

Deliverable D10.1

Concept development for equipment of sample vessel

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1 Executive Summary

Deliverable D10.1 presents the conceptual development of the equipment required for the Transport Unit (TU) within the Pods4Rail system, a modular, autonomous transport solution supported by the European Union. The document integrates the work of several interconnected work packages and focuses particularly on the configuration defined for Use Case 1, which aims to provide basic public transport services in low-demand or rural areas. This scenario relies on a modular composition including a 5 ft Entrance/Exit Unit and two 10 ft Passenger Units, each designed to accommodate up to twelve passengers while complying with both rail and road standards.

The deliverable begins by defining a comprehensive Work Breakdown Structure aligned with EN 15380, enabling traceability, modularity and future scalability across different TU sizes. The distribution of technical equipment prioritises placing components in the Carrier Unit whenever feasible to minimise weight and complexity in the TU. Nevertheless, the TU must remain operationally independent for at least fifteen minutes when detached from the carrier, which necessitates the integration of a dedicated floor-mounted battery system. The internal layout and equipment—from seating and handrails to passenger information systems and emergency devices—have been designed under the constraints of TSI LOC&PAS, TSI PRM and UNECE Regulations 66 and 107, ensuring safety, accessibility and passenger comfort.

A significant part of the analysis is devoted to the HVAC system concept, where different installation configurations and refrigerant options are examined. Two main integration strategies are assessed: ceiling-level installation, which is compatible with ISO container standards and simplifies maintenance, and above-ceiling installation, which provides improved airflow but introduces geometric incompatibilities. After evaluating current technologies and regulatory requirements, the document concludes that a vapour-compression system using R290 refrigerant offers the best balance between environmental compliance, performance and energy efficiency. R290 also enables the use of heat pumps for heating, supplemented by resistive elements for rapid warm-up or defrosting in cold conditions.

The mechanical interface between the TU and the Carrier Unit is also defined in detail. The concept is based on ISO 1161 corner castings, fully automatic twistlocks and ISO 1496 forklift pockets, ensuring compatibility with existing handling infrastructure and enabling automated, safe and repeatable coupling operations. Several alternatives for securing the unit during forklift-based transshipment are evaluated, with the preferred solution being an automated twistlock mechanism mounted directly on the forklift, capable of engaging with a TU-mounted counterpart to ensure safety and operational efficiency even when passengers are on board.

In parallel, the deliverable specifies the electrical and communication interfaces needed for energy transfer, data exchange and operational safety. A high-voltage interlock (HVIL) connector is proposed for safe high-voltage handling, complemented by a multi-coupler interface that integrates low-voltage power and communication signals. These components may also be combined into a single, compact interface to facilitate automated operations and reduce the system footprint. The workflow foresees mechanical engagement followed by the

automatic opening of protective covers and subsequent electrical coupling, all monitored by integrated sensors to ensure safety and reliability.

Finally, the document outlines a robust strategy for localisation and communication, essential for autonomous operation and traffic coordination. The proposed approach combines adaptive GNSS with inertial sensors, magnetic-field-based localisation for GNSS-denied (Global Navigation Satellite System) environments and ultra-wideband ranging for high-precision docking. Communication relies on a heterogeneous network incorporating 5G/6G V2X (Vehicle-to-Everything), advanced Wi-Fi, UWB (Ultra-Wideband) and distributed Software Defined Networking to guarantee continuity of services, low latency, redundancy and resilience. Cybersecurity is embedded from the outset through encryption, intrusion-detection mechanisms and the integration of post-quantum cryptography to ensure long-term protection.

Overall, Deliverable D10.1 provides a coherent, future-proof conceptual basis for the equipment and interfaces of the Transport Unit, ensuring compliance with existing regulations, compatibility with automation and readiness for future developments within the Pods4Rail ecosystem. It lays the groundwork for subsequent detailed design activities, supporting seamless integration with the Carrier Unit, handling systems and traffic coordination architecture across the project.

2 Abbreviations and acronyms

Table 1: Abbreviations and acronyms

Abbreviation / Acronym	Description
ACM	Air cycle machines
C/N0	Carrier-to-Noise Ratio
COP	Coefficient of Performance
CU	Carrier Unit
DOP	Dilution of Precision
Dx.x	Deliverable x.x
ECC	Elliptic curve cryptography
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EU-RAIL MAWP	EU-RAIL Multi Annual Work Plan
FDE	Fault Detection and Exclusion
FR	Frequency Range
FRS	Functional Requirement Specification
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GWP	Global Warming Potential
HS	Handling System
HV	High-Voltage
HVAC	Heat Ventilation and Air Conditioning
HVIL	High Voltage Interlock Loop
ICT	Information and Communication Technologies
IMU	Inertial Measurement Unit
ISAC	Integration of Sensing and Communications
KNN	K-Nearest Neighbours
LOS	Line of Sight
MEC	Multi-Access Edge Computing
MLP	Multi-Layer Perceptions
MMS	Mobility Management System

Abbreviation / Acronym	Description
MPG	Main Product Group
NFV	Network Functions Virtualization
PG	Product Groups
PQC	Post-quantum cryptography
PTC	Positive-temperature-coefficient
RF	Random Forest
RIS	Reconfigurable Intelligent Surfaces
RL	Relative Localization
RSA	Rivest-Shamir-Adleman
RTT	Round Trip Time
RU	Rack Unit
SDN	Software Define Network
SIL	System Integrity Level
SLAC	Simultaneous Localization and Calibration
SLAM	Simultaneous Localization and Mapping
SPG	Sub Product Groups
SRC	Short range communication
SVM	Support Vector Machines
T2G	Train-to-Ground
T2T	Train-to-Train
TSI	Technical Specifications for Interoperability
TU	Transport Unit
Tx.x	Task x.x
UC	Use Case
UNECE	United Nations Economic Commission for Europe
URLLC	Ultra-reliable low-latency communication
UWB	Ultra-Wide Band
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2S	Vehicle-to-Satellite

Abbreviation / Acronym	Description
V2V	Vehicle -to-Vehicle
V2X	Vehicle-to-everything
VCTS	Virtually Coupled Train Sets
WBS	Work Breakdown Structure
WLS	Weighted Least Squares
WP	Work Package

3 Background

The Pods4Rail project is clustered into three Work Streams (WS) (Figure 1). The WS1 contains of five WPs dealing with the "Identification of use Cases, Business Cases/CBA, operating concept." The WS2 also contains five WPs dealing with the "Moving Infrastructure vessel and operation System". Finally, the WS3 comprises three WPs dealing with "Moving infrastructure carrier incl. Locking System and handling System".

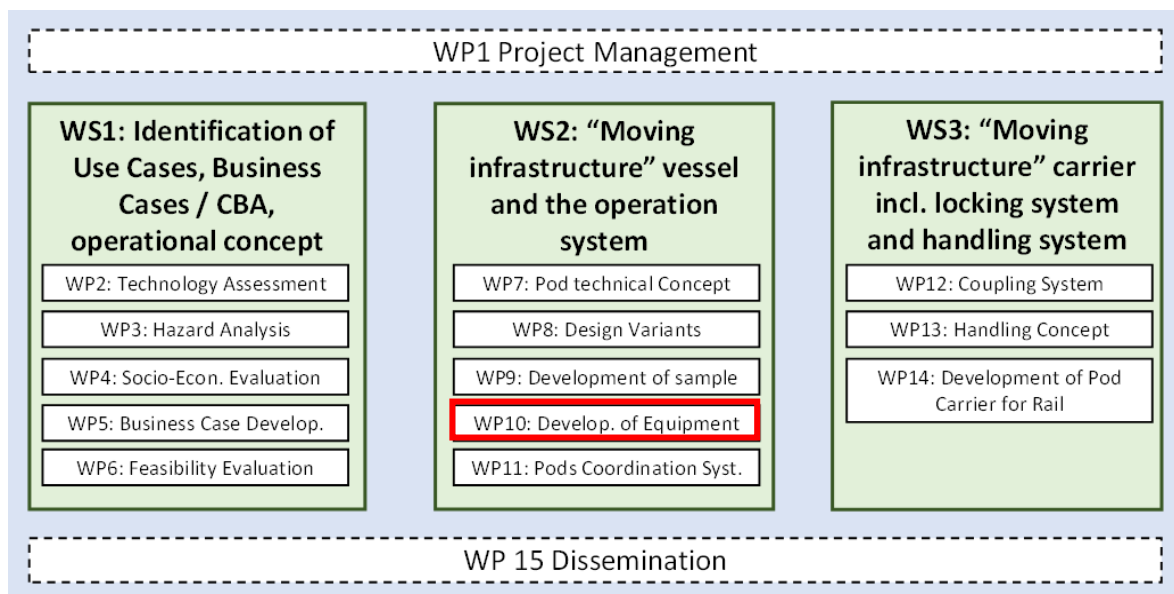


Figure 1: Pods4Rail division into three Work Streams

The work reported in this Deliverable has been performed within WP10 "Concept development for equipment of sample vessel" as part of WS2 "Moving infrastructure vessel and the operation system".

This document groups in a single document the deliverables D10.1 Concept proposal for the positioning of the relevant components in the specific sample vessel, D10.2 Concept proposal of HVAC for specific sample vessel, D10.3 Concept proposal for the interfaces between pod and carrier and D10.4 Concept proposal for the localisation of the pod, within the framework of the flagship project of Area 7, Pods4Rail, as described in the EU-RAIL MAWP".

4 Objective/Aim

Given the design of the Pods System, which includes a planned separation between the Transport Unit¹ (TU) and the Carrier Unit (CU), the equipment must be appropriately distributed between these two components. The configuration and intended function of the TU directly influence the type and arrangement of this equipment. All necessary requirements must be met, even when the Pod System is detached from the CU for extended periods (e.g., during handling, parking, etc.).

Therefore, this WP focuses on the conceptual development of the equipment (e.g., HVAC systems, automation) for the sample Pod System developed in WP9.

It is also essential to integrate various types of sensing devices to locate and track the Pod System. Localisation technologies and communication technologies such as 5G and 5G V2X and Ultra-Wide Band (UWB), along with cybersecurity considerations, are also included in the scope of this work.

Close collaboration with other Work Packages is crucial. This WP builds upon the outcomes of WP4, WP7 and WP 12 and works in close coordination with WP8 and WP9, which are being developed in parallel with WP10.

Table 2 summarizes the objectives of WP4 and WP7, as well as the objectives of WP8 and WP9.

Table 2: Summary of objectives of WP4, WP7, as well WP8 and WP9

Work Package	Objective of the WP and associated task
WP4 - Task 4.4 High-level functional requirements specification	The purpose of T4.4 is to set-up a functional requirement specification (FRS) for the general system, including a description of scope and system boundaries, which serves as input for the design specifications.
WP7 - Technical Concept for Vessel System	WP7 focuses on the conceptualization of the technical aspects of the pod system. This extends from the development of technical concepts for pod system to the description of an operating system for their safe and efficient movement through the transportation environment. WP7 covers the Concept proposal for the pod system (T7.1), the Concept proposal for interfaces (T7.2) and the Concept proposal for operation system (7.3)

¹ The Grant Agreement (GA) uses the term “vessel”. However, we will use “Transport unit” instead of “vessel” because this is the term defined in WP2: “Transport unit: The transport unit (for passengers and/or freight) includes the safe carriage of passengers or goods, as well as the functionalities that ensure their comfort and safety during transport. It does not include other concepts considered in this deliverable, such as handling systems and operating systems”.

Work Package	Objective of the WP and associated task
WP12 - Definition and concept development of the coupling system	The objective of WP12 is to define the requirements for a standardised, digital, and fully or semi-automated coupling system between the Pods4Rail Transport Units (TUs) and Carrier Units (CUs), addressing mechanical, electrical, communication, and safety aspects. And also to develop a technical concept for such a coupling system tailored to a dedicated use case.
WP8 - Design Variants of the Vessel	The objective of WP8 to produce a compilation of possible derivable design variants for Passenger transport and goods transport with a description of the technical concept and a proposal for the structural components.
WP9 - Detailed Concept of a Sample Vessel for one Use Case	WP9 designs one specific variant using renderings and 3D models. Essential aspects for the intended use are presented and, if necessary, further details like interiors, passenger seats, cargo boxes, etc. are considered here.

Table 3 includes a brief description of the objectives of WP11, WP13 and WP14, which use the results obtained in WP10.

Table 3: Brief description of the objectives of WP11, WP12, WP13 and WP14

Work Package	Objective of the WP and associated task
WP11 - Concept development for traffic coordination of pods system	The purpose of WP11 is to define the concept and requirements for coordinating pod traffic, covering infrastructure, routing, automation, and logistics. It ensures efficient operation through traffic rules, ETA management, virtual coupling, and integration with maintenance and autonomous driving systems.
WP13 - Concept for the handling, loading/unloading technologies	WP13 lays the foundations for the logistical aspects of the concept, which are necessary for the unhindered transfer of TU to the CU, the handling, storage, loading and unloading of the pod system.
WP14 - Development of a “moving infrastructure” carrier for rail, road and ropeway	The aim of WP14 is to develop the CU (considering propulsion, energy storage, vessel, control, etc.) to technically define important components / interfaces and to integrate them into an overall pod system.

The specific objectives of each task of WP10 are described below (Table 4).

Table 4. WP10 task objectives

Task	Objectives
T10.1 – Concept proposals for equipment and power supply of the equipment of the TU	This task aims to provide a positioning concept for the technical equipment on the specified TU, as well as CAD models showing the relevant equipment in the TU envelope.
T10.2 – Concept proposals for the HVAC for passenger pod	The aim of this task is to analyse and compare different HVAC systems and determine the most suitable one considering the main components.
T10.3 – Concept proposals for the interfaces between TU and CU	The objective of this task is to specify the electrical and mechanical interface for the concrete sample TU, and to describe the interface concept with regard to mechanical design, dimensioning and positioning.
T10.4 – Concept proposals for the localisation and communication	The objective of this task is to analyse advanced sensing and communication technologies to enable precise localization, tracking, and trajectory prediction of the TU, as well as to provide a concept for the magnetic field aided TU localization and identification, and a concept for a short-range communication and ranging between TU and CU or other TU.

5 Concept proposals for equipment and power supply of the equipment of the TU

The task 10.1, which is elaborated in this chapter aims to define a layout and integration concept for the TU's technical equipment. It focuses on optimal placement of components within the TU, in coordination with mechanical design, and on distributing equipment between the TU and CU to improve installation, cost, and functionality.

5.1 Introduction

The objective of this task is to develop a layout and integration concept for the technical equipment of the TU, tailored to the defined use case. This includes determining the optimal placement of key components within the TU, considering their dimensions and how they fit within the overall structural envelope.

The positioning of these components is defined in close collaboration with the mechanical design activities in WP9. Additionally, the distribution of equipment between the TU and the CU is carefully considered to optimize factors such as installation effort, cost efficiency, and functional complementarity.

Regarding the TU's energy supply, various innovative energy transfer solutions between the TU and the carrier are being evaluated, with inputs from previous tasks. The most suitable system will be selected based on performance, feasibility, and integration potential.

5.2 Methodology for the concept proposals for equipment and power supply of the equipment of the TU

Since WP9 and WP10 work in parallel and have to be coordinated, it was decided by common agreement between the two WP's that WP10 would carry out an analysis based on the design constraints that may affect the layout and the integration concept for the technical equipment of the TU, analysing different possibilities and proposing a list of analysed possibilities with advantages and disadvantages. Starting from the detailed concept of a sample vessel for one selected use case (UC), which was developed in WP9 and includes several suitable options regarding the TU's configuration, WP10 proposes different integration options for the TU's technical equipment. Main inputs for this task are taken from the concept proposal of the TU in WP7 (Pods4Rail Deliverable D7.1, 2024), also requirements are cross checked and implemented if necessary from other WP's, e.g. (Pods4Rail Deliverable D4.4, 2025).

5.2.1 Step 1: Selected Use Case

According to the Grant Agreement for WP10, Task 10.1 focuses on the placement of relevant components with a clear distinction between the TU and the CU. The methodology explained in this chapter, is based on the term "Specified Use Case". This term refers to the selected

Use Case (UC) from WP4-D4.1 “Description of use cases”, defined in more detail in WP8-D8.1 “Basic design concept proposal vessel variants” (Pods4Rail Deliverable D8.1, 2025), that is going to be studied in this Work Package. The selected UC itself only contains a TU-type, but since WP10 is including the CU also, the UC here is defined by the whole pod configuration with CU and several TUs. The chosen Use Case is UC1 “Basic Public Transport”, as it is the same scenario that has been analysed in WP9, (see Figure 2) with the Configuration A, consisting of:

- One 5 ft Entrance/Exit Unit
- Two 10 ft Passenger Unit (long version with windows).

UC1 refers to a Basic Passenger Public Transport use case, designed for low-demand scenarios with a maximum capacity of 12 passengers per unit. This solution is primarily intended for sparsely populated (rural) areas where conventional train connections are not economically viable.

UC1 is conceptually linked to other use cases, including Premium Passenger Public Transport, First Class Public Passenger Transport, Mass Passenger Public Transport, and Premium Passenger Private Transport.

Further technical details about the specified Use Case and its configuration are available in D7.1 “Technical Concept for vessel System” (Pods4Rail Deliverable D7.1, 2024).

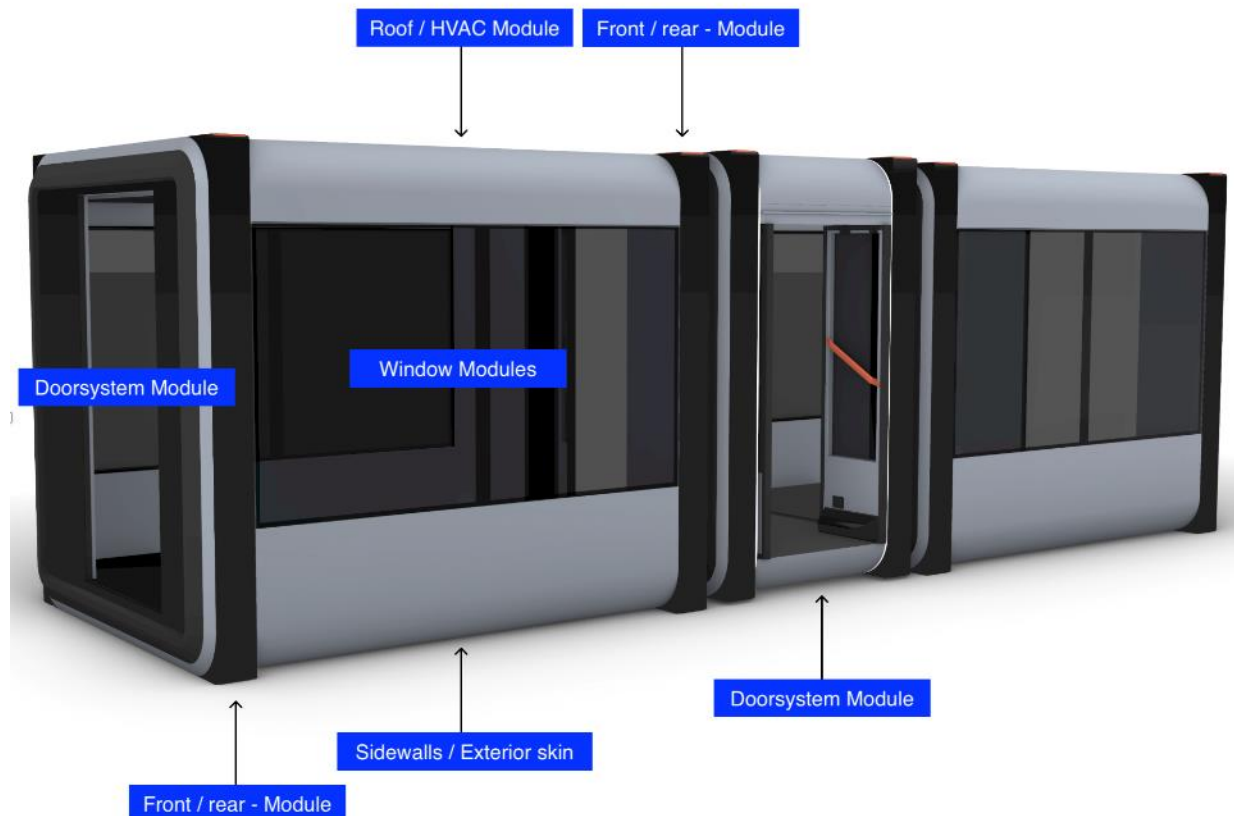


Figure 2: TU composed by 1x 5 ft Entrance/Exit Unit and 2x 10 ft Passenger Units (© moodley)

The Passenger Unit is made up of standardized, modular units designed to maximize standardization with minimal components. Each Passenger Unit has the same width, height, and front design, measures 10 feet in length, and includes door systems, window segments, and roof or external attachments. Transitions between TUs are seamless and sealed with flexible lips.

The 5 ft Entrance/Exit Unit allows access to the TU through doors on both sides (left and right) as well as at the front and rear (aisle doors). These doors enable smooth transitions between neighbouring TUs, and efficient boarding and alighting from the outside platform

5.2.2 Step 2: Distribution of components between TU and CU

The main objective of Task 10.1 is to develop a layout and integration concept that defines the location and spatial arrangement of the technical components of the TU, tailored to the needs of UC1 - Basic Public Transport. This includes identifying relevant components, determining their technical characteristics (dimensions, weight, power consumption, etc.), and distributing them appropriately between the TU and CU.

Section 5.3.1 of document D7.1 organized the functional Pod architecture using a variant matrix that includes configuration units and relevant components. The requirements for each Main Product Group (MPG) were defined in WP4, Task 4.4. As a result, each variant has a specific configuration with the necessary components (according to EN 15380).

Section 5.3.1 of D7.1 also defined the MPG distribution between TU and CU, as shown in Table 5.

