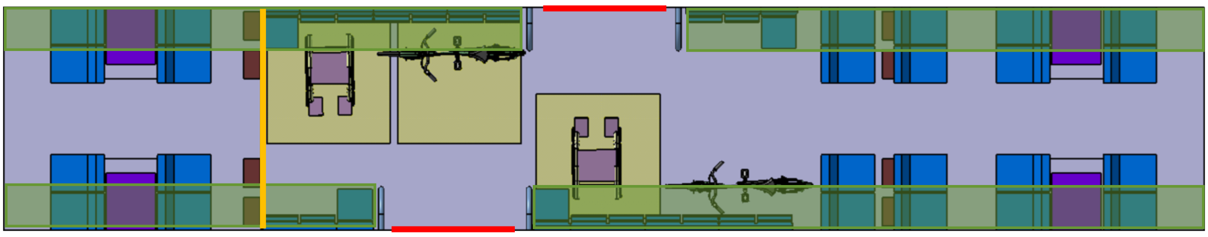


Figure 43: Top-down view of Commuter Setup, Layout 2

4.2.4.3. Commuter layout 3

The private section can be adjusted as needed. It can be expanded by another full wall on the opposite site of the vehicle. Also, moving the full wall adds fixed seats into it. Vice versa, the private section can be reduced, as illustrated in Figure 44. A replacement of foldable seats with fixed seats, leads to a decrease of space in the multi-use area, while still preserving three wheelchair spaces. Comparing to the configurations before, this arrangement holds up to 45 seats, whereas the fixed seats rise up to 30.

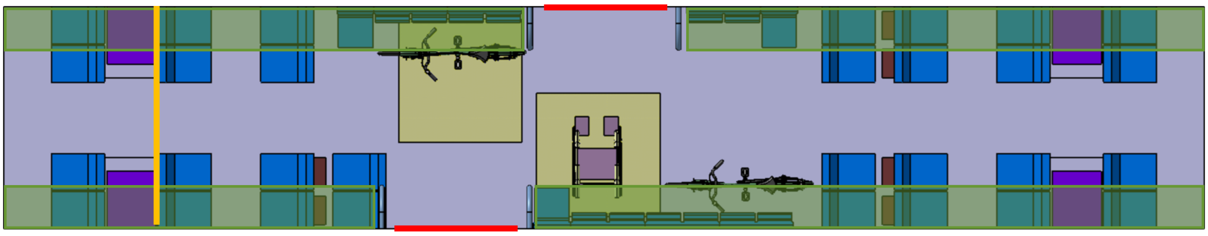


Figure 44: Top-down view of Commuter Setup, Layout 3

The vehicle can be adjusted individually on its area of use. If less passengers wanting to work on the vehicle, the private section can be designed small, as well as the multi-use area can be made bigger.

4.2.5. Cargo Setup

Every seat, rack and wall is mounted to the inner walls, floor and / or ceiling of the train using the same C-rail system, thus the interior of the vehicle can be easily removed except for the server racks. The empty train can be used to autonomously transport cargo to remote locations during periods of lesser passenger volume such as weekends and during nights. A combination of both passenger and freight transport e.g. during weekends is also possible. To do so, a full wall can be added to separate the passenger from the cargo section. Additionally, it protects the freight from unauthorized access, as well as passengers from potential harm due to insufficient secured freight. The railing system can be used to secure the cargo by mounting belt loops. The vehicle is able to fit up to 23 Euro-pallets, as shown in Figure 45. For comparison, a European 40 tonne articulated truck can fit up to 34 Euro-pallets. Other cargo solutions like Euro-boxes, rolling carts or just loose packages are possible, as the c-rail system provides a very flexible cargo security solution. The wheel housings and the server racks at the ends of the vehicle cannot be used for pallets, although smaller cargo or cargo with additional needs like elevated security requirements or cooling can be accommodated here. The doors are dimensioned to fit a Euro-Pallet crosswise for ease of loading and unloading.

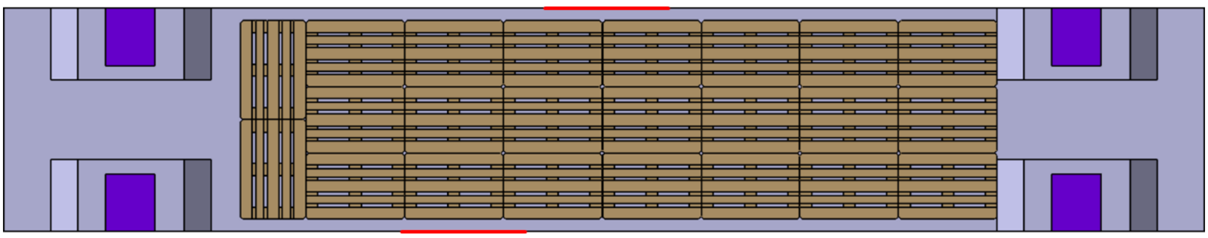


Figure 45: Top-down view of Cargo Setup

4.2.6. Special Setups

In rural areas it is more difficult to provide sufficient medical care, food supplies and other daily needs to the population than in bigger cities. Due to a lower population density, each grocery store, pharmacy and similar businesses have less customers which leads to declining revenue while on the other hand having higher expenses due to more complex supply chains. As a consequence, the distances to grocery stores in rural areas are so big, that it is hard to reach it by foot [36]. in addition, to work in a rural area is much less attractive for medical personnel due to better wages, better promotion prospects and overall better infrastructure provided by bigger cities [37].

In order to counteract these effects, the vehicle can be set up as a mobile, rolling service provider. The vehicle can be equipped with a variety of different interiors, bringing different services autonomously and cost efficiently to remote villages. This is possible due to the vehicle's autonomous drive system, battery system for independence from electrified lines and good electrical power and data supply for a variety of different interiors. Rolling stores, doctor's offices, labs, pharmacies, post offices, libraries, local authority's offices, the list goes on. As an example, two of these additional services, a kiosk setup and a doctor's office are shown in Figure 46 and Figure 47 respectively.

4.2.6.1. Kiosk Setup

The first idea is to set up a kiosk, covering the grocery store as shown in Figure 46. In the middle of the vehicle, a large vending machine is installed, proving passengers with necessary goods. Additionally, a package station covers the post office, offering people to send mail and packages. Vice versa it can be used to deliver mail and packages. The arranged seats offer people to wait to get in line, to consume or to socialize. However, these seats can be replaced by shelves, more vending machines, etc., if necessary. The ends of the vehicle can be designed as storage units for additional supplies, cooled storage for perishable goods or office space for staff, although the vehicle is capable to be run remotely. Similar projects using busses show the demand for such vehicles [38].

