



Deliverable D 14.1

Overall Concept Study for Vessel Carrier (and Basic 3D model)

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1 Executive Summary

Within the concept for an intermodal transport system in the Pods4Rail project, this task establishes the conceptual approach for the Carrier Units (or vehicle, vessel), considering the results from work packages 7, 10, 11, 12, and 13. This approach is independent of the specific aspects of rail and road transport, as well as other modes of transport. The aim of this document is to present the common basis for the derivations of the differently required carriers. The main scope of this task lies in the design of the Carrier Units (CU) structure for various applications (rail transport, road transport, ropeway, etc.), drive technology, information and communication technology (ICT), power supply, energy storage, virtual coupling technology, secure attachment between the Transport Unit and the CU, operational flexibility, and so on. This work package develops the conceptual principles for the Carrier Unit.

The methodology of this task includes reviews of functional, technical and user requirements that were set in previous tasks, considered for quantitative and qualitative suitability analysis for relevant subsystems. Also, it was considered to reach a high level of streamlined design approaches for the overall system across several transport domains.

One main outcome of this task is a concept approach for highly standardised, yet individual railway, road and ropeway CU, that pair high flexibility and standardisation together with individual domain specific needs. The concept proposals show that relevant technologies such as electric drivetrain components, automation technology and other costly and complex systems can be used over several transport domains. This promises high potentials for economic and rapid market abilities. Another outcome is, that some subsystems have to stay individual for each domain, such as wheel-suspension systems, because they are depending on the selected domain.

Limitations of this task are, that further investigations are needed, for example regarding structural architectures and mechanical design of the vehicles. This project development stage is too early to give reliable outcomes or final designs. Also, it has to be considered, that the suggested concepts are often based on today's state of the art, at least as a starting point, which means that the future development could lead to higher freedom in the subsystem and component design.

2 Abbreviations and acronyms

Abbreviation / Acronym	Description
ADAS	Advanced Driver-Assistance Systems
API	Application Programming Interface
ARS	Aachen Rail Shuttle
AWD	All-Wheel Drive
BEV	Battery Electric Vehicle
CU	Carrier Unit(s) (or Vehicle)
DAC	Digital Automatic Coupling
DAC	Digital Automatic Coupler
DC	Direct Current
ECM	E-Corner Modules
E-GMP	Electric Global Modular Platform
EMU	Electric Multiple Unit
EV	Electric Vehicle
HS	Handling System
ICT	Information and Communication Technology
IWM	In-Wheel Motors
LTO	Lithium-Titanate Oxide
MIH	Mobility in Harmony
MPG	Main Product Groups
OEM	Original Equipment Manufacturer
OTA	Over-The-Air
R&D	Research & Development
SbW	Steer-by-Wire
SEA	Sustainable Experience Architecture
SMEs	Small and Medium-sized Enterprise
SPFW	Self-Propelled Freight Wagon
SPG	Subproduct Groups
SUV	Sport Utility Vehicle
TU	Transport Unit
UC	Use Case
V2X	Vehicle to everything
WLTP	Worldwide harmonized Light vehicles Test Procedure
WP	Work package

3 Background

The present document constitutes the Deliverable D 14.1 “Concept study for vessel carrier, Basic 3D model” in the framework of the Flagship Area 7, project Pods4Rail as described in the EU-RAIL MAWP. The Deliverable D14.1 within WP 14 is very much related to WP 7, 8 and 9. The results of all three WP are given within this document. This WP summarises the fundamental work done in WPs 7, 8, 9 and 13 of the Pods4Rail project to provide the technical framework for the design concept for road, rail and ropeway, which will be further detailed in D14.4.

4 Objective/Aim

This document has been prepared to provide concept proposals for general aspects of the design and development of the Pod System Carrier Units. One objective is to analyse and explain operational strategies of the vehicles as well as technical boundary conditions and their application into a concept approach. Another objection is to give outlooks into strategies of streamlining vehicle technologies independent of the transport domain. Therefore, this document aims to explain challenges and differences of relevant system components in today's vehicles. Also, it is aimed to outline the chances to overcome these differences and reduce the system complexity.

This document also aims to highlight the vehicle development and specific subsystems in order to be confirm to standards and domain specific infrastructure and to reach an innovative system with flexibility and efficiency.

5 General description of Carrier Units for every transport domain

5.1 General

The Pods4Rail system is designed to make supermodal transport possible with efficient and safe transport solutions. This is why it is aimed to reach a high system standardisation. This chapter describes concept approaches for every transport domain, followed by specific aspects of rail (Chapter 6) and road (Chapter 7).

5.2 Methodology

The methodology applied in this chapter establishes a coherent conceptual framework for the CU across different transport domains, namely rail, road and ropeway systems. It builds on the results of previous work packages (e.g., WP7, WP8, WP9, WP11, WP12) and translates their requirements into a unified concept approach while accounting for domain-specific constraints.

As a first step, functional, technical, operational and user requirements were reviewed and structured. These requirements were categorised into cross-domain requirements applicable to all transport modes, and domain-specific requirements linked to infrastructure and operational conditions. This structured requirement set forms the basis for all subsequent analyses.

In a second step, representative operational strategies and real-life use cases were defined for each transport domain. These use cases describe typical mission profiles, operational constraints and interactions with infrastructure and terminals. They provide the operational context for evaluating for evaluating the feasibility and flexibility of different CU concepts.

Based on the requirements and use cases, the CU was functionally decomposed into key subsystems, including vehicle structure, energy supply and storage, drivetrain components, automation and communication systems, and coupling and interface mechanisms. Each subsystem was assessed qualitatively with regard to its suitability for cross-domain standardisation or its dependency on domain-specific boundary conditions.

A core element of the methodology is the assessment of streamlining and convergence potentials within vehicle architectures. Different architectural principles and subsystem variants were compared in terms of standardisation potential, modularity, technical feasibility and future scalability.

Finally, the results were synthesised into preliminary CU design concept proposals for each transport domain. These concepts represent an intermediate project outcome and provide guidance for subsequent detailed developments. Identified limitations and open issues are explicitly acknowledged and addressed in later work stages, notably in Chapter 6 and 7.

5.3 Operational strategies for every Carrier Unit

5.3.1 Selection of reference Use Cases and real-life scenarios

UC1, “basic public passenger transport”, as introduced in Pods4Rail document D4.1 (Pods4Rail D4.1, 2024), represents a core service model of the Pods system and provides seamless mobility across rail and road environments within an integrated public-transport framework. Consistent with the scenario outlined in document D4.3 (Chapter 6.2) (Pods4Rail D4.3, 2024), UC1 emphasises the deployment of small-capacity Pods operating within a coordinated rail–road public transport network. Rather than focusing on technical or operational specifics, the use case highlights how Pods can be flexibly allocated across corridors of varying demand, enabling reliable passenger services in both urban and regional contexts.

For the purposes of this deliverable, the discussion concentrates on the overall functional principles of a dual-modal deployment - rail-based and road-based - demonstrating how the Pods concept can enhance passenger interchange, improve service continuity, and reduce transfer frictions within heterogeneous infrastructures. This high-level approach supports the assessment of system-level benefits such as increased network resilience, improved accessibility, and optimised resource utilisation, which are central to the innovation potential of a combined rail/road public-transport system.

5.3.2 Chances of standardised supermodal Carrier Units

The Pod system which is developed in the Pods4Rail project aims to combine the efficiency and sustainability of the railway sector with the flexibility and cost effectiveness of the road transport. By following this approach, the proposed CU concepts can increase opportunities for better future transport. To reach the best outcomes, the following aspects are considered for the concept development.

Not every transport domain has to fulfil every Use Case, which means that not every Transport Unit has to be transported on every CU. Therefore, the Carrier will be able to perform high flexibility by adapting to every TU-dimension. Also, it will be considered in the development, that different loads are being transported in the system. In that way it will be possible to transport people or cargo in various configurations.

It was found out, that regulations regarding maximum vehicle weights are different in every domain. For example, for railway lines, the smallest possible line is “Category A”, which requests for a technical limit of 16 tonnes per axle. The railway CU is following this category, which makes it possible to use it on every rail line category, also those with higher loads.

The developed Carrier system is aiming to reach a high interoperability (supermodality) and adaptability, because of that, some implications of arise for the overall transport system:

The system is not designed to eliminate all other vehicle types. It will still be suggested to use specialised vehicle types, such as bigger trains (for mass transport over long distances) or bigger trucks (for heavy duty cargo transport) on the road. The system is designed to balance high

capacity, high flexibility, high adaptability with design to domain specific principles. In this way, the best of each domain (precisely the railway and road domain) can be combined. For ropeway systems, all general principles can be adopted and changed adequately. With these functionalities, the pod system gives advantages compared to today's state of the art technologies

5.4 Technical boundary conditions for the vehicle concept

5.4.1 General

The technical boundary conditions for the design of the vehicle result from the results of the "High-Level functional requirements specification" D4.4 (Pods4Rail D4.4, 2024) and the requirements derived therefrom, as set out in D7.1 "Concept proposal System" (Pods4Rail D7.1, 2024).

5.4.2 Weight balance of the final carrier unit concepts

According to the CU development, as described in this document, the following configurations are suggested and taken as reference from Pods4Rail Deliverable D7.1, chapter 5.3.3.

The calculations for the weight balance are shown in Table 1. In order to guarantee a valid comparability, the reference weight of the TU is the same throughout all CU types. The estimated weight of the ropeway CU is set to 0,8 t, in accordance with expert knowledge and benchmark. The values for the weight of the TU are taken from the mentioned Deliverable. However, in reality, the TU will be lighter and also the CU could be lighter. As a consequence, the maximum total weight of the vehicle will be lighter as well, or the maximum possible load will be higher with identical maximum total weight.

Table 1: Weight balance for all three types of CU

	Rail CU	Road CU (25ft)	Road CU (15ft)	Ropeway
Carrier Unit				
Estimated weight (based on references)	10 ton	6 ton	4,2 ton (= 70% * 6 tons)	0,8 ton
Reference Scenario with passengers				
Reference UC	UC1			
10 ft TU load	2 x 3,5 ton		1 x 3,5 ton	
5 ft TU load	1x 1,75 ton		-	
Passenger + Luggage load	20*(80 kg + 20 kg) = 2 ton		10*(80 kg + 20 kg) = 1 ton	
Max. total weight (CU + TU + load)	$(2*3,5+1,75+2,0+10,0) = 20,75 \text{ ton}$	$(2*3,5+1,75+2,0+6,0) = 16,75 \text{ ton}$	$(3,5+1,75+1,0+4,2) = 9,45 \text{ ton}$	$(3,5+1,0+0,8) = 5,3 \text{ ton}$
Reference Scenario with Cargo				
Reference UC	UC18			
Maximum vehicle weight (based on legislation)	32 tons (bs. of axle load limitation)	18 tons (bs. of 2-axle limitation)	18 tons (bs. of 2-axle limitation)	
Tare weight 10 ft Container	1,3 ton			
Tare weight 5 ft Container	1 ton			
Possible cargo load (Assumption: same total weight as in UC1)	$(32-2*1,3-1,0-10,0) = 18,9 \text{ ton}$	$(18-2*1,3-1,0-6,0) = 8,4 \text{ ton}$	$(18-1,3-1,0-4,2) = 11,5 \text{ ton}$	$(5,3-1,3-0,8) = 3,2 \text{ ton}$

5.4.3 Charging strategy, energy harvesting and power supply

The charging strategy is defined as follows:

- Rail: Can use pantograph or BEV with 100% independent operation;
- Road: Can also use pantograph in some cases, like electric buses, but mainly conductive via plug in station or while driving with TU;
- Standard charging: “Energy-TU” (conductive via electrical connector) charges while driving when not fully utilised or in storage system;
- Intermediate charging: At station (conductive with chargers etc. in station);
- Autonomous conductive charging;
- Ropeway: will not be self-propelled;

5.4.4 Access and loading strategies

Access and loading strategies for ground-bound carriers are unified by a “Single Entry Unit” that can be shared by both rail and road vehicles, ensuring a consistent low-floor, wide-opening interface. For the rail domain, passengers always board from train platforms that are designed to the standard dimensions of 0.55 m platform height, and at least 12 m platform length, which are matched by the Entry Unit’s door and ramp/stair geometry (see Pods4Rail D8.1 (Pods4Rail D8.1, 2024) and Pods4Rail D9.1 (Pods4Rail D9.1, 2024)). Nevertheless, different platform heights can arise.

For the road vehicles, a two-scenario approach can be followed:

1. The same Entry Unit provides the same low-floor access as on rail, suitable for high-capacity use cases when the Road CU is stopping at a bus platform (e.g. UC1 - basic public transport); or
2. A shortened Road CU variant that retains the Entry Unit’s modular chassis and control architecture but increases operability for narrow streets like low-floor minibuses. In both cases the same mechanical and electrical interfaces are used, enabling rapid re-configuration of the cabin layout and simplifying maintenance across the fleet. This scenario can support stopping at places without desired bus platforms (entering from ground level).

This principle of same access will be input for the concept development and platform variant evaluation as described in Chapter 5.7.

5.5 Streamlining Vehicle Architectures

5.5.1 General Vehicle Architectures

In order to reduce costs and complexity, it can be suitable to simplify the pod system. This could be reached by streamlining vehicle architectures across road, rail, and ropeway domains. A central question is whether identical parts or systems can be employed to reduce cost, complexity, and supply-chain risk while respecting divergent safety, regulatory, and functional constraints. This brief synthesis projects an exemplary trajectory of component convergence toward 2045, by highlighting some of the key system elements.

Presently, only very few components can be truly identical across domains in a useful matter due to different technical requirements, regulatory frameworks, and infrastructure interactions. Nevertheless, there are components which are needed in every or more than one CU. Some of these same components can be used identically, some are the same sort of component, but have different characteristics. An overview of the component list is shown in Table 2. Additionally, all the characteristics explained are listed.

Table 2: Overview of the components list for the CU

Designation system according to EN 15380				Integration				Source
MPG	MPG designation	SPG	SPG designation	Rail	Road	Ropeway	Others (ship/ air)	
B	Vehicle Body	BE	Head of vehicle					Expert Knowledge
B	Vehicle Body	BA	Vehicle Body					Pods4Rail D4.4/ Component List ROAD-CU (Input DLR U-Shift Project)
B	Vehicle Body	BB	Underframe					Pod4Rail D4.4
B	Vehicle Body	BC	Side walls					Pod4Rail D4.4 (other projects DLR)
B	Vehicle Body	BG	Weld-on/add-on parts					FP6; Pods4Rail D4.4, FuN
B	Vehicle Body	BH	intermediate floor					other projects DLR
C	Vehicle fitting out	CF	External additions					Pod4Rail D4.4
E	Running gear	EA	Running gear					Pods4Rail D7.1 and WP10 Task 10.1 and 10.3
E	Running gear	ED	Suspension, damping, balancing gear					other projects DLR
F	Power system, drive unit	FB	Power supply					Pods4Rail D4.4; https://www.axtoneglobal.com/getmedia/1b292b2d-1e00-4931-9c6d-4e205ac0520b/AX-KL-6-Crash-b.pdf
G	Control apparatus for train operations	GA	Control apparatus for train operations					Pod4Rail D4.4
H	Auxiliary operating equipment	HB	Converter Equipment					Pod4Rail D4.4
H	Auxiliary operating equipment	HD	On-board supply system					other projects DLR
H	Auxiliary operating equipment	HE	Cooling Unit for power and drive system					Pods4Rail D4.4
J	Monitoring and safety equipment	JB	Measuring and protective devices					Pod4Rail D4.4
J	Monitoring and safety equipment	JD	Safety equipment					EN16404
J	Monitoring and safety equipment	JE	Data transmission device					Pod4Rail D4.4 & other projects DLR
J	Monitoring and safety equipment	JG	Miscellaneous equipment					Pod4Rail D4.4; D10.1; D7.1
K	Lightning	KB	Exterior lighting equipment					Pod4Rail D4.4
N	Doors, entrances	ND	Entrances, steps (not inside)					Pod4Rail D4.4
P	Information facilities	PB	Visual information facilities					Pod4Rail D4.4
S	Vehicle linkage devices	SB	Automatic Coupling devices					Pods4Rail D4.4
S	Vehicle linkage devices	SE	Towing gear (Emergency coupling)					
S	Vehicle linkage devices	SG	Vehicle-vehicle interface for media, signals, power					Pods4Rail D4.4
T	Carrier systems, enclosures	TE	Electronic rack systems					

Notes: **Green**: component is necessary with identical properties throughout the carriers, **Orange**: component is necessary but with different properties throughout the carriers, **Red**: not necessary in this carrier

In the following, the important subproduct groups are explained shortly and examples of components are given. Just the three means of transports are looked into more detail: Rail, Road and Ropeway.

Vehicle body

For the structural and chassis elements, weight differentials (≤ 18 t for road, > 20 t for rail) and crash-tolerance requirements preclude shared load-bearing frames. Only high-level design principles - such as a longitudinally scalable low-floor architecture - can be mirrored. Variability in the connection to the ground (wheel-rail, tire-road, cable-rope) limits the reuse of mounting hardware or chassis connection points. Furthermore, the main vehicle body subgroups are needed for all CU, although the components vary in detail between the CU.

Vehicle fitting out

These are external additions on the vehicle, like a transition or interface of the CU and TU in x-direction. They can be equal if they are needed in the carrier type.

Running gear Motors and Powertrains

Road vehicles experience rapid, high-amplitude load swings, whereas rail vehicles operate under long-duration, moderate loads with highly uniform torque profiles. Luxury road cars demand large, high-output motors, whereas small commuter cars use compact units. Consequently, motor topologies differ significantly based on the use case and vehicle category, even though shared high-voltage architectures (e.g., 400 V) are possible at a system level. For the ropeway carrier unit there will be no active running gear nor propulsion.

Power system, drive unit

All CU power is supplied by a battery. While the battery's chemistry technology can be standardised (e.g., Li-ion), the physical package, capacity, and charging strategy diverge. Rail systems favour high-voltage and high-capacity packs, whereas road vehicles rely on lower-voltage, conductive charging; ropeways may require self-sufficient, low-energy storage. The dimensioning of the batteries can still follow the same methodology. For the ropeway carrier unit there will be no active running gear nor propulsion.

Auxiliary operating equipment

Provides the CU with converter equipment, as an auxiliary converter (DC/DC). Additionally, an on-board supply system, like an electronic supply device and a cooling unit for power and drive system, such as a battery thermal management system.

Lighting

Is equipped onto the CU as exterior lights. The light system is declared for the Rail CU in the standard EN 13272 (EN, 2019). For the Road CU on the other hand, it is stated in the road traffic licensing regulations (Hella KGaA Hueck & Co., 2026). The key challenge is to categorise the Road CU into one of the given vehicle categories. As a consequence, several categories combined suit the Road CU, such as the camper van, bus, truck and special bodies. On the other hand, the Rail and Road CU share a similar vehicle design, so that it could be possible to unitise the positioning and designing of the light system. Above and beyond that, adoptions of the legislations are necessary.

Doors, entrances

The doors and entrances can follow the same principle for rail and road vehicles, because in both domains, passengers are supposed to enter on specific platforms from the side. Depending on the final CU design, the geometry and mechanics of the exact system can be different due to different platform and floor heights, but the same modular system can be used. Additional to the chosen electric stairs, it will be possible to use other systems such as ramps and lifting cassettes. Examples can be seen in Pods4Rail D7.1 (Appendix) (Pods4Rail D7.1, 2024).

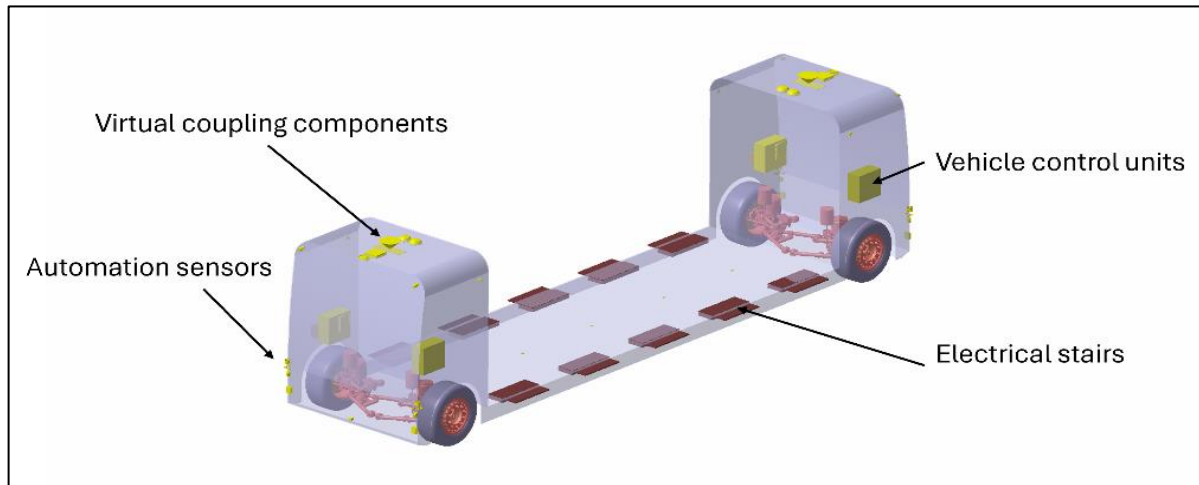


Figure 1: Overview of electric entry systems and automation components in the Carrier Unit (shown at the schematic Road CU) (DLR)

The electric stair system is installed on each side below every 5 ft TU-slot in order to guarantee access with every load configuration. Also, it is possible to locate entrance systems in the Entrance Unit.

Information facilities

For the case of the CU, the visual information facilities, such as a Passenger Information System is placed onto all CU, in order to inform the passengers, that this is the right carrier.

Vehicle linkage devices

There are different linkage devices, that the CU needs, such as an automated coupling device, which are the fully automatic twistlocks in all CU. Furthermore, in the case of an emergency, an emergency coupling, operated by tow hooks, is needed in Rail and Road CU. Also, a vehicle-vehicle interface for media, signals and power is needed, more specifically a charging interface and conductive energy transfer. Furthermore, since the development of the interfaces was already part of Pods4Rail D7.1 (Pods4Rail D7.1, 2024), D12.1 (Pods4Rail D12.1, 2025) and D10.1 (Pods4Rail D10.1, 2025), this document will not give additional details to this topic. The location of the interfaces in the final concept is shown at the schematic Road CU in Chapter 7.2.

Carrier systems, enclosures

Simple electronic rack systems, like fuse boxes are needed to store the electrics bundled. Further investigations of a fuse box, especially for the Rail CU is in the Annex 9.3.

5.5.2 Components for Automation and Digitalisation

In the following, the important subproduct groups are explained shortly and examples of components are given. Just the three means of transports are looked into more detail: Rail, Road and Ropeway.

Components for communication and navigation

Additionally to these components, a separate component list of sensors for communication and navigation is investigated, as shown in Table 3, following D11.1 (Pods4Rail D11.1, 2025). Each sensor is identified with its position on the Rail CU by an ID, which is illustrated in Figure 2. This figure is a schematic representation and not the final version, made by Moodley. As with the previous components, the source of information is listed. This configuration from the Rail CU is adaptable and therefore the same as for the Road CU.

The aim is to reduce the number of different sensors for the Rail and Road CU. As a consequence, all sensors are suitable for both CU, Rail and Road.

The Ropeway CU doesn't need active sensors for driving operation, all necessary sensors are in the TU. A limited set of sensors will be needed, e.g. to interact with the TU.

Table 3: Component list of sensors for communication and navigation

ID	Sensor	Position	Source
A-1	Communication	front, rear. Antenna integrated into the roof in the upper section of the carrier	https://ieeexplore.ieee.org/document/8494832
A-2	Communication	front, middle, rear. Standard rail antenna for mounting on the top	https://www.antonics.com/produkt/omplecs-r-top-200-amr-mf-05-5-mimo-4x4-l-1/
B	Communication	front, rear. mmWave antenna in the front area (facing forward)	https://tmytek.com/files/TMYTEK_SF_One-Stop+Shop+AiP+Solution+for+5G+mmWave+O-RU_GL.pdf
C	GNSS antenna / Navigation	All units should be attached at the rear and front, top and centre.	https://www.antonics.com/produkt/omplecs-r-top-200-amr-1500-b-l1-l2-h2/
D-1	Transceiver-Unit (V2X)	The antennas should be connected at the front and rear with such a box	https://wpstap-ap-southeast-2-media.s3.amazonaws.com/cohda/wp-content/uploads/media/2025/11/CW_DL_Product-Brief-sheet-Nov25-MK6-OBUE.pdf
D-2	Transceiver-Unit, USRP as computing unit	The antennas should be connected at the front and rear with such a box	https://www.ettus.com/wp-content/uploads/2024/01/X300_X310_Spec_Sheet_2024-01-23.pdf
E	Com+Ranging Transceiver	bottom, front, rear, middle	
F	magnetic field-based localization	One is sufficient; a second is possible for better localization. Magnetic field sensors should ideally not be placed near direct current power lines or near batteries or devices through which high currents flow.	D10.1 chapter 8 and D11.1

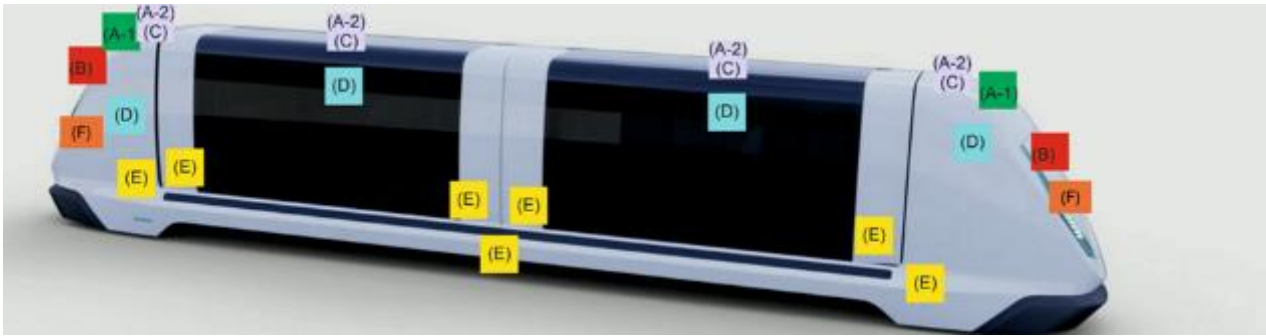


Figure 2: Position of the sensors from Table 3 at the Rail CU (moodley, DLR)

The development of automation systems and sensors is not part of the Pods4Rail project. Should the planned system described in the Pods4Rail project be implemented, the sensors required for autonomous operation must be state-of-the-art and have proven their technical suitability. Suitable solutions are outlined in Pods4Rail D11.1, Chapter 5.4. These solutions are based on developments from the automotive and railway sectors, such as the EU-Rail project R2Dato (Europe's Rail, 2026a).

Monitoring and safety equipment

In the CU, different components are necessary to monitor and ensure safety (Pods4Rail D11.1, 2025). According to Table 2, they include sensors for automated driving, safety equipment such as fire extinguishing systems and computing technologies. The general principle can be the same for every domain, since the functions automated driving, perception, communication and controlling have to be fulfilled by every carrier. A specific setup of these components is not in the scope of this task.

Digital Layer:

The Pods system relies on a digital layer that enables secure, reliable and up-to-date vehicle functionality across modes through continuous software-enabled capabilities. Rather than detailing specific automotive or modular-platform implementations, this deliverable adopts a high-level perspective aligned with the communication, localisation and processing concepts established in Pods4Rail D11.1. In that document, the system architecture is defined as a distributed framework that integrates on-board processing, over-the-air update mechanisms, robust V2X/rail communication channels, and coordinated data-management functions supporting autonomous operation across rail and road networks. Accordingly, the present deliverable refers to D11.1 for the full specification of the digital and computational building blocks, emphasising here only their role as essential enablers of safe, adaptable and interoperable multimodal Pod operations.

5.5.3 Strategic Pathways for Component Convergence

Despite the challenges of different requirements by each domain, several developments promise significant standardisation gains:

1. Energy Architecture Standardisation: A common high-voltage bus (e.g., 400 V) paired with modular, domain-specific energy converters can decouple the power train from the core battery

module. This modularity supports economies of scale while preserving regulatory compliance by each domain.

2. Control and Automation Platforms: Shared control functions and harmonised software architectures support coordinated automation across rail and road domains. The detailed definition of these platforms, including control allocation and diagnostic principles, is provided in Pods4Rail D11.1.

3. Communication and Connectivity: A unified communication layer with standardised interfaces enables consistent data exchange and interoperability across vehicle types and infrastructures. Full specifications of the communication architecture are presented in Pods4Rail D11.1.

4. Mechanical and Electrical Interfaces: Standardised connector families, plug-and-play mechanical couplings, and universal mounting parts reduce assembly variability.

5. Exterior Design Language: A cohesive aesthetic—including lighting modules, sensor housings, and HMI components—can be shared across domains, benefiting manufacturing, maintenance strategies and consumer recognition.

6. Structural Integrity and Crash Safety: If active safety is able to replace passive safety in future autonomous systems, it will be possible to converge structural elements between carrier domains. Therefore, shared platform designs can be highlighted with similar design principles or even same structural modules adapted for required load cases.