Table 5: Main Product Group (MPG) distribution between TU and CU

MPG of the TU	MPG of the CU
B Vehicle body	B Vehicle body
	E Running gear
C Vehicle fitting out	F Power system, drive unit
D Interior appointments	G Control apparatus for train operations
H Auxiliary operating equipment (battery, ...)	
J Monitoring and safety equipment	
K Lighting	
L Air conditioning	
M Ancillary operating equipment	
N Doors, entrances	
P Information facilities	
	Q Pneumatic/hydraulic equipment
	R Brake
S Vehicle linkage devices	
T Carrier systems, enclosures	
U Electrical wiring	

The general criterion to be used is that components should be located as far as possible in the CU and, if any component must be distributed between the CU and the TU, the smallest possible part should be placed in the TU. An example is the battery system where the main part corresponding to the traction batteries will be located in the CU, while the TU will contain a minimum battery with a 15-minutes autonomy to guarantee electrical power during for example the TU transshipment processes.

5.2.3 Step 3: Identification of the components to be included in the TU

In this line, the first step to be taken regarding Task 10.1 is the identification of relevant components for UC1, followed by the identification of their corresponding technical characteristics (dimensions, weight, power, etc.). Subsequently, the distribution of these components between the TU and CU must be determined (CEN/TC 256, 2006).

To maintain consistency and traceability, the component list follows the structure of (CEN/TC 256, 2006) a Work Breakdown Structure (WBS) of components to be implemented in the TU, aligned with EN 15380. The idea of working with a WBS has been extracted from WP7 (D7.1-Chapter 5.3 “Architecture”) where for each mode of configuration unit, an identification of main components and distribution TU/CU have been done using the MPG concept as defined in EN 15380 (CEN/TC 256, 2006).

This methodology ensures traceability, compliance with EU standards, and promotes collaboration through a shared component identification system. It uses a structured format that supports future automation and integration with maintenance and inventory systems.

EN 15380 defines a hierarchical coding system for railway vehicles and components, organized into:

- MPG (Main Product Groups) – 1-letter code
- SPG (Sub Product Groups) – 2-letter code
- PG (Product Groups) – 3-letter code

The classification is based on inputs from technical documents WP4-D4.4 and WP7-D7.1. After an initial review, the component list is validated to ensure it includes all relevant TU items. This list is then reviewed with WP10 partners for technical and architectural consistency.

Components are further categorized for either CAD modelling or high-detail rendering. Finally, the WBS Excel file is updated with additional data such as position, dimensions, and weight.

With all the information said, the following columns have been considered in the final table, as shown in Table 6:

- Column A: Source D7.1. This column is filled in case the information has been extracted from D7.1. In that case, the name of the chapter where the information can be found is included. If not the case, the column must be empty.

- Column B: Source D4. This column is filled in case the information has been extracted from D4.4. In that case, the name of the tab of the original 4.4 Excel file where the information can be found is included. If not the case, the column must be empty.
- Column C: Elements/Characteristics/Requirements. This column is a first extraction of information where there are not necessarily tangible elements since most of the rows are composed of phrases, different forms of requirements, etc. It is worth mentioning that not all rows in the list correspond to physical elements per se; some refer to functional characteristics or operational requirements. However, it has been decided to include them all in this first phase of the elements' identification, as oversimplifying the list could result in the loss of potentially useful information for further development.
- Column D: Tangible elements. This column has been used as a basis to identify the tangible components in order to simplify the work and to define the main elements that are going to be considered between the Transport Unit and the Rail Carrier Unit.
- Column E: Remarks. This column includes additional and relevant information regarding the corresponding tangible identified element.
- Columns F, G: MPG. MPG assignment
- Columns H, I: SPG. SPG assignment
- Column J: Integration: This column informs whether the element/component is intended for CAD modelling or rendering modelling.
- Column K: Position: Information about the position of the element in the TU.
- Column L: Mass (kg)
- Column M: Dimension (L x W x H) (mm)

The completed WBS table will serve as a foundational input for subsequent tasks, including 3D CAD and rendering modelling, system integration, and preliminary design assessments within WP10 as well as WP9 and subsequent work packages.

An extract of the table with the requirements is shown in Table 6.

Table 6: Extract of the WBS table

A	B	C	D	E
Source D7.1	Source D4.4	UC 1	Elements/Characteristics/Requirements	Tangible elements
Concept Proposal for Interfaces	-	Reinforced Edges and Corners for Structural Integrity	Reinforced corner profiles	-
other projects	-	Cable duct		cross section through the complete TU
Concept Proposal for the Vessel	-	Maximize the size of the windows surrounding the seating	Panoramic passenger windows	Enhances visibility and passenger experience
-	Transport Unit	Secure Seating Arrangements, Safety Belts	Bolted seats with seat belts	Safety belts typically for high-speed or sleeping cars
-	Transport Unit	Sleeping Berths, Tables	Fold-down sleeping berths, fixed/folding tables	Found in night trains or long-distance service
-	Transport Unit	Stable rails and handles	Vertical and horizontal grab poles	Located near doors, corridors, and seats
-	Transport Unit	18. External Sensors for Vulnerable Road Users (VRUs) Interaction with Pod	Luggage Racks	Overhead or end-of-car luggage shelves
Concept Proposal for the Vessel	-	Conductive Energy Transfer	Overhead or end-of-car luggage shelves	Vary by train type (commuter, long-distance)
-	Coupling System	Power Supply from Carrier Unit to Transport Unit (Electrical Coupling)	High-voltage electrical connectors between TUs/TU-CU	Located at mentioned connections
Concept Proposal for the Vessel	Transport Unit	Onboard Battery for Energy Supply (Auxiliary Battery for Onboard systems)	Electrical coupling system	Includes high/low voltage and communication lines
-	Ops and Planning	Central Unit with Coordinating Intelligence	Auxiliary battery packs (Li-ion or similar)	Powers lighting, HVAC, PIS during standby
-	Ops and Planning	Central Unit with On-Board ATP System (ERTMS)	Vehicle control unit (VCU)	Main processor for coordination and monitoring
-	Rail Carrier Unit	Central Unit with Integration to GSM-R and Future FRMCS Compatibility	ATP-compatible onboard computer	Interfaces with train control systems like ERTMS/ETCS
-	Incident Management	Central Unit with Cybersecurity Attributes	GSM-R modem and FRMCS-ready modules	For future-proof rail communication
-	Incident Management	Central Unit with Software to Detect Deviations from Normal State	Protected onboard IT system	Includes firewalls and intrusion detection
-	Rail Carrier Unit	Central Unit for Communication with Railway Safety Systems	Diagnostic software platform	Detects anomalies and alerts operators
other projects	Transport Unit	Emergency Stop Functionality from Inside and Outside	Interface module with safety systems	Links train systems with national infrastructure
-	Transport Unit	Climate Control/HVAC Systems (Roof-Mounted, Air Ducts)	Structural elements	Overrides train movement
-	other projects	Sliding step (gap bridge)	Emergency stop buttons inside/outside	-
-	Transport Unit	External and Internal Doors (with Low-Floor Accessibility)	Roof-mounted HVAC units with ducts	Designed for accessibility and insulation
-	other projects	Fire extinguishing system in addition to fire extinguisher	Structural floor, doors	necessary for travel in some European countries (Italy) specially when passenger could sleep in the TU
-	Coupling System	Signal Coupling between Carrier and Transport Unit	Sliding or plug doors	Include damage detection sensors
Concept Proposal for Interfaces	-	Signal Coupling between Carrier and Transport Unit	Standard UIC connectors	Vary by train type
Concept Proposal for Interfaces	-	In order to provide an interface that is as simple and economical as possible, the interface in the roof area and in the floor should be designed identically.	Roof-mounted connector hub	Reduces complexity and costs
Concept Proposal for Interfaces	-	Forklift Pockets for Transport Unit Handling	Interface in the roof area and in the floor	For easy ground handling
-	Transport Unit	All Transport Units shall have same contact points for placing on/n carrier or ground	Fork insertion slots	For international compatibility
Concept Proposal for Interfaces	-	TUs have corresponding corner castings at the corners as shown in Figure 24. These devices/corner castings arranged in the roof should be used by the HS engaging with the roof in order to lock and also to stabilise the TU.	Common interface pads/castings	For handling and locking via HS
ISO 1161-compliant castings				

F	G	H	I	J	K	L	M
MPG designation	MPG designation	SPG designation	SPG designation	Integration	Position	Mass [kg]	Dimension (L x W x H) [mm]
B	Vehicle body	BA	Vehicle body	CAD	Corner Castings, mass per piece	4,5	180 x 162 x 121
				CAD	Roof or roof	77x100	
C	Vehicle fitting out	CB	Window	CAD			
D	Interior appointments	DC	Seats, sleeping berths, tables	CAD	Depending on Output WP8, mass per piece	21	560 x 435 x 1275
D	Interior appointments	DC	Seats, sleeping berths, tables	CAD	Only tables! depending on Output WP8, mass per piece	20	Depending on use case
D	Interior appointments	DB	Rails, handles (inside)	CAD	2 per each entrance, mass per piece	27	Diameter: 33,7
D				CAD	Depending on Output WP8		Depending on use case
D	Interior appointments	DE	Luggage racks	CAD	Depending on Output WP8		Depending on use case
F	Power system, drive unit	FB	Power supply	CAD	High Voltage output from WP7 (either Conductive or Electrical Coupling)		box with 50-100 mm edge length
F	Power system, drive unit	FB	Power supply	CAD	High Voltage output from WP7 (either Conductive or Electrical Coupling)		box with 50-100 mm edge length
F	Power system, drive unit	FB	Power supply	CAD	bottom (3KWh, only 15 min self-sufficient operation)	29,5	14 Liter
G	Control apparatus for train operations	GA	Control apparatus for train operations	CAD	Control cabinet (2 pieces are needed)		
G	Control apparatus for train operations	GA	Control apparatus for train operations	CAD	Control cabinet		
G	Control apparatus for train operations	GA	Control apparatus for train operations	CAD	Control cabinet	total: 200	total: 400 x 600 x 2000
J	Monitoring and safety equipment	JD	Safety equipment	CAD	Control cabinet		
J	Monitoring and safety equipment	JC	Indicating, recording, display devices	CAD	Control cabinet		
J	Monitoring and safety equipment	JE	Data transmission devices	CAD	Control cabinet		
				CAD	where a place is	100	800x250x400
J	Monitoring and safety equipment	JF	Communication equipment	CAD	near doors on door pillar	0,8	106 x 70 x 70
L	Air conditioning	LA	Air conditioning	CAD	Roof / ceiling (exact Dimensions part of WP10)	65,5	max. 1965x1367x183
				CAD	Under the flooring integrated in the structural part	21,5	550x800x150
N	Doors, entrances	NA	Doors, Entrances	CAD	front and back of TU, mass per piece	135	Internal: 1950 x 550
				CAD	where a place is	80	500x725x240
S	Vehicle linkage devices	SG	Vehicle-vehicle interface for media, signals, power	CAD		0,5	300 x 50 x 220
T	Carrier systems, enclosures	TA	Carrier systems, enclosures	CAD	Roof / ceiling	134	
T	Carrier systems, enclosures	TA	Carrier systems, enclosures	CAD			
T	Carrier systems, enclosures	TA	Carrier systems, enclosures	CAD			200 x 100 x through all
T	Carrier systems, enclosures	TA	Carrier systems, enclosures	CAD	look at pattern WP7		
T	Carrier systems, enclosures	TA	Carrier systems, enclosures	CAD	Corner Castings, mass per piece	4,5	180 x 162 x 121

5.2.4 Step 4: Selection of the components to be considered for the layout and the integration concept for the technical equipment of the TU

On the one hand, the previous Step 3 has described a completed WBS of the different components. On the other hand, WP8 in its Deliverable D 8.1 “Basic design concept proposal vessel variants” (Pods4Rail Deliverable D8.1, 2024) describes the design requirements of the predefined UCs regarding layout and equipment of each TU.

The selected UC1 focuses on delivering cost-effective public passenger transport with high capacity and standardized workflows. The design of the TU relies on commonly used materials and equipment from road and rail transport, making it suitable for mass production and integration into existing systems. It is intended for short-distance travel, accommodating a relatively large number of passengers with a focus on functionality over comfort. The TU features standard seating, handrails, standard passenger information systems, HVAC, emergency equipment, and small luggage storage. The exterior includes automation sensors, door systems, and standard interfaces and passenger information system, while the structure incorporates vehicle body structure, batteries, and control units.

Each CU includes a dedicated entrance unit designed to provide passenger access and facilitate connections between neighbouring TUs and the platform. This unit features doors on both sides, as well as at the front and rear, allowing flexible boarding and interconnection. While it may include some service components due to its welcoming function, it is not intended for passengers to remain in during travel. The entrance unit prioritizes accessibility, featuring a low-floor design and entry-assisting technologies, but does not include comfort equipment or the necessary equipment for a self-sufficient operation like it is described in D 7.1 (Pods4Rail Deliverable D7.1, 2024), since it is always connected with the CU. Its interior is equipped with handrails, lighting, a minimal passenger information system, door buttons, emergency equipment, and standard materials. Optional features may include storage for luggage or onboard equipment. The exterior includes basic passenger information displays, handrails, door buttons, and standard mechanical and electrical interfaces. Structurally, it consists of a simple vehicle body without any specialized equipment.

In this way, by grouping and matching the WBS obtained in step 3 and the design criteria established in WP8, the WBS for the 10 ft passenger module and the 5 ft entrance module can be obtained for the physical elements to be included in the physical distribution layout. This is shown in Figure 3 and Figure 4.

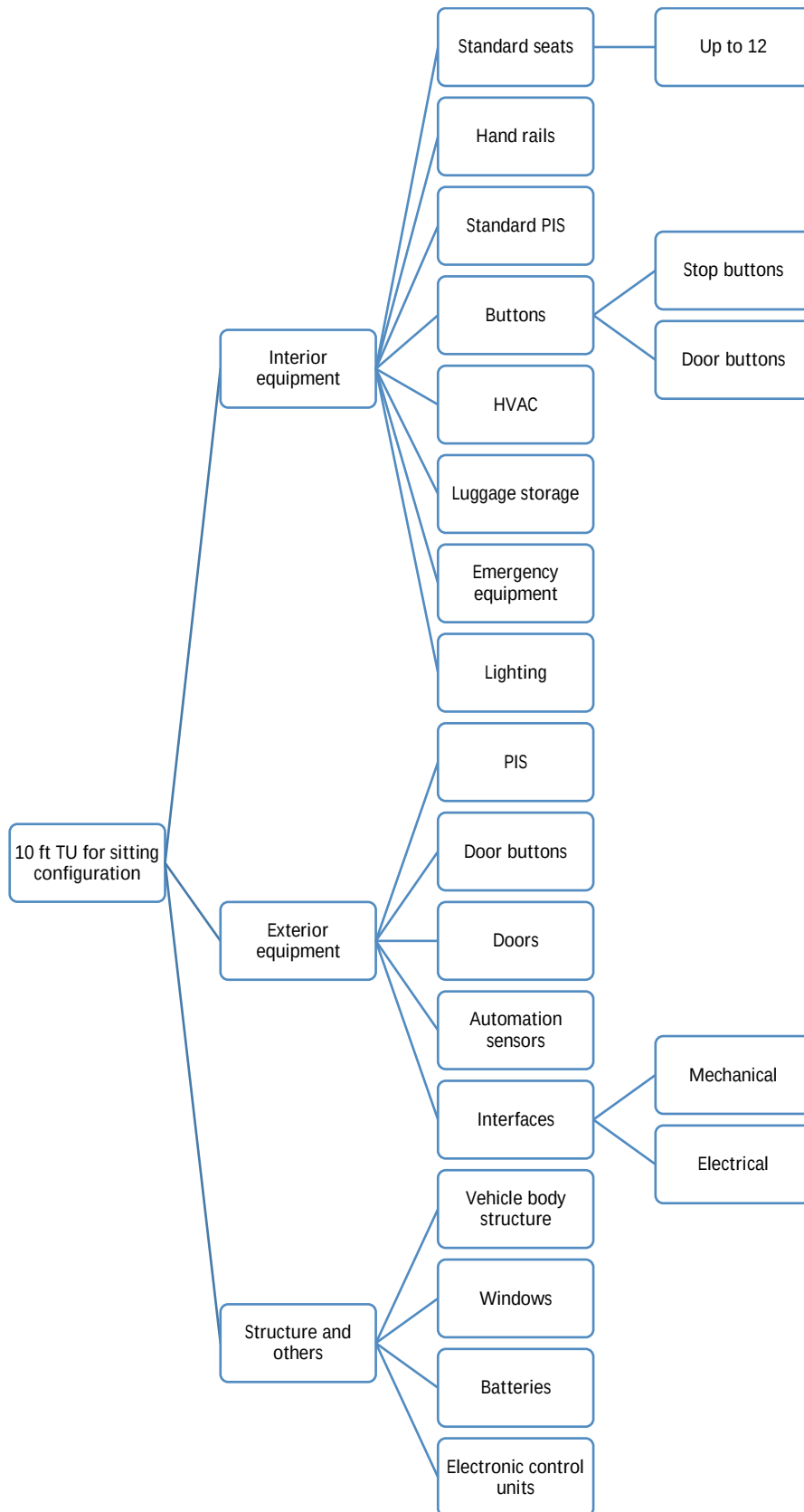


Figure 3: WBS for the 10 ft TU for equipment configuration

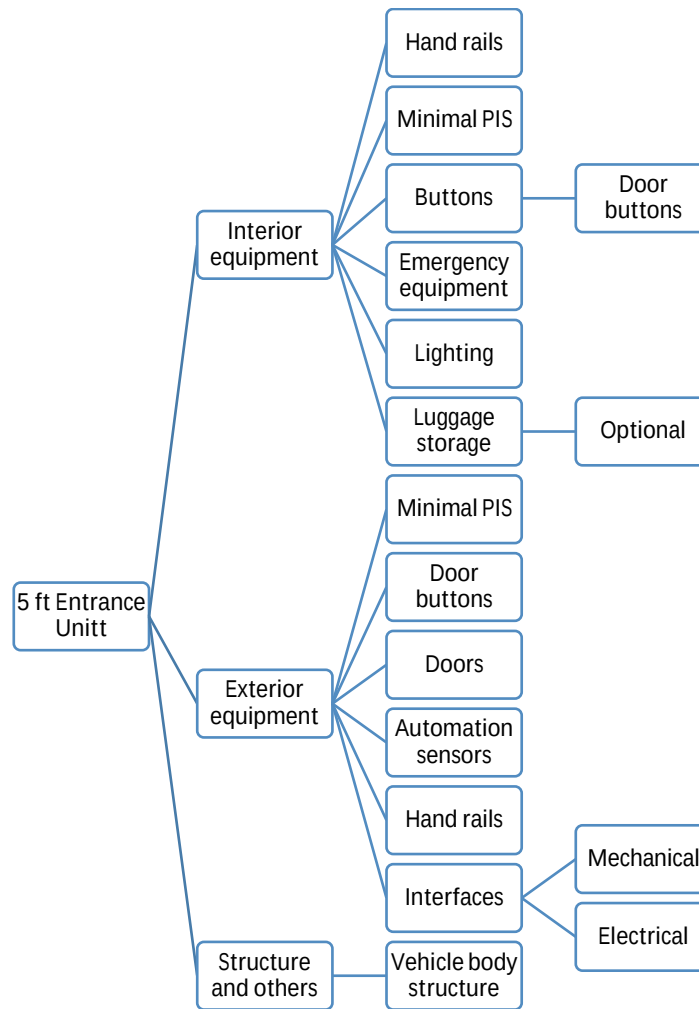


Figure 4: WBS for the equipment of 5 ft Entrance Unit

The entrance unit was defined as a 5 ft unit only needed for the Rail CU. For the Road CU, the entrance unit is not necessarily part of the configuration, since the entrance can be done directly with the other TU or it can be part of the front and rear structure of the carrier. Furthermore, the analyses of the previous WPs showed that there are different UCs that require different TU sizes. It is therefore clear that the physical WBS developed in this WP must be considered scalable and modular. On the other hand, a separate WBS would have to be created for each UC and each modification. This is in conflict with series production and cost-effective production.

The physical WBS of the UC1 with a 10 ft TU serves as the basis (Figure 3). This and the relevant components developed in the following Chapter 5.3 were defined in such a way that they can be scaled to a 5 ft or 20 ft TU. Only details, such as the number of batteries, need to be changed, but not their relation and basic dimensions. This was already taken into account in (Pods4Rail Deliverable D7.1, 2024), in which a standardised and fully scalable pattern of interfaces was developed. This was the necessary basis for further work.

For the interior equipment, this means, for example, that the interface to the required battery of the TU does not differ in its design and position for two 10 ft TUs and one 20 ft TU. The battery can be split for a 20 ft TU and occupy the two positions of the two 10 ft TUs. This would correspond to holistic modularity and scalability. The structure, cable ducts and interfaces could be duplicated. This is necessary due to the redundancy in some UCs. It is also possible to combine the battery (or any other component) on an interface with twice as much power/space. This makes it possible to utilise synergy effects (lightweight design, costs). At the same time, the modularity taken into account does not restrict operation (e.g. different charging scenarios and positions). The modularity and scalability of the interfaces and WBS, which was taken into account from the outset, now leads to standardisation and consistency of the processes.

5.2.5 Step 5: Main constraints

This section includes the main design and dimensional restrictions that affect the distribution of the various elements. These include restrictions affecting the overall dimensions of 5 ft and 10 ft modules, doors, vehicle structure and couplings.