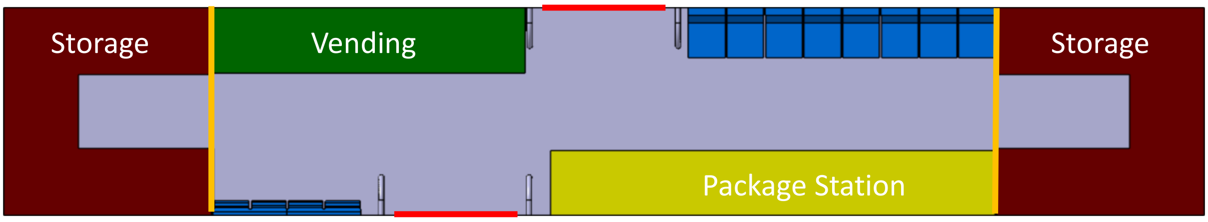


Figure 46: Top-down view of Special Setup, Kiosk

4.2.6.2. Doctor's Office Setup

Another idea to establish the vehicle is as a rolling doctor's office, as shown in Figure 47. This setup gives an overview of the space utilization within the vehicle. Inside, there is enough space for storage, a waiting room for patients, a treatment room with a toilet and an office for the doctor himself. This rolling doctor's office was also realized using a bus [39].

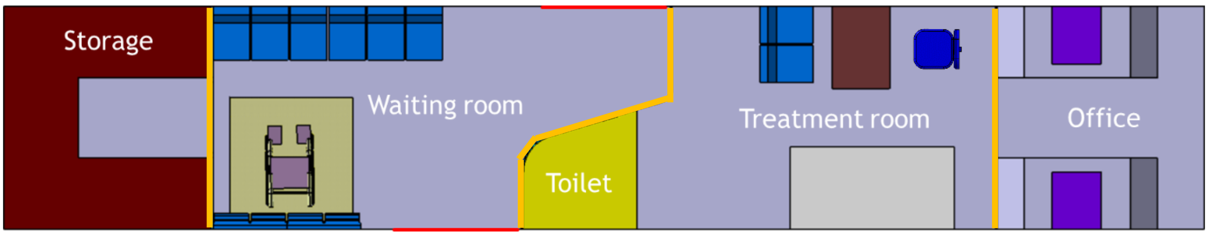


Figure 47: Top-down view of Special Setup, Rolling doctor's office

4.2.7. Interiors: Conclusion

The interior setups presented give an overview of the possible arrangements for different use cases. Due to the C-rail system, the interior design is highly adaptable, enabling operators to customize the interior to a wide variety of passenger needs. Seats, cargo and luggage racks, standing space, spaces for prams, bicycles and wheelchairs can be arranged according to the operators and passengers' needs making the vehicle suitable for different use cases over all Europe with high utilization and efficiency. The low-floor vehicle body keeps every setup easily accessible.

4.3. Door system

On of the first systems to be used by passengers is the door. It has to be big enough to enable easy and fast boarding and alighting for people, wheelchairs, bicycles, luggage and cargo. In addition, the use should be as easy as possible for a wide variety of different people with different needs, different abilities and different luggage.

To keep cost low, a standard COTS double wing door provided by Wabtec Corporation is considered. As the vehicle has only one door per vehicle side, failsafe functionality is mandatory in case of an emergency. So, the door control system is redundant, as this complex electronic system is the most likely to cause failures. The door has a free width of 1300 mm, so a Euro pallet can fit through it lengthwise or crosswise. The free height is 2000 mm. To increase visibility for visually impaired passengers, the doors have to contrast greatly from the rest of the vehicle. A ramp or step is not necessary due to the floor height of 550 mm being very close to most platform heights in use on rural lines, which simplifies the door system and also decreases costs. For actuation, both automatic control and push buttons are utilized as both options are preferred by some user groups.

4.4. HVAC

The Heating, Ventilation and Air-Conditioning (HVAC) system for a small lightweight vehicle should be aligned with the environmental stress and equally with the thermal comfort of the passengers. For this purpose, a thermal wagon model was built, which was adapted to a small vehicle (50 passengers) and a larger vehicle (121 passengers).

4.4.1. HVAC Boundary Conditions

The HVAC boundary conditions are mandatory for the modelling. The preliminary boundary conditions of the vehicle can be seen in the following table.

Table 14 Relevant specifications for simulation of the FutuRe rolling stock

	Small Config.	Large Config.	Annotation
Number of Passengers	50	121	
Dimensions (L x W x H)	10.6 x 2.8 x 2.2 m	16 x 2.8 x 2.2 m	
Wall Area	94.8 m^2	156.6 m^2	Material: Aluminium alloy
Window Area	26.4 m^2	39.65 m^2	Material: Glass
K-value	Walls: 2 W/m^2K Windows: 2 W/m^2K	Derived from [40] Derived from [40]	
Heat Transfer Coefficient	Inside: 10 W/m^2K Outside (parking): 10 W/m^2K Outside (moving): $7.14 * v^{0.78}$ W/m^2K	[41]	

Solar Irradiation	Wall: 70 % absorbed, 0 % transmitted, 30 % reflected Window: 0 % absorbed, 30 % transmitted, 70 % reflected	Roof + 1 x Sidewall Roof + 1 x Sidewall	
Air Speed at Vehicle Surface (v)	Parking: 10 km/h Moving: 70 km/h		

As the reference normative framework, the EN 50591 [42] standard is used, which provides information on how to calculate the annual energy consumption of rail vehicles by means of measurement or calculation. The standard provides 16 operational points (see Table 15) in which the energy demand of the HVAC system can be calculated.

Table 15 Operating point according to EN 50591 for summer and winter zone II [42]

Operating Point:		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ambient Temperature	°C	-10	0	10	15	22	28	35	-20	-10	0	15	22	35	0	15	28
Relative Humidity	%	90	90	90	90	80	70	50	90	90	90	80	80	50	90	80	50
Occupancy	%	0	100	50	50	100	100	100	0	0	0	0	0	0	0	0	0
Solar Load	W/m^2	0	0	0	0	0	600	700	0	0	0	0	0	700	0	0	700

4.4.2. Thermal vehicle body model

To model the HVAC energy demand of the LWRV, a thermal vehicle body model (TCBM) was built up in Dymola including all known vehicle parameters (see Table 2) as well as the relevant standards (EN 14750-1). The TCBM is shown in Figure 48. It contains the following parts: passenger compartment (orange), HVAC system with temperature control and dehumidification (blue), heat transfer with environment via walls and windows (green), solar irradiation (red) and passenger heat and vapor emission (grey). Furthermore, the vehicle is assumed to be fully airtight, and no door openings are assumed for the calculations.