By mid-decades, the bulk of cost-sensitive components (e.g., batteries, power electronics, control systems, and interface standards) are projected to converge. The primary impediment will remain chassis and structural incompatibilities rooted in expected crash safety and ground interaction physics. However, even partial convergence in critical subsystems will yield measurable reductions in unit cost, maintenance effort, and supply-chain fragility. The trajectory toward a shared component ecosystem is clear: a strategic focus on energy modules, control platforms, and standardised interfaces will deliver the most immediate and substantial benefits. While structural divergence persists, the remaining domains offer fertile ground for cross-industry collaboration, ultimately supporting a more sustainable, cost-effective mobility landscape.

5.6 Application of Requirements

5.6.1 General

The components and their packaging for the CU are heavily dependent on the requirements that arise. These requirements were defined in the previous work of Pods4Rail (in particular D4.1, D4.4, D7.1, D10.1, D11.1, D12.1). In addition, normative requirements are placed on the CU, which must also be considered. The detailed table can be found in the Annex A. The methodological approach is identical for road and rail carrier development - but the technical aspects are different.

These requirements are summarised thematically in the following chapters and their influence on the selection of components is described. The development of the CU can then be carried out based on these requirements (chapter 5.7.1).

5.6.2 Specific Requirements for the Rail CU

The general requirements of the CU in rail applications are described below in Table 4 and the resulting consequences for the design of the rail CU are presented. IDs 1 to 4 form the basis of the system, which are necessary for basic operation within the defined requirements of the Pods4Rail project. For bidirectional operation, this includes a symmetrical arrangement of all necessary sensors and protection against external factors such as weather or destruction. Furthermore, the sensors and components must be selected in such a way that they are independent of the TU and therefore of any use case. This also means that the carrier must be able to cover every TU and every use case in terms of interfaces and energy requirements.

Table 4: Exemplary table structure for the general requirements for rail carrier design

ID	Requirement	Comments
1	fully operable without a TU (e.g. communication system, lightings, etc.)	CU should integrate all necessary components for a complete automated driving.
2	drivable in both directions	Sensors, interfaces and crash-elements have to be symmetrical
3	The carrier should be able to cover all relevant use cases (rail domain)	In order to reach a high coverage, every TU size is addressed (5 ft, 10 ft, 20 ft), loading area should meet the requirements of D7.1 Note: Not every use case makes sense on the road
4	The vehicle shall be able to operate without loss or reduction of functions in severe snow, ice and hail conditions.	covering / heating is necessary for all interfaces and critical parts

The basic geometric requirements for the Rail CU are covered by ID 5 to 9 (Table 5). These requirements were defined in order to also be able to serve all branch lines in Europe. The loading surface is therefore at a height of 280 mm above the top of rail. This height can be varied to a limited extent using sliding steps and/or ramps and adapted to requirements. This means that a carrier concept should be aimed for in which the loading area is positioned between the axles. Furthermore, a small centre distance leads to uneven running and reduced comfort, which must be compensated for by the suspension systems. A centre distance of 9000 to 10000 mm should therefore be aimed for.

Table 5: Geometric requirements for the Rail CU

ID	Requirement	Comments
5	Clearance Gauge: G1 loading area: 25 ft / 7634 mm	Length is not that relevant, but depending of the length (wheelbase), the width have to be adjusted
6	Axle load max. 16 t and max. 5 t / meter	Smallest line categories should be drivable, because the system should be operable on each main and branch line

ID	Requirement	Comments
7	Entry high 550 mm above Top of Rail (TOR)	Standard entry height in EU, Entry on TU should be on 550 mm, the bottom structure of the TU is 230 mm, the floor panelling 40 mm. Therefore, the loading height of the CU should be around 280 mm for a barrier-free entry. Derivation possible through steps or ramps
8	Wheelbase in y: 1435 mm / standard gauge	
9	Wheelbase in x: not too short (riding comfort) but also not too long (constriction of width)	Only a skateboard platform is suitable, because of the low height of the loading area. Wheelbase of Axis around 10 m

Details of the mass estimation are shown in ID 10 - 15 in the Table in Annex A. In relation to the above-mentioned axle load, the total mass of a 5 ft TU is therefore limited to 4.4 tonnes and the pure payload to 2.65 tonnes. This means that the payload for freight containers for the pod system must also be limited. If these have a standard mass of up to 30.48 tonnes for a 20 ft container, this may weigh a maximum of 17.6 tonnes in the pod system, and a 10 ft freight container accordingly only 8.8 tonnes. These payload restrictions must be communicated in the supply chains. The requirements for the energy system and the required range are explained in detail in chapter 6.1 and will not be discussed here. The requirements defined here can also be found in the corresponding annex.

The requirements in Table 6 are closely related to the elaborations of chapter 6.2. According to the requirements of the previous work of the other WPs and other EU projects, a Digital Automatic Coupling (DAC) is recommended. Furthermore, a type of buffer is still required to absorb the corresponding energy in the event of a crash and to ensure the survival space of the passengers. Whereby crash loads are the only loads to be considered. The permanently installed integration of an additional toilet module on a carrier must be assessed critically from a systemic and economic point of view. In view of the low frequency of use of such a toilet module, the negative effects clearly outweigh the functional added value. Therefore, an additional sanitary TU should be loaded only for longer journeys.

Table 6: Operational requirements for the Rail CU

ID	Requirement	Comments
20	The carrier should be able to operate virtually coupled, but shall be able to operate in mixed operation, therefore a Digital automatic Coupling device should be integrated. Should follow the UIC code 571-4: Standard Wagons - Wagons for Combined Transport - Characteristics.	Virtual coupling as standard, a draw hook should be provided for recovery cases for compatibility with existing systems. Buffer elements not absolutely necessary, as no shunting / classic train formation.
21	When a use case for long distance passenger transport is selected, the vehicle shall include sanitary facilities in at least one of the TUs mounted on the carrier.	Additional space and mass requirements reduce the available payload and transport efficiency Increased vehicle mass leads to higher energy consumption during operation Deterioration of the total cost of ownership (TCO) with low utilisation frequency
22	All components that are subject to regular maintenance or inspection intervals should be accessible and replaceable without an increased level of effort.	Provide maintenance hatches that are also accessible via an emergency release.

ID	Requirement	Comments
23	The rail carrier unit shall integrate passive safety equipment and components in compliance with the current standards for railways that shall be present for some use cases (e.g. energy absorption components towards collisions in a mechanically coupled pods scenario).	Sensors in the vehicle, energy absorption via integrated structure in front area

5.6.3 Requirements for the Road CU

Additional to general requirements, there are technical and operational requirements applicable for every Road CU (Pods4Rail D4.4, 2024; Pods4Rail D5.1, 2024). Technical requirements are a limitation of the total vehicle dimensions and the suitability to protect the TU in regard to crash safety (as far as it is agreed for a fully autonomous vehicle). Operational requirements are the ability to drive up to 80 km/h and to reach a driving range of at least 300-300 km. User requirements include low entry levels for easy accessibility for passengers.

In regard to geometrical requirements (as shown in Table 7) the Road CU is mainly affected by a simple accessibility for users and loads, especially from bus platforms. Therefore, the dimensions of desired doors of the transport units as well as the floor height of every transport unit has to be considered. In order to achieve a comparison with other road vehicles some benchmarking was made for small buses and transporter vehicles. For a good manoeuvrability and performance of the automated vehicle it is considered to be fully operable in autonomous mode and able to drive on standard road scenarios. Therefore, a specific ground clearance and slope angles will be inputs for the mechanical design.

Table 7: Geometrical requirements for the Road CU

ID	Topic	Requirement	Source	Comments
Entrance and Exit / Cargo Loading Scenarios				
12	Side Doors width	800-1100 mm	Pods4Rail D4.4	Side-entrance (bus stop level) is preferred
14	Floor height passenger TU	270 mm	Pods4Rail D10.1	230 mm bottom structure + 40 mm insulation
15	Entrance on Road level	0 mm	Pods4Rail D4.4	Low-Entry accessibility as good as possible
16	Entrance on bus stop level	180 mm (average; 130-230 mm possible)	Pods4Rail D4.4	Can be reached with electric ramp
17	Electric Van/ Transporter loading height	550-600 mm	Benchmark	Distance from ground to loading area varies between models
18	Buses (low floor) loading height	350-400 mm	Benchmark	Additional kneeling function for city buses
19	Mini-Buses loading height	250-400 mm	Benchmark	
Technical Boundaries				
20	Automation Field of Views	360 degree view		Relevant for Packaging depending on sensor type
21	Ground clearance	180-200 mm for Truck category	ECE-R58-03	depends on carrier design (length, wheel base, ...)
22	Minimum slope angle	20 degrees	Pods4Rail D4.4	depends on carrier design (length, wheel base, ...)

To summarise the most relevant criteria for the concept developments, Table 8 shows the five main requirements that are influencing the choice of platform variants, following in chapter 7.1: The Road CU will be limited in the dimensions, it has to perform a minimal crash safety for passenger protection and it has to provide low-floor access for passengers, preferred from bus platforms beside the road. Barrier-free access has to be given at least for the specific PRM-TU.

Table 8: Critical criteria for the Road CU platform variants

No.	Criteria	Requirement
1	Max. Carrier Dimensions	12.00 x 2.55 x 4.00 m (L x W x H)
2	Crash safety	The CU must provide crash safety for the (not protected) TU
3	Side-entry	Side entry has to be possible (bus stops).
4	Low-floor access (bus stop/road)	Low entry at bus stops and/or road level, incl. assisting device
5	Barrier-free access for PRM-TU	Only for specific PRM-TU

5.7 Evaluation of carrier platform approaches

5.7.1 Evaluation of different platform principles for the Road CU

5.7.1.1 General

In order to decide which platform variant is the most suitable for the Road CU, an analytical methodology was developed that consists of the following steps:

1. Clustering of platform principles
2. Description of platform variants for each principle
3. Analysis of accessibility for each platform variant
4. Evaluation of the platform variants based on given requirements

The same methodology was then applied to the Rail CU.

According to modularity approaches six major platform principles can be highlighted (Figure 3). They are differing in the way of movement of the Road CU as well as the loaded transport units. The principles of including a whole drivable platform (as in principle a, d, e and f) and the reduction into individual drive axles (as in principle b and c) can be figured out.

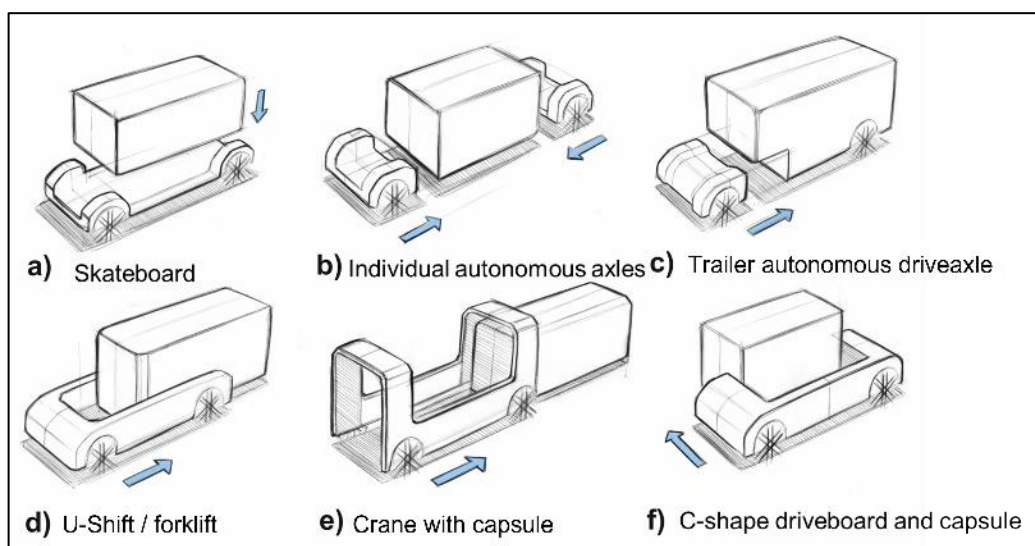


Figure 3: Overview of platform principles for road vehicles (DLR)

In general, all platform principles are possible for the Road CU, but due to the mentioned requirements and system approach not all of them are likely to perform well, so the following chapters will point out some key aspects of the suitability assessment.

5.7.1.2 Functionality and accessibility analysis for the Road CU

A total number of 23 platform variants were derived for the concept development. Since not all of them are able to fulfil all requirements, the first step of the comparison is to analyse the critical criteria, that were defined in Chapter 5.6.3. By applying those criteria not suitable options will be eliminated. The comparison in Table 9 shows that 14 variants are not able to fulfil the relevant criteria, therefore 9 variants are left for analysing their accessibility solutions. A whole list of concepts is given in Annex 9.2.

Table 9: Comparison of platform variants regarding fulfilment of critical criteria

Variant	Max. Carrier Dimensions fit to road standards	Crash safety (with TU-protection) possible?	Side-entry possible?	Low-floor access (bus stop/ road) possible?	Barrier-free access with specific PRM-TU possible?	Suitability (round 1)
A1)	Yes	Yes	Yes	No	Yes (with TS01)	Not suitable
A2)	Yes	Yes	Yes	Limited	Yes (with TS01)	Possible
A3)	Yes	Yes	Yes	Limited	Yes (with TS01)	Possible
A4-a)	Yes	Yes	Yes	Yes	Yes (with ramp)	Possible
A4-b)	Yes	Yes	Yes	Yes	Yes (with ramp)	Possible
A4-c)	Yes	Yes	Yes	Yes	Yes (with ramp)	Possible
A5)	No	Yes	No	Limited	Limited	Not suitable
A6)	Yes	Yes	Yes	Limited	Yes (with lift)	Possible
A7)	Yes	Yes	Yes	Limited	Limited	Possible
B1)	Yes	No	Yes	Yes	Yes (with ramp)	Not suitable

B2)	Yes	No	Yes	Yes	Yes (with ramp)	Not suitable
B3)	Yes	No	Yes	Yes	Yes (with ramp)	Not suitable
C1)						Not suitable
D1)	Yes	Yes	Yes	Limited	Yes (with lift)	Possible
D2)	Yes	Yes	Yes	No	No	Not suitable
D3)	Yes	Limited	Yes	Yes	Yes (with ramp)	Possible
E1)	Yes	No	Yes	Yes	Yes (with TS01)	Not suitable
E2)	No	No	Yes	Yes	Yes (with TS01)	Not suitable
E3)	Yes	No	Yes	Yes	Yes (with TS01)	Not suitable
F1)	No	Limited	Yes	Yes	Yes (with ramp)	Not suitable
F2)	No	Limited	Yes	Yes	Yes (with ramp)	Not suitable
F3)	No	Limited	Yes	Yes	Yes (with ramp)	Not suitable
F4)						Not suitable

Regarding the accessibility analysis, two main factors have to be compared: firstly, the loading abilities of each variant can differ. That means the possibilities and consequences of a flexible transshipment. Secondly, the entrance abilities and usability for end users have to be compared. Table 10 shows the results of this comparison. Four platform variants show disadvantages in the efficiency and usability, therefore five of the variants can be considered as suitable for the Road CU.

Table 10: Comparison of usability and accessibility for Road CU platform variants

Variant	Possible transshipment scenarios (from D7.1)	Loading Capacity	Multiple TU possible	Independent transshipment	Possible directions of entry	Recommended assisting devices [stairs, lift, ramp, none]	Suitability (round 2: technical)
A2)	TS02/ TS03/ TS04	5/10/20/20+ ft	Yes	Yes	left/right	Lift, Stairs	Not suitable
A3)	TS02/ TS03/ TS04	5/10/20/20+ ft	Yes	Yes	left/right	Lift, Stairs, Ramp	Possible
A4-a)	TS02/ TS03/ TS04	5/10/20 ft	Yes	Yes	left/right	Ramp	Possible
A4-b)	TS02/ TS03/ TS04	5/10/20 ft	Yes	Yes	left/right	None	Not suitable
A4-c)	TS02/ TS03/ TS04	5/10/20 ft	Yes	Yes	left/right	Ramp	Possible
A6)	TS02/ TS03/ TS04	5/10 ft	Yes	Yes	left/right	Stairs, Ramp	Possible
A7)	TS02/ TS03/ TS04	5/10/20 ft	Yes	No	left/right	Stairs, Ramp	Not suitable
D1)	TS02/ TS03/ TS04	5/10/10+ ft	Yes	Yes	left/right	Stairs	Not suitable
D3)	TS01/ TS02/ TS03/ TS04	5 ft	No	Yes	Rear	Ramp	Possible (for single-TU)

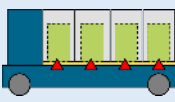
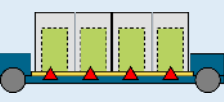
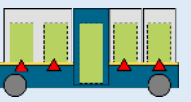
The best five solutions contain low floor skateboard platforms as well as high floor skateboard platforms with additional entrance units. They can be considered as the most promising and will be evaluated on a quantitative basis in the following chapter. The platform variant D3) “Single TU” is considered as highly suitable for single-TU use cases, which means it would be the most suitable solution for a Road CU that is specifically designed for a transport of only one TU with sizes up to

10 ft length. Since this project is focused on a scalable platform with ability to transport up to 20 ft TU, it will not be considered further.

5.7.1.3 Evaluation of the most suitable variant for the Road CU

The methodology for the platform evaluation is following the methods from previous works in this project. Firstly, evaluation criteria are defined in the project group, secondly those criteria are ranked by using a pairwise comparison matrix (see Annex 9.2). Lastly each platform variants evaluated by the degree of fulfilment for all defined parameters. The result of this evaluation is presented in Table 11.

Table 11: Evaluation table for most suitable Road CU platforms

Road CU platform variants (only most suitable options preselected)					
Variant (Figure)					
Variant (Code)	A3)	A4-a)	A4-c)	A6)	Weighting
Complexity of the carrier	4	3	3	4	16%
Carrier dimensions	4	3	2	5	9%
Safety of Access (entry/loading)	3	5	4	5	21%
Complexity to reach easy access	2	5	5	3	5%
Loading of different TU-sizes	5	5	5	2	21%
Adaptability of the CU	5	4	4	3	0%
Ability to not need a PRM-TU (self-lifting)	2	5	4	3	7%
Space for main components	5	4	3	5	20%
SUM	3,95	4,30	3,73	3,95	

The evaluation shows, that platform variant A4-a) “Low floor platform with high front modules” is the best solution. It fulfils the main requirements of easy accessibility from the side as well as crash requirements by providing structural integrity from every side. Also, this platform variant is highly flexible and efficient for quick transshipment processes with more than one TU. It is very similar to the Rail CU platform variant and therefore likely suitable to integrate same system elements and processes. Another advantage is that several access scenarios are possible and the platform offers enough space to integrate major components. In the following concept development this platform design will be chosen.

5.7.1.4 Proposed Optimal Architecture

This chapter introduces platform architectures from the state of the art and suggests suitable options for the Road CU. A description of rail vehicle platform designs and parallel systems of autonomous platform, that are also researched on, is shown in Annex F.

The comparative analysis of electric vehicle (EV) platforms reveals a clear trend towards modularity, scalability, and integration of advanced power electronics as fundamental enablers for next-generation mobility. Proprietary architectures such as Hyundai's E-GMP (Hyundai Motor Group, 2025), Stellantis' STLA (Stellantis, 2025), and ZF's heavy-duty solutions (ZF Group, 2025) demonstrate high technological maturity and robust industrial deployment, offering optimised performance and safety guarantees for large-scale manufacturing. These platforms prioritise vertical integration and closed ecosystems, which ensure reliability but limit external innovation and flexibility.

Conversely, semi-open architectures like Geely's SEA (Geely Group, 2025) and CATL/Huawei's CIIC (CATL & Huawei, 2025) illustrate a cooperative approach within industrial consortia, enabling shared development while maintaining proprietary control over critical technologies. This model supports regional supply chain resilience but does not fully democratise access to platform specifications.

The MIH Open Platform (MIH, 2025), developed by Foxconn and its consortium, stands out as the only initiative explicitly designed as an open ecosystem. By providing open standards, reference designs, and API (Application Programming Interface) frameworks, MIH reduces entry barriers for SME (Small and Medium-sized Enterprise) and accelerates innovation across the global EV supply chain. This openness fosters interoperability, encourages third-party integration, and supports the emergence of software-defined vehicles, positioning MIH as a strategic enabler for disruptive business models and collaborative R&D (Research & Development). Table 12 summarises a comparison of the different electric vehicle platforms analysed.

Table 12: EV Platforms comparison

Platform	Energy System	Propulsion Type	Steering	Suspension	Openness	Advantages	Disadvantages
REEcorner (REE Automotive, 2025)	BEV	In-wheel motors	Steer-by-wire	Independent	Proprietary	High modularity	Complex, costly
E-GMP (Hyundai Motor Group, 2025)	BEV	Central motor	Conventional	Independent	Proprietary	Efficiency, fast charge	Closed
STLA (Stellantis, 2025)	Multi-energy	Modular	Conventional	Flexible	Proprietary	Versatility	Complexity
SEA (Geely Group, 2025)	BEV	Central motor	Electric assist	Lightweight	Semi-open	OTA, scalable	Limited access
ZF AxTrax (ZF Group, 2025)	BEV	Electric axle	Conventional	Heavy-duty	Proprietary	Retrofit-friendly	Closed

Platform	Energy System	Propulsion Type	Steering	Suspension	Openness	Advantages	Disadvantages
Chilwa (Maazibuko Motor Company, 2025)	BEV	Central motor	Conventional	Robust	Semi-open	Terrain-adapted	Low maturity
CIIC (CATL & Huawei, 2025)	BEV	Central motor	Steer-by-wire	Independent	Semi-open	ADAS-ready	Restricted
Blue Arc (Shyft Group, 2025)	BEV	Central motor	Conventional	Heavy-duty	Proprietary	Fleet optimised	Closed
MIH (MIH, 2025)	BEV	Modular	Flexible	Flexible	Open	Innovation-friendly	Lower maturity

Overall, the state of the art indicates that platform openness correlates strongly with innovation potential and ecosystem diversity, while proprietary solutions remain dominant in high-volume, performance-critical segments. For Pods4Rail, these insights underline the importance of balancing technological maturity with openness to ensure scalability, interoperability, and cost efficiency in future rail traction systems. The following information pertains to the proposed optimal architecture.

Energy System

A battery-electric skateboard architecture with scalable voltage is recommended. This configuration ensures compatibility with high-power charging infrastructures and supports future proofing for ultra-fast charging technologies, as demonstrated by platforms such as Hyundai's E-GMP (Hyundai Motor Group, 2025) and Geely's SEA (Geely Group, 2025). The scalability of voltage also facilitates integration with diverse traction requirements, enhancing operational flexibility.

Propulsion

A distributed drive system, ideally based on corner modules or dual-motor all-wheel drive (AWD), is proposed. This design provides redundancy, improved dynamic control, and enhanced safety, aligning with REEcorner's disruptive modular concept (REE Automotive, 2025). Distributed propulsion mitigates single-point failures and optimises traction performance under variable load conditions, which is critical for Pods4Rail's operational reliability.

Steering

Steer-by-wire technology should be adopted to eliminate mechanical linkages, enabling design freedom and autonomous readiness. This approach, already implemented in REEcorner (REE Automotive, 2025) and CIIC (CATL & Huawei, 2025) platforms, supports advanced driver-assistance systems (ADAS) and future autonomous functionalities. It also reduces weight and simplifies integration with digital control layers.

Suspension

An independent adaptive suspension system is recommended to accommodate comfort and load variability. Adaptive systems enhance ride quality and stability, particularly under mixed operational scenarios, and are consistent with premium EV architectures such as SEA (Geely Group, 2025) and E-GMP (Hyundai Motor Group, 2025).

Openness

A semi-open or open ecosystem is essential to foster innovation while maintaining safety and interoperability standards. The MIH Open Platform (MIH, 2025) exemplifies how openness accelerates development and encourages third-party integration. For Pods4Rail, this openness will enable collaborative R&D and reduce dependency on proprietary ecosystems, which often limit scalability and increase lifecycle costs.

Digital Layer

Integration of centralised computing with over-the-air (OTA) capability is critical for software-defined functionality. This feature ensures continuous updates, cybersecurity resilience, and adaptability to evolving operational requirements, as demonstrated by SEA (Geely Group, 2025) and E-GMP (Hyundai Motor Group, 2025) and CIIC (CATL & Huawei, 2025) platforms.

This hybrid architecture combines the modularity and openness of MIH, the redundancy and flexibility of REEcorner, and the industrial maturity of E-GMP. Such a synthesis ensures:

- Scalability across vehicle types and operational contexts.
- Autonomous readiness through steer-by-wire and advanced digital integration.
- Ecosystem collaboration, reducing barriers for SMEs and promoting innovation.
- Operational reliability via distributed propulsion and adaptive suspension.

Control System

A unified control architecture is recommended to ensure safe, stable and fully autonomous operation. The system should integrate fully active or semi-active suspension control to optimise ride dynamics and load compensation; steer-by-wire actuation for redundancy, design flexibility and precise trajectory execution; and advanced traction and braking control to maintain stability under variable adhesion and operational conditions. These functions rely on a comprehensive sensing suite providing the situational awareness required for automated driving, with the full allocation of control and perception modules defined in Pods4Rail D11.1.

5.7.2 Evaluation of different platform principles for the Rail CU

The platform principle is one of the most critical design decisions for the rail CU. It defines how TU are positioned, accessed, and loaded onto the CU. It also influences the available space for integrating energy and propulsion systems, suspension and running gear, and other major components. The platform principle must balance multiple requirements: low-floor accessibility for passengers, structural strength for load distribution, dimensional compliance with European rail standards, safety for crash scenarios, and operational flexibility for different TU sizes and transshipment scenarios.

The selection of the most suitable platform principle for the Rail CU builds upon the platform principle development work already completed for the Road CU in T14.3 (see Chapter 5.7.1). Here, six main platform principles were developed and assessed (concepts A-F). Among these, the platform principle A) “Skateboard Platform” was identified as the most suitable, with the platform variant A4-a) “Low floor platform with high front modules” selected as the best solution.

Considering the rail-specific requirements and constraints (see Chapter 5.6.2), the platform variant A4-a) was deemed the most suitable for both Road and Rail CU. This platform principle offers a low-floor, integrated design that maximises usable length, provides good accessibility, and is compatible with standard infrastructure and modular TU handling. It enables the CU to be both operationally efficient and technologically advanced, supporting autonomous operations across diverse infrastructure types while maintaining compatibility with standard European rail network constraints. Its implementation in detailed CAD models provides a solid foundation for all subsequent development activities in vehicle body design, chassis/bogie specification, energy architecture definition, and component integration planning.

5.7.2.1 Evaluation of Existing EV Platform Architectures as a Basis for the Rail CU Concept Design and Proposed Optimal Architecture

The definition of an optimal architecture for the Rail CU requires an understanding of current rail-vehicle platform concepts, emerging autonomous-rail solutions, and the degree to which these systems align with Pods4Rail's requirements for modularity, energy autonomy, and digital integration. To establish this context, Annex D provides an overview of relevant platform designs and parallel developments in autonomous rail systems, highlighting their structural layouts, energy concepts and automation-enabling features. This comparative perspective is essential for identifying architectures that can support the hybrid operational envelope envisioned for Pods4Rail - combining lightweight vehicle structures, adaptable propulsion units and high levels of automation. Table 13 summarises the key characteristics of the platforms analysed, providing a basis for assessing their suitability as reference configurations for the Rail CU within the Pods4Rail system.

Table 13: Rail platforms comparison

Platform	Chassis Design	Running Gear	Propulsion System	Energy System
Parallel Systems Autonomous (Parallel Systems, 2025)	Flat modular frame for container freight; autonomous-ready architecture	Conventional rail wheelsets integrated with traction motors	Battery-electric; approx. 300 kW per driven axle	Lithium-ion battery pack; range up to ~500 miles/charge (company claim)
Intramotev TugVolt/ReVolt (Intramotev, 2025)	Retrofit kit added to existing wagon chassis	Standard bogies retained; traction motors added	Battery-electric; approx. 200 kW per driven axle	Onboard battery packs; designed for short-range yard ops
RWTH Aachen ARS (RWTH Aachen, 2025)	Ladder-frame chassis housing all technical equipment; modular body concept	Two powered, self-steering single wheelsets (not classic bogies)	One motor per wheelset; continuous power ~160 kW	Central traction battery (LTO chemistry), 152 kWh; range up to 220 km
ERJU FP5 TRANS4M-R (TRANS4M-R, 2025)	Standard wagon frame with non-invasive retrofitting	Conventional bogies adapted for direct-drive traction motors	Electric motors mounted on axles	On-board battery storage sized for operational profiles
Smart Wagon + DAC (Europe's Rail, 2024)	Conventional freight wagon frame with digital coupling and telematics	Standard bogies	Not self-propelled; DAC and telematics only	Auxiliary battery for digital systems; no traction capability

The Pods4Rail project aims to develop a flexible, autonomous-ready traction system that supports modular operations, energy efficiency, and digital integration. Based on the comparative analysis, the optimal architecture should combine:

- Modularity for multi-purpose use (passenger and freight / mixed).
- Autonomous readiness for future automation scenarios.
- Energy scalability to meet diverse operational profiles.
- Digital interoperability for integration with smart infrastructure.

Based on these principles, the proposed architecture is as follows:

Chassis

Adopt a ladder-frame modular chassis in skateboard configuration (Figure 4) similar to RWTH Aachen's ARS concept (ARS, 2025), which allows the separation of the rolling platform from the payload module. This design maximises lifecycle utilisation and supports multi-mission deployment.