Given that TU modules can be used for both rail and road transport, the requirements for passenger transport in both modes must be met. The following sections will include, where appropriate, a comparative analysis in order to establish restrictions that satisfy both rail and road, based on the TSI (Technical Specifications for Interoperability) and UNECE (United Nations Economic Commission for Europe) regulations and provide a structured overview of the critical elements related to safety, accessibility and habitability that must be taken into account in the vehicle design

For buses, the requirements are drawn from: (García et al., 2016)

- Uniform provisions concerning the approval of large passenger vehicles regarding the strength of their superstructure (UNECE Reg 66, 2011)
- Uniform provisions concerning the approval of vehicles of category M2 or M3 as regards their general characteristics of construction [2018/237] (UNECE Reg 107)

For trains, the requirements are drawn from:

- Rolling Stock - Locomotives and Passengers TSI (TSI LOC&PAS, 2014)
- Persons with Disabilities and with Reduced Mobility TSI (TSI PRM, 2014)
- “Guidelines on habitability and accessibility in passenger train design” (García et al., 2016) document referencing the following UIC leaflets: UIC 567: General provisions for coaches (UIC 567, 2023) and UIC 560: Doors, footboards, windows, steps, handles and handrails of coaches and luggage vans (UIC 560, 2023)

5.2.6 General dimensions

D7.1 proposed the main dimensions for the TU. The main dimension for the 5ft and 10ft modules appear in Table 7. The values of Deliverable 7.1 were adopted, adapted to new developments and findings from WP8 and brought into line with possible designs and standard manufacturing processes. For example, the thickness of a roof structure that has integrated insulation and fulfils the safety requirements for fire protection is set at 40 mm (Boese et al., 2025).

Table 7: Transport Unit key data

		5 ft Entrance Unit	10 ft Passenger Unit
External dimensions	Length [mm]	1500	3010
	Width [mm]	2440	2440
	Height [mm]	2590	2590
Internal dimensions ²	Length [mm]	1360	2870
	Width [mm]	min. 2320	min. 2320
	Height [mm]	min. 2260	min. 2260
Seats (-)		--	8 - 12
Standing (normal)		2	35 ³
Front doors		1120	1120
Usable passage width [mm]			
Side doors or Swing doors		1100	1100
Usable passage width [mm]			
Emergency exit (e.g. window area)		—	700 mm x 550 mm
Roof structure [mm]		approx. 40-60	approx. 40-60
Sidewalls [mm]		40 - 60	40-60
Bottom structure [mm]		230	230
Floor panelling and insulation [mm]		40	40

According to the Table 7, the physical dimensions for each module regarding the outer dimensions and gauging dimensions for the interior including wall thicknesses are shown in Figure 5. It turns out that there is still 148 mm clearance in the height below the assumed values. This provides more space and comfort for the passenger, or for other equipment that can be accommodated in the roof area for additional UC.

² Assumption: sidewall thickness including insulation is only 40-60 mm thick (common values for rail applications)

³ Exceptional Payload for regional trains: 5-10 standing Persons per m² (default 7 Persons). 10 ft TU has a useable area of 5 m² so 35 Persons (EN 15663, 2018)

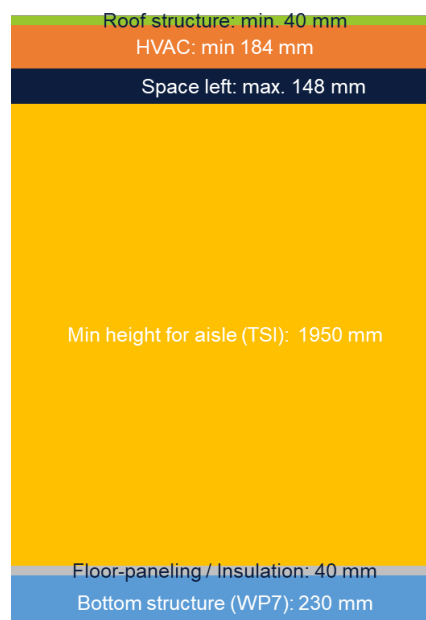


Figure 5: Outer dimensions and gauging dimensions for the interior

5.2.7 Doors, aisles and additional dimensions

Table 8 summarizes the main dimensional requirements affecting road and rail vehicles declared by their specific standards, with particular focus on external doors, aisles, and additional emergency exits.

Table 8: Doors, aisles and additional dimension for rail and road modes

Aspect	Road mode (UNECE Reg 66, 2011)	Railway mode (TSI LOC&PAS, 2014), (TSI PMR, 2014)
I - Service Doors	Min. 2 doors in the vehicle (1 service door) Minimum door width: 550 mm Minimum door height: 1100 mm Aisle width: 550 mm	Minimum usable width when open for exterior doors (PMR): 800 mm Wheelchair access doors (interior and exterior): 1000 mm
II - Emergency Exits	Min. 3 exits (Class II); includes doors, windows, or roof hatches (count only as one of the emergency exits).	Up to 40 passengers: 2 emergency exits at least At least one emergency exit on each vehicle side
III – Emergency Doors	Minimum door height: 1400 mm Minimum door width: 550 mm Minimum aisle width in front of the door: 300 mm	No specific dimensions found in TSIs. Internal and external emergency-opening device must be present. The number and dimensions of doors shall allow the complete evacuation within three minutes by passengers without their baggage.

Aspect	Road mode (UNECE Reg 66, 2011)	Railway mode (TSI LOC&PAS, 2014), (TSI PMR, 2014)
IV – Emergency Windows	Height of bottom edge from floor: 650-1200 mm (Hinged windows); 500-1200 mm (Breakable glass).	No specific requirement found in TSI (depends on operator/national rules).
V – Evacuation Hatches	Minimum number of evacuation hatches: at least 1 (Class II). Vertical clearance: 1600 mm Location: Not in areas with technical components that may be dangerous.	No specific requirement found in TSI (depends on operator/national rules).
VI – Location of Exits	At least one door must be on the front half of the vehicle (Service Door). At least one exists must be on the front or rear of the vehicle. One door is permitted at the rear if it is not a service door. If there is only one hatch, it is placed in the middle third of the compartment.	No specific requirement found in TSI (depends on operator/national rules).
VII – Minimum Exit Dimensions	Minimum height of emergency doors: 1400 mm Minimum width of emergency doors: 600 mm Emergency windows: 500x700 mm rectangle must fit in the area Escape hatches: 600x700 mm rectangle must fit in the area.	Minimum clear opening: 1400 mm wide x 2000 mm high; or smaller doors with equivalent capacity.
Gangways / Aisles	Continuous clearance corridor width $\geq$ 550 mm (recommended 600 mm) Corridor height $\geq$ 1900 mm from the floor.	Aisle width $\geq$ 520 mm for central aisles according with UIC 567. Aisle width $\geq$ 450 mm (to 1000 mm height), $\geq$ 550 mm above according to TSI. Turning space $\varnothing$ 1500 mm for wheelchairs.

Figure 6 illustrates the application of these requirements, showing inward-swinging side doors and pocket sliding doors at both ends of the transport unit. In addition, a minimum clearance of 1120 mm is provided. Larger doors with electric ramps or similar aids could be incorporated if required in other configurations.

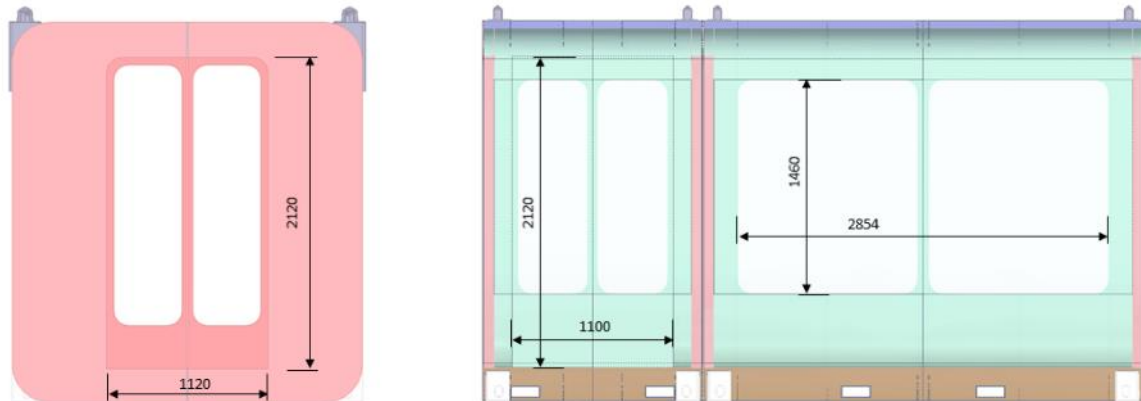


Figure 6: Doors and additional dimensions

The mentioned aisle has the advantage that it can be made narrower, and more space is available for other equipment or comfort requirements. The minimum width of the aisle up to a height of 1000 mm for UC1 should therefore be assumed to be 450 mm. Above this, a width of 550 mm must be guaranteed (see Figure 7a). This corresponds to the requirements of both road and rail vehicles.

For rail vehicles in particular, the minimum clearance between two connected vehicles of a train section or, in this case, two TUs on the same CU must be 550 mm over the entire height (see Figure 7b).

For the sake of completeness and for it to be considered in future designs regarding the inclusion of PMR accessibility, the width of the aisle required for the transition to a PRM unit is also listed here (Figure 7c). These reference values can be found in (TSI PRM, 2014).

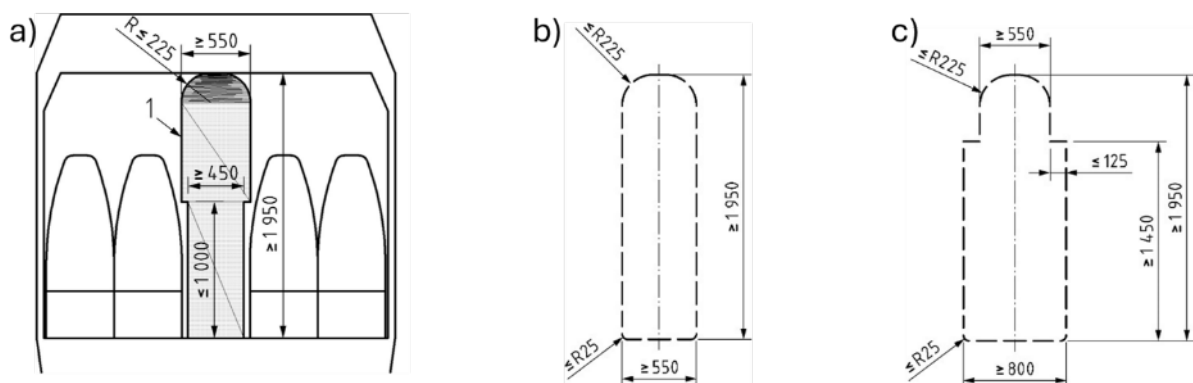


Figure 7: Minimum clearway profile a) in a TU; b) between connecting vehicles of a single trainset, c) to and from wheelchair spaces

In addition to doors and aisles, emergency windows must also be considered. For road vehicles, regulations specify that the lower edge of hinged windows should be positioned

between 650 mm and 1200 mm from the floor, or 500–1200 mm for breakable glass panes. In contrast, the TSIs do not define specific requirements for emergency windows, leaving this to operator or national rules. For UC1, these values provide a useful reference framework to ensure adequate passenger evacuation options in the event of an emergency.

By contrast, evacuation hatches—while required in certain road vehicle classes—will not be considered in the UC1 design. This exclusion is based on the modular configuration and size of the transport units, where alternative evacuation routes (doors and windows) are sufficient to meet safety and accessibility objectives.

Finally, the UC1 design also complies with regulatory provisions regarding the number and location of exits. For a vehicle of this capacity, at least two service doors and a minimum of three emergency exits are required for road applications, while railway regulations specify at least two emergency exits for vehicles carrying up to 40 passengers, with one on each side. The number of doors/emergency exits (including emergency windows) and the placement of doors at both sides of the vehicle ensures compliance with these requirements and facilitates rapid passenger flow.

In addition, the corridor height and clearances follow the minimum standards defined for both road (≥ 1900 mm) and rail applications (1950 mm). Considering UC1's limited passenger capacity, the design also satisfies the railway requirement that complete evacuation must be possible within three minutes without baggage. Together, these measures confirm that UC1 provides a safe and regulation-compliant evacuation concept while maintaining flexibility and modularity.

5.2.8 Body structure

TU modules can be manufactured in several ways using different materials and different technologies. In general terms, a welded structure for such a UC is proposed as shown in Figure 8. The image illustrates the basic welded frame structure of the unit.

The structural framework is composed of steel beams. This includes the roof structure, side wall structure, and the floor beams, all contributing to the overall strength and stability of the unit.

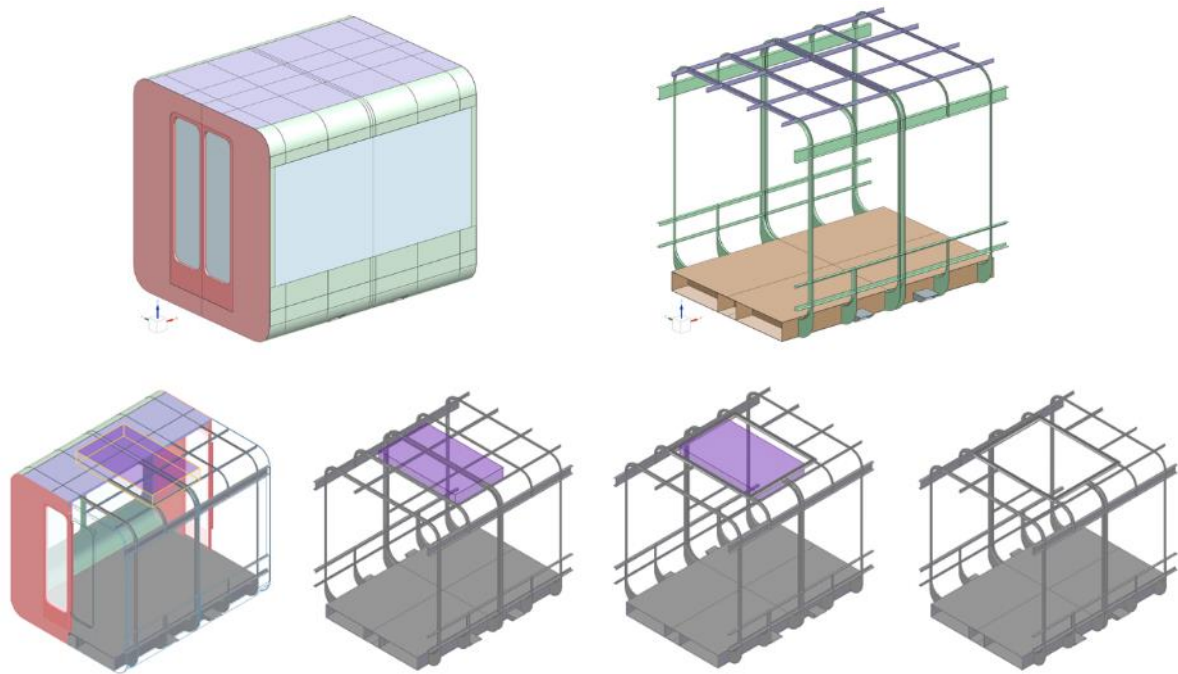


Figure 8: Basic structure of the welded frame of 10 ft TU

The main limitations of the structure are that it must be sized to accommodate equipment at ceiling level (such as HVAC) or on the floor (such as the battery). Thus, the separation between the two upper central beams must allow for the accommodation of ceiling equipment such as HVAC. Similarly, given that the separation between the forklift pockets is standard (1090 mm), the beams on the floor must be spaced to accommodate the battery and other components such as electronic control equipment.

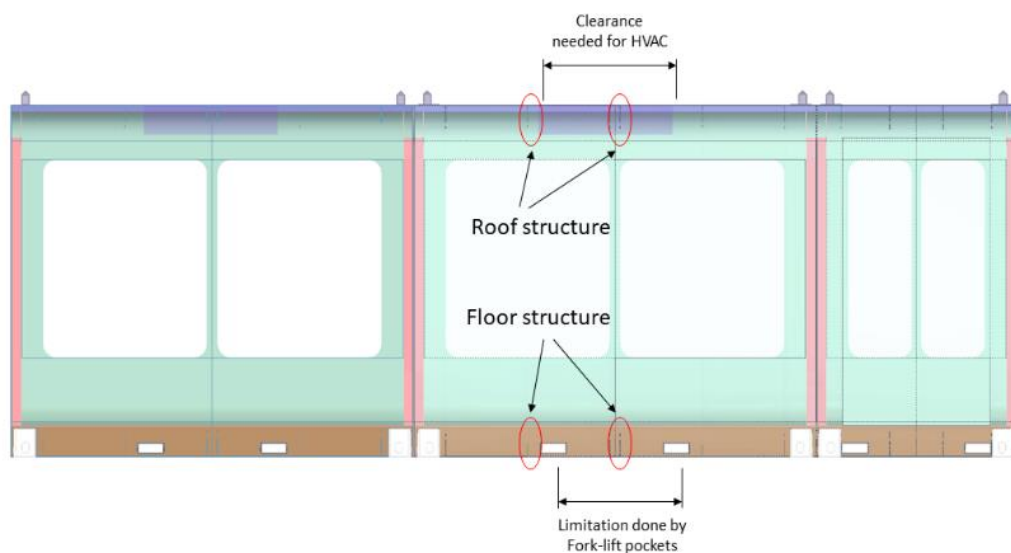


Figure 9: Vehicle body constraints

5.3 Placement for relevant components for the specified use case

5.3.1 HVAC system

D7.1 (Pods4Rail Deliverable D7.1, 2024) established a possible idea to integrate a compact HVAC unit in the ceiling of the TU. In this case, the unit is designed to fit efficiently into the ceiling while maintaining an interior height of 2100 mm, ensuring sufficient headroom and a spacious feel for passengers.

A subsequent analysis carried out in this WP considers two options, one based on the initial proposal indicated in D7.1 and the other placing the HVAC above the ceiling level, as shown in Figure 10.

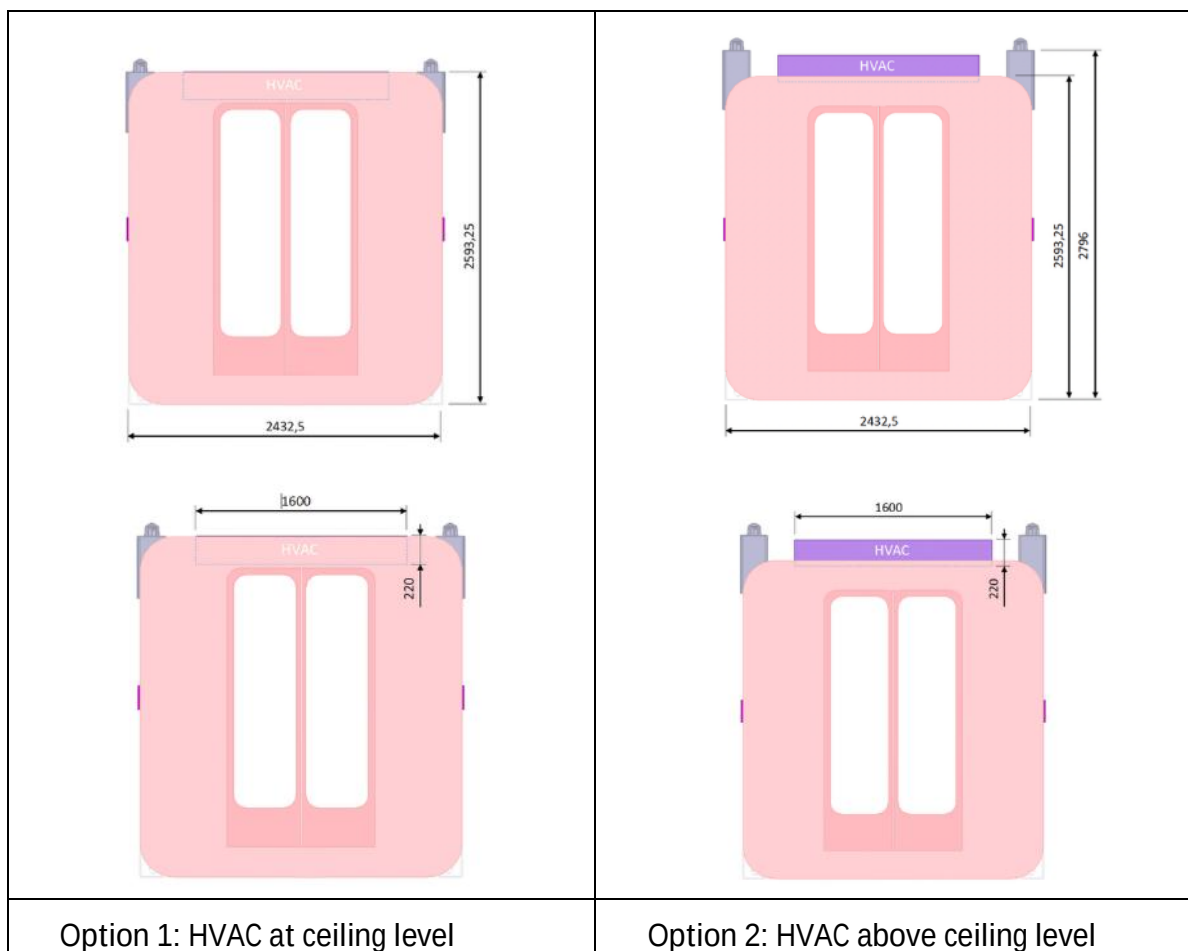


Figure 10: HVAC-unit integration options

On the other hand, Figure 11 shows a view of the HVAC position from a bird's eye view.