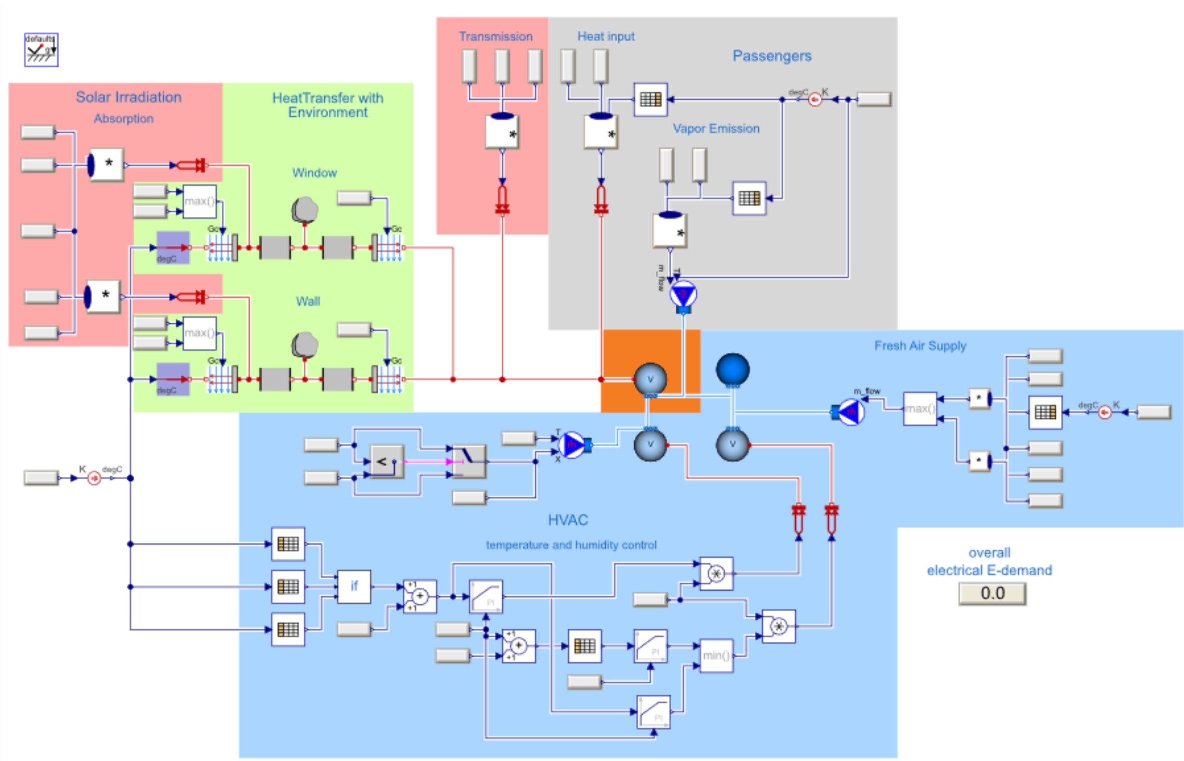


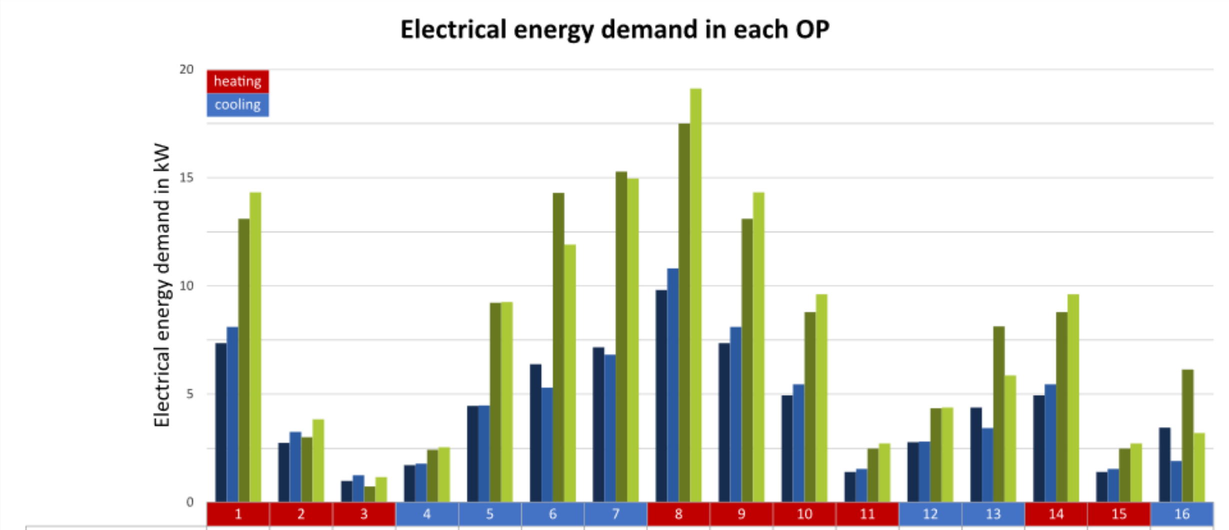
Figure 48 Dymola HVAC model [43]

The model is used to calculate the thermal energy demand in each OP. To obtain the electrical energy requirement, a constant coefficient of performance2(COP) of 2 is chosen for cooling mode as a first approach. For heating a COP of 1 is assumed. These empirical values are derived from expert knowledge from the FutuRe project. However, the electric energy demand calculated does not account for any additional auxiliaries such as the doors, cabin and exterior lighting, passenger information systems and other. [43]

4.4.2.1. Electrical Energy Demand

Figure 4 provides the electrical energy demand for the small and large vehicle configuration calculated by the TCBM. Operating points for cooling operation are highlighted in blue and for heating operation in red. For cooling OP 7 is the most demanding. For heating the most demanding OP is OP 8. Furthermore, it can be seen that moving the vehicle generally leads to a higher energy demand in winter (heating), as more heat is extracted from the vehicle body by the moving air. In summer operation (cooling), the additional airstream from the driving velocity can reduce energy demand.

[2] Ratio between the heating/cooling capacity generated and the electrical power used.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Small config. - parking	7.35	2.75	0.98	1.71	4.45	6.38	7.16	9.81	7.35	4.94	1.39	2.78	4.37	4.94	1.39	3.44
Small config. - moving	8.10	3.26	1.25	1.79	4.48	5.30	6.82	10.81	8.10	5.45	1.54	2.80	3.43	5.45	1.54	1.90
Large config. - parking	13.10	3.01	0.73	2.42	9.22	14.29	15.28	17.50	13.10	8.79	2.48	4.34	8.13	8.79	2.48	6.14
Large config. - moving	14.32	3.83	1.16	2.54	9.26	11.90	14.97	19.12	14.32	9.62	2.71	4.38	5.86	9.62	2.71	3.20

Operating point

Figure 49 Electrical energy demand in each OP for the large and small FutuRe vehicle [43]

4.4.2.2. HVAC System Dimensions

Different approaches can be taken to find a suitable air conditioning unit for the FutuRe vehicle. One approach is to purchase existing systems, such as the modular air conditioning system "MACS 8.0" from Liebherr-Transportation Systems [44], shown in Figure 50 (left). This particular system is modular, meaning that multiple units can be combined to achieve the needed heating and cooling capacity. One unit can provide 8 kW of heating and cooling, so four of those units could be combined to provide sufficient heating and cooling for the large FutuRe rolling stock configuration. The smaller configuration would only need 2 MACS systems. One MACS module weighs around 125 kg (0.064 kW/kg) and measures 1 x 1.6 x 0.22 m (L x W x H; 22.73 kW/m^3). This translates to a weight of 250 kg and 500 kg for the small and large FutuRe vehicle.