Running Gear

Implement self-steering independent wheelsets rather than classic bogies, as demonstrated by ARS concept (ARS, 2025). This configuration improves manoeuvrability in tight spaces and reduces structural complexity, which is advantageous for modular pods.

Propulsion System

Use a distributed battery-electric drive with one motor per wheelset, ensuring redundancy and dynamic control. This approach aligns with REEcorner principles (REE Automotive, 2025) in road EVs and RWTH Aachen's demonstrator (RWTH Aachen, 2025), enhancing safety and traction performance.

Energy System

Integrate a scalable battery pack architecture with advanced chemistries for high cycle life and fast charging. The ARS platform demonstrates feasibility with 152 kWh packs, while Parallel Systems shows the potential for extended range through modular energy scaling.

Digital Layer

Ensure full digital integration, including telemetry and OTA capability, to support predictive maintenance and automated yard operations.

Rail carrier unit with skateboard chassis

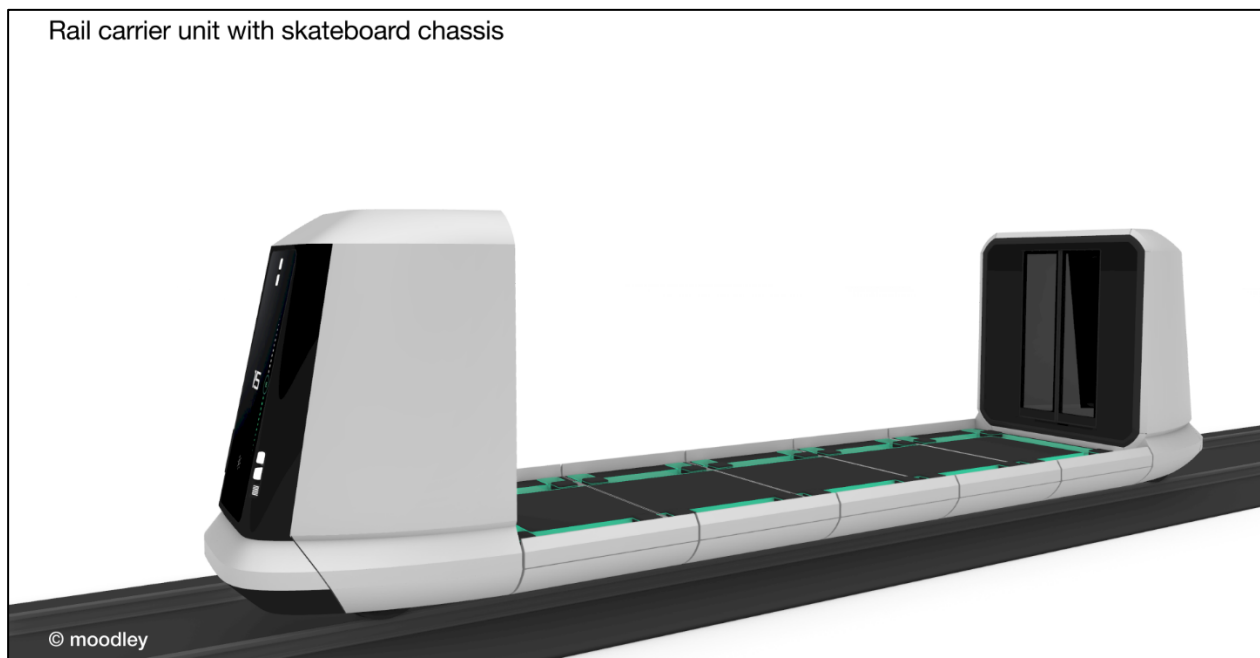


Figure 4: Conceptual design and visualisation of skateboard chassis of rail CU with ladder frame structure (moodley)

Rail CU with pantograph

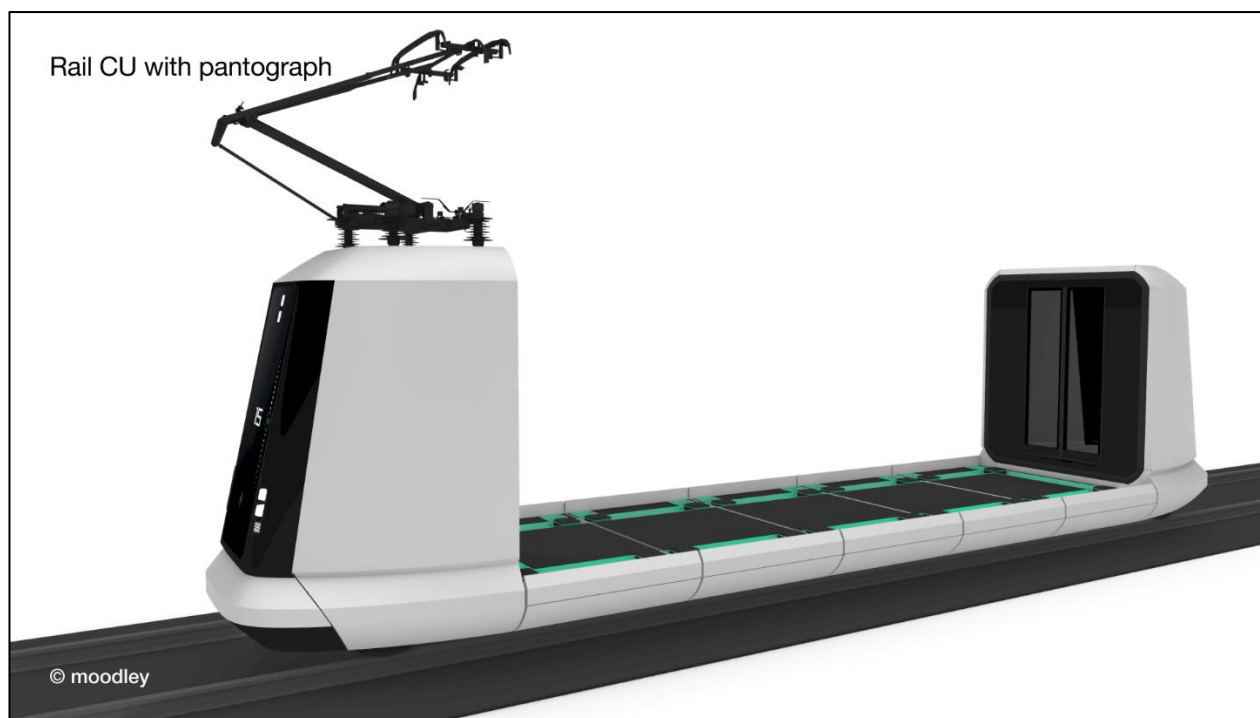


Figure 5: Conceptual design and visualisation of rail CU with pantograph (moodley)

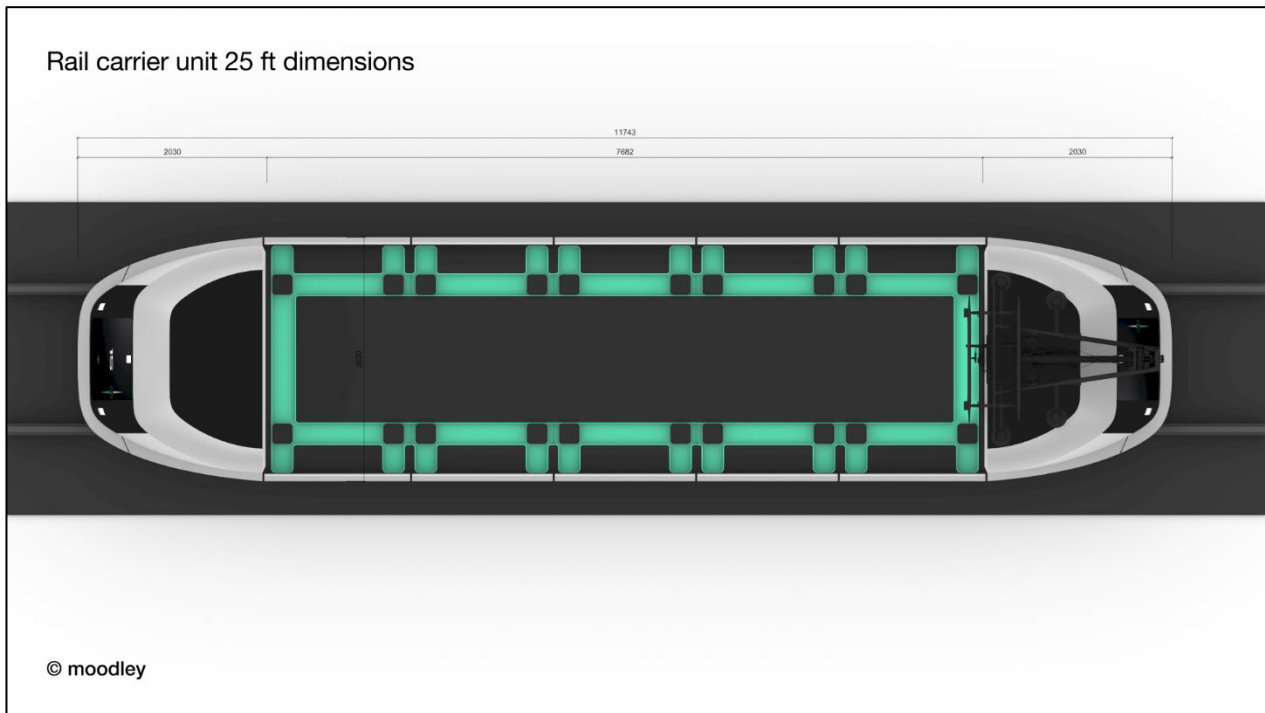


Figure 6: Conceptual design and visualisation of rail CU 25 ft dimensions showing the integration of twist-lock connections within the modular carrier architecture, top view (moodley)

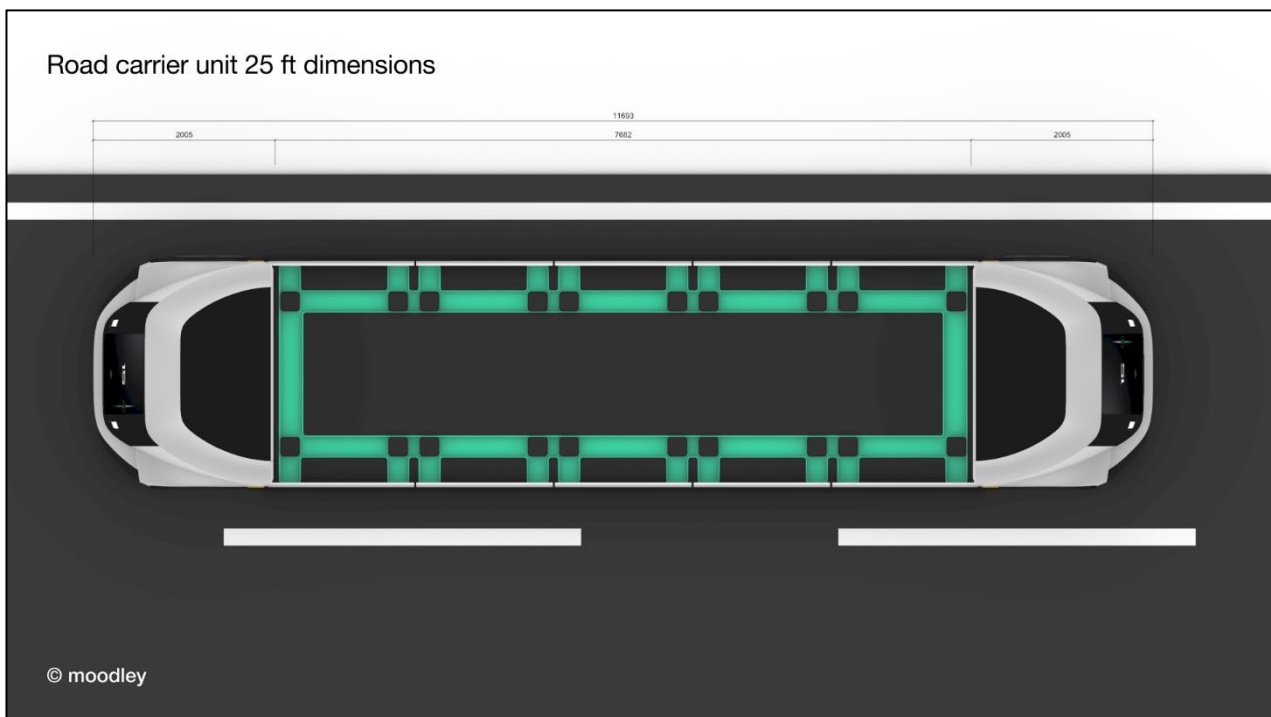


Figure 7: Conceptual design and visualisation of Road CU 25 ft dimensions, top view (moodley)

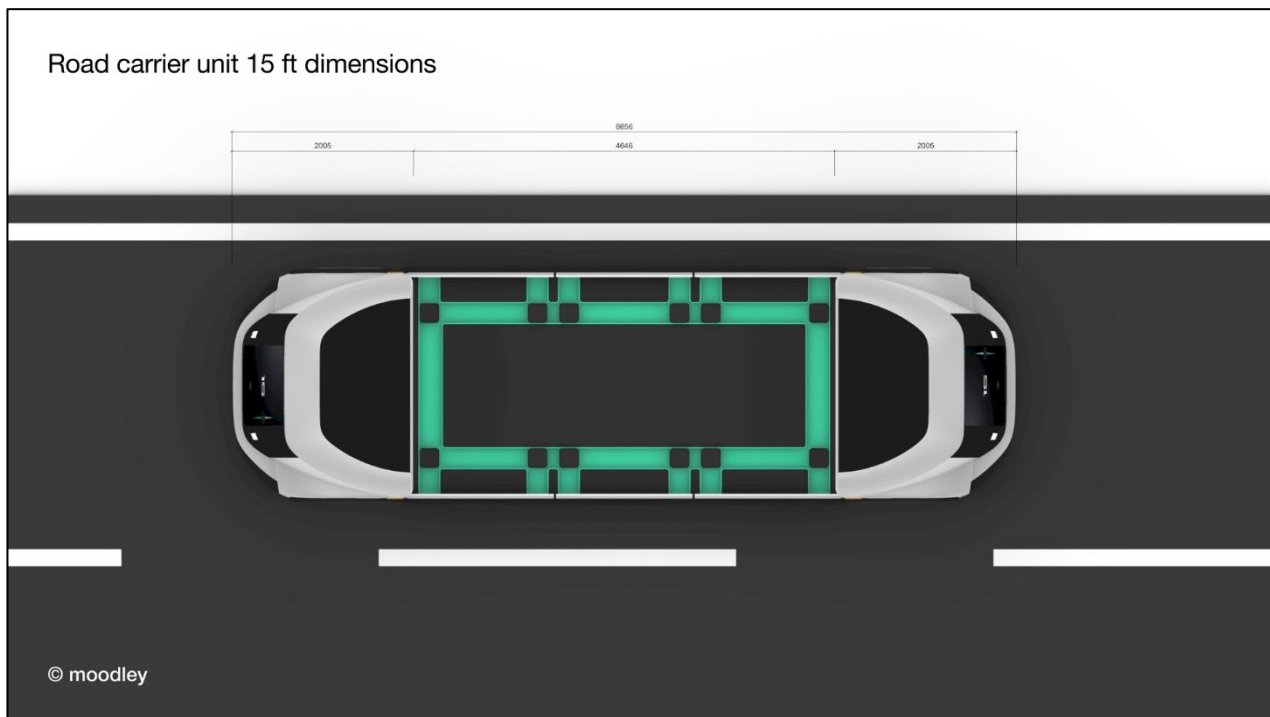


Figure 8: Conceptual design and visualisation of Road CU 15 ft dimensions, top view (moodley)

5.8 Final Carrier Unit concept proposal

5.8.1 Rail CU concept proposal

The concept of the Rail CU follows the general principles outlined in Chapter 5, combining high standardisation and modularity with domain-specific requirements. It is designed for both passenger transport (UC1) and freight transport (UC18). In UC1, the Rail CU carries passenger TU with seating, standing space and luggage, while in UC18 it carries container-type TU for cargo, using the same basic vehicle platform. The Rail CU features a symmetrical design for bidirectional transport. It respects the technical limits of European railway infrastructure, in particular Category A lines with a maximum axle load of 16 tonnes, enabling it to operate on a wide range of routes. The final Rail CU concept for a 25 ft configuration combining 5 ft and 10 ft TU is shown in Figure 9. The overall dimensions are approximately 12.75 m × 2.5 m × 3.2 m (length × width × height). The concept proposal emphasises the One4All philosophy by supporting various TU configurations and sharing key components with Road CU.

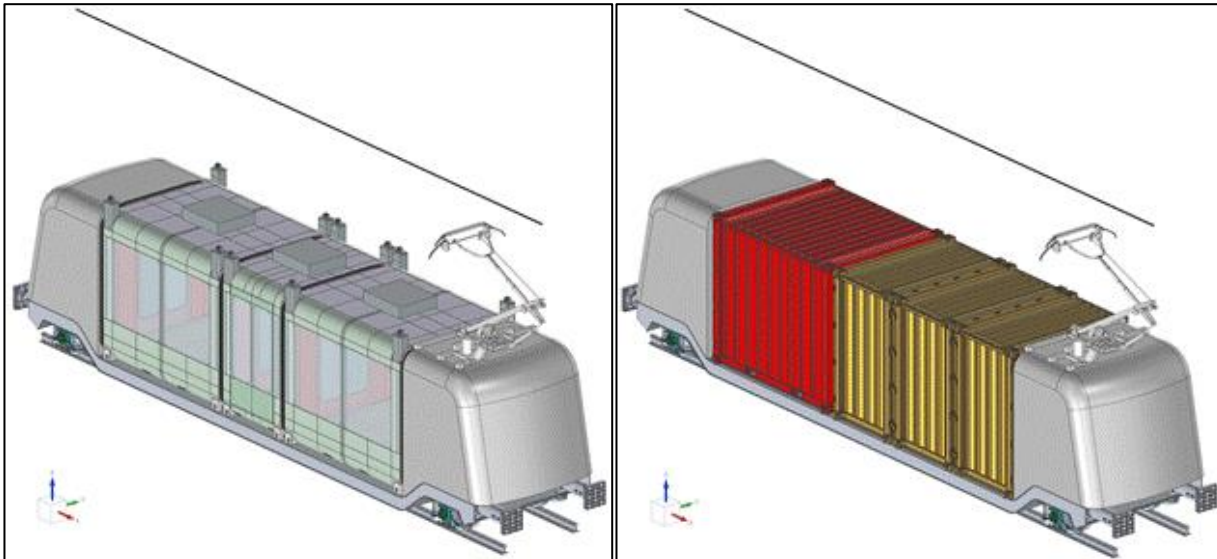


Figure 9: Principle sketch of concept proposal for rail CU for UC1 (passenger transport, left) and UC18 (freight transport, right) (UWB)

5.8.2 Road CU concept proposal

The concept of the Road CU is defined by flexibility and modularity. It can be used for several use cases due to its adaptability in loading capacity and accessibility. The Road CU is built in a symmetrical design to allow bidirectional driving. It is equipped with intelligent entrance systems as well as advanced manoeuvrability. The concept is shown based on the selected UC1 (basic public passenger transport). Two versions of the Road CU can be considered as standard setups. A shorter version with a loading capacity of 15 ft (meant to transport one 10 ft passenger TU and one 5 ft Entrance Unit) and a longer version with an increased capacity of 25 ft (similar to Rail CU with additional 10 ft passenger TU). The Road CU concept proposal is shown in Figure 10.

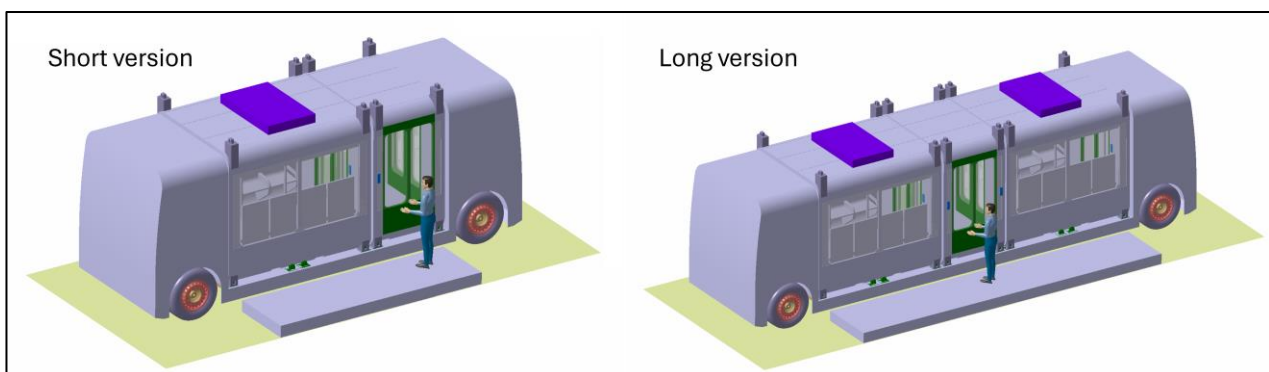


Figure 10: Principle sketch of concept proposal of the Road CU for UC1 (passenger transport) in a short version with extended capacity (left) and a longer version with standard capacity (right) (DLR)

For every passenger scenario, it is preferred to enter from a platform at the side of the vehicle. Nevertheless, the concept is highly flexible and also offers additional access without a platform from ground level depending on the user needs and TU-configuration. The overall dimensions for

the configuration with 15 ft capacity are around 8.8 m of length, 2.5 m width and 3.0 m height. It will be able to drive on every road besides all other road users.

5.8.3 Ropeway CU concept proposal

The ropeway CU is intended as the third supermodal carrier type—next to road and rail—enabling Pods4Rail to operate in terrain where conventional mobility systems become inefficient or impossible. Ropeway systems offer advantages such as low ground impact, high energy efficiency, continuous operation, and suitability for complex topographies, making them relevant for Pods4Rail use cases in urban, interurban, and mountainous environments.

As written in Task 14.4, the technical scope is restricted to 2S pendulum aerial ropeway systems, which consist of fixed track ropes for load bearing and a separate haul rope for cabin propulsion. The CU attaches to the haul and track ropes via a hanger system, which forms the essential mechanical interface between TU and ropeway infrastructure.

Based on existing ropeway manufacturers and reference systems, the deliverable derives typical structural dimensions and weight ranges for ropeway carriers. Standard European ropeway cabins with a capacity of around 10 passengers show tare weights between 2.3 and 3 tons, with typical component masses estimated for the carriage (400–900 kg), hanger (250–400 kg), and detachable grips (50–120 kg). These benchmarks support the sizing of the Pods4Rail ropeway CU, which is expected to carry a 10-passenger TU with a similar tare mass.

A major finding is the definition of the TU-CU interface: Unlike road or rail CU, the ropeway hanger system cannot transmit power or communication signals. Therefore, the structural interface relies exclusively on mechanical twist-lock connectors, building on standards established in earlier Pods4Rail work packages.

For further details related to connector platform dimensions and hanger lengths between for mono cable gondola systems, it is recommended to proceed in Deliverable 14.4 (Pods4Rail D14.4, 2026).

6 Specific development of the Rail Carrier Unit

6.1 Energy system

6.1.1 Estimation of power demand and battery capacity

To assess the energy consumption and battery-capacity requirements of a representative regional railway tailored to the operational characteristics of UC1, a real-world line meeting these boundary conditions has been selected as the reference scenario. The Mariazellerbahn in Austria fulfils these criteria as a regional, medium-distance secondary line with performance parameters that align with Pods4Rail's intended operational envelope. Its maximum speed of approximately 80 km/h corresponds to the target cruising speed defined for the Pods-based Rail CU, ensuring methodological consistency when evaluating traction power demand and energy profiles. Furthermore, its total length—roughly 90 km—provides an appropriate benchmark for determining the necessary energy autonomy of a battery-electric rail vehicle operating end-to-end without intermediate recharging, which reflects typical endurance expectations for European regional services. In addition, the service pattern and infrastructure characteristics of the Mariazellerbahn closely resemble those defined for UC1, where small-capacity passenger transport is delivered over secondary railway corridors. For these reasons, the line offers a realistic and representative operational framework for analysing the battery-sizing, energy-consumption and endurance requirements of the Pods4Rail Rail CU. The main characteristics of the line are summarised in Table 14 and Figure 11:

Table 14: Line characteristics and main parameters

Parameter	Value
Length:	91.3 km
Maximum speed:	80 km/h
Max gradient:	28 ‰
Minimum curve radius	78 m
Number of stations/stops	27

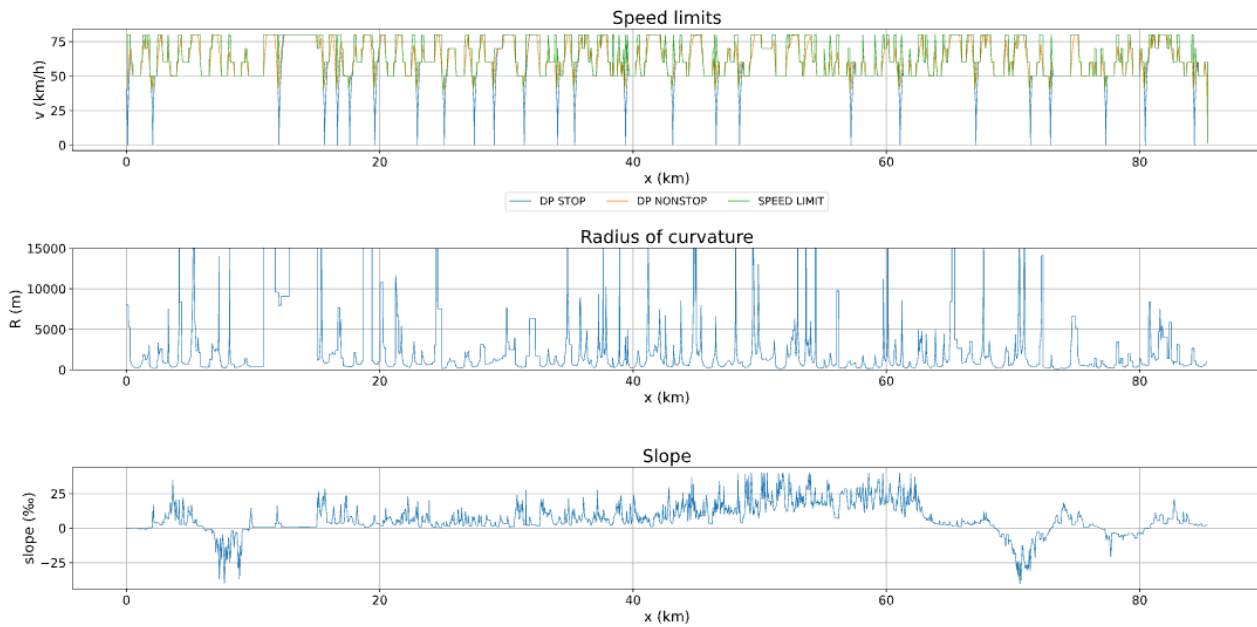


Figure 11: Line characteristics and main parameters. (a) Speed limitations and maximum speed able to be reached by the vehicle. (b) Vertical alignment with slopes

The model defining the train motion of this work is based on the principles of longitudinal train dynamics (LTD). Hence, the train is considered as a point mass with one degree of freedom, where the traction/brake system, rolling resistances, air intake, aerodynamic drag, and slope and curve resistances are applied. The dynamic equations which are considered are as follows:

$$\dot{s} = v$$

$$M\dot{v} = -A - B v - C v^2 - F_e + F$$

where s and v denote the position and train speed, F is the driving/braking force, F_e is the resistance force due to the track, M is the train's mass, A is a term that includes the rolling resistance plus the bearing resistance, B is a coefficient related to the air intake, and C is the aerodynamic drag coefficient.

The resistance force F_e includes two components F_g and F_R which are defined as follows:

$$F_e = F_g + F_R$$

$$F_g = -Mg \times slope$$

$$F_R = -M \times 6/R$$

The values of the slope and R depend on the line profile and the position s of the train on the line and are, therefore, known at each time. CFD simulations of the pod geometry further validate the aerodynamic coefficient obtaining, $C_x=0.31$ (Figure 12).