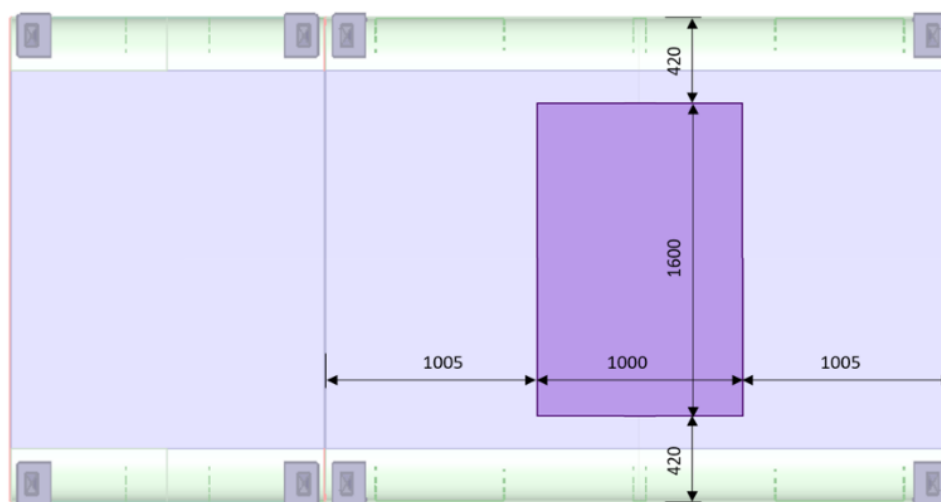


Figure 11: HVAC position from a bird's eye view

Furthermore, analysing different existing HVAC systems for railways, Table 9 shows their main dimensions.

Table 9: HVAC dimensions for several existing models

Model	Sector	Power (kW) ⁴	Length (mm)	Width (mm)	Height (mm)	Refrigerant	Link
Liebherr MACS 8.0	Rail	8 C 8 H	1000	1600	220	R407C	liebherr-modular-air-conditioning-system.pdf
Thermo King RAC HS	Rail	7.2 C 5.5 H	1450	1470	480	R407C	TK_RAC-HS_08-2022_EN_V1.0_LR.pdf
Thermo King RAC 40-60	Rail	4-6 C 6.5 H	1080 - 1164	826 - 904	441 - 484	R407C	TK_RAC-40-60_08-2022_EN_V1.0_LR.pdf
Thermo King RAC LFR	Rail	4-6.5 C 5 H	1300	832 - 840	400	R407C	TK_RAC-LFR_08-2022_EN_V1.0_LR.pdf
Thermo King RSA	Rail	5.2 C 3 H	1406	1001.5	453.5	R407C	TK_RSA_08-2022_EN_V1.0_LR.pdf
NK RVKE 16-E	Rail	5.6 C 4 H	800	800	750	?	Noske Kaeser - Klimaanlage für Züge und Bahnen.

⁴ C – Cooling H – Heating

Model	Sector	Power (kW) ⁴	Length (mm)	Width (mm)	Height (mm)	Refrigerant	Link
Konvekta HVAC 3705	Rail	6 C 4.5 H	1000	897.5	410	R744	Produktuebersicht Schiene dt-engl eBook WEB 0821.pdf
Konvekta HVAC 3706	Rail	5.1 C 4 or 6.25 H	1000	1150	415	R744	Produktuebersicht Schiene dt-engl eBook WEB 0821.pdf
Konvekta HVAC 3709	Rail	5.4 C 5.5 H	820	1130	430	R744	Produktuebersicht Schiene dt-engl eBook WEB 0821.pdf
Konvekta HVAC 3710	Rail	5.5 C 4.5 H	800	1145	430	R744	Produktuebersicht Schiene dt-engl eBook WEB 0821.pdf
Konvekta HVAC 3401	Rail	7 C 5 H	800	1500	350	R134a	Produktuebersicht Schiene dt-engl eBook WEB 0821.pdf
Konvekta HVAC 3404	Rail	4.5 C 4.5 H	800	1100	255	R134a	Produktuebersicht Schiene dt-engl eBook WEB 0821.pdf
Konvekta HVAC 3405	Rail	5.1 C 4.5 H	1000	897.5	330	R134a	Produktuebersicht Schiene dt-engl eBook WEB 0821.pdf
Konvekta HVAC 3406	Rail	5.1 C 4 or 6.25 H	1000	897.5	330	R134a	Produktuebersicht Schiene dt-engl eBook WEB 0821.pdf
Konvekta HVAC 3407	Rail	5.1 C 4.5 H	800	1300	330	R134a	Produktuebersicht Schiene dt-engl eBook WEB 0821.pdf

As can be seen in Table 9, analysis of the HVAC systems shows that their geometric dimensions do not vary according to power, but rather that all systems have similar dimensions.

On the other hand, from the geometric analysis and the limited space available in the TU, the most critical dimension is the height of the device. As Figure 5 shows, roof components must not be larger than 332 mm in the vertical direction. Larger components would violate the clearance profile of the aisle (1950 mm). For reasons of comfort, it is therefore desirable to make the HVAC as flat as possible. Placement outside the TU on the roof is not possible due to the requirement of forkability or connectivity of HS or CU that reach the TU from above. Therefore, based on the analysis carried out, the most suitable equipment is Liebherr MACS 8.0, even though it has more power than necessary, with dimensions of 1000 x 1600 x 220.

Comparing both possibilities, Table 10 shows the advantages and disadvantages of each of the two options considered.

Table 10: HVAC options comparison

Option	Advantages	Disadvantages
HVAC at ceiling level	- Compatible with standardised ISO688 containers, enhancing stackability. - Easier access for routine checks and repairs from the interior. - Direct air distribution into the cabin, potentially faster cooling/heating. - Can be integrated with lighting panels or luggage racks. - Easier to include sound insulation between unit and cabin.	- Less efficient air intake/outlet - More visible units may affect cabin aesthetics. - Reduce perceived or actual headroom. - May require visible ducts if not integrated cleanly. - Slightly lower centre of gravity.
HVAC above ceiling level	- More efficient air intake/outlet - Can reduce interior disruptions during servicing if accessible from outside. - Ducting can allow more even airflow distribution if designed well. - Frees up full cabin height if system is fully above ceiling. - Natural separation may reduce noise inside the cabin.	- Not compatible with standardised ISO688 containers (height) - More complex ducting and insulation may be required. - May require roof access or depot lifts for maintenance. - Raises centre of gravity, affecting dynamic performance marginally.

5.3.2 Batteries

The TUs are equipped with electronic devices, such as doors, HVAC, PIS, light, etc. In order to supply them constantly with electronic power, whether the TU is on the carrier, transfer or parking, electrical connectors to the carrier are not sufficient – because a standalone time of 15 minutes must be guaranteed. Therefore, a battery is needed to ensure electronic power at all time. Nevertheless, electrical connectors could be set up additionally, to charge the battery of the TU while on the carrier. To remain sustainability, lower the costs of production and to fully use the space of the TU, the battery modules could be placed in the vehicle floor, closer to the carrier, as shown on the left side of Figure 12. This reduces the amount of necessary wire between connector and battery modules, which decreases costs and weight of the TU. Additionally, instead of reducing interior space to place the batteries, under-utilised space under the floor is used. Another benefit of placing the battery modules in the vehicle floor is, that due to its high weight, the TUs centre of mass is lower which results in higher stabilization.

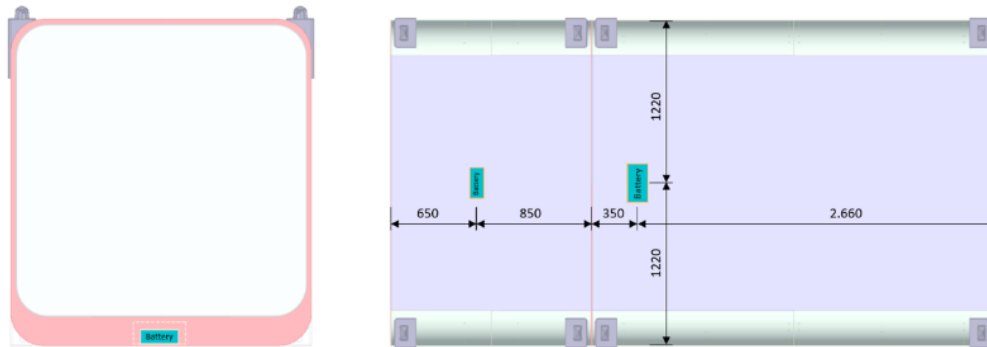


Figure 12: Battery integration

Each battery module could be installed in specially designed trays in the underfloor, integrated into the main frame. This ensures stability, safety and reduces vibrations. The modular structure allows easy battery upgrades. So, the battery can either be placed in the centre between the forklift pockets, as in Figure 12, or on the sides, outside of the forklift pockets, as in Figure 13. The latter configuration is constrained for the 5ft TU by limited space availability. Furthermore, for all TU sizes, the battery modules must be selected symmetrically to maintain equilibrium. Above and beyond that, the battery modules must be easily accessible for maintenance processes, which could be simplified through access hatches or quick-release mechanisms. In addition, further arrangements for general, fire and collision protection must be determined, as well as a cooling system, that may need to cool down the batteries.

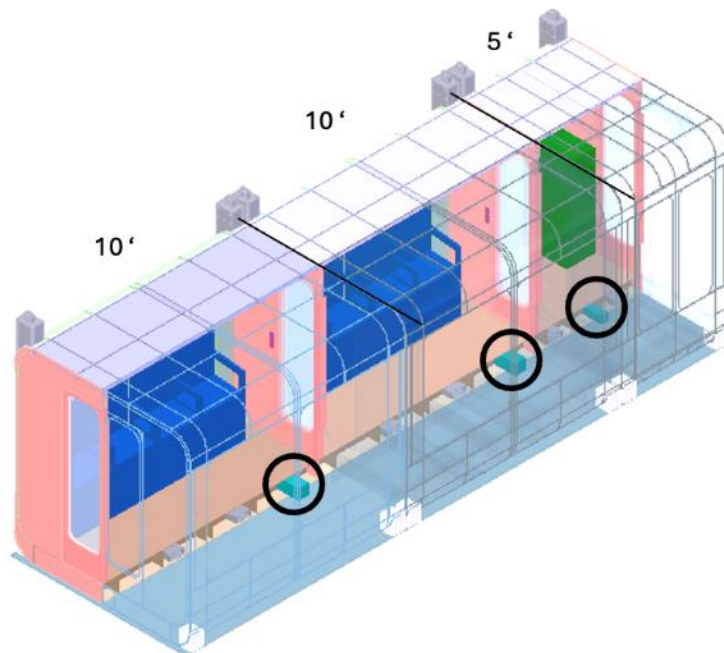


Figure 13: Batteries location

The battery modules are exclusively needed in the passenger's module, as it will be transferred and removed from the carrier and is not anymore connected to another HS which supplies the TU with energy. Therefore, the electrical connectors between carrier and TU, respectively between TU and HS are disconnected. However, the entrance module always stays on the carrier and therefore is constantly connected and supplied with electrical power by the carrier. Additionally, no passengers are in the entrance module while transshipment, so that no electronic power is needed for the doors, nor other electronic devices.

Depending on the TUs size, the size of the battery modules varies, but could easily be extended due to its modularity. The size of a battery for a 10ft TU is 6,6 litres, as declared in D7.1, Table 13 (Pods4Rail Deliverable D7.1, 2024). The other sizes are also shown in that table, but not further discussed in this chapter.

The design is intended to also complain with (UNECE Reg 107) requirements for batteries: the battery compartment must be separated from the passenger compartment and the driver's cabin and must be ventilated with external air. Also, battery terminals must be protected against short-circuit risk.

5.3.3 Seating arrangements

The seating arrangement is an essential part of the interior design. Table 11 includes the main dimensions affecting road and rail modes in terms of external seating arrangement according to the specific standards regarding railway and/or road operations that have been presented some sections before.

Table 11: Seating arrangement requirements for rail and road modes

Aspect	Road mode (UNECE Reg 66, 2011)	Railway mode (TSI LOC&PAS, 2014), (TSI PMR, 2014)
I – Passenger Seats	Seat width (cushion width) ≥ 400 mm Width of the space above the cushion depth ≥ 500 mm Seat depth ≥ 400 mm (Class II). Cushion height: 400–500 mm from the floor.	Free space between armrests: 500 mm (1st class) / 480 mm (2nd class). Backrest should be as wide as the seat at its bottom. Seat depth ≥ 430 mm Seat height 390–430 mm. Backrest height ≥ 500 mm.
II - Distances Between Seats	Seats in line: ≥ 680 mm Seats facing: ≥ 1300 mm.	Seats in line: ≥ 940 mm (2nd class) / 1010 mm (1st class) Seats facing: ≥ 1450 mm. Minimum distance between back of one seat and the rearmost point of the seat in front: 680 mm. Minimum space between the frond edge of one seat and the seat in front: 230 mm. Minimum free space at knee level: 790 mm (1st class) / 700 mm (2nd class).

The table outlines requirements for seat dimensions and distance between seats. This information provides a useful reference framework for subsequent and more specific interior designs. No further breakdown is provided in this section, as these seating arrangements are only present in the 10 ft module. It has been determined that the 10 ft module of UC1 does not meet PRM or accessibility criteria and neither does the 5 ft entrance module as there are insufficient interior dimensions: the 5 ft unit would need to be extended by at least 160 mm to meet the accessibility requirements (Pods4Rail Deliverable D8.1, 2025).

A key factor of the passenger unit are the seats. In order to fulfil the determined capacity, the seat arrangement marks a significant variable. The basis is given in the Deliverable of WP7, in Table 19, in which the number of seats is declared (Pods4Rail Deliverable D7.1, 2024). Therefore, the 5ft entrance unit holds no seats, while in the 10ft passenger unit up to 10 seats are set. Standing space is also desirable, to be capable of transporting many passengers in high demand.

To get an overview of possible seat arrangements, 10ft passenger units are used in this UC. As the design of the TU is given, symmetry must be provided, in order to place the TU independently from its side and direction. Therefore, the doors are located in the centre of the walls. Therefore, the aisle must be preferably in the middle – at least at the ends of the TU, towards the doors. Additionally, the seating arrangement must keep an aisle free throughout the TU for passengers being able to walk through it from one door to the other door. This guarantees the accessibility of both doors. For short travel time, passengers should be able to access their seats quickly and easily, in order to reduce boarding time.

In the following paragraphs, the possible seat arrangements are presented. The illustrating figures contain luggage, which will be focused on in the next section. Before the seats' arrangements can be configured, the kind of seat must be declared. Therefore, the main differentiation is between foldable and fixed seats. Foldable seats can be used in high demand, to give passengers the opportunity to sit, while also preventing more space for more passengers to stand in. A disadvantage is, that these seats are in general uncomfortable and therefore, just recommended for shorter travel time or during peak hours of passengers commuting to work, university, school or else. Fixed seats on the other hand, reduce the standing space, but are more comfortable. Consequently, they are preferable for longer travel time. In this chapter, the focus relies on fixed seats. For the dimensions of the seats, standard seats are used, shown in Figure 14.

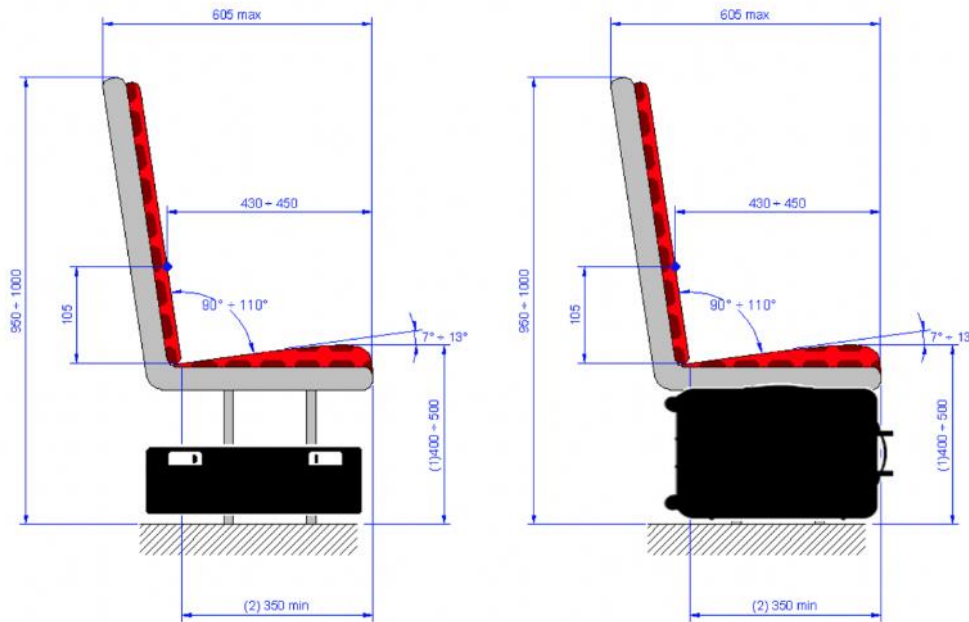


Figure 14: Seat dimensions

The shown seat dimensions comply with both rail and road regulations. According to road standards, the cushion width must be at least 400 mm, with a minimum width above the cushion of 500 mm. The free space between armrests, which depends on the vehicle class (1st or 2nd), is expected to range from 480 to 500 mm according to rail regulations.

Regarding cushion depth, road regulations require a minimum of 400 mm, while rail regulations specify 430 mm. Figure 14 shows a depth of 430–450 mm, satisfying both sets of requirements.

For seat height, road regulations specify 400–500 mm, and rail regulations require the seat to be 390–430 mm above the floor. The dimensions in Figure 14 fall within 400–500 mm, meeting the more restrictive limits and ensuring compliance with both rail and road standards.

Of the various seating configurations proposed in D8.1 (Pods4Ral D8.1, 2025) and D9.1 (Pods4Ral D9.1, 2025), two have been selected as the most suitable for the UC in question. The two configurations – left side: medial seating configuration and right side: lateral seating configuration are shown in Figure 15.



Figure 15: Different seating arrangements. (a) Lateral seating configuration (b) Medial seating configuration (© moodley)

In the medial seating arrangement, the two rows of seats are placed in the middle of the TU with all seats facing the windows in a back-to-back configuration. In opposition, in the lateral seating arrangement the seat backs rest towards the window; this allows a face-to-face interaction between the users. The advantages and disadvantages for the medial and lateral configurations are compared in Table 12.

Table 12: Seating arrangement options

Option	Advantages	Disadvantages
Lateral seating configuration	- Encourages social interaction; good for groups/families. - Can be efficient in wider cabins. - Comfortable for short trips and group travel. - Easier aisle access and movement; fewer obstructions.	- Less privacy; close face-to-face contact can feel awkward. - Limited legroom when knees face each other. - Legs and bags may block the aisle. - Debris and items may accumulate between facing seats.
Medial seating configuration	- More privacy; reduced eye contact with strangers. - Passengers will be able to have a direct vision of landscapes. - More individual comfort and sense of space.	- Reduced group interaction. - Less suitable for families or groups who want to face each other. - Possibility of increasing the seats capacity.

Furthermore, additional information extracted from road and rail regulations for lateral seating configuration is summarized as follows:

- The minimum seat width must be 480 mm (in accordance with road and rail regulations). As the total space of the 10-foot pod is 2870 mm, for the lateral seating configuration, there is room for five seats in a line, one of which can be slightly wider and used for disabled people or configured as a double seat (Figure 16). This allows for a maximum capacity of 10 people.
- For face-to-face configurations, the distance between seats is 900 mm, higher than the minimum aisle required by the rail and road regulations. Due to the minimum width of the seats and the aisle required to access the module doors, this configuration only allows for a maximum of 6 seats.



Figure 16: Frontal view: 8 seats / TU 10' versus 12 seats / TU 10' (© moodley)

Once a preferred or mixed configuration is selected, these dimensional limits will be applied to guide the final seat placement.

Deductively, the lateral seating arrangement is to prefer, if groups and families are expected to ride on the TU, as well as if shorter travel time is planned. However, the medial seating arrangement is preferable for longer travel times and individual passengers in lower demand, due to higher comfort and more privacy.

The seats of the TUs could also be designed modular, which enables flexibility and adaptivity. Therefore, the seats can be arranged for different areas, and as demand changes throughout time and days. For instance, the lateral configuration could be set up for commuters traveling short time to work, university, school, or else. Whereas the medial configuration could be set up for passengers, travelling long time, e.g. for vacation (increasing of capacity could be analysed). As a consequence, the TU ensures a high flexible utilization and is more efficient, economic and more suited to the passenger's current need.

5.3.4 Luggage

Passengers tend to travel with some sort of luggage for vacation or commuting, whether it is a laptop bag or backpack, a sports bag or a suitcase, in which they carry their clothes, laptops, books, lunch boxes or a bottle of water. In conventional transportation systems, luggage space is reserved in form of racks and/or overhead storage. Therefore, luggage storage must be set up in the passenger units as well.

As space is limited within the TU, the right kind of storage and its location is of major importance. The aim is to use the available space, without reducing the number of seats or standing space. At the same time, it is to be noticed, that space must be kept free for the doors to open, as well as space for the door-drives, which are located above the doors. Furthermore, the luggage must be stored securely, preventing it from moving during transshipment of the TU. In addition, the luggage must be accessible for passengers without disturbing others.

Therefore, research show different varieties of racks and locations. In order to analyse the different options of storages, the dimension of the hand luggage is set to 550 x 400 x 200 mm. This is the standard dimension, which also applies to aeroplanes, among other things and ensures an equivalent analyzation.

The initial idea of installing overhead luggage racks above the seats was discarded because, although this would make it easier to see which seats were free, it would inconvenience seated passengers when others reached for their bags. It also limits the already restricted headroom further and cannot ensure safety, since sudden or jerky movements could cause items to fall.

Therefore, a first option considers stowing small luggage underneath the seat, just as in an aeroplane. This can be realized with an integrated luggage compartment in the seat. As a consequence, the luggage compartment and the seat are combined, in one piece, which remains the seat configuration flexible.

In addition, if the racks reach the floor, the luggage remains cleaner, since dropped liquids or road dirt cannot reach the bottom of the compartment. Furthermore, there is no need to clean underneath the seats, like road dirt, but the luggage compartment itself, like dust. Nevertheless, it is easy to access, for all kind of passengers, whereas passengers standing have no opportunity to store their luggage.