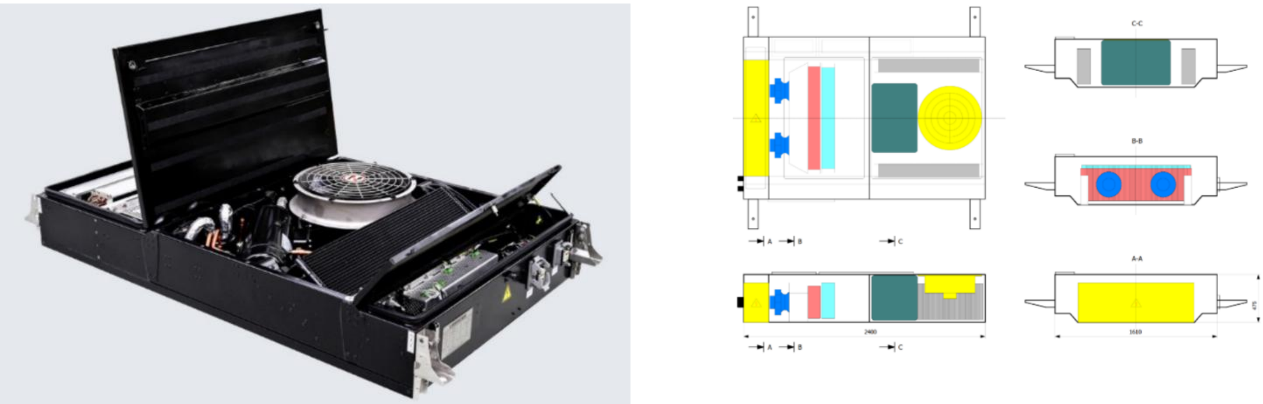


Figure 50 left: Liebherr-Transportation Systems MACS 8.0 HVAC unit (left) [44] right: Wabtec HVAC System for large vehicle configuration (Source: Wabtec)

Another approach is to develop a HVAC unit which directly suits the needs of the vehicle. Such a system could look like the one shown in Figure 50 (right). This system was drafted by Wabtec and would suit the large FutuRe vehicle's needs. It can provide 30 kW of cooling and 22 kW of heating capacity, while measuring 2.4 x 1.61 x 0.475 m (L x W x H; 16.3 kW/m^3 cooling; 12.0 kW/m^3

heating). The weight is approximately 500 kg (0.060 kW/kg cooling; 0.044 kW/kg heating).

Comparing the specific weight and volume of the two systems shown, it can be observed that directly developing a system to suit the vehicles needs can have benefits regarding weight and volume of the system. Furthermore, installing multiple MACS system will also lead to higher system complexity and perhaps maintenance effort/cost, due to each system having its own cooling cycle. However, using a modular system might bring lower costs compared to a newly developed one.

5. Train control system architecture

This document provides a comprehensive technical overview of core concepts related to modern railway systems, including Automatic Train Operation (ATO), Train Control and Monitoring System (TCMS), European Train Control System (ETCS), and associated technologies. It has been formulated for the purposes of technical design and partner presentation, aiming to establish a solid technical foundation for future development and implementation.

5.1. Automatic Train Operation (ATO)

Automatic Train Operation (ATO) is an operational method that automates defined elements of train driving in accordance with specified Grades of Automation (GoA). The primary objectives of ATO are to reduce energy consumption, increase line capacity, and improve timetable adherence and punctuality.

Grades of Automation (GoA) define the distribution of responsibilities between human personnel and automated systems. GoA1 (non-automated train operation) corresponds to conventional driving, where the train driver is fully responsible for traction, braking, and ensuring safe train movement. GoA2 (semi-automated train operation) introduces an ATO onboard system (ATO-OB) that automatically manages traction and braking, including accurate station stopping, while the driver remains present to supervise the system. ATO over ETCS for GoA2 has been standardized within Shift2Rail and incorporated into the 2022 Technical Specifications for Interoperability (TSI). GoA3 (driverless train operation) enables automated driving without an active driver; trained staff may still be present onboard, but they do not directly control the train. GoA4 (unattended train operation) represents full automation with no staff present onboard under normal operating conditions. GoA3 and GoA4 require fundamental changes in system architecture, as driver responsibilities must be replicated through technical functions in the absence of continuous human intervention.

Reliable ATO operation depends on several infrastructure and system prerequisites. Operational data from the Traffic Management System (TMS) is required to maintain compliance with the working timetable. Infrastructure-related data from wayside systems is needed for the calculation of optimal speed profiles. Accurate train localization is required both for speed profile calculation and for precise stopping at platforms. In higher Grades of Automation, particularly GoA3 and GoA4, environmental perception is required to replace human situational awareness; this includes the ability to detect obstacles and interpret the operational environment. Continuous communication between onboard and trackside systems must be ensured, using interfaces defined in relevant standards such as the SUBSET specifications.

ATO forms part of a broader system-of-systems architecture and must be integrated with other core subsystems. Within ETCS (the European Train Control System), ATO operates on top of the Automatic Train Protection (ATP) layer. ATO itself is not safety-critical; all safety-related supervision and enforcement are handled by ETCS. ETCS supervises train movement, monitors speed, and enforces permitted movement authority, while ATO commands traction and braking within the safe operational limits enforced by ETCS. The interface between the ATO onboard unit (ATO-OB) and the ETCS onboard unit (ETCS-OB) is formally defined in SUBSET-130.

ATO also interfaces with the Train Control and Monitoring System (TCMS), which manages functions such as traction control, braking, and door operation. For higher Grades of Automation, the Automatic Processing Module (APM) functions as the effective "brain" of the virtual driver, issuing operational commands to TCMS. Integration of ATO requires adaptation of locomotive TCMS implementations according to SUBSET-139, which defines the signals exchanged between the ATO-OB and the rolling stock subsystems. A key challenge in this area is the definition of a fully standardised, interoperable Plug & Play interface to support retrofit integration with differing TCMS architectures across fleets.

In addition, the trackside ATO component (ATO-TS) interfaces with the Traffic Management System (TMS). Through this interface, dispatcher tasks such as route setting and train regulation can be partially or fully automated.