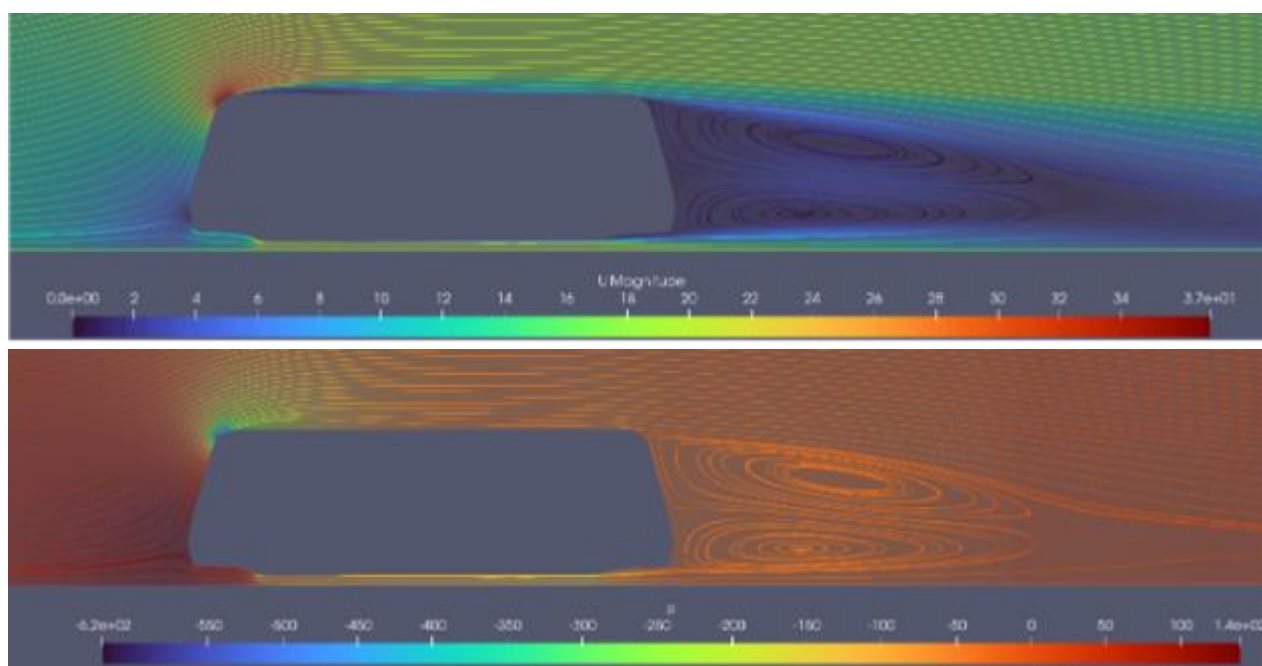


Figure 12: CFD Simulations for estimating the aerodynamic drag (UPM)

To evaluate this scenario, two pod configurations, one for rail and other for road will be assessed with the aim of obtaining the energy consumption across the entire line and serving as a basis for sizing the battery for fully autonomous driving. Table 15 summarises the main characteristics and parameters for both pods.

Table 15: Pod characteristics (25 feet module)

Transport mode	Passengers	Freight
Mass (tonne)	20.75	32.00
A (N)	220	
B (N/(m/s))	2.79	
C (N/(m/s) ²)	1.47	
Acceleration at maximum speed (m/s ²)	0.1	

Figure 13 shows the traction curves and rolling resistance. The power of the traction system has been designed so that, in the worst-case scenario (32 tonnes of freight), the pod is capable of overcome a 30‰ gradient at a speed of 80 km/h. Under these conditions, the power required for the traction system is 325 kW.

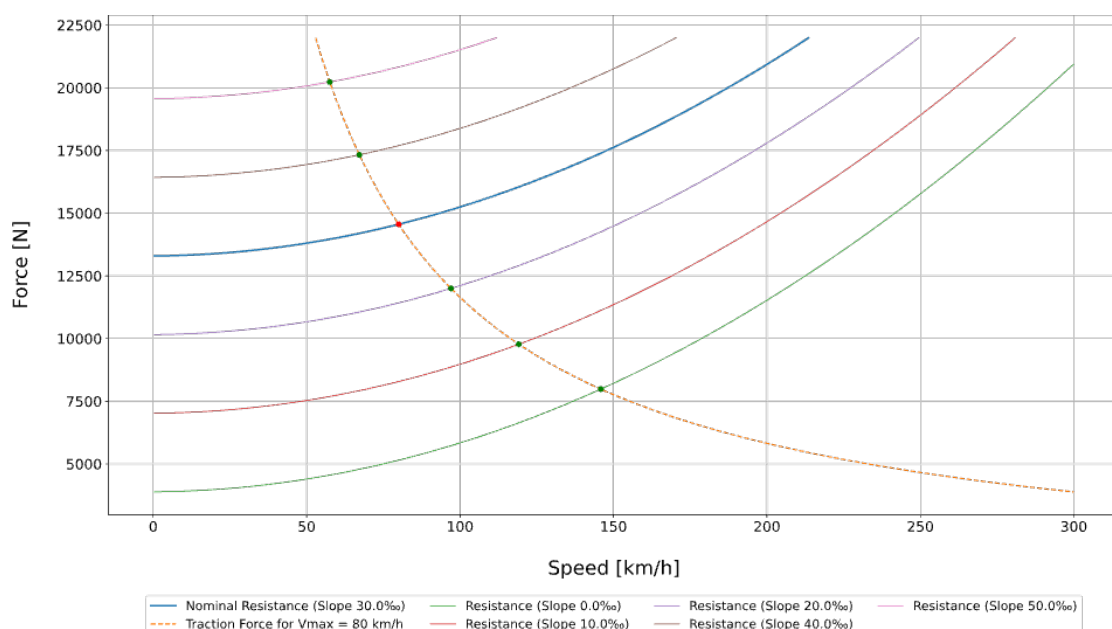


Figure 13: Traction curves and rolling resistances for the pod

The behaviour of the pod on the line described previously has been simulated using the model previously presented. These calculations have been made considering a system with regenerative braking, with an efficiency of 80%.

Figure 14 shows the results obtained for passenger services, while Figure 15 shows the results for freight services.

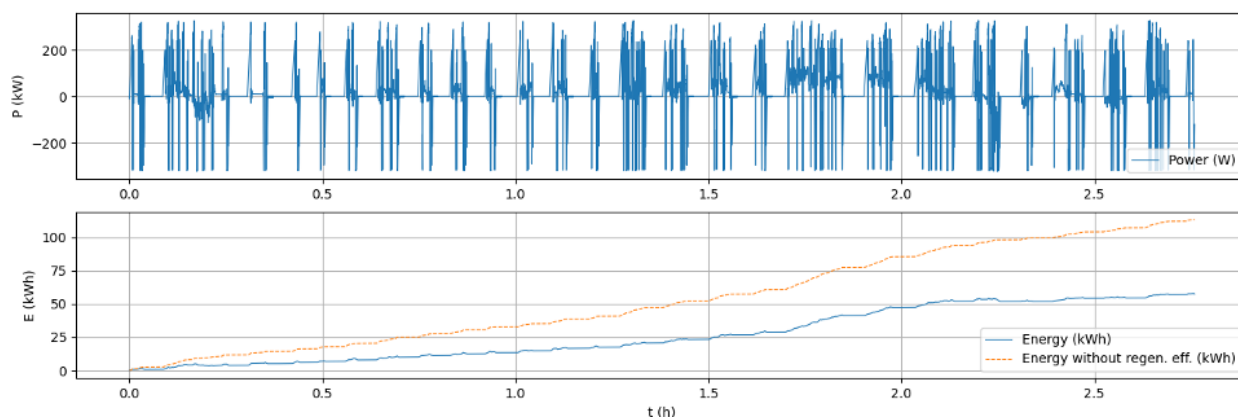


Figure 14: Power required and energy consumed for passenger service

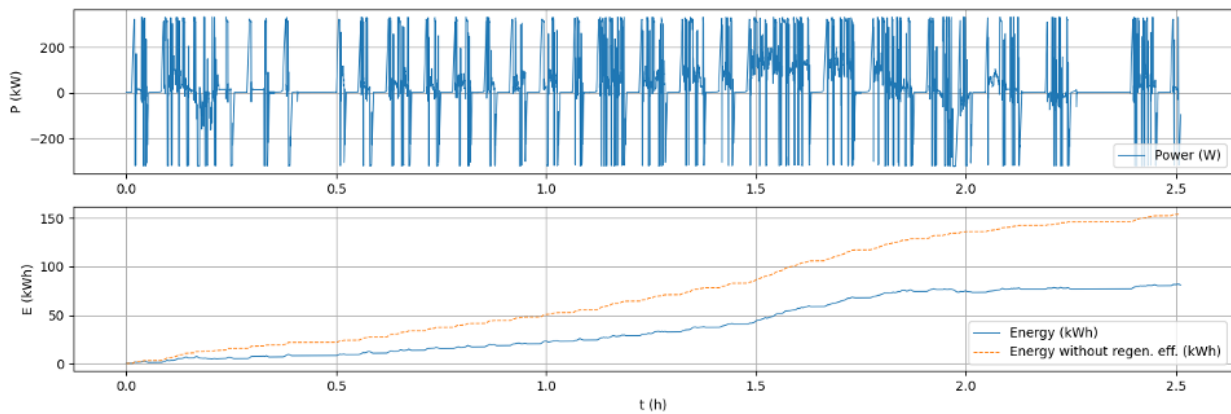


Figure 15: Power required and energy consumed for freight service

The results obtained show that the simulated route (93 km) takes between 2 hours 30 minutes and 2h 45 min, depending on the scenario, with a consumption of 58 kWh for passenger service, while for freight the consumption is 82 kWh, all considering regenerative braking. If we extrapolate to a range of 300 km, the estimated consumption would be 275 kWh for the most worst-case scenario, which is that of freight.

The previous energy consumption represents solely the traction energy required to move the vehicle under the operating scenario considered. However, a complete battery sizing process must additionally incorporate several efficiency-related factors that significantly influence the total on-board energy demand. First, the round-trip efficiency of battery systems typically ranges between 85% and 95%, depending on temperature, state of charge and degradation level; thus, the usable energy must be increased to compensate for conversion losses. In this case, we will consider 90%. Second, the efficiency of the traction chain—including inverters, motors, and mechanical transmission—further reduces the effective energy delivered to the wheels, with a range falling between 70% - 90% (World Bank, 2026). In this case we will consider 90%. Finally, auxiliary loads such as HVAC, lighting, control systems and passenger comfort equipment constitute a substantial share of railway energy consumption. An estimation of these items has been done in D7.1. In addition, it is also considered that the battery will leave 20% of its available capacity as a safeguard.

These additional factors must therefore be incorporated to derive a realistic and technically robust battery capacity. In consequence the capacity of the batteries results 498 kWh.

6.1.2 Concept proposal for Energy Architecture of the Rail CU

The proposed energy architecture for the Rail CU builds on the principles defined in Section 5.7.2 and responds to the specific operational, safety and interoperability requirements of autonomous rail-based Pods. The concept adopts a distributed battery-electric propulsion system, with one traction motor per wheelset, ensuring both functional redundancy and improved dynamic controllability. This configuration aligns with emerging autonomous-rail demonstrators, where decentralised traction allocation enhances tolerance to single-point failures and allows for refined torque distribution under varying adhesion conditions.

To supply this distributed propulsion system, the Rail CU incorporates a scalable battery-pack architecture designed around modular energy units that can be sized according to route length, duty cycle and operational constraints. The battery system is envisaged to employ advanced cell chemistries offering high cycle life, improved thermal stability and compatibility with high-power charging. These characteristics are essential to meet the stringent availability requirements of Pods4Rail, where rapid turnaround and long service life are fundamental. Modular battery integration also supports flexible placement within the vehicle frame, enabling efficient weight distribution and simplified maintenance procedures.

The proposed concept further assumes compatibility with regenerative braking to maximise energy recovery and reduce overall consumption, as well as integration with the digital control and monitoring functions defined in Pods4Rail D11.1 (Pods4Rail D11.1, 2025). This ensures that battery health, thermal management and power allocation are supervised by a unified digital layer capable of optimising energy usage in real time. Such coordination is particularly relevant for autonomous operation, where predictive energy management based on traffic conditions, gradients and vehicle-to-infrastructure communication can significantly enhance efficiency.

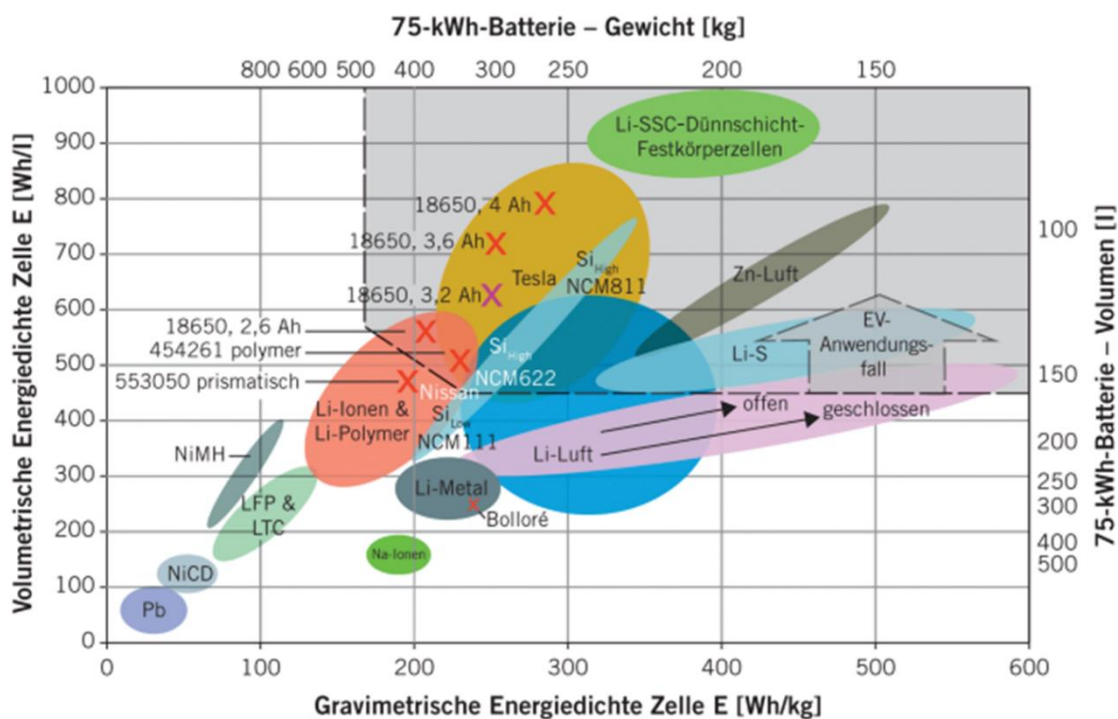


Figure 16: Overview of battery technologies in relation to weight, volume and energy density (Birke, 2018)

The diagram provides a comprehensive overview of the performance of various battery cell chemistries and places them in relation to their gravimetric and volumetric energy densities. The horizontal axis shows gravimetric energy density in watt-hours per kilogram (Wh/kg), while the vertical axis displays volumetric energy density in watt-hours per litre (Wh/l). Additionally, the top and right axes indicate the approximate weight and volume of a sample 75-kWh battery used in

electric vehicles. This makes it clear how a cell's energy density directly influences the total weight and required installation space of a battery system.

In the lower left corner, older and less energy-dense technologies such as lead-acid batteries (Pb), nickel-cadmium (NiCd), and nickel-metal hydride batteries (NiMH) are shown. These technologies offer low energy per weight and volume and thus result in very heavy and bulky batteries when scaled to 75 kWh.

Slightly further to the right and higher up are lithium iron phosphate systems (LFP), which offer high safety, long lifecycle, and stable behaviour, despite lower energy density compared to modern lithium-ion systems. However, they require significantly more volume and weight to store the same amount of energy.

At the centre of the diagram lies the largest group: conventional lithium-ion cells and lithium-polymer variants. Within this group, numerous cell formats are shown, such as 18650 cells with various capacities. With energy densities between roughly 150 and 280 Wh/kg and 350 to 700 Wh/l, they represent today's industry standard in electric vehicles. Technologies like NCM111, NCM622, and NCM811 demonstrate the evolutionary trend toward higher nickel content and higher energy density. Cells with increased silicon content on the anode side—such as “Tesla Si-high”—move further into the high-performance region.

Further to the right, with significantly higher energy densities, are future battery technologies such as lithium-metal, lithium-sulphur (Li-S), and lithium-air (Li-Air). These concepts theoretically offer energy levels far above today's lithium-ion technologies and could drastically reduce the weight and volume of battery systems. However, they currently face major technological challenges, including short cycle life, unstable chemical behaviour, and insufficient durability. Zinc-air systems also appear as a potential future solution, though not as extreme in their projected performance as lithium-air.

Of particular interest are the regions representing solid-state batteries (Li-SSC thin-film solid-state cells), which are positioned in the very high energy density area of the diagram. These technologies are viewed as highly promising because they combine high energy density with improved safety potential.

The diagram also highlights technological development paths: arrows indicate the progression from open to closed systems, as well as directions of advancement within lithium-air development.

Overall, the graphic reveals a clear hierarchy: while older battery technologies are no longer relevant for high-energy applications, lithium-ion systems remain the current standard. Solid-state, Li-S, and Li-Air technologies mark potential pathways into the future, provided their significant technical hurdles can be overcome. At the same time, the diagram makes evident just how crucial energy density is for the weight and volume of a battery pack - an essential factor for electric mobility, portable electronics, and stationary energy storage.

6.2 Description of the vehicle body architecture

The architecture of the Pods4Rail rail CU is designed as a modular, standardised platform capable of transporting different sizes of TU while ensuring fully automated mechanical and electrical coupling. The CU can be designed as a modular ladder-frame chassis consistent with the skateboard configuration described previously, enabling a clear separation between the rolling platform and the interchangeable TU payload modules.

To further align with the system-level design principles, the CU structure should also emphasise a low-floor arrangement, improving accessibility, reducing the overall loading height for automated vertical handling, and ensuring compatibility with multimodal infrastructures. These adaptations reinforce the intended modularity, lifecycle flexibility, and cross-platform interoperability.

Structurally, the CU acts as chassis optimised for rail dynamics, incorporating ISO-standard corner castings arranged to accept 5 ft, 10 ft, and 20 ft TUs in multiple configurations, as illustrated in the schematic layouts where mechanical couplers are placed at the corners of each potential 5 ft footprint while electrical couplers occupy the central positions for each TU slot. This arrangement allows the CU to host combinations such as one 20 ft TU, two 10 ft TUs, or four 5 ft TUs (with also the entry module), with unused twistlocks retracting automatically to avoid interference when longer units are mounted.

The mechanical interface uses fully automated twistlock mechanisms integrated into the CU upper frame, enabling vertical guidance, interlocking, and sensor-based verification of secure attachment, following the standardized workflow where the TU is lowered vertically, twistlocks engage, and sensors confirm completion.

A ladder-frame structural concept, potentially realised in welded steel, may be explored to address rail-specific dynamic load conditions, while considering relevant structural and crashworthiness standards, as well as multimodal compatibility and future expansion to ropeway or road CUs.

Electrical architecture can be centralised in a dedicated coupling module located beneath the TU footprint, protected by automated covers that open only once mechanical locking is confirmed; vertical-moving connectors then provide high-voltage power distribution for HVAC, lighting, communication systems, and TU auxiliary loads. Redundant or symmetric connector placement ensures operability even when certain slots remain unused or when couplers are damaged.

The CU structure can also incorporate routing for communication systems enabling TU–CU synchronisation, condition monitoring, and status verification, forming a digitally supervised interface that supports autonomous operation.

Main structure and list of selected key components is as follows:

- Among the considered options, a ladder-frame structure with longitudinal beams and transverse crossbeams may be used as a primary load-bearing concept.
- Reinforced twistlock mounting zones/twistlock pockets with retractable automated twistlock assemblies (major mechanical interface);

- Central electrical coupling module area (TU–CU power interface);
- Rail bogies (wheelsets, axles, suspension, motors);
- Battery;
- Rail braking system interfaces (mounting points for brake equipment);
- End couplers for train integration;
- Crashworthy structural zones;
- Cable routing channels embedded in chassis.

The possible low-floor Rail CU structure is shown in Figure 17. Additionally, a dimension chain is presented in Figure 18, showing multiple variants based on the distance between the rail upper height and the TU floor (550 mm, 700 mm, 800 mm).

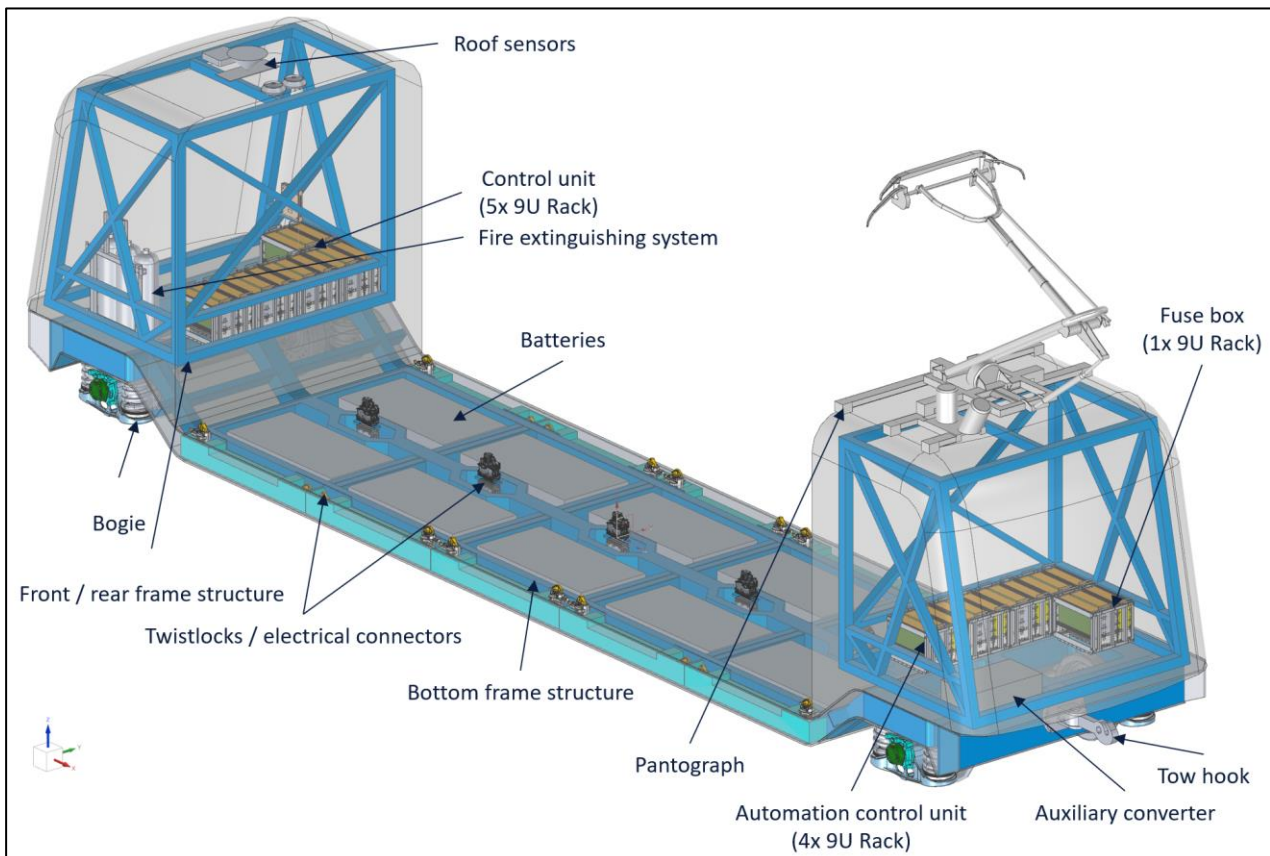
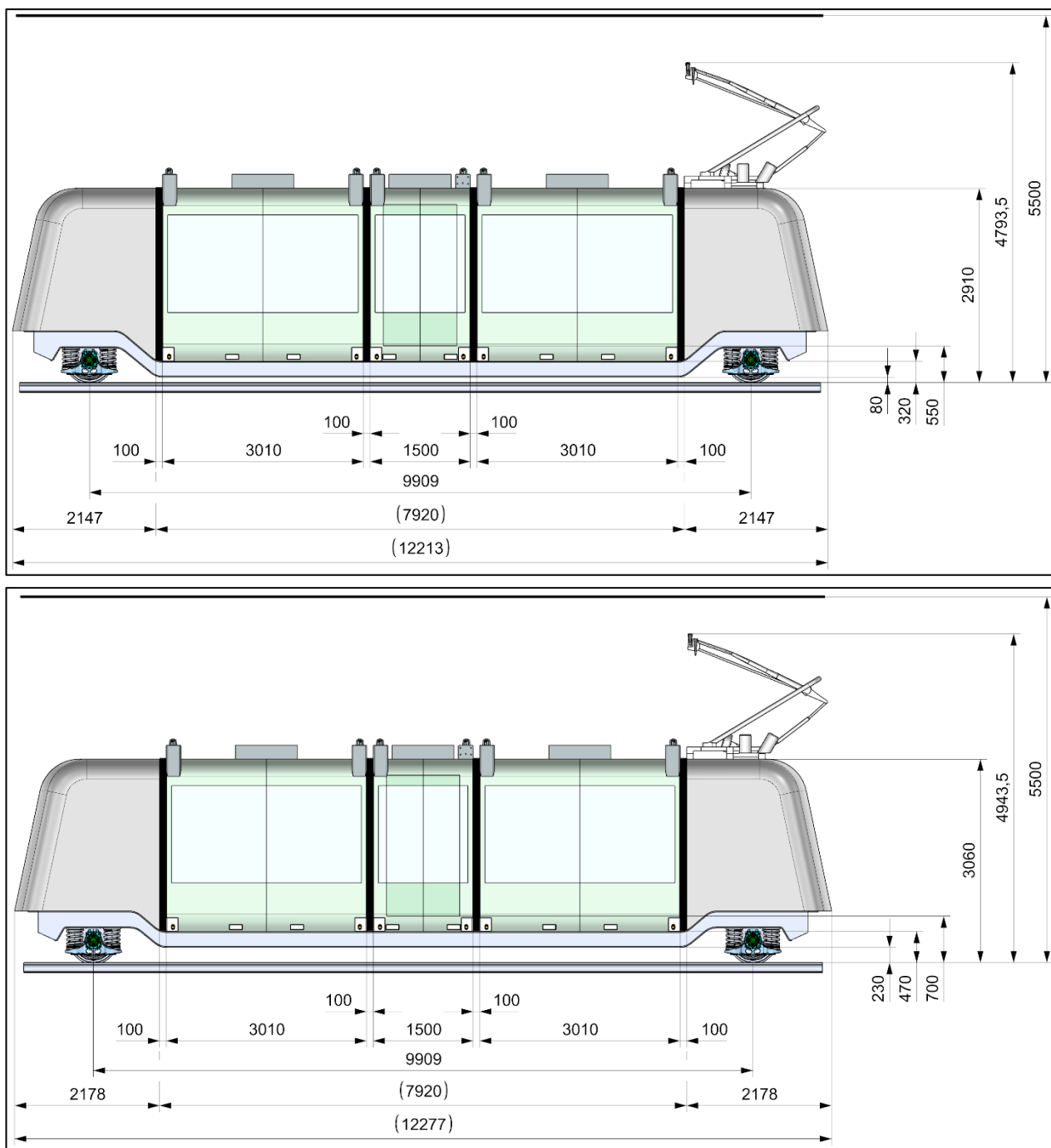


Figure 17: Principle sketch of a Rail CU structure with bottom frame and front/rear structures (UWB)



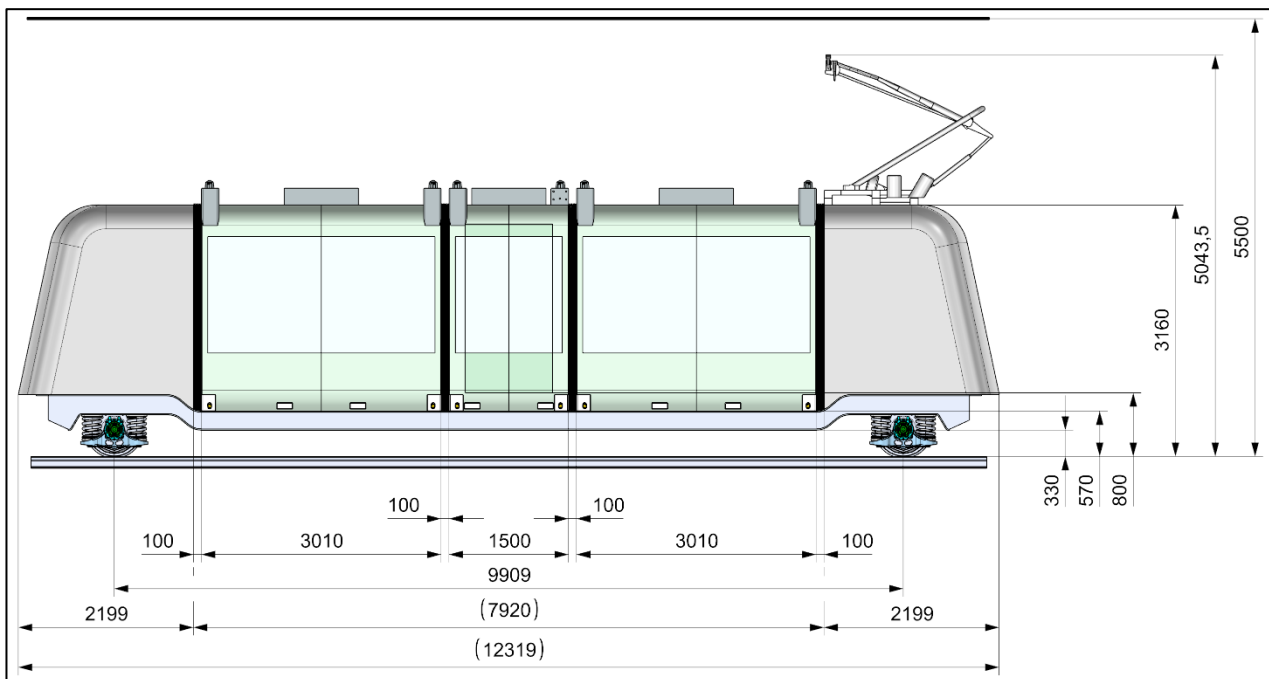


Figure 18: Principle sketch of dimension chain of the Rail CU (left to right: distance between the rail upper height and the TU floor 550 mm, 700 mm, 800 mm) (UWB)

6.3 Bogie Concept

The development of a bogie concept suitable for the Rail CU requires a thorough review of existing self-steering technologies and their applicability to lightweight, autonomous and energy-efficient rail vehicles. The state-of-the-art analysis conducted within this deliverable shows that self-steering bogies offer significant benefits in terms of reduced wheel–rail interaction forces, improved curving performance, and lower energy consumption - features that align closely with the Pods4Rail objectives of minimising infrastructure stress and enabling highly efficient operation.