Additionally, the seat dimensions are critical, as shown in Figure 14. This solution is just feasible, if the case fits completely under the seat and all the dimensional restrictions related to seatings already described in previous sections are respected.

In that line, all seated passengers have the possibility to store their smaller luggage under the seat, like in an aeroplane. This solution can be used for both the lateral and the medial seating configurations.

The second option is a luggage rack, which is substituted with a seat, illustrated in Figure 18. On one hand, this guarantees much storage space for passengers seated and standing, as well as the accessibility and the ability to monitor the luggage. On the other hand, it takes

away one seat, which is required from the description of Deliverable 7.1. Therefore, this type of storage may only be used for vacation time and e.g. to get to the airport.

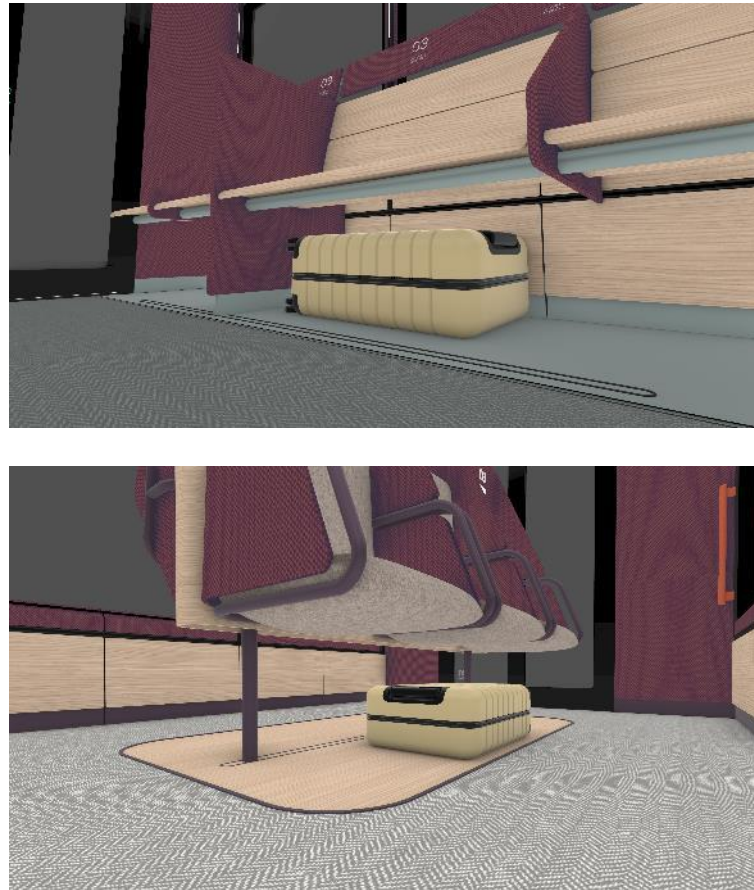


Figure 17 : Option 1 - Luggage under the seat in the lateral and in the medial seating configuration (© moodley)



Figure 18: Option 2 - A luggage rack in the lateral and medial seating configuration
(© moodley)

The advantages and disadvantages are faced in Table 13 for the two options.

Table 13: Luggage positioning options

Option	Advantages	Disadvantages
Luggage under the seat	Space-efficient Keeps luggage close to passenger No need for vertical lifting	Limited to small/medium bags Reduces legroom Hard to access while seated Depends on the seats' dimensions
Luggage rack reducing a seat	Accommodates large luggage Easy loading/unloading More secure storage location	May disrupt passenger layout Less optimal for high-occupancy times

To summarize the luggage storage, the best option is option number two, with integrated luggage-space in the seats. The reason why is, that the safety is higher for passengers as well as no space is reduced due to additional racks. This allows passengers to store smaller luggage under-seat, whereas bigger luggage should be placed between the passengers' legs and should be hold on to at all time, to prevent it from moving.

5.3.5 Handrails

Handrails and grab bars are critical for passenger safety, accessibility, and comfort in both rail and road operation modes. They support passengers in maintaining balance during vehicle motion and provide guidance along aisles and access routes, especially for persons with reduced mobility (PRM).

Table 14 summarizes the main requirements of these components affecting road and rail vehicles.

Table 14: Grab Bars / Handrails requirements for rail and road modes

Aspect	Road mode (UNECE Reg 66, 2011)	Railway mode (TSI LOC&PAS, 2014), (TSI PMR, 2014)
IV - Grab Bars / Handrails	Diameter 20–45 mm ≥ 100 mm length ≥ 40 mm clearance between the bar and wall. ≥ 35 mm clearance – exception applicable for doors, seats or access routes.	Handholds on aisle-side seats unless within 200 mm of another. Handhold height: 800–1200 mm; contrast with background. Maximum of 2000 mm apart from each other in areas with fixed longitudinal seats. Outside diameter: 30-40 mm. ≥45 mm clearance Min. curve radius 50 mm Required in gangways: if <1000 mm wide & >2000 mm long → adjacent handrails; if ≥1000 mm wide → in gangway.

According to the previous table, the following recommendations must be considered if the inclusion of these elements is decided:

- Height and Placement: Handrails should be within 800–1200 mm from the floor for standing and seated passengers. Clearance from walls or adjacent objects should allow safe and comfortable grip.
- Contrast and Visibility: Use high-contrast colours relative to surrounding surfaces to aid visually impaired passengers.
- Gangways and Aisles: For narrow gangways (<1000 mm), parallel handrails on both sides are recommended. For wider gangways as it is the case of the UC1 configuration, single handrails along one side may be sufficient. The placement of

the handrails will be strongly related to the type of seating arrangement that has been chosen.

- Integration with Seats and Doors: Ensure handrails do not obstruct movement near doors, seats, or access routes, while remaining within easy reach.

5.3.6 Control units

Certain control devices are required to control the TU and communicate with other operators in the system (control centre, connected CU, other TUs, etc.). The assumption here is that the Entrance Module is always connected to the CU during operation. In the event of disconnection, it does not need to have any intelligent functions or communication. In addition, there are no people inside this module when it is not connected to the CU. For this reason, the entire control and communication unit for the Entrance Module is integrated in the Carrier.

This is not possible for TUs that are also intended for passenger transportation. The TUs must be able to self-supply for 15 minutes. They are not connected to the CU or any other supply unit. For this reason, control and communication devices are required in each TU. These are usually combined in a control cabinet. The components required for the selected UC1 and a 10 ft TU are discussed here.

A TU does not require a vehicle control unit; this can be completely integrated in the carrier. Nevertheless, a central control unit is required to coordinate all the TUs functions and bring them together in one interface. At the same time, it also derives necessary measures, checks compliance with the necessary requirements and transmits corresponding instructions to subsystems. Faults can thus be bundled and forwarded to a possible control centre. The systems are integrated into 19" racks in a control cabinet as standard. In addition to the central control system, emergency systems, e.g. for fire extinguishing systems, must be integrated for each TU. The communication and data transmission systems must also be placed in the control cabinet. These are also required by each TU due to the necessary self-supply. In addition to the radio intercom systems, the communication systems also include WIFI modems (for dimensions see Figure 19a). Ideally, these are decoupled from the control cabinet and placed in a position that enables optimum signal transmission. It is therefore recommended to place them in the area of the roof structure (Figure 19b).

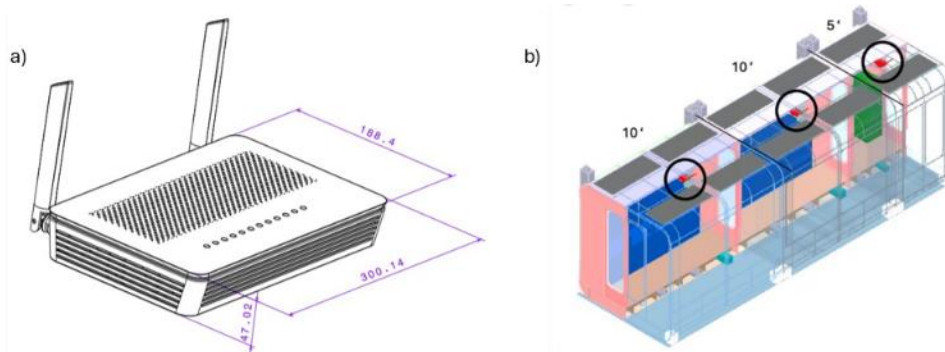


Figure 19: a) Dimensions and b) Placement of WIFI modems

The integration of various sensors (temperature, pressure, etc.) is also necessary for the well-being of the passengers. Furthermore, positioning systems are required for coordination in the overall system so that the TU can be located independently of a CU at any time. Diagnostic and monitoring devices or data loggers are needed, which check the functionality of the TU and its devices at regular intervals. They send a report to the control centre or initiate the necessary steps for troubleshooting in the event of irregularities. The electronics required to monitor, regulate and control these components are also housed in the control cabinet. Protection and switching devices (fuses, relays, etc.) are also housed there.

Cooling of all the components in the switch cabinet requires the integration of fans. It is assumed that 5 fans with a size of 120 x 120 x 25 mm (e.g. Noctua NF-A12x25 PWM) [source] are sufficient. To accommodate all the required components and their associated hoses, cables, wires and housings, a control cabinet with a volume of approx. 100 litres is required. According to the standardization by 19" racks, a width of 19" (482.6 mm) is recommended. Typically, the depth varies between 600 and 1200 mm, while the height is specified in standardized rack units (RU) (1.75"; 44.45 mm).

With these boundary conditions, the following enclosure sizes are possible (Table 15):

Table 15: Possible dimensions of the control cabinet

Option	Width	Height	Length
A	19" (482.6 mm)	4 RU (177.8 mm)	1165.4 mm
B		5 RU (222.2 mm)	932.3 mm
C		6 RU (266.7 mm)	776.9 mm
D		7 RU (311.2 mm)	665.9 mm

Option C or D are best suited for practical and compact integration into the TU, as the dimensions take up little space in the longitudinal direction. Another option is to divide the control cabinet into two parts.

This results in smaller components. Both options are compared below in Table 16.

Table 16: Control Unit options

Option	Advantages	Disadvantages
Electronic control units as compact design	- Compact design - Simple cabling (shorter and direct cable routes, fewer plug connections) - Lower unit costs (possibly fewer fans required) - Simpler Electromagnetic Compatibility (EMC) shielding	- Heavier mounting - Limited placement options - Limited accessibility (comparatively large housing) - No redundant components - Thermal hotspots possible, more complex cooling architecture required
Electronic control units as two (or more) components	- Better modularity and maintainability - More flexible installation and placement options - Redundancy for important components easily possible - Thermal decoupling of individual systems or components	- Modularity sometimes requires more components (connectors, fans, etc.) - More cable routes, more complex wiring - Increased documentation effort (maintenance documents, variety of variants, ...) - Synchronization and communication between units must be provided and ensured. Additional components may be necessary.

5.3.7 Passengers Information System

The Passenger Information System (PIS) is a critical component in enhancing the passenger experience, providing timely, accurate, and accessible information throughout the journey. In autonomous vehicles capable of operating in both rail and road modes, the PIS must be carefully designed to meet the specific requirements and standards of each mode, while ensuring a seamless, consistent, and safe experience for all passengers.

The PIS should consolidate information from multiple sources—including GPS, onboard sensors, and external data feeds—to deliver real-time updates on schedules, delays, and service changes. This integration guarantees that passengers receive reliable and consistent information, regardless of whether the vehicle is operating in rail or road mode.

User interfaces must be intuitive and universally accessible, accommodating passengers with a wide range of abilities. This includes clear visual displays, audible announcements, and tactile feedback mechanisms, ensuring that information is comprehensible and actionable for everyone, including persons with reduced mobility or sensory impairments.

The system should be capable of processing and integrating data from diverse sources, including traffic management systems, railway signalling systems, and other relevant infrastructure. This ensures that passengers are continuously provided with accurate and up-to-date information throughout their journey.

In emergency situations, the PIS must support immediate and clear communication with passengers, delivering instructions and updates to maintain safety. This functionality includes both audible and visual alerts, along with explicit guidance on evacuation procedures, emergency contacts, and other critical safety measures.

Table 17 shows the main requirements for PIS extracted from both rail and road regulations.

Table 17: Passengers Information System requirements for rail and road modes

Aspect	Road mode (UNECE Reg 66, 2011)	Railway mode (TSI LOC&PAS, 2014), (TSI PMR, 2014)
II – Alarm and Communication Systems	Alarm system that detects both high temperature and smoke. Visual indicator to notify when a door is not properly closed. All emergency doors must have a sound device to warn the driver when they are not properly closed.	Mandatory equipment: Audible communication from train crew/driver (remote) to passengers. Passengers must be able to contact train crew via: Passenger alarm or passenger communication devices. Every passenger area (except toilets and gangways) must have at least one clearly visible alarm device to warn the driver of danger. If system is not working alarm activation must still apply the brakes directly. The communication device interface to passengers shall be indicated by a harmonised sign: include visual and tactile symbols and shall emit a visual and audible indication that it has been operated.

Although these regulations were not originally developed for autonomous vehicles, they are fully applicable to this UC1 case. In the absence of a driver or onboard crew, all passenger communications—including alarms, emergency calls, and requests for assistance—will be handled entirely by the Passenger Information System (PIS). The system will ensure that all alerts are detected, processed, and acted upon in real time, maintaining passenger safety and compliance with the relevant standards.

The PIS comprises several components, such as the processor, computer, screens and acoustic signals. In this section, only the screens and the visual processing of the information to be conveyed are discussed. Acoustic signals have little influence on the interior or packaging, as they do not have to be integrated into the overall picture, unlike large screens. The control and processing unit can also be implemented in the existing control unit.

Two options were examined in Task 10.1 for the implementation of visual information for passengers: use of conventional screens, or screens as part of the user experience

Both options offer various advantages which are discussed below. The investigations in Pods4Rail showed that the integration of existing systems (including their further development, such as the integration of personalized requirements) can be used for the first phase of system implementation. These can be implemented quickly and without major

hurdles in TUs and offer good overall system integration. The second option, the integrated user experience in the PIS, is a necessary further development of the system for a period of 30 - 50 years.

Use of conventional devices for fast implementation:

Conventional PISs is a central element of modern public transport systems and are primarily used to provide passengers with relevant travel information. In this context, conventional PISs are systems that are based on permanently installed screens or LED displays and provide standardized content such as route, next stop, time or delay information. This information is displayed either statically or sequentially. Flexible and short-term integration of additional content is not planned. The functionality of such systems is divided into 3 defined steps:

1. Data acquisition and provision: the system receives real-time data from train control systems (e.g. GPS position, timetable, door status). This data is processed centrally or locally.
2. Data processing and control: An on-board computer translates the raw data into usable information. This includes stop logic (recognition of the next stop), calculation of arrival times and synchronization of visual and acoustic outputs.
3. Information output: The content is output via visual media and acoustic signals.

This mode of operation and fixed implementation of the PIS in the train control system and local processing means that user requirements must also be collected and output centrally. For this reason, there is no greater adaptability to the user. Possibilities for more personalization are only possible with additional external systems (e.g. smartphones). Here, for example, information about the destination or a live menu with ordering service can be implemented. However, real-time analysis of the surroundings and direct interaction with the passenger is not possible.

However, conventional systems like in Figure 20 offer a high level of robustness and availability and are standardized in many countries (e.g. in accordance with TSI PRM or DIN EN 15153). This ensures a uniform quality of information and makes it easier for passengers to find their way around. The dimensions of such a system are showed in Figure 20. But as the figure also shows, there are a lot of options, how the PIS could be integrated in the interior. Important is that the system must be visible for all passengers at the end.



Figure 20: Conventional PIS devices

Screens as part of the user experience:

Although conventional PISs fulfil their purpose, they impair the spatial and aesthetic quality of the interior spaces. In a relatively small TU, where the available space is limited and passenger perception is particularly sensitive, the information design should be deliberately restrained and at the same time highly functional. In the long term, a very simple design such as that found in buses today will not be sufficient to meet all the needs of customers and operators. For this reason, future technologies were considered that enable passengers and PIS users to interact with the PIS via their personal communication devices (smart glasses, smartphones, etc.). The possibilities of augmented reality and holographic mapping were examined and, above all, how this affects the interior concept and packaging of the 10 ft TU in UC1. The contents presented are possibilities but cannot be implemented directly. They are therefore partly contrary to the basic idea of Pods4Rail to build a supermodal system in the near future. Nevertheless, it is necessary to consider these technologies and their influence on the interior. Only in this way can the developed system be adapted to the changes in the long term and continue to be attractive for users.

The central question was what information passengers need in order to optimize their travel experience. In addition to the classic elements (route, next stops, some delay information), aspects such as transfer information, real-time alternatives in the event of disruptions and personalized information are increasingly coming to the fore. A key point is analysing the right information at the right time. It is essential to avoid cognitive load and information overload. A modern PIS should not only provide information but also enable interaction. This can be realized via mobile devices, wireless interfaces or context-based projections (Figure

5). The aim must be to create a system that is intuitively understandable, conveys safety and can be accepted and operated by all passengers. This applies regardless of previous technical knowledge or limitations.

A clear information architecture is required to ensure coherence. This determines how content is prioritized, grouped and distributed across different channels. The transfer process is particularly important here: travellers must be seamlessly informed about connection options, alternative routes and possible disruptions without this leading to overloaded displays. At the same time, however, this information should be provided in a personalized manner and matched to the planned itinerary. Adaptive systems that dynamically adjust content to the journey context are ideal here (see Figure 21). The future of passenger information systems lies in the combination of minimally invasive, well-integrated hardware and intelligent software that provides context-sensitive information. By dispensing with oversized screens in favour of more subtle, integrated solutions, an attractive, modern and functional interior design can be achieved.

In any case, this option requires careful design to ensure compliance with current rail/road standards; some regulations may need adaptation.



Figure 21: PIS as part of the user experience

In the following table, both options are compared throughout the analysis of their corresponding advantages and disadvantages.

Table 18: PIS options

Option	Advantages	Disadvantages
Conventional PIS - Use of conventional devices	Reliable and well-tested Easy for all passengers to understand No personal tech required Fully compliant with current rail and road standards	Limited customization Static content May be hard to see/hear in crowded or noisy areas

Option	Advantages	Disadvantages
PIS as part of the user experience - Use of personal devices (mobile/ cell phones) and augmented reality (window integration) or holographic images	Highly interactive and personalized Real-time updates and rich content Innovative passenger experience	Depends on passengers owning compatible devices Privacy and data concerns Higher implementation cost and complexity Requires careful design to ensure compliance; some regulations may need adaptation

Both PIS options present distinct benefits and challenges. The conventional system offers reliability, regulatory compliance, and proven accessibility, making it a safe choice for immediate implementation. The futuristic system, on the other hand, provides a highly interactive, personalized, and immersive passenger experience, though it requires careful design to meet regulatory and accessibility requirements, and a higher initial investment and maintenance. The choice between these approaches will depend on project priorities, including innovation, passenger engagement, cost, and compliance considerations, and may even allow for a hybrid solution combining the strengths of both systems.

For instance, as a hybrid solution, a highly viable approach is to start with a conventional PIS. Over time, as the system is used and operational experience is gained, it can be gradually upgraded toward a futuristic PIS, incorporating personal device integration, augmented reality, or holographic technologies. This phased strategy allows for a smooth transition, mitigates risks associated with emerging technologies, and enables continuous enhancement of the passenger experience without compromising safety or compliance.

5.3.8 Emergency equipment

This section outlines the requirements for emergency equipment in vehicles operating in both rail and road modes. The equipment includes fire extinguishers, first aid kits, pictograms, and safety signs, all intended to ensure passenger and staff safety in case of emergency situations.

While alarm and communication systems, as well as emergency exits and evacuation procedures, have already been covered in previous sections—including the Passenger Information System (PIS), which itself forms a critical part of a vehicle's emergency equipment—this section focuses on additional emergency devices required to ensure regulatory compliance, fire safety, and first aid readiness. Table 19 summarizes the key requirements for both road and rail modes.

Table 19: Emergency equipment requirements for rail and road modes

Aspect	Road mode (UNECE Reg 66, 2011)	Railway mode (TSI LOC&PAS, 2014), (TSI PMR, 2014)
I - Pictograms / Safety Signs	Pictograms with letters not less than 10 mm and numbers not less than 12 mm must indicate: maximum number of seats, standing passengers, wheelchair spaces and number of luggage mass. Necessary to ISO pictograms for emergency exits.	Pictograms must indicate in the driving cab: max speed, vehicle ID, emergency exits.
I - Fire Extinguishers	At least one space for extinguishers, one of them near driver; 15 dm ³ minimum space.	Adequate extinguishers in passenger/staff areas; water + additive extinguishers recommended. The equipment and the areas that intrinsically impose a fire risk shall be equipped with a system that will detect fire at an early stage. The unit equipped with measures to control the spread of heat and fire effluents through the train.
III - First Aid Kits	At least one space ≥ 7 dm ³ for first aid kits.	No specific requirement found in TSI (depends on operator/national rules).

In addition to fire extinguishers, first aid kits, and safety signage, emergency equipment in autonomous vehicles should include fire detection and suppression systems capable of identifying smoke, high temperature, or hazardous gases, and controlling the spread of heat and smoke within the vehicle. Emergency lighting and photo-luminescent signage should guide passengers safely during low-visibility conditions or power failures.

Evacuation equipment should be designed to support all passengers, including those with reduced mobility, and may include ramps, escape windows, or other tools for rapid exit (Exits and Emergency Exits described in previous sections). Passenger safety devices, such as seat belts and wheelchair restraints (not for this UC1 case but for considering in future applications with full PRM compliance), should also be provided where applicable.

Integration with the autonomous vehicle systems is crucial: the PIS and other automated systems should manage emergency responses, including automatic braking, door operation, and real-time passenger alerts, without the presence of a driver or onboard crew. Also, a safe, stable and intuitive communication possibility between passengers and a control centre should be provided.