The logical architecture of ERTMS/ATO for higher Grades of Automation, including GoA3 and GoA4, consists of multiple functional components. The Automatic Driving Module (ADM) is the onboard module responsible for direct control of train movement, including traction and braking. The Automatic Processing Module (APM) represents the core decision-making logic of the virtual driver and is responsible for mission execution and handling abnormal or degraded situations. The Perception Module (PER) replaces the visual and spatial perception of a human driver using sensor fusion. The Repository (REP) serves as the onboard data hub, collecting, validating, structuring, and distributing relevant information. The Localization (LZ) function provides odometry and positioning data to support precise movement control and stopping accuracy in accordance with operational requirements.

5.2. Train Control and Monitoring System (TCMS)

The Train Control and Monitoring System (TCMS) functions as the onboard "brain" of the train. It is implemented as a distributed control system that provides a centralized platform for monitoring and controlling all train subsystems. TCMS is responsible for integrating all onboard functions, collecting diagnostic data, and managing degraded operational modes.

TCMS covers a broad set of functions that are critical for safe and efficient train operation. In the area of traction and braking control, TCMS interprets speed and braking requests from the driver or from the Automatic Train Operation (ATO) system and applies the required traction or braking effort. In higher Grades of Automation (GoA3/4), TCMS assumes full responsibility for traction and braking control. TCMS also manages auxiliary systems such as doors, lighting, HVAC (heating, ventilation, and air conditioning), wipers, and horns. It continuously monitors performance parameters, collects error codes, evaluates the health status of onboard subsystems, and supports troubleshooting processes through diagnostics and monitoring. As part of train configuration management, TCMS automatically detects coupling and uncoupling of train units, determines the resulting logical train topology, and ensures coordinated braking across the consist. TCMS further supports passenger-facing services, including the Passenger Information System (PIS), by generating announcements and presenting station and service information. In addition, TCMS records legally relevant and safety-critical operational data, and it provides communication and information services towards ETCS and other external infrastructure systems.

From an architectural perspective, TCMS can be organised in a centralized or decentralized configuration. In a centralized architecture, control is handled by a single central computer. This approach is conceptually simple but requires extensive wiring, increases weight, and creates a single point of failure. In a decentralized (distributed) architecture, control is shared among several cooperating units installed throughout the train. This approach significantly reduces cabling by applying a "drive-by-data" concept, with associated benefits in reduced weight and cost, improved modularity and scalability, and higher resilience. Its drawbacks include increased design complexity and a greater reliance on reliable real-time synchronization and communication. Modern TCMS implementations typically combine centralized decision logic with physically distributed subsystems.

TCMS must comply with the European interoperability framework, specifically the Locomotive and Passenger Rolling Stock Technical Specification for Interoperability (Loc&Pas TSI) and the Control-Command and Signalling Technical Specification for Interoperability (CCS TSI). Applicable international standards include IEC 61375, which governs open onboard communication networks under the Train Communication Network (TCN) framework, and EN 50126 / EN 50128 / EN 50129/ EN 50716, which define requirements for functional safety, including safety-relevant functions up to Safety Integrity Level 4 (SIL4). System redundancy, including measures such as dual communication links and ring topologies, together with comprehensive diagnostics, is essential to ensure fault tolerance. Cybersecurity is an increasing priority within TCMS, and is addressed through network segmentation, firewalls, encryption, and continuous security monitoring.

5.3. ATO Integration into TCMS

The integration of Automatic Train Operation (ATO) into the Train Control and Monitoring System (TCMS) is essential for achieving higher Grades of Automation (GoA3/4). At these automation levels, TCMS must assume tasks that have historically been carried out by a human driver. In this role, TCMS effectively functions as a "digital driver" within the broader ATO and Automatic Train Supervision (ATS) architecture.

This integration is based on both functional and communication interfaces. From the functional perspective, the Automatic Processing Module (APM) issues instructions to the TCMS to execute operational tasks. TCMS then carries out automated actions such as traction control, braking, and door operation, using data provided by the Automatic Driving Module (ADM) and APM. TCMS is expected to support delayed door closure commands initiated by ADM and, in GoA3/4, to isolate a specific coach by locking its internal doors upon request from the APM.

From the communication perspective, the primary interface is defined in SUBSET-139, which specifies the ATO Onboard (ATO-OB) to Rolling Stock Functional and Physical Interface Specification (FFFIS) at the application layer. This interface covers the exchange of signals related to traction, braking, and door control. TCMS may also be awakened via the C48 interface. In addition, remote control clients (RC-Client) may request access to the Driver Machine Interface (DMI) of TCMS, ATO, and the Automatic Train Protection (ATP) subsystem, including ETCS, for the purpose of remote operation.

Several implementation challenges remain. Legacy rolling stock requires specific adaptations to allow installation of ATO-OB, due to differences in existing vehicle control architectures. Although interface interchangeability between different suppliers has already been demonstrated, a fully standardised, retrofit-ready Plug & Play interface for TCMS integration is still not completely established. Furthermore, ATO specifications must explicitly address freight train requirements, including traction and braking characteristics, and the handling and supervision of train integrity.

5.4. European Train Control System (ETCS) and ATO over ETCS (AoE)

The European Train Control System (ETCS) is the foundational element of Europe's unified railway traffic control architecture and serves as the Automatic Train Protection (ATP) system. Its primary function is to ensure the safe movement of trains across the network by supervising train speed, enforcing movement authorities, and managing braking.

ETCS operates in several defined levels. At Level 0 (L0) and Level 1 (L1), ETCS provides basic supervision on legacy infrastructure or relies on balise-based updates of movement authorities, where information is transmitted to the train at fixed locations. ETCS Level 3 (L3), also referred to as Moving Block, enables dynamic train separation. By moving away from fixed block sections, Level 3 supports higher capacity, lower infrastructure cost, and increased operational reliability. This level is designed to support Automatic Train Operation (ATO) up to Grade of Automation 2 (GoA2).

ATO over ETCS (AoE) is an operational concept in which ATO functions are deployed on top of ETCS. Under this arrangement, ETCS is responsible for all safety-related aspects of train control, including speed supervision and enforcement of permitted movement, while ATO manages automatic driving commands such as traction and braking within the safety envelope provided by ETCS. The objective of this concept is to enable automated driving in ETCS-equipped areas while maintaining full interoperability.

An interoperable ATO over ETCS solution for GoA2 has been standardised within the Shift2Rail programme and incorporated into the 2022 Technical Specification for Interoperability for Control-Command and Signalling (CCS TSI). The onboard functional interface between ATO and ETCS is formally defined in SUBSET-130. Ongoing work within the X2Rail-4 ATO project aims to update these specifications and extend ATO over ETCS concepts toward higher Grades of Automation, including GoA3 and GoA4.

Interoperability is a core requirement for ATO over ETCS. Trains equipped with ATO from one supplier must be able to operate on infrastructure equipped with ETCS/ATO from another supplier. Pilot implementations of GoA2 operation have demonstrated both interoperability and cross-vendor compatibility in practice. The specification covering GoA2 ATO over ETCS has been included in the 2022 CCS TSI, providing a regulatory and harmonised framework for deployment.