Based on this assessment, the proposed concept adopts a single-axle self-steering bogie equipped with an integrated traction motor, ensuring both mechanical simplicity and high curving capability while also meeting the requirements for distributed propulsion defined for the Rail CU. The inclusion of direct propulsion in the bogie supports the overall energy-architecture concept of one motor per wheelset, enhances dynamic control, and facilitates redundancy for autonomous operation.

To substantiate this choice, Table 16 provides a comparative overview of the three principal self-steering solutions examined. The comparison highlights differences in mechanical architecture, steering mechanisms, propulsion integration and potential suitability for lightweight autonomous rail applications, forming the basis for selecting the single-axle configuration as the most appropriate bogie concept for Pods4Rail. A more detailed information of these bogies can be found in Annex E.

Table 16: Comparison of existing self-steering bogie concepts

Bogie Concept	Mechanical Architecture	Self-Steering Principle	Propulsion Integration	Advantages	Limitations	Relevance for Pods4Rail Rail CU
The CFD Group concept design (CFD Group, 2025)	Conceptual lightweight bogie architecture using a simplified single-frame layout; emphasis on low unsprung mass and modular integration	Yaw-relaxation through controlled compliance or geometric alignment, enabling natural radial steering	High compatibility – designed to accommodate a wheelset-mounted motor or inboard drive	Very low structural mass; promising curving behaviour; adaptable to new lightweight vehicles	Concept remains at conceptual/virtual development level; validation and durability data limited	High – aligns well with lightweight Pods4Rail requirements but requires further validation
The Aachener Rail Shuttle (ARS) bogie concept (ARS, 2025)	Single-axle bogie with two independently powered wheelsets; ladder-frame housing equipment; developed for autonomous shuttle operation	Passive self-steering via independent wheelset alignment and low yaw stiffness; optimised for sharp-curve operation	Fully integrated propulsion – one motor per wheelset (maturity at demonstrator level)	Excellent curving performance; proven prototype; good match for autonomous operation and distributed propulsion	Lower load capacity; specific to lightweight shuttles; requires advanced control to avoid hunting	Very high – closest existing solution to Pods4Rail Rail CU operational profile
Fr8Rail 4 bogie concept (Fr8Rail, 2022)	Optimised two-axle freight bogie; retains conventional mechanical structure with innovations for reduced forces and energy use	Self-steering via radial alignment facilitated by improved bush stiffness, linkages or controlled yaw damping	Medium compatibility – possible to integrate motors, but conceptual work focuses on unpowered freight bogies	Mature railway engineering; robust under high loads; validated in freight contexts	Higher mass; not optimised for small autonomous vehicles; more complex than single-axle designs	Medium – robust reference but sub-optimal for lightweight autonomous Pods

6.3.1 Bogie concept designs for CU

Section 6.3.1 consolidates the bogie-related findings introduced previously by presenting the concrete design proposals developed for the Rail CU. The section builds on the previously established conclusion that self-steering bogies offer significant advantages for lightweight autonomous vehicles - namely reduced wheel-rail forces, improved curving behaviour and lower energy consumption - which directly support the Pods4Rail objectives of infrastructure protection and operational efficiency. Within this context, the bogie concepts examined here translate the earlier state-of-the-art assessment into specific engineering configurations that account for propulsion integration, braking interfaces and structural limitations, all of which must align with the CU modular low-floor architecture and distributed-drive requirements as defined in the Rail CU development framework.

Design 1

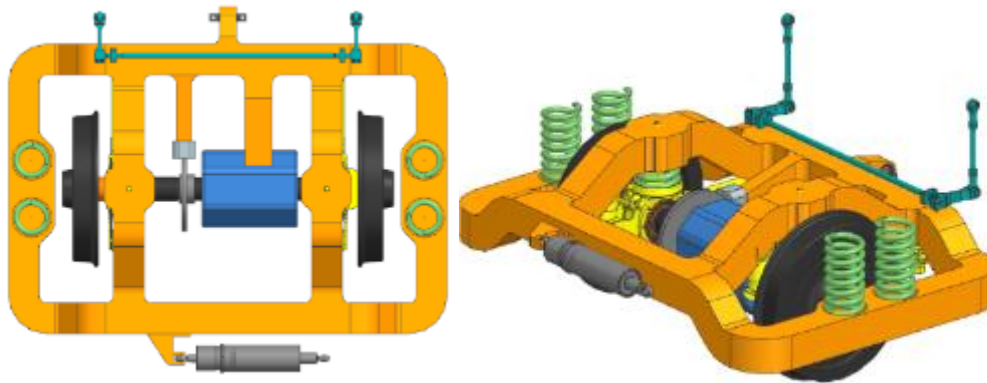


Figure 19: Bogie concept – Design 1

For a two-axle CU with a maximum speed of 80 km/h, it is necessary to ensure good driving characteristics, including smooth passage even through small curves. This can be achieved by a single-axle revolving bogie with double suspension and a pivot point outside the transverse axis of the bogie. One bogie is traction, the other may or may not be in traction also. The bogie has a welded steel frame made of 6 and 8 mm thick sheets. The frame is complexly shaped, consisting of two inner and two outer longitudinal beams and two transverse beams. The outer longitudinal beams are adapted to carry secondary springs; the inner longitudinal beams are adapted to support primary springs. One cross beam has a bracket for anchoring in the pivot pin; anchoring is via a silent block. The second cross member has a bracket for anchoring the return mechanism. The return mechanism will be controlled electronically, and it will turn the bogie into a curve and after exiting the curve will move the bogie into a straight line. The wheelset with internal bearings has a diameter of 770 mm, a width of 135 mm. The wheels are integral, rolled, with a silencer, pressed onto the axle. The axle is forged. The axle is equipped with roller bearings which are mounted in a bearing housing, lubricated with a disposable grease filling, maintenance-free. A coaxial traction motor and a torque transmission mechanism to the axle are mounted on the axle of the traction chassis. It is a synchronous motor with permanent magnets, air-cooled. The engine is mounted on the chassis frame (not shown in the picture). Furthermore, one brake disc is mounted on the axle. The wheelset guidance is made by two parallel composite leaf springs. One end is mounted on the bearing housing; the other end is mounted on the chassis frame.

The primary suspension is made by a helical spring with a parallel hydraulic shock absorber. The spring is mounted with its lower end on the bearing housing; the upper end is supported by the inner longitudinal member. The secondary suspension consists of two pairs of flexi-coil helical springs. These springs are around 500 mm long and allow the transmission of vertical and transverse forces, which allows the chassis to turn when driving in a curve. The springs are supported with their lower end on the outer longitudinal member, and with their upper end on the frame of the car body. The suspension is supplemented by a hydraulic shock absorber. The suspension can also be supplemented by a torsion stabilizer. Braking is provided by disc brakes, electrically controlled. The transmission of vertical forces is done by flexi-coil springs.

This concept is not considering usage of air springs, because in order to make the CU lighter, it not generally used compressed air in the design. Therefore, is not used all necessary accessories (compressor, pressure tanks, etc).

The transmission of longitudinal and transverse forces is done via a console with a silent block and via a pivot pin that extends from the body frame of CU. The disc brakes are attached to the main frame of the vehicle. They are driven electrically. The brake discs are, as mentioned above, placed in the wheel discs on both sides, or on the axle. The brake discs themselves are made of cast iron. On the side facing the wheel disc, the brake discs are ribbed for better ventilation and heat dissipation during longer-term brake effect.

Design 2

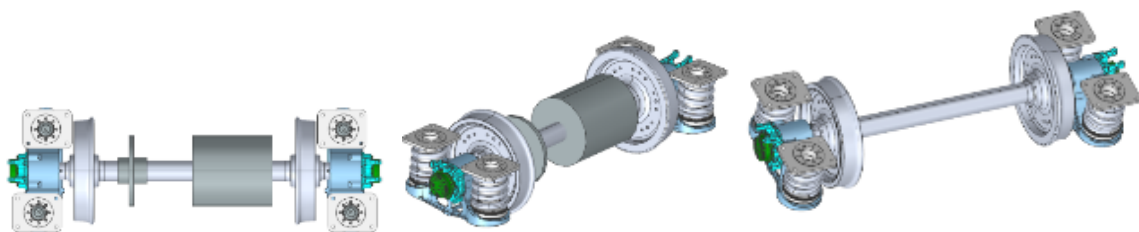


Figure 20: Bogie concept – Design 2

It is a bogie with single suspension, for cargo, non-turnable, with or without traction motor. The wheel set guidance and suspension is carried out using a combination of helical springs with a linear liquid damper and vertical guide pins. The helical springs are mounted on both sides in the saddles, with the lower saddle being equipped with a rubber pad for vibration damping. The spring mounting saddles include the aforementioned horizontal bearing housing guidance system using guide pins.

Due to the maximum speed and maximum weight of the vehicle, the wheelset was selected as an assembly of monoblock wheels with a diameter of 680 mm and axles with external pins for bearings. The bearing housings are made as castings adapted to accommodate bearing units. They also allow the connection of liquid linear primary suspension dampers. The bearing housings also include collectors located on the front of the axle for grounding the vehicle. The disc brakes are attached to the main frame of the vehicle. They are driven electrically. The brake discs are, as mentioned above, placed in the wheel discs on both sides, or on the axle. The brake discs themselves are made of cast iron. On the side facing the wheel disc, the brake discs are ribbed for better ventilation and heat dissipation during longer-term brake effect.

The vehicle is powered by an electric drive using an asynchronous motor. The expected power, given the expected vehicle weight, acceleration and braking requirements and maximum speed, is approximately 80 kW per traction motor. The power would be transferred using a single-stage gearbox with a permanent oil fill. The gearbox would be connected to the axle on the axle side by bearings directly to the axle. The traction motor would be firmly connected to the gearbox, and the entire assembly would be suspended from the main frame of the vehicle on the traction motor side using a hanger. The traction motor would be cooled using forced ventilation located directly on the traction motor.

7 Specific development of the Road Carrier Unit

Compared to other domains, the road domain offers different degrees of freedom regarding the Road CU design principles. The most important is the platform design itself, since the way to interact with a Road CU and how it will move in the surrounding can differ from other Carrier Units that are line-based, such as Rail CU or Ropeway CU. Also, it is important to analyse the fitting to road standards and to evaluate the accessibility of the platform design for passengers and freight, in accordance with the requirements given in Chapter 5.6.

7.1 Energy system

7.1.1 Estimation of power demand and battery capacity

For the road-based scenario of this deliverable, a mixed-environment driving profile has been constructed using 66% urban distance and 33% interurban distance, resulting in a total route length of 315 km. The corresponding maximum speeds of 50 km/h in urban sections and 80 km/h in interurban sections follow commonly adopted European classifications for built-up and radial-road environments. A total 18 urban and 6 interurban per circuit, iteratively repeated has been incorporated to reflect realistic operational patterns for UC1-type public passenger transport.

To ensure methodological consistency with international vehicle-testing standards, the scenario has been derived from the UN Global Technical Regulation No. 15 (UNECE, 2004), specifically adopting characteristics of the WLTP Class-B cycle, which corresponds to low-to-medium-speed operation typical of urban and peri-urban mobility (UNECE, 2018) (Figure 21).

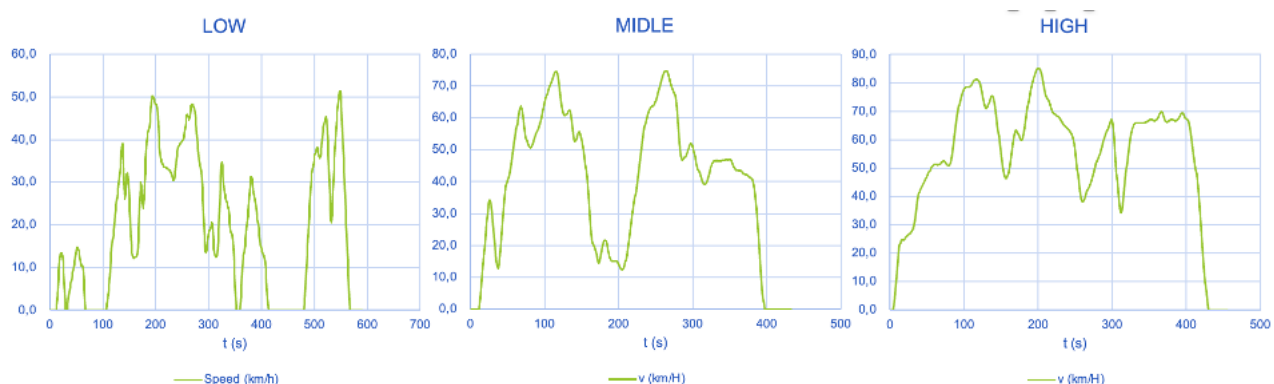


Figure 21: Cycles considered for the urban simulation scenario (UPM)

Based on this regulatory foundation, a composite driving circuit has been designed comprising an urban segment and a radial-road connection, between a major city and a nearby satellite town, repeated multiple times to meet the 315 km target.

Although not modelled on a specific city, this environment is representative of metropolitan regions such as Stuttgart or Madrid, where dense central areas are linked to residential commuter municipalities through radial corridors. To reflect realistic terrain constraints, the route incorporates average gradients of 3% and localised peaks up to 10%, values aligned with typical

elevation profiles in European suburban and interurban road networks. This scenario therefore provides a robust and representative basis for evaluating Pods4Rail road-mode performance under conditions aligned with UC1 mobility requirements. The main characteristics of the line are shown in Table 17 and Figure 22:

Table 17: Characteristics and main parameters for the road scenario

Parameter	Value
Length:	315 km
Maximum speed:	80 km/h
Max gradient:	10 %
Urban	70% 18 stops for transshipment X cycles Low speed 220 km
Suburban	30% 6 stops for transshipment X cycles High speed 95 km

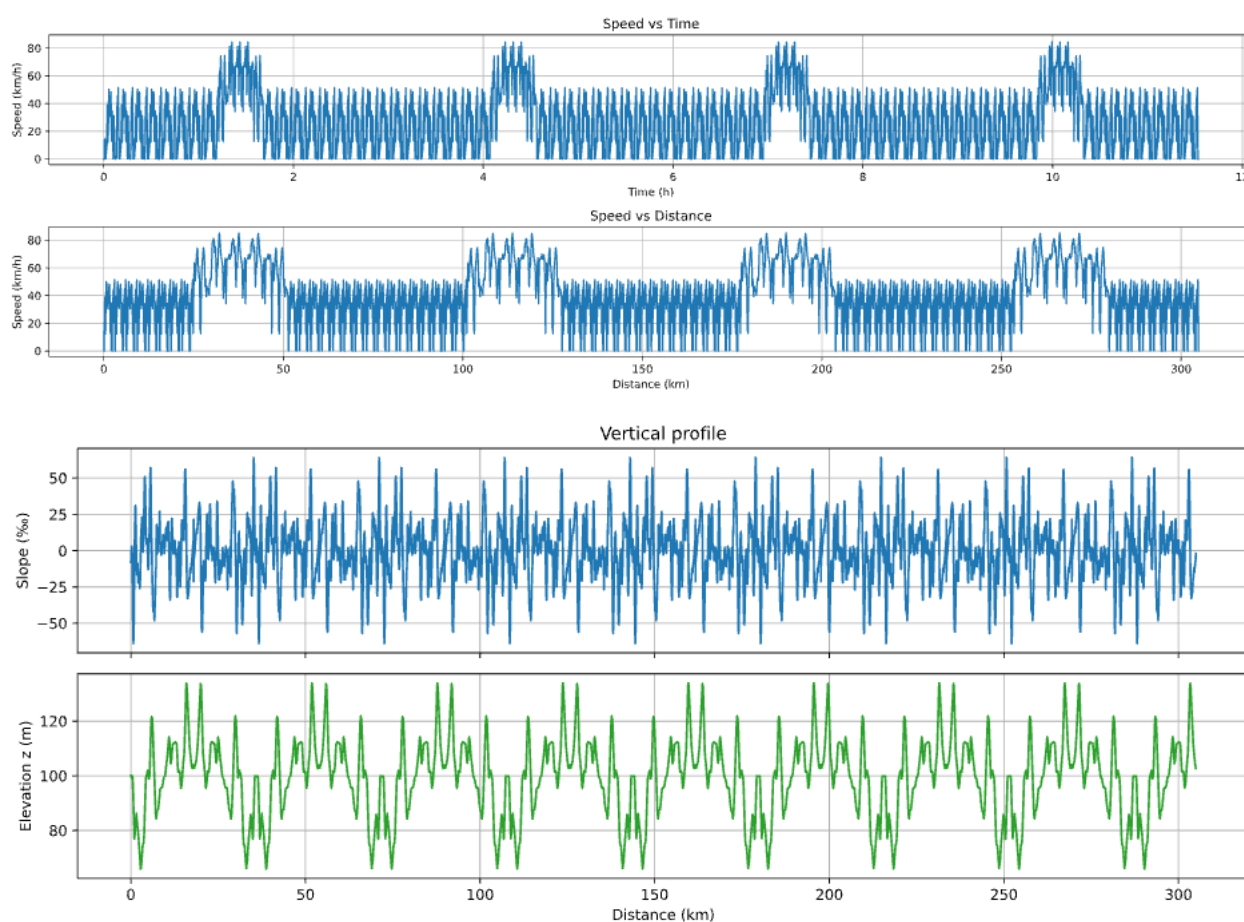


Figure 22: Circuit considered for the road scenario

To evaluate this scenario, a pod configuration will be assessed using the same methodology as for the rail CU. The goal is to obtain energy consumption data across the entire travel and use it as a basis for sizing the battery for fully autonomous driving. Table 18 shows the pod's main characteristics and parameters.

Table 18: Pod characteristics (25 feet module)

Transport mode	Passengers (25 feet)	Passengers (15 feet)	Freight (25 feet)
Mass (ton)	16,75	9,45	18,00
A (N)	1790		
B (N/(m/s))	5,79		
C (N/(m/s) ²)	1,47		
Acceleration at maximum speed (m/s ²)	1		

For the energy dimensioning of the Road CU, it has been assumed that the same CU will be used for both passengers and goods, so the dimensioning will be carried out for the case of goods, which is the most unfavourable as it has more mass. Therefore, a 25-foot CU will be dimensioned using the data for freight (18 ton) and a 15-foot CU for passengers.

Figure 23 and Figure 24 show the traction curves and rolling resistance for the 25 feet TU and for the 15 feet TU respectively.

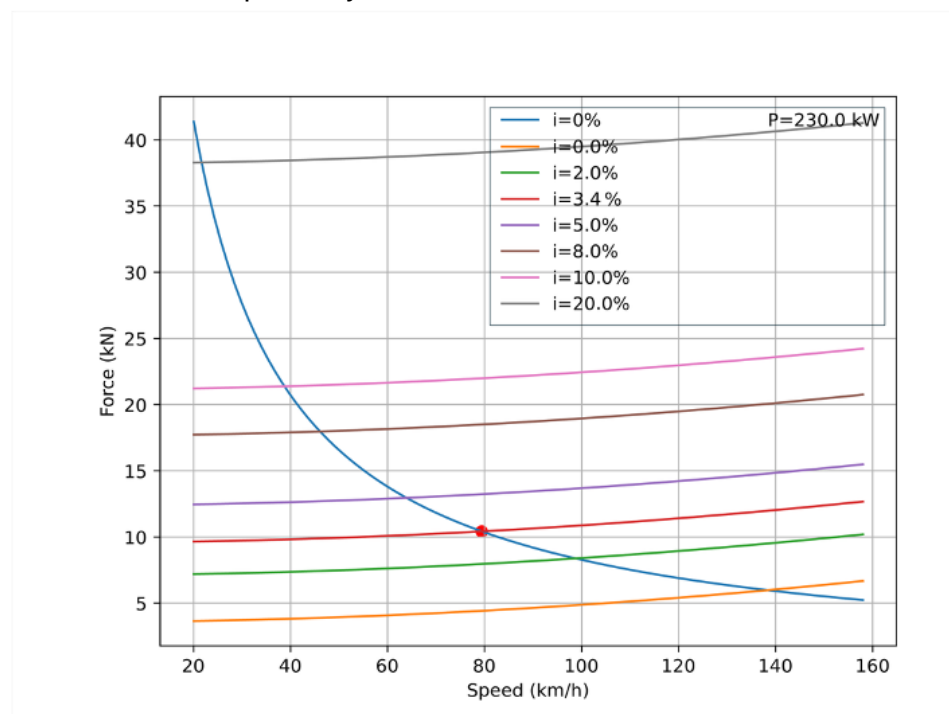


Figure 23: Traction curves and rolling resistances for the 25 feet TU for road service

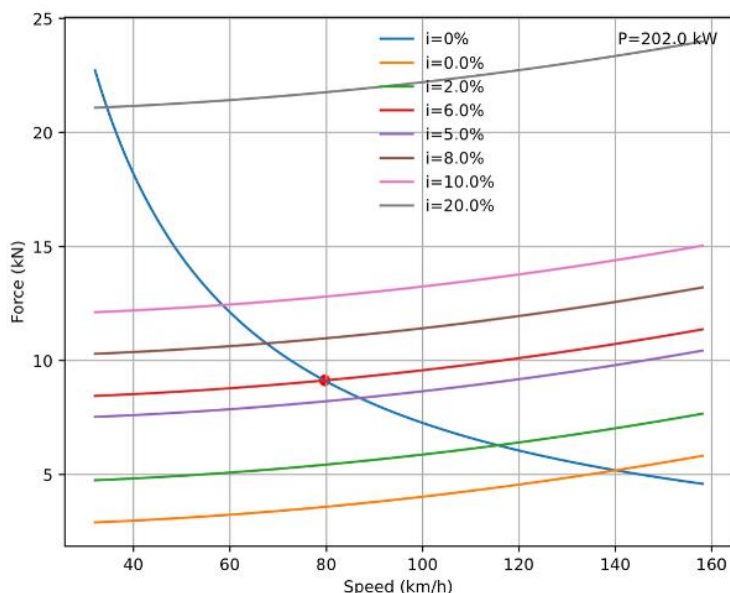


Figure 24: Traction curves and rolling resistances for the 15 feet TU

Under these conditions, for the 25-foot TU and in the worst-case scenario (freight), the power required is 230 kW allowing to overcome a slope of 3,4% at 80 km/h. On the other hand, for the 15-foot TU, only for passengers in this case, the power required is 202 kW allowing to overcome a slope of 6% for a speed of 80 km/h.

Under this hypothesis, the behaviour of the pod on the line described previously has been simulated using the model previously presented. These calculations have also been made considering a system with regenerative braking, with an efficiency of 80%. Figure 25 and Figure 26 show the results obtained for passenger services (25 and 15 feet respectively), while Figure 27 shows the results for freight services (25 feet).

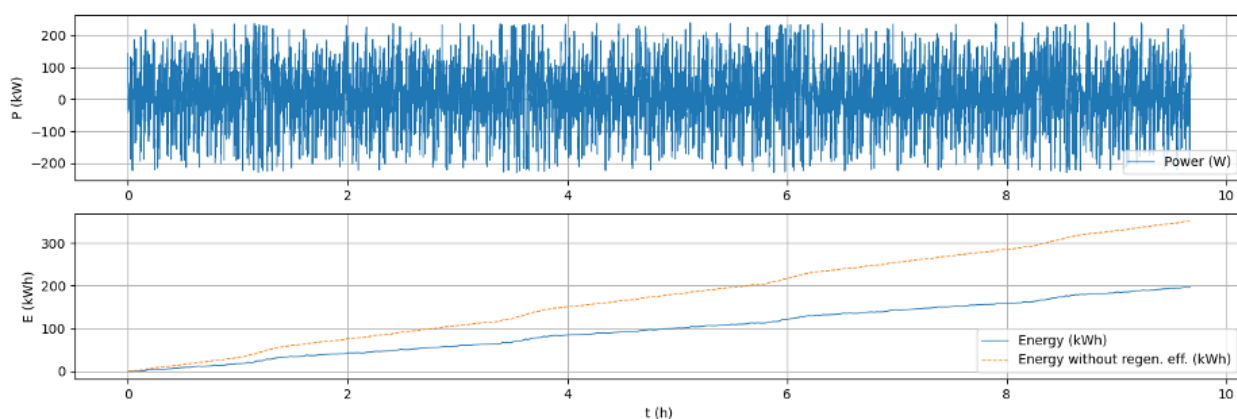


Figure 25: Power required and energy consumed for passenger service (25 feet)

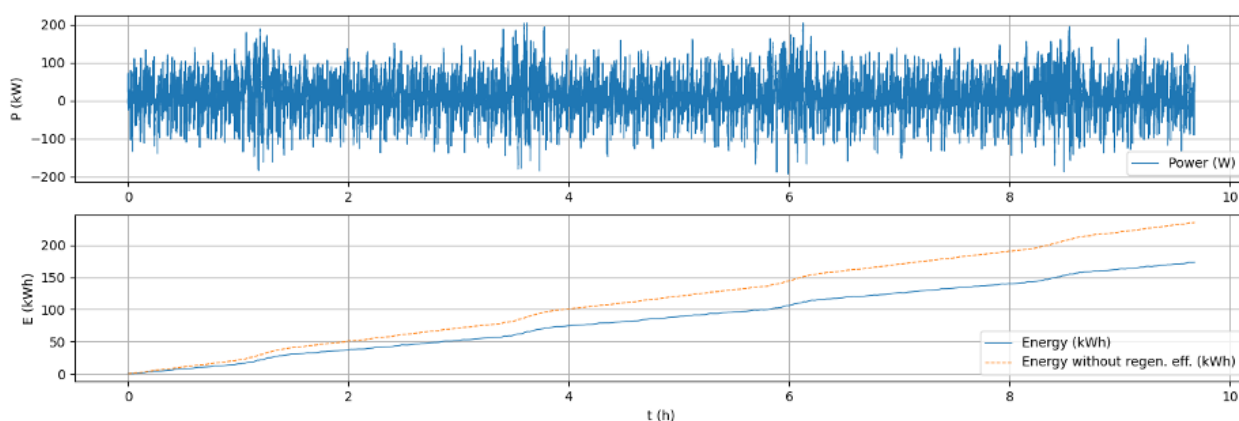


Figure 26: Power required and energy consumed for passenger service (15 feet)

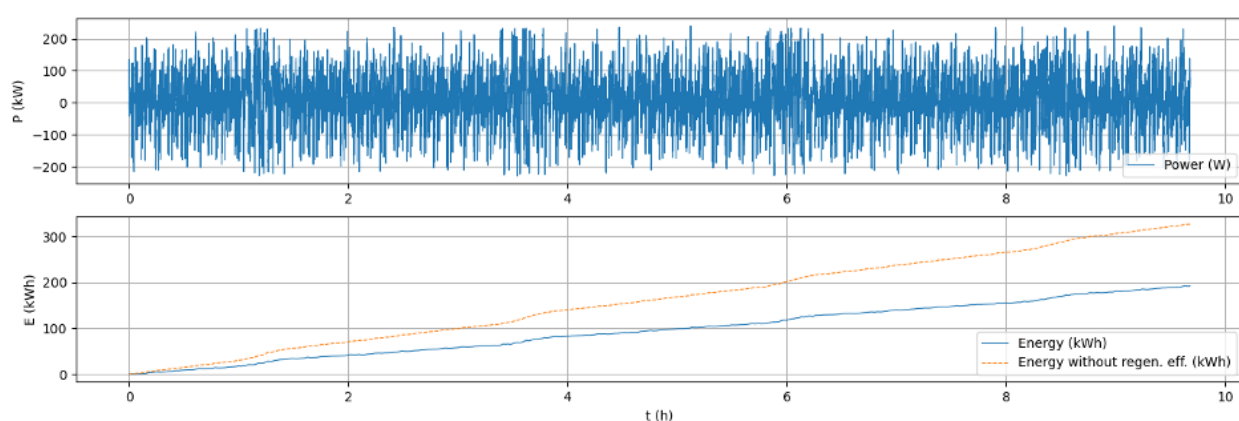


Figure 27: Power required and energy consumed for freight service (25 feet)

The results obtained show that in the simulated route (315 km) for passenger the energy consumption is 193 kWh for the 25 feet CU and 174 kWh for the 15 feet CU, while for freight the consumption is 198 kWh, all considering regenerative braking. The travel time is around 9h 43 minutes excluding stops.

As in the case of Rail CU, the above energy consumption represents only the traction energy required to move the vehicle in the operating scenario considered. To complete the entire battery sizing process, the aforementioned factors of battery efficiency (85%), traction chain performance (90%) and auxiliary consumption must also be considered. It is also considered that the battery will leave 20% of its available capacity as a safeguard.

Thus, taking all these factors into account, the battery capacity needed for driving and all auxiliary consumers is 380 kWh for the CU of 25 feet and 315 kWh for the CU of 15 feet.

7.1.2 Drivetrain and battery technologies

Several battery technologies are suitable for the Road CU, depending on the strategy of drivetrain development and battery functionalities. The battery chemistries provide different functionalities, e.g. In the ability for high power, fast charging, high energy, low ecological impacts, high safety or high amount of charging cycles.