Finally, proper maintenance and inspection procedures must be defined to ensure that all emergency equipment remains fully operational. Passengers should also have access to clear instructions—either via signage or through the PIS—on the correct use of emergency devices and evacuation procedures.

This comprehensive approach ensures that vehicles operating in both rail and road modes maintain the highest levels of safety and compliance, while also adapting to the unique requirements of autonomous operation.

5.4 Outputs for other WPs

The main outputs for other WP are the following:

Based on the concept development carried out in WP10, several technical options have now been narrowed down and can be communicated to other WPs as concrete design inputs. While some elements remain adaptable to specific use cases, the spatial constraints and preferred integration strategies for the main equipment have been defined as follows:

5.4.1 HVAC System

- The preferred solution is to integrate the HVAC modules flush with the ceiling level, as this provides a good balance between maintainability, passenger comfort and internal clear height.
- A second option—placing the HVAC above the ceiling—remains feasible where a higher internal ceiling is required, but this demands additional roof volume.
- The HVAC system is not structurally embedded within the roof, but mounted within a reserved technical envelope in the upper zone of the TU. This ensures accessibility and avoids structural dependencies.
- Approximate space allocation for HVAC has been validated and forwarded to the structural and architectural WPs.

5.4.2 Energy Storage (TU Batteries)

- TU-batteries will be integrated in the lower structure of each TU.
- This location minimises impact on passenger space and optimises weight distribution.
- Clearance, ventilation, and maintenance envelopes have been defined for use by electrical and structural WPs.

5.4.3 Passenger Seating Configuration

- A modular seating system is confirmed as the baseline, allowing adaptation to the different use cases (commuter, airport, leisure, etc.).
- Interfaces and fixing points have been standardised to enable rapid reconfiguration.

5.4.4 Luggage Accommodation

- Two validated solutions are proposed:

- Under-seat luggage space (preferred for short-distance and high-density scenarios).
 - Dedicated luggage racks (recommended for airport or long-distance profiles).
- Both options have defined dimensional constraints and can be selected per use case.

5.4.5 Handrails and Passenger Support Elements

- Handrails are confirmed as common equipment and will be installed wherever operational or safety needs are identified.
- Their integration does not impose major spatial constraints on other systems.

5.4.6 Control Units

- Control and auxiliary electronic units are designed to be versatile in placement.
- The preferred location is the roof technical area; however, alternative mounting points are available when roof space is occupied by HVAC or other systems.

5.4.7 Passenger Information System (PIS)

- The PIS can follow either:
 - Standard public transport layouts, or
 - More innovative solutions depending on the selected use case.
- Envelope and connectivity requirements have been defined to ensure compatibility across scenarios.

5.4.8 Emergency Equipment

- Each passenger TU will include at minimum:
 - A fire extinguisher
 - A first aid kit
 - Communication and emergency brake/call devices
- Installation positions have been pre-defined to ensure accessibility and standardisation.

5.4.9 General Conclusion

Overall, the interior concept has evolved from a set of optional ideas to a clear framework with preferred solutions and validated spatial envelopes. Flexibility is maintained where use-case differentiation is essential, but the core integration principles—especially for HVAC, batteries, seating, and control units—are now sufficiently defined to guide the downstream design work in other WPs.

6 Concept proposals for the HVAC for passenger pod

This chapter integrates functional and normative requirements regarding the HVAC design for passenger transport units. Technologies of heating and cooling in rail applications are being introduced. The different applicable methods are being compared.

6.1 Introduction

The objective of this task is to define the conceptual requirements for the HVAC system of the passenger TU, based on the energy demand simulations carried out in WP 7. These requirements serve as a foundation for selecting and designing an efficient climate control solution tailored to the TU operational needs.

To achieve this, various HVAC technologies are evaluated, including systems such as heat pumps and positive-temperature-coefficient (PTC) heaters. The comparison focuses on performance, energy efficiency, and compatibility with the TU architecture and operational constraints. Through this analysis, the objective is to identify the most suitable HVAC-system, taking into account the integration of key components and their impact on overall system performance.

6.2 Overview of relevant results from other WPs

In the following chapter, various inputs from previous WPs regarding the HVAC-system are compiled. Relevant results needed for this task are results from WP 4 (Pods4Rail Deliverable D4.4, 2024) and 7 (Pods4Rail Deliverable D7.1, 2024). Therefore, the first part of this chapter lists some functional requirements for the air conditioning unit. The normative and safety-related requirements are then listed in the second part.

6.2.1 Functional requirements for the HVAC-system

The functional requirements for the HVAC-system of the Transport Unit (TU) can be found in D4.4 as well as D7.1. While D4.4 list some general requirements, D7.1 provides the thermal energy demand for heating and cooling for each of the TU-sizes. Furthermore, some requirements regarding the installation space can be found. All functional requirements are compiled and listed in Table 20.

Table 20: Functional requirements for the HVAC-unit

Requirement ID	Source	Requirement	Note
OPPL1.4	Pods4Rail D4.4 (Pods4Rail Deliverable D4.4.) 2024)	The rail-bound Pod system shall be operated on passenger and freight routes in Europe (including branch lines) with a lifespan of 30 years	-
TU_D4		Air-conditioning / heaters (HVAC) shall be provided for passengers	-
TU_C10, TU_L		Air treatment according to EN 14750-1: Summer Climate Zone I; Winter Climate Zone II; Category A	used in D7.1 for thermal energy demand simulation
TU_L1		Intake/evacuation of air: TU shall provide air flow consisting of recirculated and fresh air	-
TU_L2		TU HVAC shall provide air treatment	-
TU_L3		Central roof mounted HVAC-unit with airducts in roof	-
TU_L4		GWP < 20, air-based cycle (Global Warming Potential)	Refrigerants other than air will also be considered
D7.1_1	Pods4Rail D7.1 (Pods4Rail Deliverable D7.1, 2024)	Thermal energy demand (Max. heating/cooling): 5 ft: 1.55/0.95 kW 10 ft: 4.34/2.0 kW 20 ft: 9.41/4.12 kW	-
D7.1_2		Available installation space (L x W x H): 5/10 ft: 932 x 788 x 209 mm 20 ft: not specified	Specified dimensions mentioned in design plots; not finally specified (estimates)
D7.1_3		Weight of 10 ft HVAC-unit approx. 200 kg	5 and 20 ft can be scaled with thermal energy demand

With regard to requirement TU_L4, other HVAC-units than air cycle machines (ACM) are also considered as long as they have a GWP < 20. This is because without this exception there would be only two options for the HVAC-system, which would be an ACM with heating registers or heat pump functionality. Furthermore, the requirements D7.1_2 and D7.1_3 are not fixed. They serve primarily as a guide.

To further support the selection of a suitable HVAC-system, additional requirements are listed in Table 21.

Table 21: Additional requirements for the HVAC-system

Requirement ID	Source	Requirement	Note
AD_1	Expert Knowledge	HVAC-system should be suitable for rail sector (compliance with regulatory framework, suitable for usage in battery electric pods)	-
AD_2		Specific power of HVAC-unit should be comparable or higher than state-of-the-art HVAC-systems used in rail applications	-
AD_3		System COP* should be as high as possible; Reference COP: – <u>cooling</u>: vapor-compression refrigeration system (R134a) – <u>heating</u>: resistance heating (COP = 1)	*COP – Coefficient of Performance
AD_4		Operational and maintenance cost should be comparable or lower than state-of-the-art HVAC-systems	-
AD_5		Compliance with regulatory framework (e.g. Regulation (EU) 2024/573 („F-gas regulation”))	-
AD_6		Technology Readiness Level (TRL) as high as possible (TRL > 6)	Implementation of first demonstrator planned by 2030 (Pods4Rail Deliverable D2.1, 2023)

6.2.2 Safety related requirements for the HVAC

The heating, ventilation and air conditioning (HVAC) system is linked to passenger comfort when weather conditions fall outside acceptable limits. Moreover, exceeding these limits significantly lead to safety concerns.

As a consequence, temperature and air information may be transmitted through the information system when needed, assuming that a dedicate battery will provide a fallback transient solution in case of current shortcut. The safe state monitoring of the TU is done through the control unit (see section 5.3.6), in order to inform passenger that a given situation is monitored and under control. Actually, passenger information is a right, but it is important to communicate with them when conditions are becoming less comfortable, in order to avoid dangerous behaviours.

The PIS is to be used (see section 5.3.7). In case of safety concerns, the emergency procedure and appliance are triggered (see section 5.3.8): weather conditions, thermal insulation and the operation of HVAC must be taken into account in the planning of emergency procedures in order to ensure passenger safety.

6.3 Air conditioning of rail vehicles

The air conditioning system of a rail vehicle must guarantee comfortable conditions inside the passenger compartment (and drivers cab). For that, different factors like cabin temperature, humidity, air velocity, CO₂-concentration and others must be held within certain ranges that are defined in the applicable standards (EN 14750-1 for regional trains). This can be achieved by mitigating the various loads using the following measures: fresh air supply, heating and cooling (Ebinger & Morgenstern, 2022).

Depending on the measures that the air treatment systems combine, they are classified into three different groups (see Figure 22:). Ventilation systems represent the simplest version. They are only capable of supplying the passenger compartment with outside air. This is either uncontrolled, e.g. through windows, or controllable with the aid of fans. However, controlling the interior conditions is only possible to a limited extent or not at all. If the air treatment system is also able to heat up the passenger compartment, this is referred to as a heating system. Both static heaters (e.g. radiators in the passenger compartment) and the supply of heated air can be used here. These systems allow better control of the interior conditions than ventilation systems. At high outside air temperatures or significant loads, the passenger compartment must be cooled. If this function is added to a heating system, this is referred to as an air conditioning system (or HVAC-system). These systems include all measures to regulate the air inside the passenger compartment and represents the state of the art (Ebinger & Morgenstern, 2022).

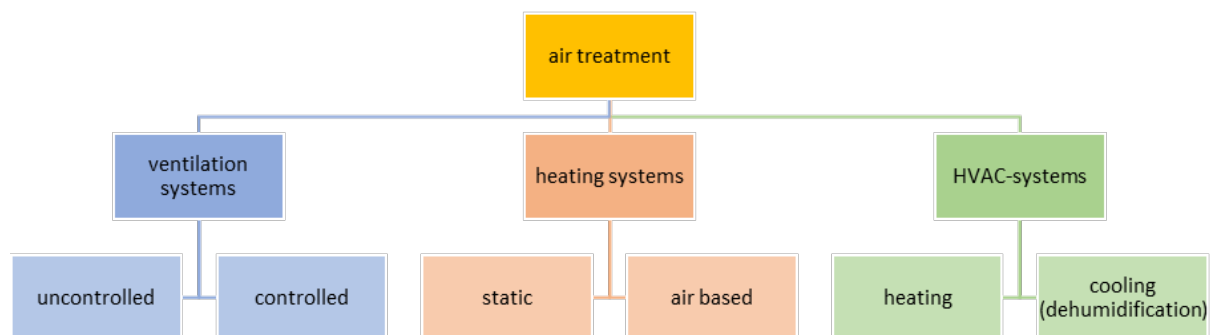


Figure 22: Classification of air treatment systems ((Ebinger & Morgenstern, 2022), translated)

As there are various options for realizing the heating and cooling functions, some relevant methods are described in more detail below.

6.3.1 State of the art for heating and cooling in rail applications

In rail applications the following technologies are in use for cooling (Ebinger & Morgenstern, 2022), (Aigner R. et al., 2019):

- vapor-compression refrigeration systems (VCRS),
- air cycle machines (ACM) and
- ventilation (free ventilation through openings or forced via fans).

The latter of which is mostly used in addition to an active cooling measure to reduce energy demand under certain climatic conditions.

For heating, the following are used (Ebinger & Morgenstern, 2022), (FINE-2, 2020), (Faiveley Transport GmbH, 2025):

- hot water heating,
- resistance heating and
- heat pumps.

The first option mentioned is often found in vehicles with internal combustion engines, where the engine's cooling water can be used for interior heating. However, water can also be heated up using water heaters fuelled by electricity or some type of fuel. (Ebinger & Morgenstern, 2022)

6.3.2 Methods for Cooling

This chapter explains the relevant methods for cooling which will later be used for the comparison. However, some are already excluded beforehand due to given reasons.

Vapor-Compression Refrigeration System (ideal cycle):

Vapor-compression refrigeration systems (VCRS) are commonly used for cooling (and heating) in mobile and stationary applications. In VCRS heat is extracted by vaporizing and condensing a circulating substance, called the refrigerant. (Ebinger & Morgenstern, 2022) The general structure of such a system is shown in Figure 23. Furthermore, a schematic of the vapor-compression cycle is shown in the log p-h diagram (Figure 24).

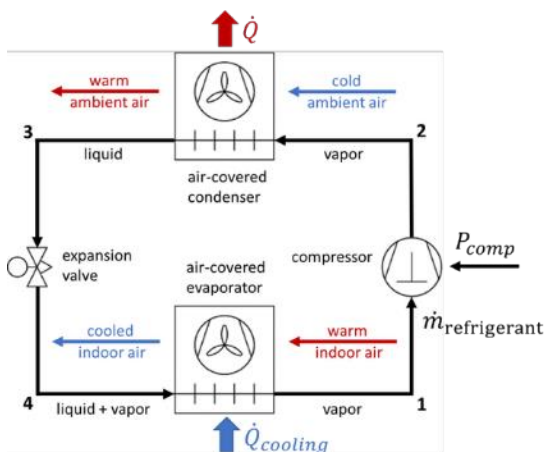


Figure 23: General structure of VCRS
((Großmann, 2020), modified)

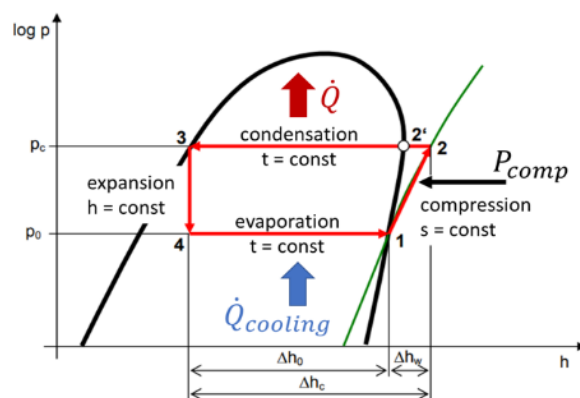


Figure 24: Schematic of vapor-compression cycle in the log p-h diagram
((Kunz, 2025), modified)

The vapor compression cycle consists of the following steps (Ebinger & Morgenstern, 2022), (FINE-2, 2020), (Kunz, 2025):

1 -> 2 - Isentropic compression with superheating⁵

This is done by a compressor, which rises the pressure and temperature of the gaseous refrigerant. The temperature in 2 must be higher than the condensing temperature of the used refrigerant.

2 -> 2' - Cooling down of the superheated refrigerant

During this process the refrigerant cools down but stays gaseous. The heat flow released (sensible heat) is dissipated to the environment.

2' -> 3 - Isobaric condensation

A heat exchanger (condenser) is used to condense the high-pressure refrigerant. The refrigerant changes from gaseous to liquid state, while pressure and temperature stay constant. The heat flow released during this process (latent heat) is dissipated to the environment by an air or water flow provided by a fan or pump (air- or water-cooled condenser).

3 -> 4 - Expansion at constant enthalpy

In this stage an expansion valve is used to expand the liquid refrigerant to the evaporation pressure. During this process part of the liquid refrigerant evaporates and the temperature of the two-phase refrigerant drops below the temperature of the to be cooled fluid (air in passenger compartment).

4 -> 1 - Isobaric evaporation

The two-phase refrigerant gets sucked into a second heat exchanger (evaporator). In the evaporator the refrigerant evaporates using heat which is taken from the fluid which is to be cooled. This process is supported by fans which route the to be cooled fluid through the evaporator.

It has to be mentioned that Figure 24 only shows a simplified version of the refrigeration cycle. In practice the refrigerant has to be overheated in 1 to prevent liquid refrigerant from flowing into the compressor, which would destroy it. This can be done by either controlling the expansion valve and subsequently overheating the refrigerant in the evaporator or by adding another heat exchanger. The additional heat exchanger can supercool the refrigerant after condensation (3) and use the dissipated heat to overheat the gaseous refrigerant after evaporation (1). Doing this will also improve the COP of the refrigerant cycle as the cooling capacity increases (Kunz, 2025).

Refrigerants:

Various refrigerants can be used in VCRS. To qualify as a suitable refrigerant a number of criteria have to be met. Refrigerants need to have an evaporation pressure larger than the atmospheric pressure and an as low as possible condensing pressure (reduces pressure resistance of system and pressure build-up in compressor). Furthermore, the evaporation temperature must be around 0 - 5°C to avoid frost formation in the system and the

⁵ Refrigerant is heated above its boiling point

condensation temperature must be high enough to release enough heat to the environment (Ebinger & Morgenstern, 2022).

Further general and operational requirements, that need to be met, are (Ebinger & Morgenstern, 2022):

- non-flammable, -explosive, -toxic, -corrosive and -hygroscopic,
- good solubility for the lubricant,
- good compatibility with all materials and sealants used,
- chemical stability and
- good environmental compatibility.

A large number of suitable refrigerants have been found. Currently, the refrigerant R134a is commonly used in rail vehicles, but it has a high global warming potential⁶. In order to prevent harmful emissions from the refrigerant, e.g. in the event of refrigerant leakage, air conditioning customers are increasingly demanding natural refrigerants instead of synthetic ones. The EU F-gas Regulation No. 573/2024, for example, is also forcing the phasing out of fluorinated refrigerants such as R134a. Similar regulations exist and are enforced in the US, Canada and other countries/regions (Ebinger & Morgenstern, 2022), (BITZER Kühlmaschinenbau, 2020), (Faiveley Transport, 2023).

Table 22 shows a list of some relevant refrigerants that could be used in the HVAC-system of the TU (GWP < 20 – TU_L4 see Table 20). A more detailed list can be found in (BITZER Kühlmaschinenbau, 2020).

Table 22: Selection of some suitable refrigerants (Ebinger & Morgenstern, 2022), (BITZER Kühlmaschinenbau, 2020), (Faiveley Transport, 2023)

Refrigerant	GWP	Safety-Group (ISO 817)	Note
R134a	1430	A1 low-toxicity; non-flammable	– Synthetic refrigerant (part of hydrofluorocarbon (HFC) group) – Commonly used in rail vehicles – Phase out due to high GWP
R1234yf	4	A2L low-toxicity; low flammability	– Synthetic refrigerant (part of hydrofluoroolefin (HFO) group) – Possible substitute for R134a due to similarity
R290 (propane)	3	A3 low-toxicity; highly flammable	– Natural refrigerant – Possible substitute for R134a due to similarity
R744 (CO ₂)	1	A1 low-toxicity; non-flammable	– Natural refrigerant – High pressures necessary (transcritical process)

⁶ Ability of greenhouse gas to trap heat in the atmosphere compared to CO₂

R729 (air)	0	A1 low-toxicity; non-flammable	– Natural refrigerant – Not usable in VCRS – Used in ACM
R718 (water)	0	A1 low-toxicity; non-flammable	– Natural refrigerant – Not available in rail sector – No further evaluation

A major advantage of natural over synthetic refrigerants is that they are certain to be available and permitted in the future. All further considerations are therefore limited to natural refrigerants.

Transcritical Process:

Due to the different thermodynamic properties of R744 (CO₂) compared to other refrigerants, such as R134a, changes to the refrigerant cycle are required. In particular, higher process pressures are needed when using R744 (approx. 5 times higher than R134a (PINTA3, 2022)). Furthermore, CO₂ has a low critical temperature (approx. 31°C), which makes it very difficult to release heat during condensation at high ambient temperatures. Consequently, CO₂-systems can be operated transcritical (above the critical temperature). (Ebinger & Morgenstern, 2022) The difference between the transcritical and subcritical process for R744 can be seen in Figure 25.

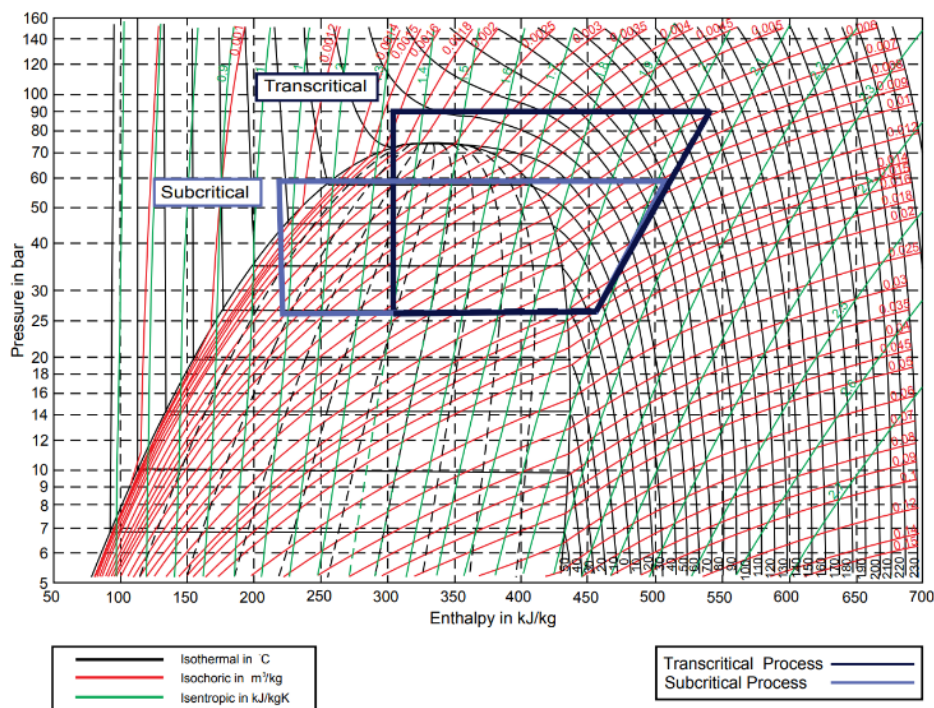


Figure 25: Pressure enthalpy graph for R744 systems in transcritical and subcritical mode (Emerson Climate Technologies, 2025)

During transcritical operation the condenser functions as a gas cooler (see Figure 23), as above the critical point no distinction can be made between gaseous and liquid phase. The

remaining structure of the VCRS does not differ from other refrigerants (Ebinger & Morgenstern, 2022), (Emerson Climate Technologies, 2025).