5.5. Technical Specifications for Interoperability (TSI)

The Technical Specifications for Interoperability (TSI) are mandatory legal standards of the European Union that define the technical and functional conditions necessary to achieve interoperability across the EU railway system. Their purpose is to ensure technical compatibility of subsystems and to enable seamless cross-border operation.

Several TSI documents are directly relevant. The Locomotive and Passenger Rolling Stock TSI (Loc&Pas TSI, also referred to as the Rolling Stock TSI) specifies requirements for the vehicle subsystem, including the Train Control and Monitoring System (TCMS), braking performance, fire safety measures, and pantograph systems. The Control-Command and Signalling TSI (CCS TSI) defines interoperable interfaces for onboard safety systems such as ERTMS/ETCS; the ATO over ETCS (AoE) specification for GoA2 has been formally included in the 2022 revision of the CCS TSI. The Operation and Traffic Management TSI (OPE TSI) sets the operational rules governing the use of the system in service.

The application of these requirements is structured and method-driven. TSIs require that risk analysis be carried out in accordance with EN 50126. Systems such as TCMS must comply with EN 50126, EN 50128, and EN 50129 with respect to functional safety, and with EN 50159 for secure and reliable data communication. The Common Safety Method for Risk Evaluation and Acceptance (CSM-RA) must be applied for all significant changes to assess and justify safety. Cybersecurity requirements are addressed through standards such as CLC/TS 50701 and IEC 62443. TSIs also explicitly require that trainsets intended for multiple working (i.e. operation in coupled formations) must act as a coherent functional unit, which enforces strict requirements on reliable and interoperable train-wide communication.

5.6. Autonomous Train Operation (GoA3/4)

The terms “Automatic Train Operation” (ATO) and “Autonomous Train Operation” or “Autonomous Rail Operation” refer to different degrees of automation and self-sufficiency in railway operations. Autonomous operation (GoA3/4) represents a higher objective that requires the extension and augmentation of traditional ATO functions, both in normal service and in degraded or exceptional scenarios.

Autonomous railway operation (often referred to as GoA3/4) is understood as the operation of trains without a driver and without the presence of onboard human assistance during normal daily operation. The objective is to increase the efficiency, capacity, and sustainability of rail transport through advanced automation. This direction is one of the main strategic goals of European research and innovation programmes such as Shift2Rail, which declare, among other targets, up to 50% improvement in punctuality and reliability, as well as a doubling of overall rail network capacity.

The key characteristics of autonomous operation can be summarised as follows. The first principle is the absence of human onboard staff: autonomous operation aims to eliminate the need for a physical driver or onboard crew. The second principle is the full transfer of responsibilities: in order to operate a train without a driver (GoA3/4), all tasks that were previously performed manually by the driver must be replaced either by automated functions or by remote control. The third pillar is technological readiness. Projects such as TAURO (Technologies for the Autonomous Rail Operation) are focused on the development of technologies that will enable the real-world deployment of unattended rail operation, in particular in the areas of environmental perception, remote operation, and automated condition diagnostics.

The architecture of autonomous operation is built on several core concepts. One such concept is “virtual coupling” (Virtual Coupling, VCTS – Virtual Coupling Train Set), which allows multiple vehicles to operate as a dynamically controlled group without relying on fixed block separation. This concept minimises headways and overcomes the so-called “braking wall,” i.e. the limit defined by braking distance, and relies on distributed intelligence and continuous data exchange between all moving units. For higher Grades of Automation (GoA3/4), the key onboard components include the Automatic Processing Module (APM), which functions as the decision-making core of the virtual driver; the Perception Module (PER), which provides real-time perception of the surrounding environment through sensor systems; and the Repository (REP), which ensures the collection, processing, and distribution of operational data. A digital map is also an essential element, providing a structured representation of the static infrastructure and operational environment.

The fundamental distinction between ATO (Automatic Train Operation) and fully autonomous operation at GoA3/4 lies in the system's capability to handle degraded modes and fault conditions autonomously, i.e. without the immediate intervention of a human driver. Classical ATO (for example in GoA2) automates traction and braking within the safety envelope defined by ETCS but still assumes the physical presence of a human supervisor who can take over in abnormal situations. Autonomous operation, by contrast, assumes that even in exceptional conditions, in the event of a failure, or when normal behaviour is disrupted, the system can ensure safe response and continued control without a human physically on board.

In this context, Remote Driving becomes a key element of autonomy at GoA3/4 because it complements and extends ATO functionality. Remote Driving is applied in four main types of situations. First, in the event of ATO failure: if the GoA3/4 system, and in particular ATO, becomes dysfunctional, it is essential that a remote operator be able to take control of the train. Second, for operation under degraded conditions: if a degraded ATO situation occurs in which ATO is no longer capable of safely guiding the train, a remotely present driver must be able to assess the situation and intervene. Third, for shunting movements in classification yards and depot areas, where fine manoeuvring is required. Fourth, for depot transfers and depot operations, where remote operation is already being trialled in tramway and urban rail environments.

For these reasons, systems intended for autonomous operation at GoA3/4 must be complemented by new automatic diagnostic and recovery functions (auto-recovery), as well as by a robust remote driving system. This capability is typically implemented by components such as RC-Client / RC-OB (Remote Control Onboard) and RC-Center / RC-TS (Remote Control Trackside), which allow a remote driver to assume full control of the train as if physically seated in the cab. In the event of an ETCS or ATO failure, operational recovery can be performed remotely via a Control Centre, which uses a train–ground communication system to supervise and manage the movement of the vehicle.

Before autonomy can be deployed at scale, several categories of challenges must be resolved. From a technical perspective, this includes sensor redundancy using LIDAR, RADAR, and camera systems for object detection and classification; precise localization of position and speed; reliable real-time communication with clearly defined fallback modes; and the implementation of the Digital Automatic Coupler (DAC) of the fifth generation, which shortens brake reaction times and therefore braking distances. From an operational perspective, the rail network must be able to support mixed traffic in which GoA2 services share infrastructure with GoA3/4 services, as well as the management of non-communicating vehicles in ETCS Level 3 environments, adaptation to the human factor (in particular, resistance from drivers to handing over control to the system), and robust degraded mode management. From a legal and regulatory perspective, autonomous railway operation must comply with the applicable Technical Specifications for Interoperability (TSI) and with the European safety framework in order to demonstrate that safety, responsibility, and interoperability requirements are met in real-world operation.

5.7. Key System Components

Modern railway systems depend on an integrated suite of hardware and software components that operate together to support control, supervision, safety, and automation. The Human/Driver Machine Interface (HMI/DMI) provides the primary interaction point for drivers and onboard staff, typically through multifunctional displays. In autonomous or semi-autonomous systems, this role extends to a remote operator interface that supports remote train supervision and, where permitted, remote train control.