The following Table 19 highlights some applicable battery technologies and gives an overview of possible state of the art energy capacities, based on suppliers' information. All given battery types are considered as suitable for the system. The mentioned data are given for one example battery configuration for a specific application. It has to be mentioned, that other configurations are possible and the specifications can be changed accordingly.

Table 19: Suitable battery systems available on the market

Supplier	ABB (ABB Switzerland Ltd., 2023)	BorgWarner (BorgWarner Inc., 2026)	Webasto (Webasto Group, 2026)	CTS (Hunan CTS Technology Co., 2026)
Domain	Rail	Road	Road	Road
Voltage [V]	718	338 or 676	280 - 400	628
Power [kW]	140-325	n.a.	50-113	66-99
Capacity [kWh]	33	53.4 (at 338 V)	35	30
Weight [kg]	550	334	295	n.a.
Dimensions [mm]	500x1990x510	2000x660x140	960x686x302	1360x630x235
Energy Density [Wh/l]	65	290	203	150
Energy Density [Wh/kg]	N.a.	160	118	N.a.

Since the battery development is improving quite fast, it is expected that the energy densities and specifications will increase in the next decades.

Related to the drivetrain, the convergence of in-wheel electric motors (IWM), e-corner modules (ECM), and steer-by-wire (SbW) architectures is increasingly regarded as a key technological pathway for next-generation electric vehicles (EV). These technologies enable radical packaging optimisation, enhanced vehicle dynamics, and a modular chassis layout suitable for autonomous and highly automated mobility platforms.

The current State of the Art related to In-Wheel Motors reveals that commercial IWMs today typically fall in the following ranges, shown in Table 20.

Table 20: State of the Art related to In-Wheel Motors in commercial IWM

Parameter	Typical Current Values	Sources
Continuous power	20–80 kW per wheel	(Elaphe Propulsion Technologies, 2025; Protean Electric, 2025)
Peak power	60–150 kW per wheel	(Elaphe Propulsion Technologies, 2025; Protean Electric, 2025)
Peak torque	500–1,500 Nm per wheel	(Elaphe Propulsion Technologies, 2025)
Mass	25–45 kg per motor	Elaphe Propulsion Technologies, 2025; Protean Electric, 2025)

And related to future trends (2026–2035), Table 21, power density of IWMs is projected to increase from 2–4 kW/kg today to 4–8 kW/kg by 2032, driven by advanced axial-flux topologies, the use of SiC-based inverters placed near or inside the wheel module, and also by improved cooling, especially oil-spray and dual-channel stator cooling, supported by data from (Protean Electric, 2025).

Table 21: Projection for 2030 for In-Wheel Motors

Parameter	Expected 2030 Range
Continuous power	50–120 kW per wheel
Peak power	120–250 kW
Torque	800–2,000 Nm
Mass	20–30 kg

7.1.3 Concept of energy architecture for the Road CU

The final drivetrain layout of the Road CU consists of a battery-electric skateboard architecture with scalable voltage. This configuration ensures compatibility with high-power charging infrastructures and supports future proofing for ultra-fast charging technologies, as demonstrated by platforms such as Hyundai's E-GMP (Hyundai Motor Group, 2025) and Geely's SEA (Geely Group, 2025). The scalability of voltage also facilitates integration with diverse traction requirements, enhancing operational flexibility.

The propulsion system is a distributed drive system, based on corner modules or dual-motor all-wheel drive (AWD). This design provides redundancy, improved dynamic control, and enhanced safety. Distributed propulsion mitigates single-point failures and optimises traction performance under variable load conditions, which is critical for Pods4Rail's operational reliability. The electric motors are located in each corner module.

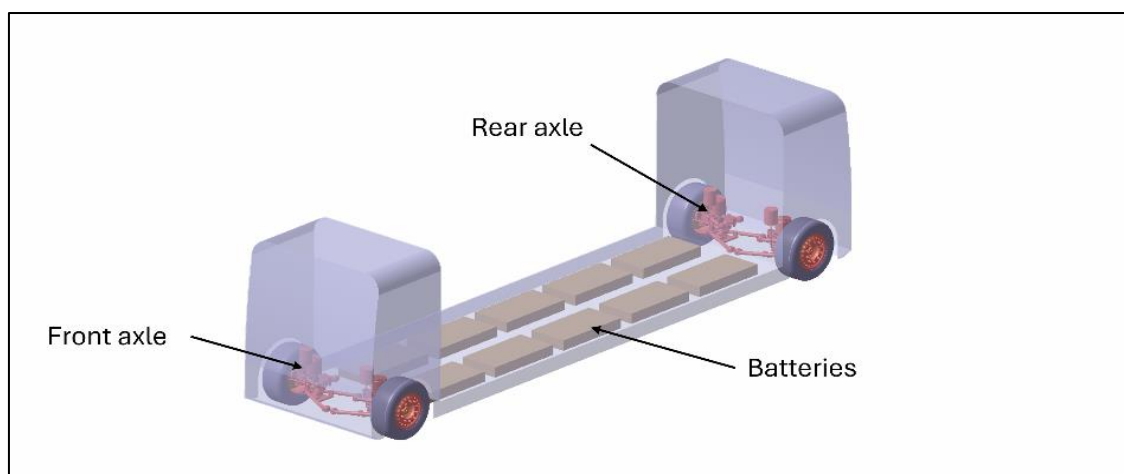


Figure 28: Schematic location of drivetrain components of the Road CU (DLR)

As mentioned in Chapter 7.1.1, an overall energy capacity of approximately 380 kWh is needed to perform all driving functions and support of auxiliary consumers over a period of about 3 h (for the worst-case scenario, with loaded freight containers and 25 ft load capacity). This amount of Energy should be installed in the Road CU, to fulfil all driving and TU-supporting functions for one operation cycle. It has to be mentioned, that this calculation is based on all the assumptions of the previous calculations.

As Figure 28 shows, 10 battery packs can be installed in the bottom structure of the vehicle. Each battery pack is estimated to provide a volume of approx. 0,148 m³ which equals to 148 l. For a common automotive battery, it can be assumed, that the battery housing takes about 10-15% of the volume, which reduces the available battery cell volume to approx. 130 l per battery pack. The whole Road CU can carry a total battery volume of 1,300 l. The energy density of several battery types is assumed to increase about 20-30% in the next two decades. Therefore, the final overall battery capacity of the Road CU can be estimated as shown in Table 22.

Table 22: Estimated battery properties for suitable battery technologies in the future

Supplier	ABB	BorgWarner	Webasto	CTS	Other Li-Ion batteries
Energy Density today [Wh/l]	65	290	203	150	450
Estimated Energy Density with 20% improvement [Wh/l]	78	348	244	180	540
Available volume per battery pack [l]	130				
Capacity per battery pack [kWh]	10.1	45.2	31.7	23.4	70.2
Capacity per 5 ft segment [kWh]	20.2	90.4	63.4	46.8	140.4
Total capacity of the Road CU [kWh] (based on space availability)	101.0	452.5	317.0	234.0	702.0
Estimated battery weight [kg] with 20% increased density	not relevant	2,357	2,402	n.a.	2,925
Estimated battery weight [kg] with 30% increased density	not relevant	2,175	2,201	n.a.	2,700
Battery weight for 380 kWh setup [kg] (based on energy demands)	not relevant	1,810	2,640	n.a.	1,460

The calculation shows that the Road CU is able to integrate more battery capacity than needed to perform all driving functions and to supply all TU-configurations, even if the HVAC-system is running in full operation. Therefore, it will be possible to reduce the required space and weights for the batteries in further developments. The investigations have also shown that additional space is available in the front and rear of the vehicle. Those areas are also suitable to integrate battery packs, if needed. Due to better driving dynamics and safety, it is recommended to prioritise the location in the bottom frame. The example calculation shows that the overall battery weight can be estimated with approx. 1400-1800 kg for a total installed capacity of 380 kWh, depending on the chosen battery technology.

7.2 Description of the vehicle body architecture

This chapter introduces the vehicle body engineering principles and concept approach for the Road CU. It is referring to Pods4Rail D8.1 (Pods4Rail D8.1, 2024), where different materials and design methods were introduced.

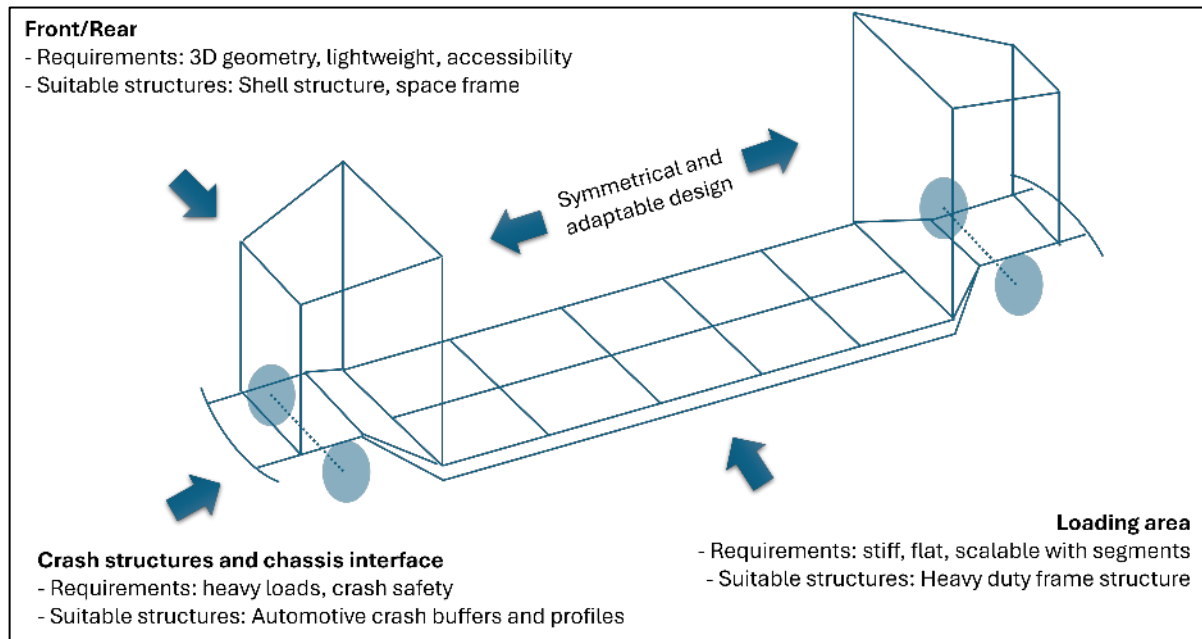


Figure 29: Principles of the Road CU vehicle body (DLR)

Basic structure principle

The Road CU is divided into different sections with different requirements. The loading area makes the biggest part of the Road CU since it has to carry up to 25 ft loading capacity. It ranges of an overall length of about 7.7 meters. Therefore, it is needed to design the loading area structure stiff and flat and to give options for length scalability. The most suitable solution is a strong frame structure, similar to ladder frames in lorries or car platforms. It is suitable because it can provide a load-bearing structure over long lengths, scalable from 5-25 ft. The connection of the twist locks is possible for high loads, greater than automotive standards, therefore no shell or panel construction is chosen. It offers a lightweight design for large platforms and offers high integration options for components, protection of the batteries and electrical connectors.

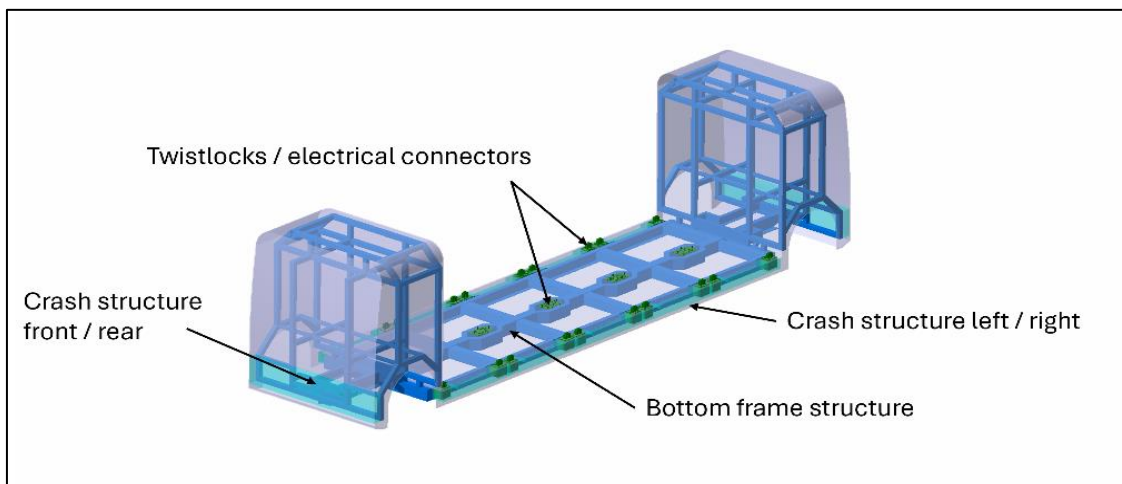


Figure 30: Picture of the Road CU structure with bottom frame and front/rear structures (DLR)

Front and rear structure principles

The vehicle body in the front and rear can be designed in a different way than the loading area, since other requirements have to be fulfilled. The front structure must provide interfaces to the wheel system, it is relevant for crash safety, and several components have to be located in the front area. Also, the design freedom is higher in this area. Because of that it is possible to choose design methods that provide stiffness and structural integrity as well as 3D geometries. Suitable structures to provide crash safety are automotive longitudinal beams, foam-aluminium sandwich panels, or skeleton frames in combination with crash boxes made of aluminium profiles or other deformable elements. It is also possible to use a shell design with 3D-formed outer and inner shells. The chosen method is a skeleton frame design which is suitable for adaptability and easy manufacturing with low infrastructure costs. But the crash safety has to be further validated in the vehicle development with specific load scenarios.

7.3 Wheels, suspension and steering systems

Two design approaches are presented in this chapter: a fully flexible wheel corner module with individual single axles and a lightweight suspension system ready for production (easy, cheap, energy saving) and with improved manoeuvrability. Innovative elements are rear-axle steering systems and semi-active suspension.

7.3.1 Concept 1: Wheel corner module

The first concept consists of a wheel corner module with full integrated steering and suspension system. The concept components are described in Figure 31.

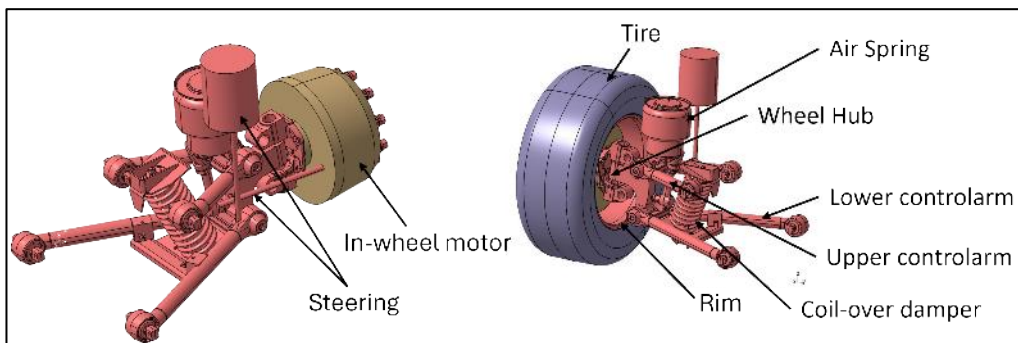


Figure 31: System overview of the wheel corner module (DLR)

Steering

Steer-by-wire technology is included to eliminate mechanical linkages, enabling design freedom and autonomous readiness. This approach, already implemented in REEcorner (REE Automotive, 2025) and CIIC (CATL & Huawei, 2025) platforms, supports advanced driver-assistance systems (ADAS) and future autonomous functionalities. It also reduces weight and simplifies integration with digital control layers.

Suspension

An independent adaptive suspension system is recommended to accommodate comfort and load variability. Adaptive systems enhance ride quality and stability, particularly under mixed operational scenarios, and are consistent with premium EV architectures. For this concept we chose a double wishbone configuration for every wheel. It consists of:

- 2 long lower control arms: Connects the wheel hub to the chassis and primarily controls the vertical movement and camber of the wheel;
- 2 short upper control arms: Helps to position the wheel, controls camber changes during suspension travel, and works together with the upper arms to guide the wheel smoothly;
- Wheel Hub: Connects the wheel to suspension and allows it to rotate freely while transmitting forces to the control arms;
- Coil-over damper: Absorbs shocks from the road and controls suspension movements, with one side attached to the lower arm plate and the other to the chassis;
- Air spring: Supports vehicle's weight and allows adjustable ride height by compressing or extending with air pressure.

Wheel

The wheel assembly includes the rim and tire, designed together to support the vehicle's weight, maintain stability, and ensure proper integration with the suspension system:

7.3.2 Concept 2: Rigid axle concept

The final concept represents a realistic and specific design for an M3-class electric vehicle, weighing less than 18,000 kg, with a typical length under 12 m (maximum 13.5 m), width of 2.55 m, and height below 4 m. The design emphasises a low, flat platform with sufficient ground clearance, avoids pressurised air or hydraulic systems to save battery energy, and relies entirely

on electric components. Mechanical design focuses on production and operational economy, using standard or adapted standard suspension parts wherever possible.

Front Axle – Rigid Suspension with In-Wheel Motors

- Suspension: A rigid axle combined with composite leaf springs provides durability under heavy loads while maintaining a low platform. There are 2 leaf springs on the front axle, each with 2 lever linkages;
- Dampers: Actively controlled using the skyhook strategy to optimize ride comfort and stability;
- Wheel Motors: Each wheel is powered by an in-wheel motor, eliminating the need for a central driveshaft or differential and freeing chassis space;
- Lift Function: The front actuators act through the lever linkages to raise or lower the vehicle and cargo platform in coordination with the rear actuators. (These actuators are not used for steering.);
- Steering: Conventional steering (rack-and-pinion or recirculating ball) operates the front wheels.

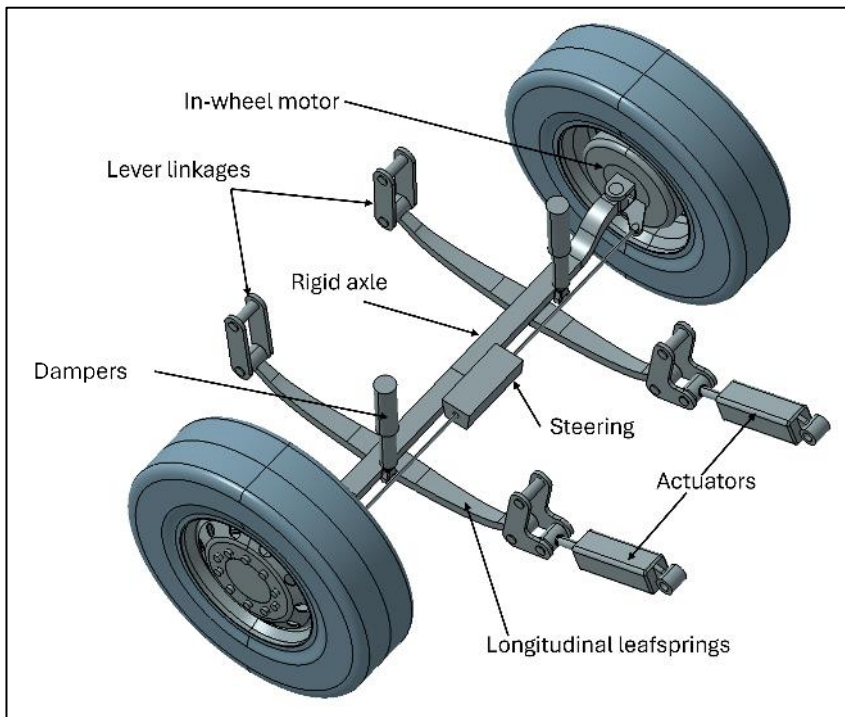


Figure 32: Leaf spring suspension system (UWB)

Rear Axle – Rigid Suspension with In-Wheel Motors, Active Kinematic Joint, and Lift/Steering Function

- Suspension: Similar rigid axle with composite leaf springs as the front, ensuring robust load-bearing. There are 2 leaf springs, each with 2 lever linkages;
- Dampers: Actively controlled with the skyhook principle for ride quality and handling;
- Wheel Motors: In-wheel motors provide independent propulsion and torque vectoring, assisting steering and stability during cornering;
- Lift and Active Rear Steering / Crab Movement:

- o Lift: Actuators at the rear ends of the leaf springs, together with the front actuators, extend or retract synchronously, raising or lowering the entire vehicle/platform evenly;
- o Active Rear Steering / Crab Movement: The rear springs' rigid anchorage is connected via a longitudinally controlled kinematic joint, allowing rotation up to 10° around the vertical axis. By actuating only the rear actuators differentially, a torsional moment is applied to the rear axle, generating active rear steering (crab movement) while the vehicle naturally shifts longitudinally. This reduces the turning radius at low speeds (<5 km/h) and improves manoeuvrability;
- Notes: This system transforms the rear axle from a purely supportive element into an active lifting and steering component, combining both Lift and Crab Movement functions efficiently, and ensuring the lift motion is synchronized with the front axle.

Ground Clearance and Cargo Platform

- The thin composite leaf springs, controlled dampers, and careful axle positioning maintain sufficient clearance to navigate curbs and debris.
- The flat floor design supports easy cargo loading and optimizes interior volume for delivery operations.

In-Wheel Motor Benefits and Considerations

- Advantages: Frees up chassis space for cargo or other components, enables independent wheel torque control and torque vectoring for improved stability, and simplifies drivetrain layout by eliminating central driveshafts and differentials.
- Considerations / Trade-offs: The added unsprung mass from in-wheel motors requires careful suspension and damper tuning to maintain ride comfort and durability.

Architecture:

The vehicle represents a medium-duty electric delivery truck or a specialized EV skateboard chassis, combining proven mechanical principles with in-wheel propulsion, actively controlled dampers, and an integrated Lift and active rear steering system. This approach optimizes manufacturability, energy efficiency, manoeuvrability, and payload accessibility, while maintaining a realistic, production-ready design.

7.3.3 Adaption of concepts from other fields

As the desired system is meant to be introduced to the market in the far future, it is possible to analyse the suitability of chassis concepts from other industries. This chapter gives a short summary of corner modules and wheel sets, that are introduced in other applications or research projects.

DLR ROboMObil (90° wheel-robot system) (DLR e.V., 2026)

- Suspension / Lifting: Integrated wheel modules include damping and steering actuators within each wheel unit, not a conventional suspension setup.
- Wheel Types: Standard wheels integrated into robotic wheel units capable of independent motion.

- Steering System: Individually steerable wheel robotics allow sideways movement and rotation on the spot via electric actuation and central control.
- Suitability for Road CU: High manoeuvrability and autonomy research value, but complex mechanics and control make it unsuitable for typical road vehicles outside experimental contexts.

Omnidirectional wheels (e.g., forklift / Mecanum / Omni) (VETEX, 2026)

- Suspension / Lifting: Typically, minimal or rigid mounting for smooth environments, not tuned for road suspension.
- Wheel Types: Special omnidirectional wheels (Mecanum/Omni) with angled rollers that enable motion in any direction.
- Steering System: Independent drive and speed control of each wheel to achieve lateral and diagonal movement without mechanical steering.
- Suitability for Road CU: Unsuitable for asphalt or high-speed conditions due to traction limits and required control complexity; ideal for indoor logistics.



Figure 33: Forklift with omnidirectional wheels (VETEX, 2026)

Aircraft landing gear concept (Aero Guide, 2026)

- Suspension / Lifting: Designed for heavy impact absorption and stroking during takeoff/landing, not continuous suspension use on roads.
- Wheel Types: Conventional landing wheels optimized for shock loads at specific events.
- Steering System: Typically, limited steering (nose wheel) focused on taxiing, not omnidirectional.
- Suitability for Road CU: Not suitable due to high energy consumption, rigidity and design focus on short high-force events rather than continuous ride comfort.

UnicarAgil (90° steering modules) (UNICARagil, 2026)

- Suspension / Lifting: Integrated dynamic modules combine drive, steering and braking, with suspension functionality bundled into module design.
- Wheel Types: Standard wheels mounted on dynamics modules capable of large steering angles.
- Steering System: Each wheel can steer up to 90°, allowing unconventional movement patterns.

- Suitability for Road CU: Innovative but overly complex and space-intensive for mainstream road vehicles; potentially useful in niche urban or low-speed manoeuvring contexts.

Goodyear spherical wheels (shown in Urban Collectif concept) (Motorsport, 2026)

- Suspension / Lifting: Not a traditional suspension; concept focuses on wheel shape for mobility.
- Wheel Types: Spherical omnidirectional wheel enabling motion in all planar directions.
- Steering System: Steering is achieved by controlling sphere rotation rather than conventional steering linkages.
- Suitability for Road CU: Not suitable due to poor comfort, inefficient energy use, and space demands compared to standard wheels on roads.



Figure 34: Concept of spherical wheels (Motorsport, 2026)

For the final road carrier, it was decided to choose the wheel corner module concept as introduced in chapter 7.5.2, because it fulfils the given requirements in the best way. For further developments and if the given requirements are changed, the other concepts can also be considered as suitable.

8 Exterior Design Principles for the Carrier Unit (CU) within Autonomous Vehicle Systems

8.1 Designed for Technology or for People?

The design of the exterior of autonomous vehicles, as illustrated by the Pods4Rail concept, raises a central question: Are we designing for technology or for people?

Autonomous pods require a re-evaluation of traditional transportation design principles. While technical functionality is indispensable for the architecture of autonomous vehicles, user trust largely depends on the exterior design making the technology visible, understandable, and simultaneously emotionally engaging. Achieving a balance between functional necessity and a clear, trust-enhancing design is therefore crucial for the acceptance of the pods.

Successful exterior design must integrate technological requirements with user-centred design principles: form language, lighting graphics, surface textures, and proportions should communicate clearly, intuitively, and comprehensibly that the vehicle operates autonomously, safely, and reliably. At the same time, aesthetic design contributes to establishing an emotional connection with users and increasing acceptance. Thus, the exterior becomes not only functional but also communicative: it signals movement intentions, supports orientation and trust, and defines the pod's identity across all operating modes (rail, road, ropeway).

The pods should not appear more technologically dominated or complex than the vehicles they are intended to replace. Technological intelligence should be made visible, but without appearing confusing or intimidating (Naiseh et al., 2025).

8.2 A Question of Meaning

Pods represent technological progress and a forward-looking vision of mobility. In the context of autonomous systems, exterior design can no longer be reduced to aesthetic differentiation or symbolic displays of power. Instead, it becomes a question of meaning: the vehicle's form must communicate its function and behavioural intent to humans in an intuitive and legible way (Bangle, 2017; Norman, 2013).

In autonomous mobility, humans remain “in the loop” – not as active drivers, but as cognitive interpreters. They must be able to perceive and “read” the vehicle to understand its operational status, including whether it has detected them, whether it is stopping, inviting boarding, or transitioning between operational modes such as road, rail, or ropeways (H. Liu et al., 2021; Y. Liu et al., 2020).

The layered visual language approach describes design as a system of simultaneously operating levels of meaning (Bangle, 2017; Hekkert, 2006). Products, especially vehicles, are interpreted, not merely observed.

A coherent visual language therefore integrates:

- Structural meaning through proportion, stance and surface logic, conveying stability, order and calm.
- Technological meaning through integrated lighting graphics and articulation of sensors, conveying intelligence, system competence and attentiveness.
- Emotional meaning through openness of form and non-aggressive presence, conveying trust, approachability and relational quality.
- Communicative meaning as the interface between vehicle and environment, through dynamic light signals, status indicators, boarding information, projected cues, and adaptive surfaces, conveying behavioural intent, system status and readiness to interact (Naiseh et al., 2025).

Technological innovation and sustainability are thus translated into progressive visual expressions that are legible rather than intimidating. The aim is not visual dominance, but communicative clarity. The pod becomes a social actor in public space, whose exterior expresses intelligence through restraint and self-assurance through the coherence of its visual product language, realised only through the interplay of these layers' way (Bangle, 2017; Norman, 2013).

In this sense, technological confidence is expressed not through aggression, but through meaningful form – a visual product language that enables humans to understand autonomous mobility, relate to it, and ultimately trust it. The vehicle should not appear as a “machine of edges,” but as a controlled, sovereign system.

8.3 Foundational Principles of Exterior Design

8.3.1 Structural Level: Modular System enables Cost Efficiency and Design Coherence

The modular strategy aims to reduce production and maintenance costs while also promoting a consistent visual language and user experience. By standardising front and rear modules, side elements, access areas, lighting modules, sensor housings, HMI components, and more, these elements can be reused across different pod operating modes (rail, road, ropeways) without compromising the characteristic design language or functionality.