At lower ambient temperatures (below 20°C to 25°C) it can also make sense to use the subcritical process for R744. By switching between subcritical and transcritical operation, the efficiency of the overall system can be improved (PINTA3, 2022), (Emerson Climate Technologies, 2025).

According to (Emerson Climate Technologies, 2025) and (Rail4Earth, 2023), the following advantages and disadvantages exist:

- + Natural refrigerant (no restrictions) with low GWP, toxicity and flammability,
- + Inexpensive and widely available refrigerant,
- + Higher efficiency in heat pump mode compared to other refrigerants,
- Very high working pressure (leak prone),
- High weight and cost of system (e.g. due to complexity and high pressure),
- Inefficiency of transcritical operation (not suited for areas with high ambient temperatures due to permanent transcritical operation).

Air Cycle Machines:

Air cycle machines (ACM) are designed to use R729 (Air) as refrigerant and differ from VCRS in their system functionality and therefore structure. In an ACM a cooling turbine is used to cool down the so-called process air, which can then be used to cool down the cabin supply air via a heat exchanger. A schematic of an ACM with a closed loop design can be seen in Figure 26. (Ebinger & Morgenstern, 2022)

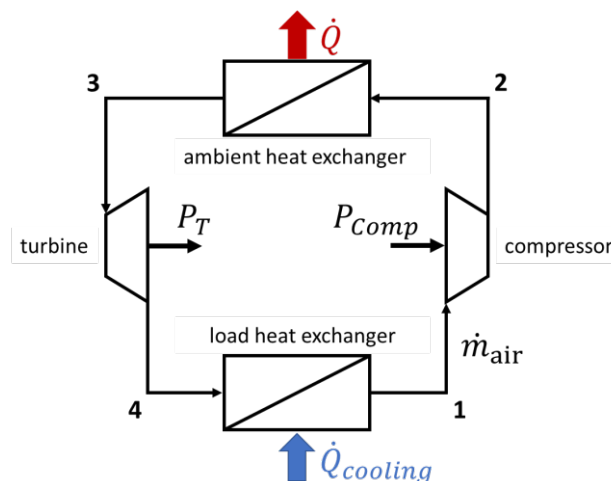


Figure 26: General structure of ACM ((Ebinger & Morgenstern, 2022), modified)

The ACM functions as follows (ideal closed cycle) (Ebinger & Morgenstern, 2022):

1 -> 2 - Isentropic change of state

The process air is drawn in by a compressor and compressed to a higher pressure and temperature. A mechanical power P_{Comp} must be applied during this process.

2 -> 3 - Isobaric change of state

The heated/hot process air is cooled down in the ambient heat exchanger, whereby the heat flow to be dissipated is discharged into the environment.

3 -> 4 - Isentropic change of state

The process air is then expanded in a turbine, whereby both the pressure and temperature decrease. The expansion turbine generates a power output P_T .

4 -> 1 – Isobaric change of state

The process air is now at its lowest temperature. Using a second heat exchanger, the so-called load heat exchanger, the process air gets heated up. The heat absorbed during this process is extracted from the cabin air, which is ultimately cooled down.

The efficiency of the ACM can be increased, for example, by mechanical or thermal regeneration. With mechanical regeneration, the power generated by the turbine P_T is used to provide part of the power needed for the compressor P_{Comp} . Doing this, only the differential power P_{diff} needs to be supplied to the process from the outside. This can be done by using a motorized turbo compressor (see Figure 27). Thermal regeneration is done by partially cooling the hot process air leaving the compressor by introducing a third heat exchanger. In this heat exchanger the hot process air is cooled by the cold process air so that only part of the waste heat is dissipated into the environment (see Figure 28).

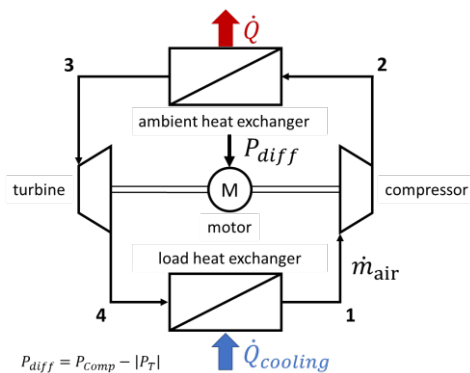


Figure 27: ACM with mechanical regeneration ((Ebinger & Morgenstern, 2022), modified)

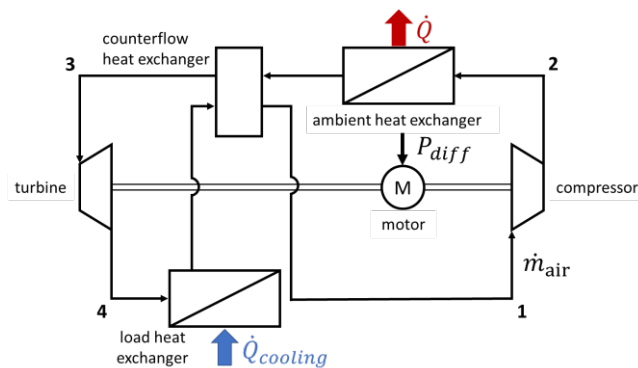


Figure 28: ACM with thermal and mechanical regeneration ((Ebinger & Morgenstern, 2022), modified)

Alternatively, the ACM can also be realized in an open process, which is shown in Figure 29 and Figure 30. This has an advantage over the closed cycle due to its simpler and lighter system structure. There are two variants of an open cycle ACMs. It can either be open to the cabin air (see Figure 29) or the environment (see Figure 30). In both cases, one of the two heat exchangers is omitted. However, only the latter of which is an improvement concerning energy consumption over the closed loop ACM. Therefore, this design is favoured (Ebinger & Morgenstern, 2022).

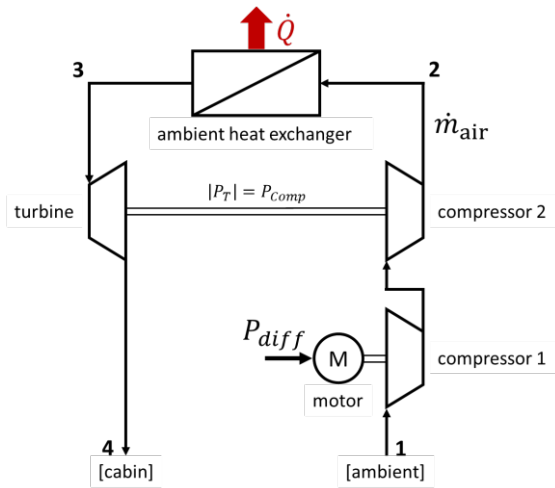


Figure 29: open cycle ACM with opening to cabin air ((Ebinger & Morgenstern, 2022), modified)

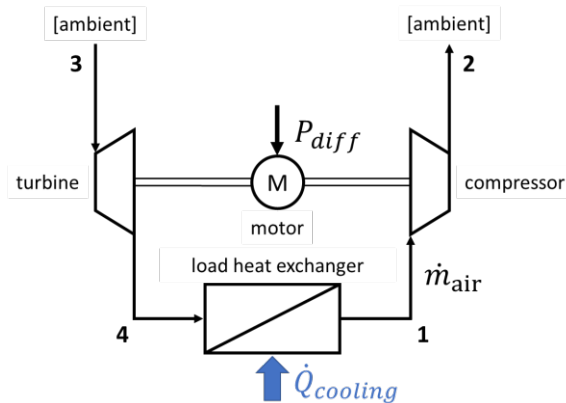


Figure 30: open cycle ACM with opening to ambient air ((Ebinger & Morgenstern, 2022), modified)

ACMs are for example used in the ICE 3. The first generation was designed with a closed cycle. However, later versions used an open cycle design. (Ebinger & Morgenstern, 2022)

Further Methods:

There exist further methods to supply cooling, however, most of the following methods are not yet developed enough. Therefore, it is not assumed that these systems can be used for air conditioning in rail vehicles for the foreseeable future. The following methods exist.

Absorption refrigeration:

The absorption refrigerator primarily uses a heat source to drive the cooling process. These work in a similar way to VCRSs, as they generate their cooling capacity by vaporizing a refrigerant. The cycle of the absorption refrigerator is almost identical to the cycle of a VCRS, but a thermal compressor is used instead of a mechanical one, which reduces the amount of mechanical work required. The thermal compressor functions as follows (Ebinger & Morgenstern, 2022):

1. Absorption of vaporized refrigerant by a solvent; heat is released
2. Increase of pressure using a pump (low mechanical effort)
3. Desorption of refrigerant by the used solvent; heat supply required
4. Pressure reduction of solvent using a valve

The process is particularly interesting if waste heat is available from upstream thermal processes, for example from an existing combustion engine, as the desorption heat is the main driving force of the thermal compressor. Furthermore, absorption refrigerators require extensive amount of space and are heavy. Therefore, they are not suitable for the pod concept, especially due to the lack of waste heat that can be utilized (Ebinger & Morgenstern, 2022), (Faiveley Transport, 2023).

Thermoelectric Refrigeration:

Thermoelectric refrigeration utilizes the Peltier effect, which is a direct conversion of electric voltage into temperature differences and vice versa (Seebeck effect). Thermoelectric refrigeration systems use so-called “Peltier-elements”, which generate heat on one side and absorb heat on the other when a current passes through a circuit of a thermocouple (see Figure 31). This can be used for cooling and heating purposes. The thermocouple is a pair of dissimilar semi-conductors (Ebinger & Morgenstern, 2022), (PIVOT2, 2020).

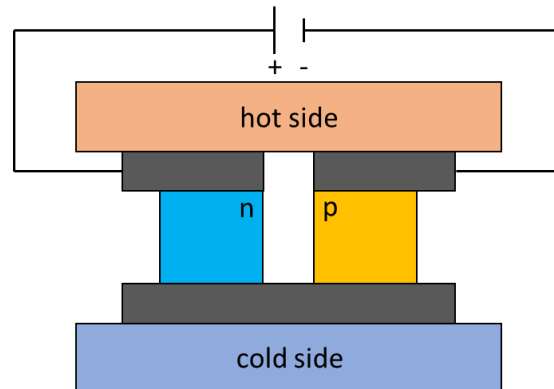


Figure 31: Schematic structure of a Peltier-element ((Ebinger & Morgenstern, 2022), modified)

The process offers the following advantages and disadvantages (Ebinger & Morgenstern, 2022), (PIVOT2, 2020):

- + Simple design without moving parts (silent),
- + No refrigerant necessary,
- + Good controllability,
- + Switching between heating and cooling mode by changing direction of current,
- + Good efficiency in heating mode compared to electrical heaters (35 - 30 % more efficient),
- Poor efficiency in cooling mode (worse than VCRS),
- Overall system weight similar to VCRS,
- Strong air movement necessary for sufficient heat transfer in railway vehicles (noisy).

The use of such a system in railway vehicles was already tested in Sweden in the 1970s, but the technology did not become established due to the disadvantages mentioned above. Today, they are mainly used in small applications such as freezers. (Ebinger & Morgenstern, 2022)

Magnetocaloric Refrigeration:

Magnetocaloric refrigeration is based on the Magnetocaloric effect. This effect leads to an increase in temperature in suitable materials (magnetizable) when they are exposed to a magnetic field and a decrease in temperature if the magnetic field is turned off again. Furthermore, if the material, which heated up due to the built up of a magnetic field, is

cooled before the magnetic field is removed, the material cools down to a temperature below the initial temperature after the magnetic field is switched off. This can therefore be used for cooling (and heating due to reversibility). The magnetocaloric cycle is shown in Figure 32 (Ebinger & Morgenstern, 2022), (PIVOT2, 2020), (Bartholomé, K., 2024a).

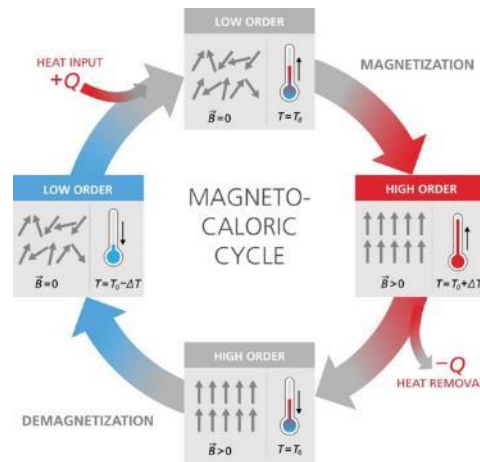


Figure 32: Magnetocaloric cycle (Bartholomé, K., Magnetocaloric systems: Efficient cooling and heating without harmful refrigerants, 2024a)

The energy efficiency and the temperatures to which cooling can take place depend heavily on the material used. At present, this method is mainly used for cooling to very low temperatures (approx. 1 K). Although, Materials have been found with which higher temperature ranges are also possible, this is still at the research stage (Ebinger & Morgenstern, 2022). An application in rail vehicles is not expected in the near future.

Electrocaloric Systems:

Electrocaloric systems are based on the electrocaloric effect. This effect leads to an increase in temperature in electrocaloric materials when they are exposed to an electric field and a decrease in temperature if the electric field is removed. This can be used to establish an electrocaloric cycle that can be used as a heat pump (see Figure 33) (Bartholomé, K., 2024b).

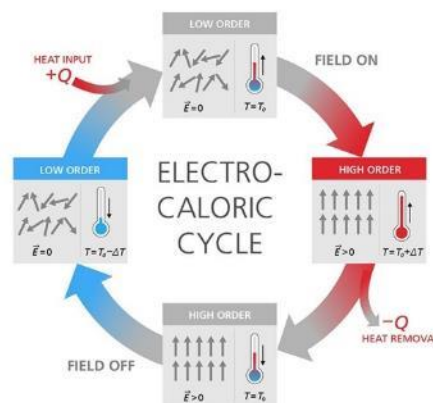


Figure 33: Electrocaloric cycle (Bartholomé, K., 2024b)

At present, this method is subject of research and was demonstrated in experimental environments, which corresponds to a TRL of about 4. Therefore, this system is not expected to be useable in railway vehicles in the near future.

Elastocaloric Systems:

Elastocaloric systems are based on the memory effect of certain metals. If these metals are subjected to a mechanical load, a crystalline phase transformation occurs, which causes the metal to heat up. If this heat is then dissipated to the environment and the mechanical load is removed afterwards, the metal cools to a temperature below the initial temperature. This can be used to establish an elastocaloric cycle that can be used as heat pump (see Figure 34) (Bartholomé, K., 2022).

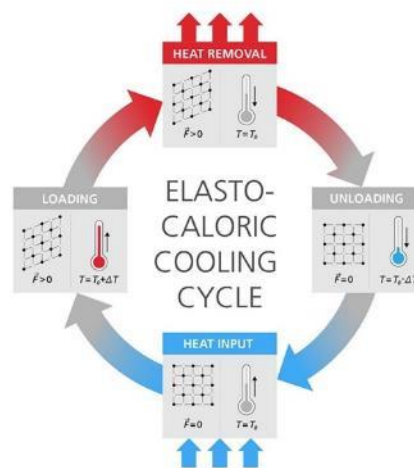


Figure 34: Elastocaloric cycle (Fraunhofer Institute for Physical Measurement Tech, 2025)

At present, this method is subject of extensive research and was demonstrated in experimental environments, which corresponds to a TRL of about 4. Therefore, this system is not expected to be useable in railway vehicles in the near future.

Thermoacoustic Refrigeration:

Thermoacoustic cooling utilizes the Thermoacoustic effect. This effect describes the conversion of acoustic energy of a gaseous medium into thermal energy during acoustic waves. Thermoacoustic coolers are based on standing acoustic waves (longitudinal), which propagate in a resonator. The resonator has an oscillator on one side, which excites the working medium (e.g. helium) into a monochromatic oscillation. The second medium required is the so-called “stack”, which must have a high heat capacity with low thermal conductivity and consists of a large number of stacked plates. The last component required are the heat exchangers, which are arranged to the left and right of the stack. (Altenbokum, 2007) The basic structure of a thermoacoustic refrigerator is shown in Figure 35.

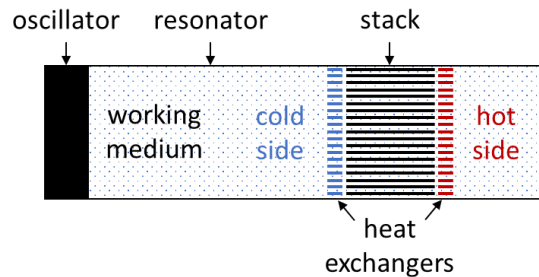


Figure 35: Principle of a thermoacoustic refrigerator ((Altenbokum, 2007), modified)

The thermodynamic cycle proceeds as follows (Altenbokum, 2007):

1. The gaseous medium is excited to oscillate and moves along the stack. At the same time, isentropic compression of the gaseous medium occurs (without heat transfer during movement). Pressure and temperature reach their maximum as soon as the gas stops moving.
2. The stationary gas exchanges heat with the stack. At this point, the temperature of the gas is higher than that of the stack.
3. The gas moves back to its starting position, whereby it relaxes (isentropic). At this point, the gas reaches its minimum temperature and pressure.
4. The stationary gas exchanges heat with the stack. The temperature of the gas is lower than that of the stack. The heat exchange continues until the stack and gas reach the same temperature and the process repeats itself.

In this way, heat can be transported from one side of the stack to the other. If heat is dissipated on the warm side, the cold side can be cooled down further and further, allowing cooling capacity to be utilized (PIVOT2, 2020).

The main advantages of such a system are that there are no moving parts, which extends the lifetime of the system, they can be used as heat pumps, need only medium/low-grade heat sources, use environmentally friendly working gases, have a high efficiency and are quiet during operation (Hu Y. et al., 2024).

At present, this process is used in cryocoolers. Using the Thermoacoustic effect for heating and cooling in residential buildings is topic of research and there are also some systems available, for example from BlueHeart Energy. However, using such a system in mobile applications, such as railway vehicles, are not yet available. Therefore, it is not assumed that this kind of system can be used for the Pods.

Stirling refrigeration:

Stirling refrigerators are based on the Stirling cycle, which was invented in 1816 by Robert Stirling. This cycle consists of two isothermal and two isochoric state changes of the working fluid (helium or hydrogen) which are repeated periodically. In a Stirling refrigerator, the Stirling cycle is reversed. Therefore, mechanical energy is converted into thermal energy (a usable cooling capacity) (PIVOT2, 2020), (Getie M. Z., et al., 2020).

The reverse Stirling cycle works as follows (Getie M. Z., et al., 2020):

- 1-2: isothermal compression – heat is rejected to external sink
- 2-3: isochoric heat transfer – internal heat transfer from working fluid to regenerator
- 3-4: isothermal expansion – heat is added from cold space
- 4-1: isochoric heat transfer – internal heat transfer from regenerator to working fluid

A basic Stirling cooler consists of two pistons, a compression and expansion space, a cold and hot heat exchanger as well as a regenerator and working fluid (Getie M. Z., et al., 2020). The Stirling process is an idealized process, as isothermal changes of state cannot be realized in reality. Furthermore, Stirling refrigeration systems are currently mostly used as cryocoolers to reach very low temperatures. Use of this technology in residential/mobile cooling applications is less developed and therefore does not seem to be viable to be used in the Pods at this current time (Getie M. Z., et al., 2020).

6.3.3 Methods for Heating

This chapter explains the relevant methods for heating which will later be used for the comparison. Generally, there is two ways to provide heating for the cabin – it can either be supplied statically or air-based. Static heating utilizes radiators or heating surfaces, which heat the cabin passively through convection. If radiators are used, those are placed in the floor region (under seats, side-wall) and distributed evenly throughout the vehicle to achieve uniform heating of the cabin. Air-based heating systems blow heated air directly into the cabin from the floor area. The ventilation ducts required for this must be integrated into the walls of the car body (Ebinger & Morgenstern, 2022), (Janicki J., Reinhard H., and Rüffer M., 2020).

Resistance heating:

Resistance heating is the most common used heating method in railway vehicles and is realized with so-called heating elements. Those elements convert electricity into thermal energy with 100 % of efficiency through a process called Joule heating ($COP = 1$). Through this process heat is generated when an electric current flows through a material. Heating elements can be included in the HVAC-system (see Figure 36) or located in the cabin as additional heating source (see Figure 37). HVAC-units consist of one or more heating elements which are connected in series. Depending on the required heat output, the heating elements are turned on or off for different lengths of time (FINE-2, 2020), (Janicki J., Reinhard H., and Rüffer M., 2020).