Input/Output (I/O) modules serve as modular interfaces between the physical world and the Train Control and Monitoring System (TCMS). They convert sensor signals and actuator commands into structured data and control messages usable by higher-level control logic. The overall system relies heavily on sensors, which are critical to both perception and positioning. Perception sensors such as RADAR, LIDAR, and camera systems provide object detection and support visual inspection of the environment. Localization sensors include speed sensors, encoders, inertial measurement units (IMUs), balise readers, and satellite positioning (GPS), ensuring accurate train position and speed determination. Safety-related sensors and subsystems include Collision Detection Warning Systems (CDWS), Train Integrity Monitoring Systems (TIMS), and Cold Movement Detectors (CMD), which ensure that unsafe train movements are prevented and that train integrity is continuously monitored.

Communication with external infrastructure is provided by dedicated communication gateways such as the Mobile Communication Gateway (MCG). This gateway connects TCMS to the ground-based systems and allows bidirectional data exchange using technologies such as GSM-R/FRMCS, 4G/5G, Wi-Fi, and GPS. To ensure fault tolerance and continuity of operation, modern rolling stock typically deploys redundant units, including dual central control units (CCUs), redundant communication links, and safety-certified CPUs and I/O modules designed to meet high Safety Integrity Level (SIL) requirements.

Time synchronization is a foundational requirement for reliable and deterministic onboard communication. Time-Sensitive Networking (TSN) and precise master clock distribution are used to guarantee that data exchange and control commands occur in real time with consistent timing behaviour across the train. The system also depends on controlled data flow and prioritization. The Repository (REP) is responsible for data aggregation and distribution across subsystems. Within the unified IP-based onboard network, strict data security measures and service-level prioritization mechanisms are required to ensure that critical control and safety-related data streams are transmitted with the highest priority and are protected against interference or unauthorised access.

5.8. Future Vision and Technology Trends

The following section provides a consolidated summary of the vision emerging from the projects and initiatives described above, with a focus on concepts that are transferable to future and follow-up solutions. The future of rail transport is shaped by the transition toward higher automation levels, full digitalization, and enhanced interoperability. These developments converge into a smart, connected railway ecosystem.

System harmonization, digitalization, and cybersecurity are the central enablers of this transformation. Harmonization efforts led by programmes such as Shift2Rail and the Europe's Rail Joint Undertaking (ERJU) are driving the standardization of interoperable solutions, in particular for ATO over ETCS. Achieving full functional interoperability is a core objective, although harmonization at the application level is not yet complete. Digitalization is advancing through the introduction of the Next-Generation TCMS (NG-TCMS), which defines a unified onboard IP-based digital platform. Rail vehicles are becoming digitally connected nodes within the wider Internet of Things (IoT), supported by the migration from GSM-R to FRMCS (the Future Railway Mobile Communication System), which leverages 5G technologies to increase data throughput. Operational concepts such as “always connected / always reporting” and “cab anywhere” are intended to support autonomous and remotely supervised operations. Virtualization and edge computing make it possible for multiple onboard applications to execute on shared hardware rather than on dedicated physical units, and rolling stock is expected to support Over-the-Air (OTA) software updates as standard capability.

As connectivity expands, cybersecurity becomes a mandatory requirement. The protection of onboard and wayside systems against malware, intrusion, and unauthorised access must be ensured through secure architectures and monitored communication channels. Compliance with standards such as IEC 62443 and CLC/TS 50701 is therefore essential.

Standardization initiatives continue to provide the framework for this evolution. Shift2Rail drives innovation and specification development across the European rail ecosystem. EULYNX focuses on the standardization of signalling interfaces to reduce vendor lock-in and improve cross-border compatibility. The International Union of Railways (UIC) is promoting the RailSystemModel (RSM) to provide a structured, interoperable representation of infrastructure topology and operational relationships.

The outlook for the next five to ten years includes several expected developments. Automation will continue to advance, with ATO evolving toward higher Grades of Automation such as GoA3 and GoA4, supported by specifications that are expected to reach maturity for these levels. Virtual Coupling (VCTS) is being developed to allow virtually coupled trains to operate with minimal separation while behaving as a coordinated unit, dramatically increasing line capacity by overcoming traditional headway constraints. The Next-Generation TCMS is positioned to become the central enabler of intelligent railway operation, orchestrating subsystems and managing the flow of data across the train. ETCS Level 3 Moving Block will focus on reducing the occurrence of non-communicating or disconnected trains and on strengthening coordination between trains. Train Integrity Monitoring Systems (TIMS) will provide continuous supervision of train completeness and train length. In freight, digitalization will be accelerated by the deployment of Digital Automatic Couplers (DAC), which will automate mechanical coupling and at the same time provide onboard electrical power and data connectivity through the consist. Future systems are also expected to support automated self-testing, condition- and mission-based diagnostics, and coordinated health monitoring functions, managed jointly by TCMS and ATO.

The long-term vision for railway systems leads toward flexible, adaptive, and highly integrated infrastructures that maximize interoperability, safety, and efficiency. The overarching aim is to reduce life-cycle costs and ensure a sustainable future for European rail transport.

6. Suggestions for regulatory framework for G1/G2 lines

For small regional vehicles to be more viable and easier to design and certify, the current regulatory framework needs to be adapted. The TSI is very complex and leads to a very high effort and high costs which is hindering the design of a small low-cost regional vehicle. The possibility of a European guideline concerning G1 and G2 line vehicles should be considered. Such a European-wide standardization framework would especially benefit cross-border traffic with uniform vehicle design and certification regulations.

The transformation of regional rail systems in Europe is intrinsically linked to the ability of regulatory frameworks to accommodate technological innovation and to acknowledge its specific needs. The Technical Specification for Interoperability (TSI) LOC&PAS and related standards currently provide a harmonized set of requirements for rolling stock interoperability; however, several constraints remain that may hinder the deployment of lightweight, modular, and digitally integrated regional trains.

This chapter intends to identify key areas in which the TSI LOC&PAS and other norms should be adapted to facilitate a new generation of high-performance, sustainable regional rolling stock.

Additional studies need to be done regarding the project and the traction and braking chapter of the TSI.

A strategic evolution of the TSI LOC&PAS is essential to support the regional railway. These proposed adaptations are fully aligned with performance and safety imperatives.

EN 13749

EN 13749 currently applies to bogie frames with two wheelsets, serving as the load-bearing structure between primary and secondary suspension. Its methodology—covering Technical Specifications, Verification, Validation, and Quality Requirements (Chapters 1 to 7)—is well established and generally formulated, making it broadly applicable. With minor adjustments to wording and scope, it can be extended to running gear frames with only one wheelset or with two independently rotating wheels.