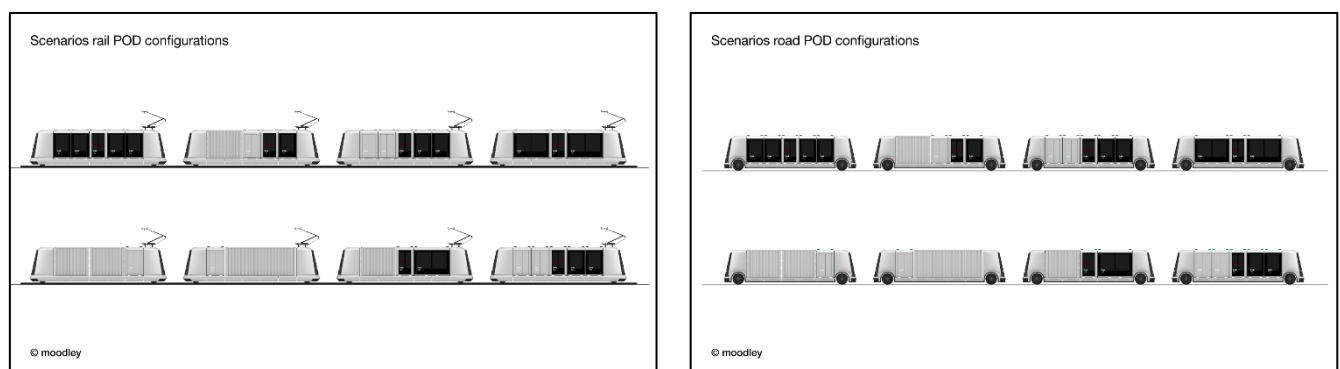


Figure 35: Side view rail CU, side view road CU, schematic (moodley)

8.3.2 Technological Level: Technical Integration

Design is a strategic decision, not purely aesthetic or self-serving. The exterior layout is intended to integrate technology and future production requirements into the vehicle's form, enabling technological scalability. Lighting is conceived as part of the vehicle's DNA, and new sensors or HMI systems are designed to be modularly retrofitted.

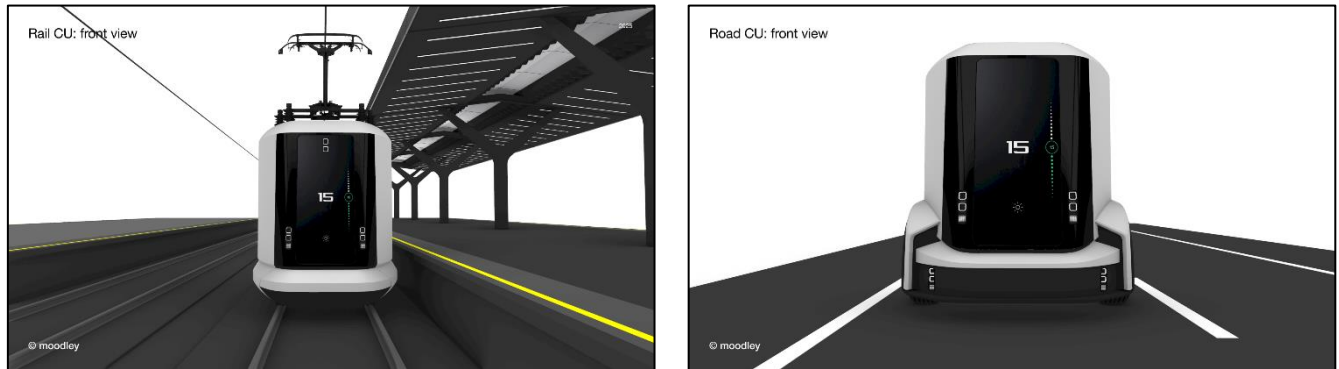


Figure 36: Side view rail CU, side view road CU, schematic (moodley)

8.3.3 Emotional Level: Timeless Minimalism and Reduction to the Essential

The approach follows a reduced, minimalist design language that combines visual clarity with technical precision. The design strives to eliminate any superfluity, focusing the vehicle's exterior surfaces and contours on their functional and emotional essence. The emphasis is on enduring design rather than short-lived trends, with harmonious proportions that make the pod appear as a "calm, self-assured object." A monochrome colour palette is deliberately chosen to avoid disturbing the form language. The result is a timeless, understated elegance that makes advanced technology visible without appearing ornamental.



Figure 37: Conceptual design and visualisation road CU, side view road CU (moodley)

8.3.4 Communicative Level: Accessibility and Inclusivity

This design principle ensures that the pod's exterior and physical interfaces are equally usable, understandable, and welcoming for all user groups, regardless of body size, mobility, gender, or cultural background. Lighting signatures, colours, and symbols are deliberately neutral and inclusive, avoiding gender stereotypes and ensuring emotional appeal, safety, and intuitive comprehension for all road users. This approach also aims to enhance the acceptance of autonomous pods.



Figure 38: Lighting signature concept and visualisation road CU and TU (moodley)

8.4 Detailed Description of the Exterior Design for Key CU Modules

The following section provides a detailed description of the externally visible key modules of the CU architecture.

8.4.1 Front and Rear Module

The front and rear module embodies understated elegance and technical precision, defined by smooth, continuous surfaces and clear, flowing lines with minimal joints. Every contour conveys calm, confidence and trust in the technology, while integrated lighting modules and sensors are subtly embedded within the form language, expressing high-tech character in a restrained and refined way. The flowing geometry along the sides creates harmonious visual transitions. In the context of autonomous vehicles, this module communicates structural stability and subtly guides users' perception of the pod's autonomous capabilities.

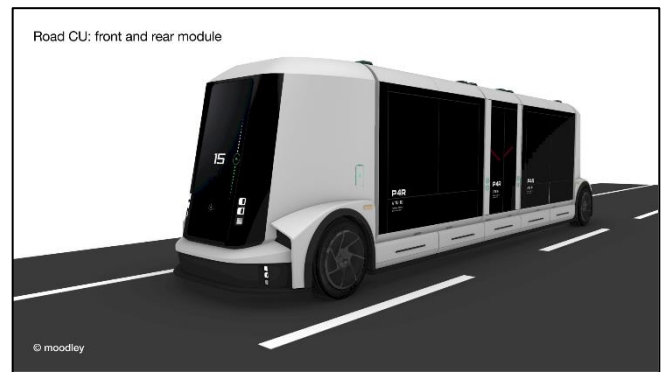
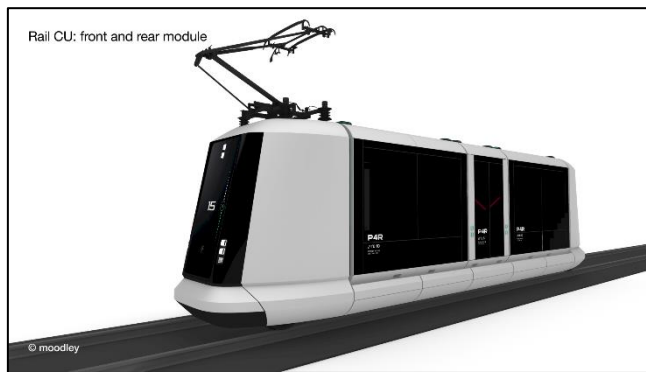


Figure 39: Conceptual design and visualisation front/rear module CU, front view rail CU, front view road CU (moodley)

8.4.2 Cladding Elements

The cladding integrates functional areas for energy efficiency and maintenance access while maintaining a coherent visual language that signals precision and reliability. Modern lightweight materials and manufacturing approaches should be combined to optimise weight, safety, modularity, and design flexibility.

8.4.3 Exterior Lighting

The lighting is a communicative layer fully integrated into the architecture, not merely functional. LED surfaces, lighting modules at the front and sides, and digital displays convey vehicle status, speed, and intent to the surrounding environment. In the context of autonomous operation, the lighting functions as a behavioural language, making the pod's actions legible and trustworthy without appearing aggressive or ornamental.

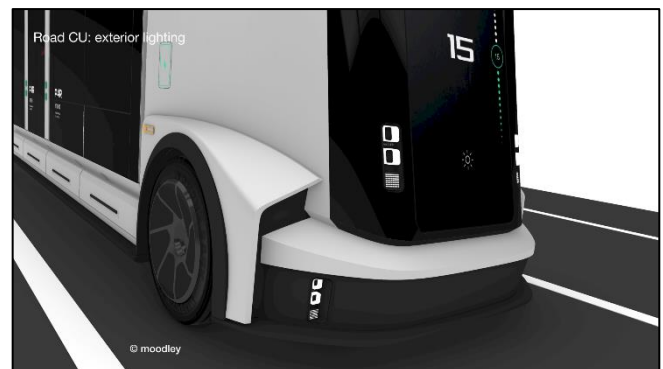


Figure 40: Conceptual design and visualisation exterior lighting CU, front view rail CU, front view road CU (moodley)

8.4.4 Sensors and Cameras

Sensors and cameras are discreetly embedded within the pod's outer skin to preserve the minimalist, futuristic aesthetic while providing complete situational awareness. Their arrangement on the front, sides, and rear enables 360-degree perception, critical for autonomous navigation.

Visually, these components are integrated coherently, signalling intelligence and attention without dominating the design.

8.4.5 Wheels and Associated Components

In the context of autonomous operation, the wheel architecture supports the relevant mode (rail or road). Visually, clutter is minimised, and wheel elements are integrated seamlessly with the body. Protective wheel covers, including measures against ice formation, also create a unified, futuristic appearance.

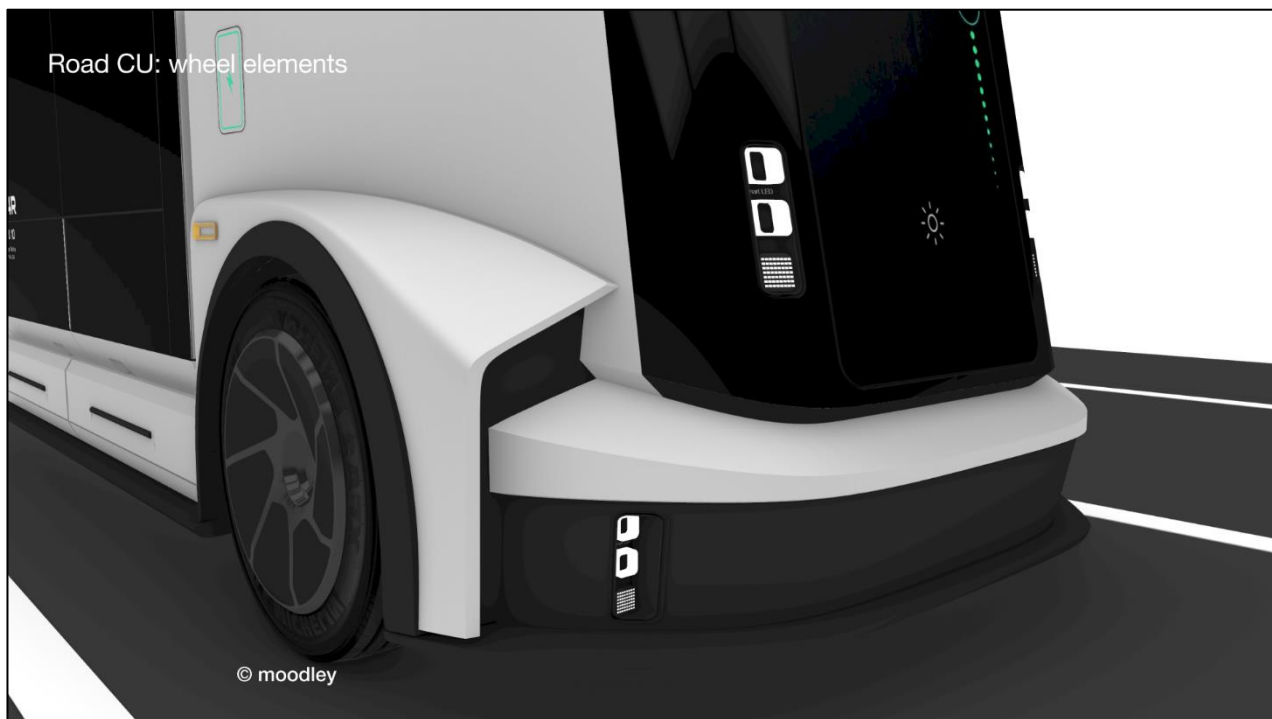


Figure 41: Conceptual design and visualisation wheel architecture CU, front view road CU, schematic (moodley)

8.4.6 Innovative lightweight material approaches

In addition to conventional metal and thermoplastic options, innovative lightweight approaches open up new possibilities for the manufacture of the Carrier Unit. These include hybrid materials such as metal-reinforced composites, fibre-reinforced thermoplastics using local or bio-based fibres, as well as sandwich structures with cores made from foams, honeycombs, or natural fibres.

The materials employed should enable targeted weight reduction without compromising the structural integrity or modularity of the Carrier system. From a manufacturing perspective, additive processes, thermoplastic injection moulding, prepreg lamination, or adhesive and bolted connections are used to integrate complex geometries and functional features, such as cable channels, attachment points, or thermal insulation, directly into the structure.

The strategic use of such materials can not only improve energy efficiency and payload capacity but also support sustainability objectives by incorporating recyclable or bio-based components. A

detailed analysis of manufacturability, process stability, and long-term behaviour is, however, necessary to determine the optimal material strategy for the CU components.

8.5 Design coherence in supermodal mobility systems

Although research on design coherence specifically in multimodal vehicles is still in its early stages, multimodality theory suggests that the consistent integration of visual modalities contributes to meaning-making and the comprehensibility of complex artefacts (such as vehicles with multiple operational modes) by leveraging unified semiotic resources (Jewitt et al., 2025).

In supermodal pods, this coherence can manifest in shared design principles across rail, road, and ropeway configurations, including continuous surfaces, consistent material expression, and harmonised interface language, to ensure recognisability and support predictable user interpretation across modes.

This approach aligns with multimodal systems thinking, where multiple modes of communication (visual, spatial, functional) are orchestrated to create a cohesive overall experience (Jewitt et al., 2025).

For the supermodal mobility system Pods4Rail, a detailed analysis of design coherence is recommended as a next step.

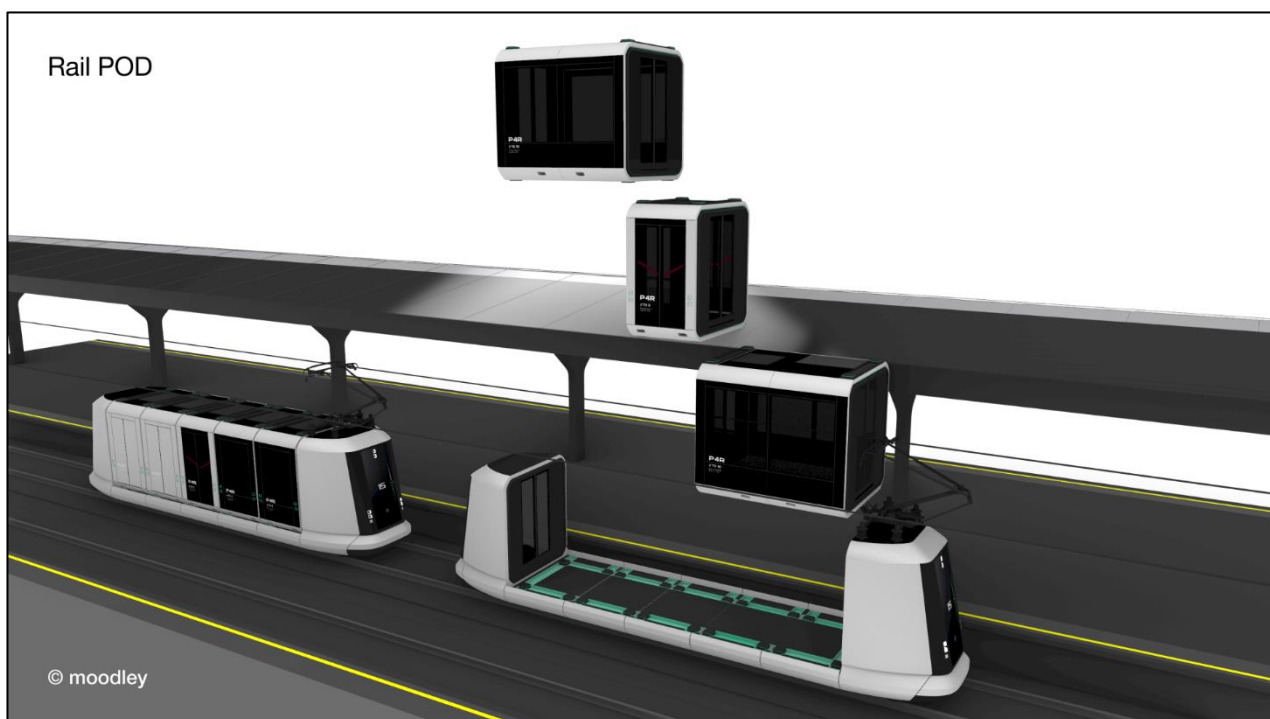


Figure 42: Conceptual design and visualisation rail pod, side view of a rail pod with different loads/TU configurations (moodley)

9 Conclusions

This deliverable presents a conceptual design study for Carrier Units (CU) within the EU-funded Pods4Rail project, aiming to enable a supermodal transport system that integrates rail, road, and ropeway transport. The study builds on prior work packages and defines a common vehicle concept framework, focusing on modularity, standardisation, and cross-domain interoperability.

The main objective is to develop scalable and flexible vehicle concepts that can transport different Transport Units (TU) across multiple transport modes while ensuring efficiency, automation readiness, and compliance with infrastructure and regulatory constraints. The methodology includes analysing functional, technical, and user requirements, defining use cases, and evaluating subsystem standardisation potential across domains.

A key outcome is the proposal of highly standardised but domain-adapted CU. While many subsystems—such as energy systems, ICT, automation, and interfaces—can be shared across domains, domain-specific components (e.g. wheelsets, suspension, structural design) must remain differentiated due to operational and regulatory constraints. This balance enables both economies of scale and operational flexibility.

The study emphasises modular “skateboard” architectures, enabling flexible loading of TU (5–20 ft) and supporting both passenger and freight use cases. Standardised interfaces (e.g. twistlocks, electrical couplings) and unified access systems enhance interoperability and reduce system complexity. A low-floor design philosophy improves accessibility and supports multimodal integration.

For the Road CU, multiple platform variants were analysed, with a low-floor skateboard platform (A4-a) identified as optimal due to its balance of accessibility, flexibility, and safety. For the Rail CU, a similar platform concept is adopted, combined with self-steering wheelsets and distributed electric propulsion, enabling autonomous-ready operation and compatibility with European rail constraints (e.g. 16 t axle load).

Energy concepts for both domains rely on battery-electric architectures with modular battery systems, regenerative braking, and scalable capacity. Estimated energy requirements are approx. 498 kWh for rail and 380 kWh for road in worst-case scenarios, highlighting feasibility for autonomous operation without continuous external power supply.

A major focus is the convergence of vehicle architectures, particularly in energy systems, control platforms, communication layers, and digital infrastructure. The integration of a digital layer (V2X, OTA updates, automation) is identified as a critical enabler for safe, efficient, and autonomous multimodal transport.

However, the study acknowledges limitations, as it represents an early conceptual stage. Further work is required on structural design, detailed engineering, crash safety, and validation. Additionally, regulatory constraints and infrastructure differences remain key challenges for full standardisation.

In conclusion, the deliverable demonstrates that a modular, standardised, and cross-domain CU concept is feasible, offering strong potential for cost reduction, scalability, and improved mobility services, while requiring continued development to address technical and regulatory complexities.

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Appendices

Annex A: Requirements for the Rail CU

The following lists all relevant requirements for the Rail CU. Firstly, the general requirements (thematic and then with a specific description) for the respective carriers were compiled. The corresponding sources such as previous deliverables, standards or other documents were assigned to these requirements. The requirements defined for the project as well as their initial sources (such as standards or the project objective / grant agreement) were identified. The last column "Comments" forms the basis for the influence that this requirement ultimately has on the components to be selected and their packaging in the CU.

According to D7.1, an initial empty mass of the TU of 3.423 tonnes is assumed for a 10 ft TU. This results in an empty mass of 1.75 tonnes for a 5 ft TU. A 5 ft TU is the heaviest TU in terms of length, as the mass of the end walls is independent of the length. The maximum empty mass for a Rail TU is therefore five 5 ft TU (8.75 tonnes). In relation to the above-mentioned axle load, a maximum mass of 32 tonnes is permissible for a two-axle vehicle. The total mass for the Rail CU is assumed to be 10 tonnes based on an initial estimate based on empirical values from other projects and the exchange with ERJU projects (e.g. (Europe's Rail, 2026c)), with 5.8 tonnes being accounted for by the bogies (see chapters 38). This means that the total weight of the TUs must not exceed 22 tonnes.

According to the requirements of the previous work of the other WPs and other EU projects, not only a virtual coupling between two Rail CUs is to be provided. For reasons of compatibility with other systems and in the event of a necessary recovery, a mechanical coupling must be provided. For reasons of harmonisation and standardisation, the Digital Automatic Coupling (DAC) is recommended, although this is very large and heavy (> 500 kg). As the DAC is only used in special cases, it is not integrated into the Rail CU as standard in terms of flexibility, energy consumption and costs.

Table 23: Requirements for the Rail CU

ID	Topic	Requirement	Source	Source (original)	Comments
1	Carrier operability	fully operable without a TU (e.g. communication system, lightings, etc.)	Pods4Rail D4.4	Pods4Rail GA	CU should integrate all necessary components for a complete automated driving.
2	Bidirectional driving	drivable in both directions	Pods4Rail D4.4	Pods4Rail D4.1	Sensors, interfaces and crash-elements have to be symmetrical
3	Use Case Coverage	The carrier should be able to cover all relevant use cases (rail domain)	Pods4Rail GA		In order to reach a high coverage, every TU size is addressed (5 ft, 10 ft, 20 ft), loading area should meet the requirements of D7.1

ID	Topic	Requirement	Source	Source (original)	Comments
4	Operability	The vehicle shall be able to operate without loss or reduction of functions in severe snow, ice and hail conditions.	Pods4Rail D4.4	LOC&PAS TSI 1302/2014/EU clause 4.2.6.1.2.	covering / heating is necessary for all interfaces and critical parts
5	Max Carrier dimensions	clearance Gauge: G1 loading area: 25 ft / 7634 mm	Pods4Rail D4.4 Pods4Rail D7.1	EN15273	length is not that relevant, but depending of the length (wheelbase), the width have to be adjusted
6	Max. Vehicle/Axle Mass (fully loaded)	16 t 5 t / meter	Pods4Rail D4.4	EN15528	smallest line categorie should be drivable, because the system should be operable on each main and branch line
7	Entry Height	550 mm above Top of Rail (TOR)	Pods4Rail D4.4 Pods4Rail D7.1 Pods4Rail D10.1		standard entry height in EU, Entry on TU should be on 550 mm, the bottom structure of the TU is 230 mm, the floor panelling 40 mm. Therefore the loading height of the CU should be around 280 mm for a barrier-free entry. Derivation possible through steps or ramps
8	Wheelbase in y-Direction	1435 mm / standard gauge		Pods4Rail D4.4	
9	Wheelbase in x-Direction	not too short (riding comfort) but also not too long (constriction of width)	Expert knowledge		Only a skateboard platform is suitable, because of the low height of the loading area. Wheelbase of Axis around 10 m
10	Max. TU body weight (5 ft)	1.75 t	Pods4Rail D7.1		assumption: half of the mass of a 10 ft TU
11	Max. load weight total (5 ft)	max. 4.4 t	Expert knowledge		based on a max axle load of 16 t, five 5 ft TU should not exceed 32 t - 10 t (CU) à each has a max. weight of 4.4 t
12	Max. TU body weight (10 ft)	3.5 t	Pods4Rail D7.1		Exact value: 3.423 t
13	Max. load weight total (10 ft)	max 8.8 t	Expert knowledge		Twice the max mass of a 5 ft TU
14	Max. TU body weight (20 ft)	7 t	Pods4Rail D7.1		assumption: twice the mass of a 10 ft TU
15	Max. load weight total (20 ft)	max. 17.6 t	Expert knowledge		standard value for a fully loaded 20 ft freight container is 30.48 t --> load capacity for freight container has to be restricted (independend of size)
16	Max. rail CU mass	10 t	Expert knowledge		CU mass = max. mass minus loading mass, has to be defined, because load capacity of freight container has to be restricted -->
17	Battery Range (based on UC)	30 km for one turn-around, no loading every turn around, Assumption: 150 - 200 km a day	Pods4Rail D7.1 UITP Report		Progress in R&I expected --> higher battery performance https://www.uitp.org/publications/light-rail-and-tram-the-european-outlook/

ID	Topic	Requirement	Source	Source (original)	Comments
18	Power supply	fully battery powered, designed for non-electrified tracks, one track is < 30 km	Pods4Rail D4.4 Pods4Rail D7.1	Pods4Rail GA	no pantograph, but at least one charging socket on each side
19	Power storage	The energy storage system shall have a modular design	Pods4Rail D4.4		
20	Coupling	The carrier should be able to operate virtually coupled, but shall be able to operate in mixed operation, therefore a Digital automatic Coupling device should be integrated. Should follow the UIC code 571-4: Standard Wagons - Wagons For Combined Transport - Characteristics.	Pods4Rail D4.4	Pods4Rail GA DACcelerate S2RE Project Deliverable D3.2	Virtual coupling as standard, a draw hook should be provided for recovery cases for compatibility with existing systems. Buffer elements not absolutely necessary, as no shunting / classic train formation.
21	Sanitary facilities	When a use case for long distance passenger transport is selected, the vehicle shall include sanitary facilities in at least one of the TUs mounted on the carrier.	Pods4Rail D4.4		Has to be discussed / benchmark --> UWB?
22	Maintainability	All components that are subject to regular maintenance or inspection intervals should be accessible and replaceable without an increased level of effort.	Pods4Rail D4.4		
23	Safety equipment	The rail carrier unit shall integrate passive safety equipment and components in compliance with the current standards for railways that shall be present for some use cases (e.g. energy absorption components towards collisions in a mechanically-coupled pods scenario).	Pods4Rail D4.4		

Annex B: Evaluation of Road CU platform variants

Evaluation criteria and weighting table of the Road CU platform variant evaluation

Table 24: Evaluation criteria (based on requirements and technical design options)

Evaluation criteria	Explanation
Complexity of the carrier	Part numbers, lightweight design, mechanical complexity, estimated production costs, etc.
Carrier dimensions	Estimated length/width/height of the carrier vehicle (The smaller the better)
Safety of Access (entry/loading)	Ability to provide safety during entry/loading
Complexity to reach easy access	How complex is it for passengers to board from bus platform / road
Loading of different TU-sizes	Ability to load all kinds of TU (5 / 10 / 20 ft)
Adaptability of the CU	How easy is downsizing (less than 20 ft) or upsizing (more than 20 ft) of the capacity?
Ability to not need a PRM-TU (self-lifting)	Good, if PRM-TU is not needed (for better inclusion and standardisation).
Space for main components	Ability to integrate batteries and other relevant components

Table 25: Pairwise comparison of the evaluation criteria

	Complexity of the carrier	Carrier dimensions	Safety of Access (entry/loading)	Complexity to reach easy access	Loading of different TU-sizes	Adaptability of the CU	Ability to not need a PRM-TU (self-lifting)	Space for main components
Complexity of the carrier		0	2	0	2	0	0	1
Carrier dimensions	2		2	0	2	0	1	2
Safety of Access (entry/loading)	0	0		0	1	0	0	1
Complexity to reach easy access	2	2	2		2	0	1	2
Loading of different TU-sizes	0	0	1	0		0	0	1
Adaptability of the CU	2	2	2	2	2		2	2
Ability to not need a PRM-TU (self-lifting)	2	1	2	1	2	0		2
Space for main components	1	0	1	0	1	0	0	
SUM	9	5	12	3	12	0	4	11
Weighting [%]	16%	9%	21%	5%	21%	0%	7%	20%

Annex C: Fuse box for a Rail CU

Due to the focus of the Pods4Rail project on flexibility and the use of different components on different modes of transport, the aim is to accommodate components in uniform modular systems wherever possible. For this reason, the control unit, fuse box and required automation control units are housed in 19" racks that are as compact as possible and standardised in the rail vehicle sector. The following table shows the identified required volumes (including housing) once again.

Table 26: Dimensions of the specific units

	Depth (mm)	Width (mm)	Height (mm)
Control Unit	600	600	200
Fuse box	800	250	400
Automation control unit	470	220	450

The first step is to search for suitable rack solutions. The manufacturer nVent SCHROFF (nVent SCHROFF, 2026) offers certified 19-inch subracks (drawers) that are inserted and secured in on-board racks using a rail system.

Three different heights (3U, 6U, 9U) of the 19-inch on-board rack are available, which are made of steel and can bear a static load of 25 kg. The height units (HU or U) represent 1.75 inches, which corresponds to 44.45 mm.

To keep the weight as low as possible (higher energy efficiency), the 9U racks are preferable, as they have the lowest specific weight in relation to their volume. The dimensions can be found in table 27.

Table 27: Listing of different rack sizes

	Depth (mm)	Width (mm)	Height (mm)	Net volume (L)	Net weight (kg)
10170-14 (3U)	341.8	496.4	156.7	27	3.93
10170-12 (6U)	341.8	496.4	290	49	5.31
10170-16 (9U)	341.8	496.4	423.4	72	6.68

Suitable subracks (drawers) are available in heights of 3U and 6U. They are made of aluminium and can each bear a static load of 15 kg. Dimensions see table 27.

Table 28: List of different subracks

	Depth (mm)	Width (mm)	Height (mm)	Net volume (L)	Net weight (kg)
21500-029 (3U)	320	426.72	156.7	21	1.83
21500-027 (6U)	320	426.72	290	40	2.96

To keep weight to a minimum, 6U subracks are preferable as they have the lowest specific weight in relation to their volume.

When using a 9U rack, a 6U and a 3U subrack must therefore be used. In this configuration, the rack and subrack have a specific weight of 1.27 kg/unit. Alternatively, if only 6U racks are equipped with 6U subracks, a specific weight of 1.38 kg/unit is achieved. Consequently, 9U racks should always be preferred whenever possible.

To determine the total requirement, the required HU of the components must be determined. In this analysis, the conversion is based solely on the given height of the components. This is converted into inches and then divided by 1.75. The required number is listed in table 29.

Table 29: Required number of on-board racks

	necessary Units	Racksize
Control Unit	45 Units	5x 9 U racks
Fuse box	9 Units	1x 9U rack
Automation Control Unit	4x 9 Units	4x 9U racks
Total	90 Units	10x 9U racks

A total of 4 automation control units is required, resulting in a total requirement of ten 9U racks to accommodate all components. This results in a total empty weight of 114.7 kg for all 10 units, consisting of the 9U rack (10170-16) with one 3U subrack (21500-029) and one 6U subrack (21500-027) each. The configuration is displayed in figure 45.

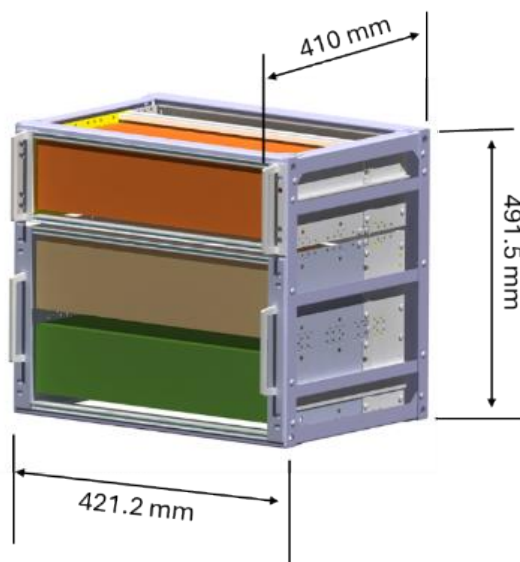


Figure 43: Selected Rack configuration with a 6U and a 3 U sub rack

Annex D: State of the art Architectures for the Rail CU

This Annex provides a comprehensive analysis of the state-of-the-art in self-propelled and battery-assisted “modular movement” platforms for rail applications, as of 2025. These platforms represent a disruptive innovation in rail freight and passenger transport, aiming to increase operational flexibility, reduce emissions, and enable digital integration within the evolving mobility ecosystem. Unlike conventional rail vehicles, which rely on locomotive-hauled configurations, these systems introduce distributed propulsion and modular architecture, allowing individual units to operate autonomously or semi-autonomously.

Then, this section examines the principal technologies currently under development or early deployment, including Parallel Systems Autonomous Platform, Intramotев TugVolt/ReVolt retrofit solutions, RWTH Aachen’s modular chassis concept (ARS), and European smart wagon initiatives. For each technology, the analysis provides:

- A brief description of the concept and operational rationale.
- Key technical characteristics, focusing on chassis design, bogie or running gear configuration, propulsion system, and energy storage architecture.
- A proposal of the architecture for the Pods4Rail concept.

The findings are intended to propose the Pods4Rail project’s rail carrier platform architecture, highlighting the trade-offs between modularity, autonomy, retrofit feasibility, and digital integration.

Parallel Systems Autonomous Platform (USA)

Parallel Systems (Parallel Systems, 2025) introduces a fully autonomous, battery-electric rail platform designed to revolutionise freight transport by replacing traditional locomotive-hauled trains with digitally coupled platoons of self-propelled units. Each module operates independently, carrying a single container, and can form virtual trains through vehicle-to-vehicle communication protocols without mechanical couplers (Figure 44). Key Characteristics:

- Chassis: A flat, lightweight modular frame optimised for container mounting and autonomous operation. The design prioritises structural simplicity and integration of sensors and computing units for navigation and platooning.
- Running Gear / Bogie: Conventional rail wheelsets integrated with traction motors, eliminating the need for classic bogie articulation. This configuration reduces mechanical complexity and supports distributed propulsion.
- Propulsion System: Battery-electric drive delivering approximately 300 kW per driven axle, enabling high tractive effort at low speeds and adequate cruising power for short corridors.
- Energy System: High-capacity lithium-ion battery packs, with company claims of up to 500 miles per charge, although this figure is contingent on load, speed, and route profile.
- Operational Rationale: Parallel Systems targets first/last-mile connectivity and short-haul corridors, where flexibility and high service frequency are critical. By eliminating locomotives and couplers, the system reduces yard complexity and enables dynamic train formation, improving network efficiency.



Figure 44: Parallel Systems concept

Intramotev TugVolt / ReVolt (USA)

Intramotev (Intramotev, 2025) offers a retrofit solution that converts existing freight wagons into battery-electric self-propelled units, providing a cost-effective pathway for incremental electrification without full fleet renewal (Figure 45). Key characteristics:

- **Chassis:** Retains the original wagon frame, with propulsion and battery modules added as retrofit components. This approach minimises structural changes and leverages existing rolling stock assets.
- **Running Gear:** Standard bogies remain in place, with traction motors integrated at axle level. This preserves conventional load distribution while enabling independent movement.
- **Propulsion System:** Battery-electric drive rated at approximately 200 kW per driven axle, optimised for low-speed yard operations and short industrial runs.
- **Energy System:** Onboard battery packs sized for short-range autonomy, typically sufficient for yard switching and first/last-mile delivery.
- **Operational Rationale:** The retrofit model addresses emission reduction and operational flexibility in yards and industrial sites, where locomotives are inefficient for short moves. By enabling wagons to decouple and move independently, Intramotev reduces switching time and improves asset utilisation.





Figure 45: Intamotev solution

RWTH Aachen “Aachen Rail Shuttle” (ARS) Platform (Germany)

The Aachen Rail Shuttle (ARS) platform (RWTH Aachen, 2025) represents a true modularity approach, framing the chassis as a multi-purpose mobility carrier capable of supporting interchangeable payload modules (passenger cabins or cargo bodies). This concept aligns with the principles of platform economy and multi-use optimisation, reducing lifecycle costs and enhancing adaptability (Figure 46). Key characteristics:

- **Chassis:** Ladder-frame structure housing all technical subsystems, including propulsion, braking, and energy storage. The design philosophy emphasises maintenance modularity and future-proofing through configurable component carriers.
- **Running Gear:** Two powered, self-steering single wheelsets¹ replace traditional bogies, improving manoeuvrability and reducing structural complexity. This innovation supports tighter turning radii and optimised weight distribution.
- **Propulsion System:** One motor per wheelset, delivering continuous power of 160 kW (peak higher), with regenerative braking complemented by pneumatic systems for safety.
- **Energy System:** Central traction battery using Lithium-Titanate Oxide (LTO) chemistry, rated at 152 kWh, enabling a range of up to 220 km on demanding routes. LTO technology offers superior cycle life and fast-charging capability, critical for high-frequency operations (RWTH Aachen, 2025).
- **Operational Rationale:** ARS demonstrates the feasibility of modular rail platforms for both passenger and freight missions. By decoupling the chassis from the payload, the system maximises utilisation and supports mission-specific configurations, a key requirement for Pods4Rail’s hybrid operational model.

¹ A self-steering wheelset is a pair of wheels mounted on a common axle that can adjust its yaw angle relative to the track without external actuation. Unlike conventional rigid wheelsets, which maintain a fixed orientation, a self-steering design allows the wheelset to align naturally with the curvature of the track due to its geometry and suspension characteristics.



Figure 46: The ARSplatform (RWTH Aachen)

Self-Propelled Freight Wagon (SPFW) – ERJU FP5 TRANS4M-R

Being under development under ERJU's Flagship Project 5: TRANS4M-R (Europe's Rail, 2026b), the SPFW introduces autonomous traction and energy systems into conventional freight wagons to enable yard automation, last-mile delivery, and distributed traction. This concept supports Europe's Rail objectives for digitalisation and sustainability by reducing reliance on shunting locomotives and optimising operational flexibility. Key characteristics:

- Chassis: Standard wagon frame with non-invasive retrofitting, allowing integration of propulsion and energy subsystems without compromising load capacity.
- Running Gear: Conventional bogies adapted for direct-drive traction motors and autonomous braking, reducing complexity and maintenance.
- Propulsion System: Electric motors mounted on axles, controlled by a Vehicle Control Unit (VCU), enabling precise speed control and regenerative braking. Target speeds: 15–40 km/h, range: 1–10 km for yard and short-haul operations.
- Energy System: On-board battery storage sized for operational profiles, supporting traction, IoT monitoring, and energy recovery. High cycle life and fast charging are prioritised for efficiency.
- Operational Role: The Self-Propelled Freight Wagon enables yard automation by removing the need for shunting locomotives, supports last-mile delivery through autonomous movement to sidings, provides power boosting and peak shaving for distributed traction and grid load management, and facilitates autonomous loading/unloading via integration with advanced transshipment technologies. These functions collectively underpin a digitalised, automated freight ecosystem enhanced by DAC and advanced communication systems

"Smart Wagon" + DAC + Telematics

Unlike the previous examples, the Smart Wagon concept focuses on digital readiness rather than full self-propulsion. It integrates Digital Automatic Coupling (DAC) and telematics systems to

enable automated yard operations, condition-based maintenance, and real-time monitoring. Technical characteristics:

- Chassis: Conventional freight wagon frame enhanced with digital components for connectivity and automation.
- Running Gear: Standard bogies; no traction motors.
- Propulsion System: Not self-propelled; relies on locomotive haulage.
- Energy System: Auxiliary battery supports telematics and DAC functions, ensuring operational continuity during coupling and data transmission.

Operational Rationale: This approach aligns with the EU's Digital Rail Freight strategy, which prioritises automation and predictive maintenance to improve efficiency and safety. While not a propulsion solution, Smart Wagons complement self-propelled platforms by enabling network-wide digital integration.

Annex E: Description of existing self-steering bogie concepts

This section includes a brief description of several existing prototypes related to self-steering bogies.

The CFD Group concept design

The described running-gear concept is a single-axle bogie featuring two wheels and a dual-stage suspension system (CFD Group, 2025). The axle may serve as either a powered or non-powered unit and is compatible with diesel-hydraulic or electric/diesel-electric traction. Its primary suspension, consisting of coil springs and hydraulic dampers. An intermediate frame provides elastic guidance, while articulated links allow controlled angular and lateral movements; these are absorbed by a secondary pneumatic suspension, which improves passenger comfort and attenuates body–bogie relative motion. Braking equipment is mounted directly on the bogie and may employ tread brakes or disc calipers. The bogie can also integrate an electric motor and gearbox when required.

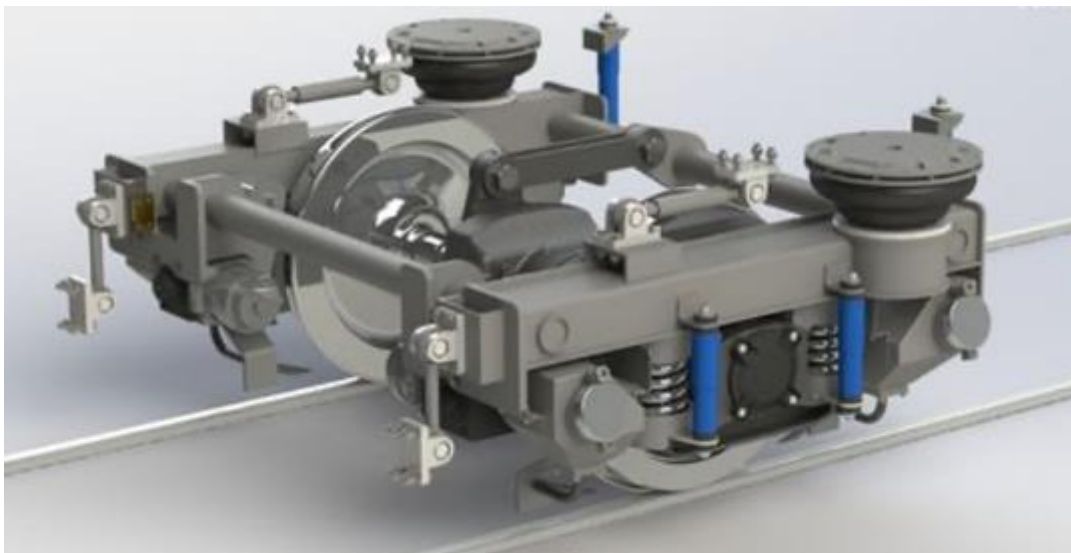


Figure 47: The CFD self-steering bogie concept

The Aachener Rail Shuttle bogie concept

The Aachener Rail Shuttle (ARS) (ARS, 2025) features a modular, lightweight chassis equipped with two self-steering single-wheel sets (wheelsets) rather than traditional bogies (Schindler, 2022). These powered, steered axles are designed for low-noise operation and improved curve negotiation, utilizing electric motors and a magnetic rail brake for enhanced safety and performance.

The running gear is located underneath the chassis. Both wheel sets are driven by one electric motor each, which is derived from motor sports and has a continuous power output of 160 kW (290 kW peak).

The chassis is supported by the primary springs of the single-axle running gears, similar to the platform of a flat freight wagon. Its vertical bending stiffness is high enough to carry the load consisting of its own weight, the subsystem equipment and the passenger compartment. But it

has a sufficiently low torsional stiffness to negotiate superelevation ramps in narrow curves without danger of derailment.



Figure 48: The ARS bogie concept

The bogie concept defined in Fr8Rail 4

This new type of bogie ensures good driving stability and derailment safety (Europe's Rail, 2022). In order to ensure these running characteristics, the suspension decouples the wheelset from the bogie frame through rubber primary springs, minimizing unsprung mass and dynamic wheel loading. In the secondary stage, the connection between the bogie and wagon frames is established through four air springs, two traction rods and both vertical and yaw dampers. The air suspension offers the lowest possible accelerations for the goods to be transported and also allows for the ride height to be varied according to operating conditions and needs.

The two traction rods transfer the longitudinal and lateral forces between the wagon and the bogies. The diagonal arrangement of the traction rods forms a virtual pivot point in the middle of the chassis frame and thus enables a load-independent radial steering of the wheelset in small radius curves. At high speeds, on the other hand, two yaw dampers limit this yaw movement and thus ensure safe running.

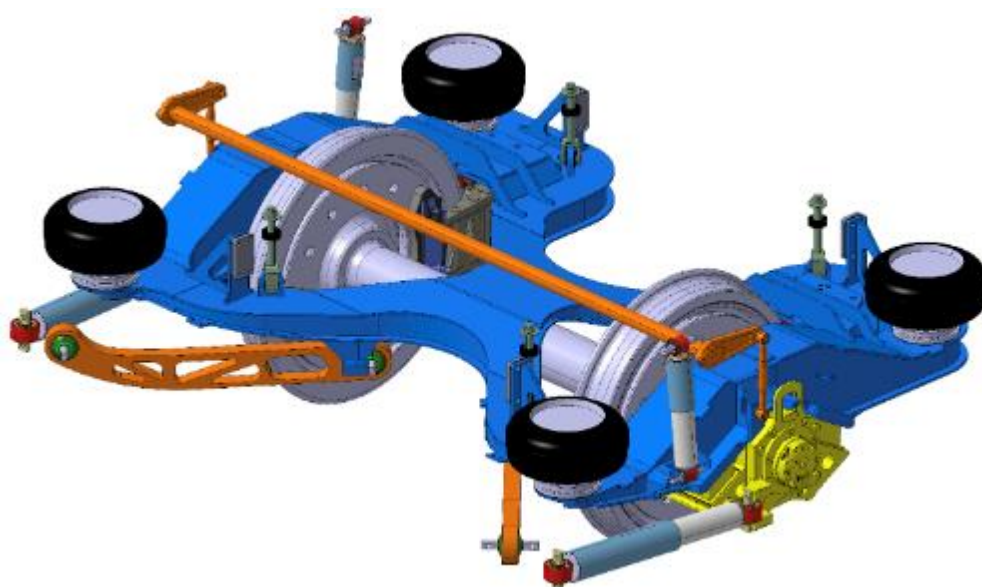


Figure 49: The Fr8Rail 4 bogie concept

Annex F: State of the art Architectures for the Road CU

This chapter provides a comprehensive analysis of major electric vehicle (EV) platforms, focusing on their energy systems, propulsion technologies, wheel and suspension configurations, and steering systems. Each platform is evaluated individually, preceded by a concise description of its design philosophy and industrial context. A comparative table summarises key characteristics, advantages, and disadvantages. Finally, an optimal architecture is proposed, combining best-in-class features to support future mobility and Pods4Rail objectives.

REEcorner / REE Platform

The REE Automotive platform (REE Automotive, 2025) (Figure 50) introduces a disruptive concept based on “corner modules”, where each wheel assembly integrates propulsion, steering, braking, and suspension systems. This design eliminates traditional mechanical linkages, creating a flat chassis that maximises design flexibility for commercial and autonomous vehicles. The main features are:

- Energy System & Propulsion: Fully electric, distributed drive system with in-wheel motors integrated into corner modules.
- Wheels & Suspension: Independent suspension per module, likely multi-link for flexibility.
- Steering System: Steer-by-wire² integrated into corner modules³, eliminating mechanical linkages.
- Advantages: Exceptional modularity, flat chassis for design freedom, redundancy for safety.
- Disadvantages: High complexity, proprietary technology limits external innovation.

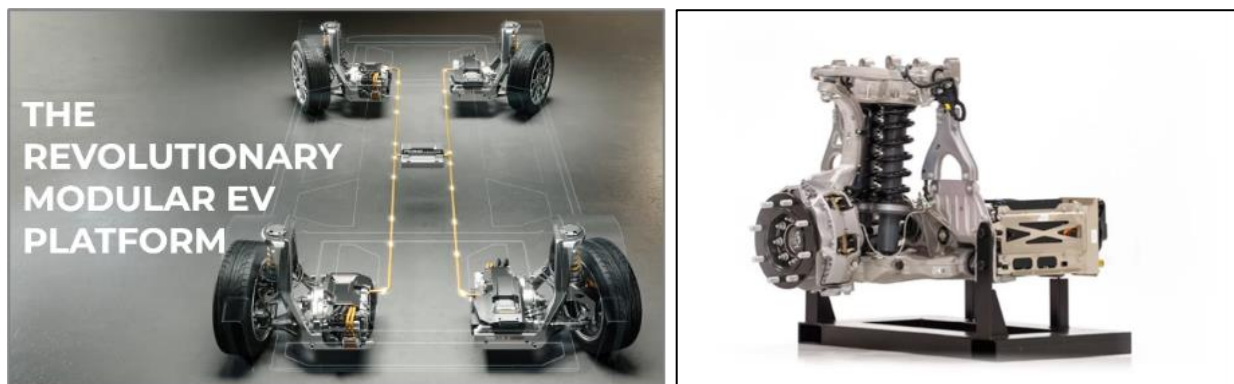


Figure 50: REE Modular EV Platform

² A steer-by-wire (SbW) steering system is an advanced automotive steering technology that eliminates the traditional mechanical linkage between the steering wheel and the road wheels, replacing it with electronic sensors, actuators, and control algorithms. In this architecture, driver input is transmitted as electrical signals to actuators at the wheels, which then execute the steering manoeuvre. This approach represents a paradigm shift from conventional rack-and-pinion systems towards fully electronic control, enabling design flexibility and integration with autonomous driving systems

³ In the context of advanced electric vehicle (EV) architectures, corner modules refer to self-contained, multifunctional units integrated into each wheel assembly, combining propulsion, steering, braking, and suspension systems within a single modular component.

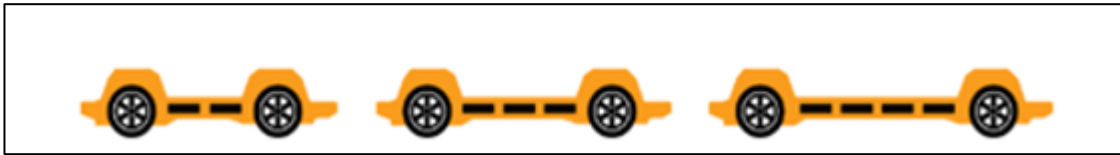


Figure 51: Customizable dimensions

E-GMP (Hyundai / Kia)

The Electric Global Modular Platform (E-GMP) (Hyundai Motor Group, 2025), Figure 52, is a Hyundai Motor Group's dedicated skateboard architecture for battery electric vehicles (EV). It prioritises weight distribution, crash safety, and high-voltage charging capability, supporting a wide range of vehicle types from compact cars to SUVs (Sport Utility Vehicle) (Hyundai Motor Group, 2024). The main features are:

- Energy System & Propulsion: Battery electric skateboard architecture⁴; centralised motor with single-speed reduction gear; supports 400V/800V systems.
- Wheels & Suspension: Independent suspension (multi-link rear, MacPherson front typical for Hyundai EVs).
- Steering System: Conventional rack-and-pinion with electric power assist.
- Advantages: High efficiency, ultra-fast charging, proven industrial maturity.
- Disadvantages: Closed ecosystem, limited adaptability beyond OEM (Original Equipment Manufacturer).



Figure 52: EV Platform 'E-GMP'

Stellantis STLA Platforms

The STLA family (Stellantis, 2025) (Figure 53) represents Stellantis' multi-energy strategy, enabling BEV (Battery Electric Vehicle), hybrid, and ICE configurations on shared architectures. This approach reduces manufacturing complexity and cost while supporting diverse vehicle segments across multiple brands. The main features are:

- Energy System & Propulsion: Multi-energy (BEV, hybrid, ICE); modular electric propulsion modules.

⁴ A skateboard architecture is a structural and functional design concept for battery-electric vehicles (BEVs) in which the energy storage system (battery pack), electric propulsion components, and associated power electronics are integrated into a flat, load-bearing chassis platform.

- **Wheels & Suspension:** Flexible suspension geometries; likely MacPherson front and multi-link rear.
- **Steering System:** Conventional mechanical steering with electric assist.
- **Advantages:** Versatility across energy types, economies of scale.
- **Disadvantages:** Increased complexity, less optimised for pure EV performance.



Figure 53: Flexible Multi-Energy Platforms

Geely SEA Architecture

The Sustainable Experience Architecture (SEA) (Geely Group, 2025), Figure 54, is Geely's modular BEV platform designed for software-defined vehicles. It integrates centralised computing and high-speed communication networks, enabling OTA (Over-the-Air) updates and advanced digital features (Geely Group, 2024). The main features are:

- **Energy System & Propulsion:** BEV skateboard; supports 400V/800V; centralised computing for software-defined vehicles.
- **Wheels & Suspension:** Lightweight suspension systems; likely multi-link rear for premium models.
- **Steering System:** Electric power steering integrated with domain controllers.
- **Advantages:** OTA capability, modular scalability.
- **Disadvantages:** Semi-open, limited to consortium partners.

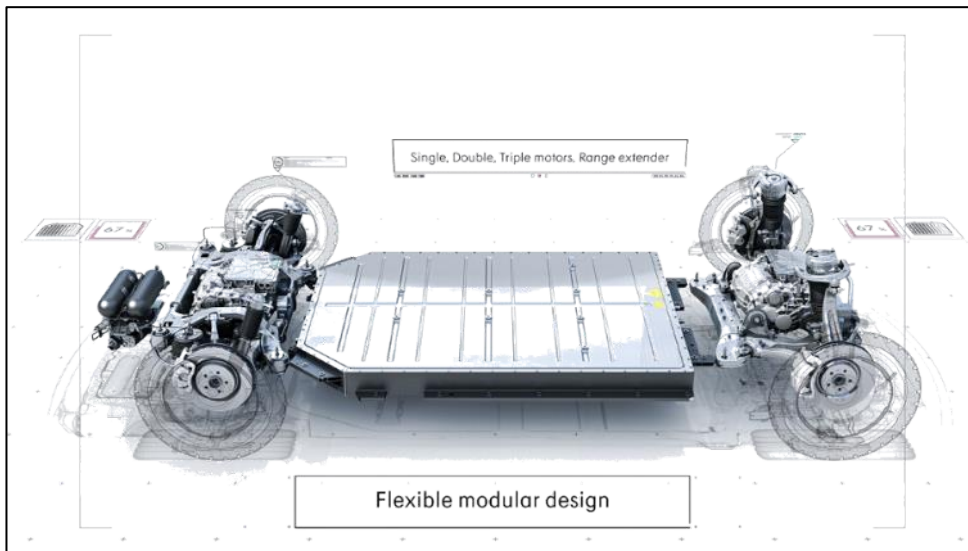


Figure 54: SEA-M platform

ZF eBeam / AxTrax / CeTrax Platforms

ZF's electrification solutions (ZF Group, 2025) (Figure 55) target heavy-duty vehicles through electric axle systems and central drive units. These platforms enable OEMs to retrofit existing chassis without full redesign, accelerating commercial fleet electrification.



Figure 55: ZF's electric axle

From an operational standpoint, ZF supports original equipment manufacturers with calibration, testing, and integration engineering, making the platforms suitable for the electrification of commercial vehicles globally.

However, ZF's systems are entirely proprietary. They do not participate in open-source initiatives or offer open-access control interfaces. External partners interact with ZF through commercial supply agreements, with limited visibility into internal software or firmware. Therefore, ZF's platforms are closed, industrial-grade electric mobility solutions.

Maazibuko Motor Company – Chilwa Platform

The Chilwa platform (Maazibuko Motor Company, 2025) (Figure 56) is an Africa's first dedicated EV skateboard architecture, designed for rugged conditions and high ground clearance. It supports regional manufacturing and affordability for utility vehicles. The main features are:

- Energy System & Propulsion: BEV skateboard; high-capacity batteries (~100 kWh); designed for rugged conditions.
- Wheels & Suspension: Robust suspension (likely double-wishbone or reinforced multi-link).
- Steering System: Conventional mechanical steering with electric assist.
- Advantages: Adapted for African terrain, promotes local supply chains.
- Disadvantages: Early-stage industrialisation limited global support.



Figure 56: Maazibuko Motor Company EV Platform

CIIC Platform

The CIIC platform (CATL & Huawei, 2025) (Figure 57) combines CATL's battery expertise with Huawei's computing and ADAS technologies. It offers a highly digitised skateboard chassis for rapid EV development among Chinese OEMs. The main features are:

- Energy System & Propulsion: BEV skateboard; integrated battery, powertrain, steering, sensors; supports 400V/800V.
- Wheels & Suspension: Independent suspension; optimised for ADAS integration.
- Steering System: Steer-by-wire with autonomous-ready features.
- Advantages: Accelerates EV development for SMEs.
- Disadvantages: Semi-open, restricted to Chinese ecosystem.



Figure 57: CIIC platform

Blue Arc (Shyft Group)

Blue Arc (Shyft Group, 2025) (Figure 58) is a commercial EV platform tailored for delivery vans and fleet operations. It prioritises payload stability, modular body integration, and telematics for urban logistics. The main features are:

- Energy System & Propulsion: BEV platform for commercial vans; large battery packs (100–200 kWh).
- Wheels & Suspension: Heavy-duty suspension for payload stability.
- Steering System: Conventional steering with electric assist.
- Advantages: Fleet-focused, modular body integration.
- Disadvantages: Proprietary, niche application.



Figure 58: EV-powered chassis features customizable length and wheelbase

MIH Open Platform – Foxconn / MIH Consortium

The MIH (Mobility in Harmony) platform (MIH, 2025) (Figure 59), developed by Foxconn, is the only truly open EV ecosystem. It provides open standards and APIs to reduce development barriers and foster global collaboration. The main features are:

- Energy System & Propulsion: BEV skateboard; scalable voltage (48V–800V); open standards for hardware/software.
- Wheels & Suspension: Flexible suspension configurations.
- Steering System: Supports steer-by-wire and conventional systems.
- Advantages: True open ecosystem, fosters innovation.
- Disadvantages: Lower maturity compared to proprietary platforms.

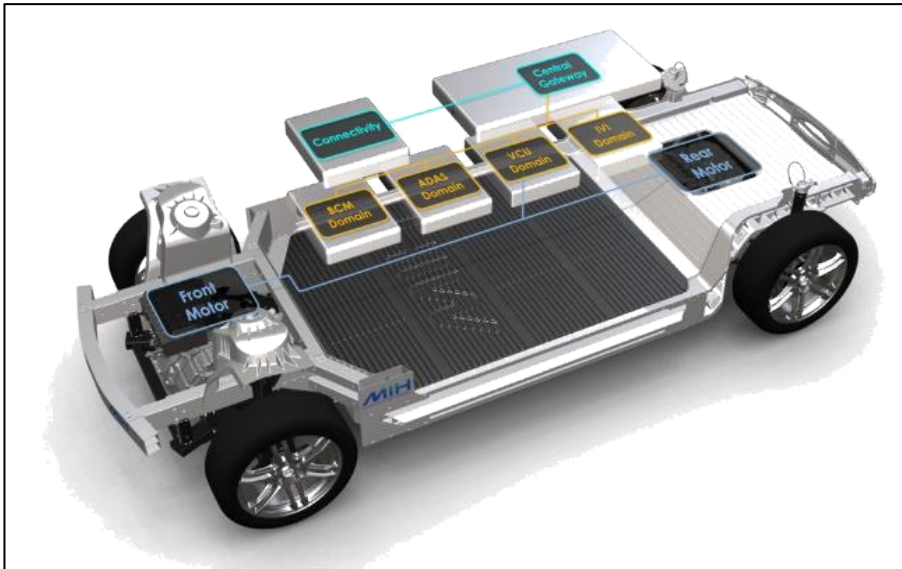


Figure 59: MIH Open Platform (Foxconn + Yulon Motor)