However, the **Annexes** of the standard require specific revisions to address the differences in load cases for these alternative architectures, particularly regarding transverse and longitudinal lozenging forces. The main proposed updates are:

- **Annex C** – *Loads due to bogie running*: Introduce new equations covering vehicle categories B-I to B-IV to reflect the altered force distribution.
- **Annex D (D.2)** – *Component inertia loads*: Include guidance on how to apply the standard to single-wheelset or independent-wheel systems, or modify acceleration parameters as necessary.
- **Annex F** – *Static test programs*: Extend test definitions and equations to include running gears for categories B-I to B-IV.
- **Annex G** – *Fatigue test programs*: Add relevant load equations and potentially new test scenarios for the same vehicle categories.

In summary, while the main body of EN 13749 is largely compatible, the annexes must be revised to reflect the structural and dynamic differences of non-traditional running gear systems.

TSI Loc&Pas – 4.2.24 Strength of the vehicle and 4.2.2.5 Passive Safety

The current structural integrity requirements are based on the EN 12663 standard, which defines and regulates various load cases, forces, and qualification methods for different rail vehicle categories to ensure the safe operation of mechanical structures on rail vehicles. Additionally, the TSI includes a section on passive safety (4.2.2.5) aimed at maximizing passenger and freight protection in the event of a collision. For this purpose, it references the EN 15227 standard, which outlines different collision scenarios for various vehicle types and applications, along with the necessary measures to minimize injuries and fatalities.

Beyond crashworthiness requirements, the structural strength of the vehicle body as specified in EN 12663 remains critically important. This standard defines both operational and exceptional loads according to vehicle category. Loads are generalized per category, with forces acting on the coupler area having a dominant influence on the mechanical design, structure, and weight of the vehicle body. For mainline trains, this force is set at 1500 kN or 2000 kN according to the TSI. Other categories covered by the standards, but not explicitly addressed in the TSI, are subject to lower loads based on specific conditions and use cases.

Using vehicle categories that are capable of operating on mainlines but subject to reduced loads could be suitable, even though this is not currently considered in the TSI. Considering the particular needs of regional lines, an update to both the standards and the TSI might be advantageous to revisions foster innovation in regional vehicle body design and general safety testing.

TSI Loc&Pas – 4.2.8.1 Traction performance

The TSI does not currently define any categorization for hybrid vehicles.
On different topics, the TSI could benefit of some slight addition to clarify some points and add room to latest technological development.

For example, in the 4.2.8.1.2 (10) article "*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.*" The text doesn't explain the safety or performance implications of these limits nor elaborate on the reasoning behind the 50% limit.

For the 4.2.8.2.1, 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. Moreover, there is no information of the requirements for the other systems not listed in the article (AC 25 kV 50 Hz system, AC 15 kV 16.7 Hz system, DC 3 kV system and 1.5 kV system).

7. Conclusions: Bringing fresh concepts for regional rail transportation into focus

The FP6 FutuRe project, funded by Europe's Rail Joint Undertaking, has embarked on an effort to revitalize regional rail transportation, addressing the urgent need for modernization and expansion into marginally viable markets. With a commitment to sustainability, efficiency, and inclusivity, deliverable D10.1 describes the significant strides in developing an innovative rolling stock concept that caters to the diverse needs of passengers, including those with reduced mobility. This concluding overview summarizes the main results and innovations achieved in D10.1, along with their implications for the future of regional rail transportation in Europe.

Mechanical Design and Structural Innovations

The project's mechanical design development has explored two promising structural design types for the vehicle's body: steel-differential and sandwich composite designs. Employing topological optimization and automatic design derivation approaches, the steel-differential design has been optimized for weight reduction and cost-effectiveness while maintaining structural integrity. The sandwich composite design, exploiting the potential of composite materials, aims to further reduce weight and enhance durability, with a thorough examination of material candidates and their interdependencies. Moreover, the deliverable discusses the potential for a hybrid structural design combining the advantages of both steel-differential and sandwich composite approaches, accompanied by the exploration of suitable joining technologies.

Innovative Running Gear Concepts

Lightweight regional rail vehicles impose unique demands on their running gear, prompting the project to evaluate and develop two promising variants: wheelset running gear and independently rotating wheel (IRW) running gear. The wheelset running gear, featuring a conventional fixed wheelset, single motor-gearbox traction system, and two-stage suspension, has been enhanced with active suspension systems to improve ride comfort and curving performance. In contrast, the IRW running gear adopts a more unconventional approach, employing topology-optimized frames and a mechatronic guidance and control system, which promises lower wear and noise emissions, particularly on tracks with small-radius curves.

Advanced Propulsion and Energy Architecture

The propulsion and energy architecture, an absolutely essential system in the vehicle's design, has been examined and optimized. The deliverable describes the evaluation of battery-only and fuel cell and internal combustion engine hybrid powertrain configurations, with a diesel combustion powertrain serving as a reference. Each configuration has been assessed based on costs, emissions, and range, considering relevant tracks and conditions. The batteries analysed employ Lithium Iron Phosphate (LFP) and Lithium Titanate Oxide (LTO) chemistries, while the fuel cell hybrid employs an LTO battery for power balance management. Hybrid battery configurations, such as those combining NMC/LTO or LFP/LTO chemistries, have been found to offer enhanced cost-effectiveness and overall system lifetime. Powertrain configurations incorporating combustion engines burning sustainable fuel from renewable sources are particularly interesting for demanding routes in cold climate zones. Furthermore, the project has developed an economic model to facilitate sensitivity analyses, enabling the assessment of different energy prices and discount rates on the overall results.

Regulatory Framework and Standardization

The deliverable also addressed the current European regulatory framework, proposing simplified Europe-wide guidelines for G1/G2 line vehicles to lower manufacturing costs and foster seamless operation across borders. The current TSI's complexity hinders the design of low-cost regional vehicles, while the TSI LOC&PAS should evolve to support lightweight, modular trains. Standards like EN 13749 require updates to accommodate alternative running gear systems. Additionally, the TSI's vehicle strength and passive safety requirements should be reviewed to facilitate regional vehicle body design innovations, and traction performance guidelines should address hybrid vehicles and future technological developments.

Braking System Innovation

The FutuRe vehicle's braking system prioritizes weight reduction without compromising safety and performance. While the current vehicle concept employs compressed air brakes, the project discusses the potential of airless technologies. The braking system comprises full TSI-compliant braking for G1 vehicles and BoStrab-standard deceleration for G2 vehicles, utilizing a blend of electrodynamic, friction, and magnetic track brakes for emergency and service braking. Automated holding and parking brakes are to be managed by a central control device.

Impact and Future Prospects

D10.1 represents a significant step forward in the development and concretization of the FutuRe regional rail vehicle. It is the author's hope that the project's achievements in mechanical design, running gear development, propulsion and energy architecture optimization, regulatory framework simplification, and braking system innovation will collectively contribute to a more competitive, efficient, and sustainable regional rail sector.

By fostering innovation and collaboration, FutuRe stands at the forefront of a new era for regional rail transportation, one that prioritizes environmental responsibility, operational efficiency, and passengers' diverse needs.

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