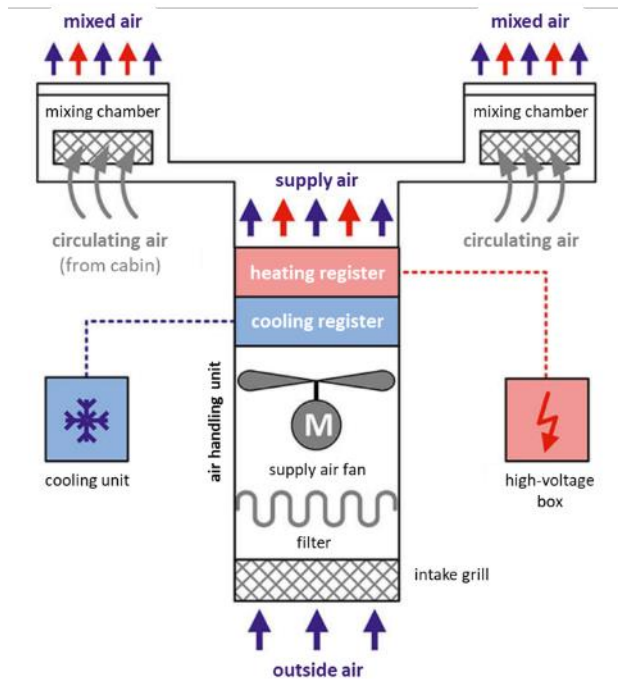


Figure 36: HVAC design with heating elements integrated in the air handling unit ((Janicki J., Reinhard H., and Rüffer M., 2020), modified)

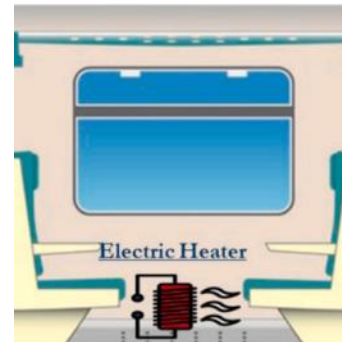


Figure 37: Heating elements located in the floor area of the cabin (Barone, et al., 2025)

The simplest heating element is a metal wire. Other materials that can be used are so-called positive-temperature-coefficient (PTC) heating elements. The resistance of those elements increases significantly with rise in temperature, so they maintain a constant temperature when supplied with a fixed voltage. Therefore, they don't need temperature sensors to be regulated.

Hot water heating:

In hot water heating systems, water is heated by water heaters. The hot water is then used to heat the passenger compartment statically using water radiators or air-based using water-to-air heat exchangers. For rail vehicles which consist of multiple carriages the transport of hot water is not practical, so air-based supply is preferred. Using air-based heating, it has to be taken into account during regulation that the heated air cools significantly over longer distances through the train (BUŠS D. and EIDUKS J., 2019), (Janicki J. and Reinhard H., 2008). Especially in diesel-powered rail vehicles, waste heat from the engine can be used to heat up the passenger compartment. However, also other heat sources, such as fuel or electric water heaters, can be used. Although, using fuel heaters has the drawback of needing an independent fuel tank (Ebinger & Morgenstern, 2022), (BUŠS D. and EIDUKS J., 2019), (Janicki J. and Reinhard H., 2008).

As additional water is required for hot water heating and there is no diesel engine installed in the pods whose waste heat can be utilized, this type of heating is not considered further.

Heat pumps:

Heat pumps can be used to cover heating demand. They work essentially the same way as vapor-compression refrigeration systems or air cycle machines although with an inverted process. This means that heat is rejected into the cabin rather than into to the exterior. To make this possible, the cycle must be adapted. This is shown for a VCRS in Figure 38. This allows the flow direction of the refrigerant to be reversed. As a result, the two heat exchangers change their functionality (FINE-2, 2020).

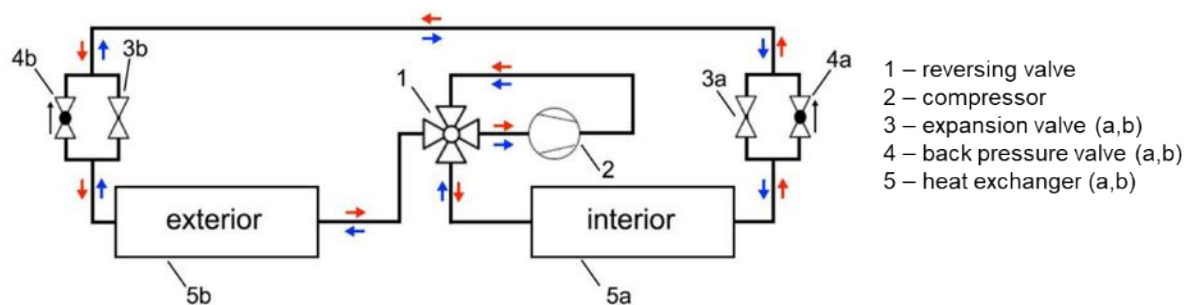


Figure 38: VCRS with reversible process – BLUE: mass flow in cooling mode – RED: mass flow in heating mode (Trygstad, 2017)

Depending on the temperature ranges in the climatic zones and the necessary heating capacity, the entire heating demand can be supplied by heat pumps. If the heat pump alone is not sufficient, additional resistance heaters can be installed in the vehicle (e.g. for extreme temperatures or defrosting). The main advantage of heat pumps is the increased COP (> 1) compared to resistance heaters (COP = 1). The exact COP and operating temperatures vary with the refrigerant used. This can be seen in Figure 39.

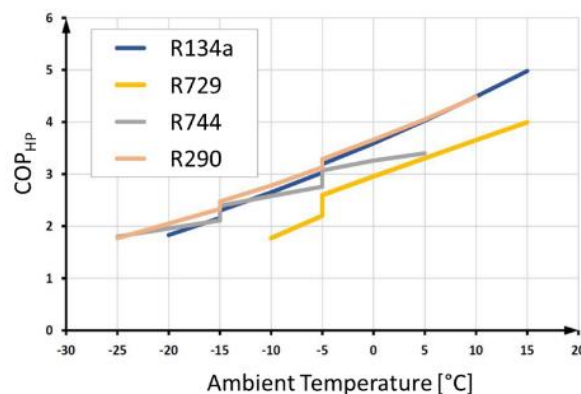


Figure 39: COP of different heat pumps (heating mode) (Faiveley Transport, 2023)

The disadvantage, however, is the higher maintenance effort and the associated costs (e.g. due to higher compressor running time). (FINE-2, 2020)

Other technologies that can be used for cooling and, by reversing the cycle, also for heating are thermoelectric, caloric and thermoacoustic refrigeration systems. Furthermore, the Stirling cycle can be used for heating and cooling purposes.

Infrared-Heating:

Infrared heaters utilize the principle of infrared radiation to generate heat. Infrared is a part of the electromagnetic spectrum that is nonvisible. When infrared hits a surface that can absorb it, this energy is converted into heat. This type of heating is called "direct heating" because it takes place directly on the surface without the air acting as a heat transfer medium. The design of infrared heaters is relatively simple. They consist of a heating conductor through which an electric current flows and which heats up as a result. Depending on the temperature of the heating conductor, it emits a certain wavelength of infrared radiation (Vattenfall, 2025).

Heating the passenger compartment of rail vehicles in combination with lowering the ambient air temperature has already been investigated at the DLR (TRL = 5). It has been shown that this enables energy savings without any loss of passenger comfort. However, the energy savings are not high enough to justify the additional costs of installing such systems (Parise R. et al., 2022).

However, it could be an interesting option to make the transport system more attractive.

6.4 Comparison of different methods for heating and cooling

In the following, the previously presented methods for heating and cooling are evaluated. The requirements to be met by the different technologies can be found in Table 20 and Table 21 respectively. The comparison of the different preselected cooling methods is shown in Table 23.

Table 23: Comparison of the pre-selected cooling methods

exceeds requirements	Method for cooling				Sources
fulfils requirements	VCRS R134a	VCRS R290	VCRS R744	ACM R729	
does not fulfil requirements					
TU_L4 GWP < 20	GWP = 1430	GWP = 3	GWP = 1	GWP = 0	(Ebinger & Morgenstern, 2022)
D7.1_1 Cooling demand achievable	yes	yes	yes	yes	(Faiveley Transport, 2023)
D7.1_3 Weight < 200 kg (10 ft)	Baseline for comparison	Comparable to R134a	Worse than R134a	Worse than R134a	(Faiveley Transport, 2023)
AD_1 Usability in rail sector	Commonly used in rail vehicles	Available at manufacturers	Demonstrated in European PINTA project	Already used in rail vehicles (ICE3)	(Ebinger & Morgenstern, 2022), (Faiveley Transport GmbH, 2025), (PINTA3, 2022)
AD_2 Specific energy density ≥ state-of-the-art	Baseline for comparison	Comparable to R134a	Worse than R134a	Worse than R134a	(Faiveley Transport, 2023)
AD_3 COP ≥ R134a	Baseline for comparison COP: 5.5 – 2 (10 – 45°C)	Comparable to R134a COP: 5.5 – 2 (10 – 45°C)	Lower than R134a COP: 5 – 1.2 (10 – 45°C)	Lower than R134a COP: 1.8 – 0.6 (10 – 45°C)	(Faiveley Transport, 2023)
AD_4 Cost and availability Refrigerant availability: Component availability: Refrigerant price: Component price: Maintenance effort:	Baseline for comparison	+ Better = Comparable + Lower = Comparable = Comparable	+ Better - Worse + Lower - Worse - Higher	+ Better - Worse + Lower - Worse - Higher	(Aigner R. et al., 2019), (Faiveley Transport, 2023), (PINTA3, 2022), (Rail4Earth, 2023)
AD_5 Compliance with F-gas reg.	Phase out of R134a	Natural refrigerant	Natural refrigerant	Natural refrigerant	F-gas regulation
AD_6 TRL > 6	TRL 9	TRL 9	TRL 9	TRL 9	

6.5 Outputs for other WPs

According to Table 23 the most suitable option for cooling, which is available at the moment, seems to be a VCRS with R290 as refrigerant. Although this refrigerant is a flammable substance, R290 stands out due to its similarity in overall performance in comparison to VCRS with R134a.

The most suitable method for heating is the use of a heat pump due to its favourable COP compared to resistance heaters. The refrigerant to be used is the same as for cooling. However, especially for defrosting or to quickly heat up the cabin before usage it could be useful to also install some resistance heaters. Alternatively, the R290 heat pump could be designed for the heating case to make sure that sufficient heating power can be supplied.

7 Concept proposals for the interfaces between pod and carrier

The objective of this Task is to define in greater detail the interface between the specific TU and its carrier units, building upon the findings of WP7.2 and WP12. This includes establishing the technical requirements for the TU with respect to its interaction with the CU. A conceptual proposal for the interface will be developed, with particular attention given to the mechanical and electrical coupling, as well as the integration of energy transfer and communication systems where necessary.

7.1 Methodology

The Pods4Rail deliverables are structured in a logical and interdependent sequence. WP4 (Pods4Rail Deliverable D4.4, 2025) defined high-level functional requirements for the overall Pods System, identifying around 500 requirements across 11 system areas, including the coupling system between Transport Units (TUs) and Carrier Units (CUs). These requirements guided the technical specifications developed in subsequent work packages. Work Package 7 (Pods4Rail Deliverable D7.1., 2024) established the initial technical concepts and design boundaries, evaluating mechanical, electrical, and data interfaces as well as transshipment processes and handling systems. It analysed interface solutions for flexibility, standardization, and safety, considering various transport scenarios and storage requirements.

Building on this foundation, Work Package 12 (Pods4Rail Deliverable D12.1, 2025) formalized requirements and developed a detailed mechanical coupling concept between TU and CU. It addressed system-level needs for safe and efficient integration and introduced an automated, standardized coupling interface to enable faster, safer operations with digital monitoring and control.

The mechanical coupling between TU and CU ensures secure attachment under significant loads, complying with EN 12663 and EN 15227 standards. The chosen solution is an automated twist lock mechanism, widely used in intermodal freight and standardized under ISO 1161 and ISO 1496. Automation is achieved through sensors and actuators for lock verification, with manual release for emergencies, plus vibration damping and fail-safe features.

Electrical coupling enables power transfer for onboard systems such as lighting, HVAC, and control electronics, using modular connectors inspired by Scharfenberg couplers and rated for 24–120 V DC. High-voltage safety is ensured through HVIL connectors, while each TU includes an auxiliary battery for limited operation when detached. Communication combines wired and wireless technologies for redundancy and real-time control, and each TU has a unique digital ID for authentication, and continuous monitoring ensures lock status, power flow, and system health, supported by encryption and compliance with ERTMS and TSI safety frameworks.

In this way, work packages WP10 and WP11 will extend this effort by defining electrical and power-transfer interfaces and data communication, signalling, and system coordination, ensuring full system integration.

Overall, Pods4Rail envisions a modular transport framework where TUs and CUs operate as decoupled but coordinated subsystems, with coupling interfaces guaranteeing mechanical stability, electrical connectivity, reliable data exchange, and secure digital confirmation of coupling states.

7.2 Mechanical interface

In the Pod system, the TUs the component that moves between different CUs using the HS infrastructure. Due to this mobility, each TU has several physical interfaces that must be considered during system development. These interfaces vary depending on the type of TU and the CU/HS it connects to. Additional interfaces are required if the TU is set up next to another TU, stored in a storage system or positioned on the floor. It should be noted that, for the reasons described in D7.1 (Pods4Rail Deliverable D7.1, 2024), no mechanical interface is provided between two TUs. Figure 40 and the attached legend provide a further overview of the most important interfaces for each TU.

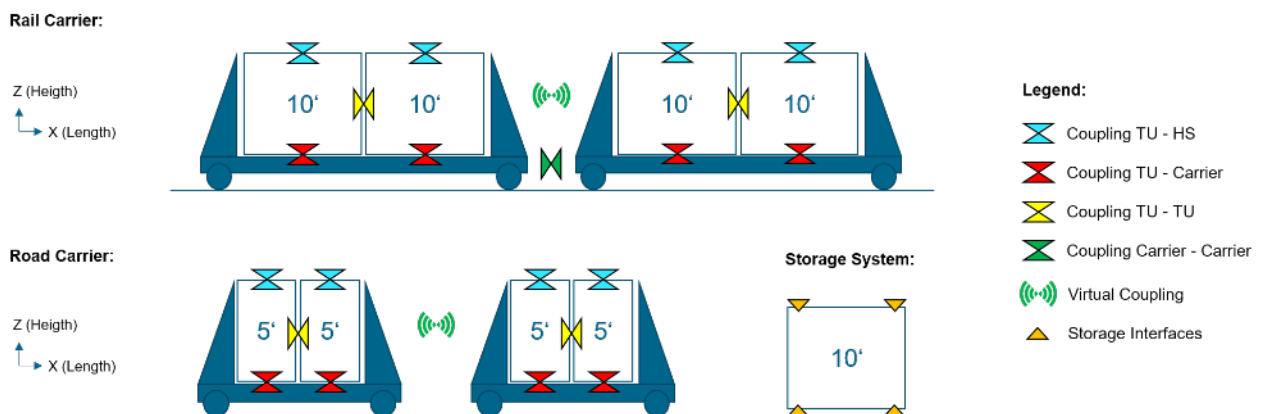


Figure 40: Vision of the Pod system and schematic overview of interfaces of the Transport Unit (taken from Pods4Rail D7.1)

To ensure safe and accurate placement of the TU within a CU, the TU must be positioned precisely. The HS system must align the TU within specific tolerances, matching the interface areas of both units. Positioning interfaces may include contact elements, support structures, or non-mechanical solutions like sensors or cameras. Additional components such as guide rails can help fine-tune alignment. These interfaces define how the TU moves and is positioned inside the CU, and they can be integrated with mechanical coupling or locking systems to enhance functionality and reduce weight. The following Figure shows the roughly defined dimensions in D7.1 (Pods4Rail Deliverable D7.1, 2024) of the TU and the possible integration of the main mechanical interfaces (Twistlocks and Corner Castings) which has worked out in their general functionality in WP7 and WP12. In this Task it is necessary to specify these interfaces in a more detailed way, that they can be implemented in such a pod system.

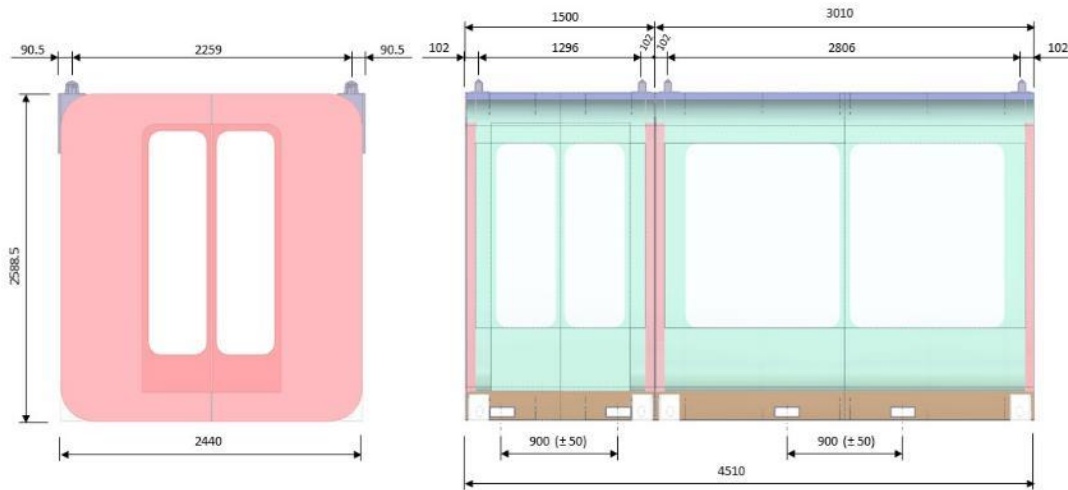


Figure 41: Dimensional constraints for mechanical couplings (adapted from Pods4Rail D7.1)

The mechanical interfaces must ensure physically secure connectivity between the CU or HS and the TU. At all times and under every transshipment process. This will be worked out in detail in the following chapters. On the one hand, the requirements for functionality, exact interface positioning and integration into the TU are considered. Direct cooperation with WP14 is necessary, as this is where the positioning of the corresponding interfaces in the CU is worked out.

7.2.1 Specific requirements for the TU

Once the TU has been loaded onto the CU, it must be physically secured to ensure stability during transport. This must be achieved through the mechanical interface. This must act as a locking mechanism to prevent movement and ensure the load and crash safety requirements of the entire pod system are met. The specific requirements for the UC with a 10 ft unit considered in this WP10 are presented below. The following three mechanical interfaces are necessary for the system based on the findings from WP7 and partly from WP12; these are shown graphically in Figure 42:

- Corner castings in the floor structure of the TU: These represent the mechanical interface on the TU side between the TU and the road or rail CU. They are also necessary if the TUs are to be stacked directly on top of each other in a storage system.
- Fully automatic twistlocks in the roof structure of the TU: These represent the mechanical interface on the TU side between the TU and a CU (e.g. a Ropeway CU) or a HS, which picks up the TU from above. They also form the mechanical interface to a TU that is stacked on top of the TU in a storage system.
- Forklift pockets in the floor structure: These are required for the transshipment process with existing equipment, for example in places where no HS can be realised or where corresponding HS are already available and only need to be slightly modified.

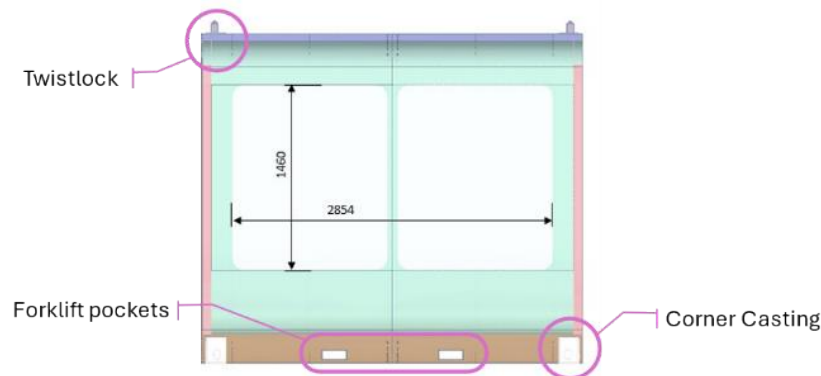


Figure 42: position of the considered mechanical interfaces

These mechanical interfaces must fulfil the functional requirements developed during the course of the project (D7.1 (Pods4Rail Deliverable D7.1, 2024): Table 20, Table 30 - 35, Table 37, Table 39 - 40, Table 42, and D12 (Pods4Rail Deliverable D12.1, 2025) Table 1). These requirements are summarised below and prepared for the CAD model. The requirements are categorised as follows:

- **Standardisation:** How can the assembly be designed so that it complies with existing standards and thus maximises compatibility with existing interfaces? Furthermore, we are investigating how the interfaces can be standardised for different charging scenarios and applications (including stackability).
- **Integration:** The exact positioning of the individual interfaces in the TU is defined and how these interfaces are integrated into the structure. For this purpose, connection points and the joining technologies to be used are discussed.
- **Load conditions:** What loads are expected at this interface in extreme cases? It should be noted that the given values of the EN 12663-1 are a first initial estimate of possible loads. The pod system is a completely new approach in which the loads are absorbed in different ways and the system will also be exposed to different loads as defined in current standards. It is therefore not possible to refer directly to existing standards in the design. A key finding of the project is that a new development of supermodal standards is required, which fulfil the various requirements of the different types of transport without bluntly superpositioning them. This would lead to an extremely conservative design and would not fulfil the goal of an energy-efficient future. Furthermore, the loads mentioned are only guidelines. In the concept phase and definition of the pod system and, above all, the independent TU considered here in the Project Pods4Rail, no design / calculation of the TU is carried out.
- **Influence on other interfaces:** Each interface also has an influence on the opposite side. From this point of view, the influence of the interface is to be analysed.
- **Further restrictions:** This takes into account factors that must be considered in the design of the respective interfaces via the hard factors. For example, tolerance

compensation, ensuring functionality under extreme conditions or ensuring secure locking in various transport modes.

- Scalability: What is necessary for other TU sizes, other CU and different configurations due to different UC.

These concrete influences on the CAD model are summarised in Table 24 and Table 25, and serve as a starting point for the concrete implementation of the mechanical interfaces in this WP and as preliminary work for the development of a specific TU in WP9 and the various CUs in WP 14.

Table 24: Integration and load requirements of the mechanical interfaces of the TU

Interface	Standardisation	Integration	Load conditions
Corner casting (TU-CU)	- ISO 668 (ISO 668, 2020) - ISO 1161 (ISO 1161, 2016) - The defined Pattern (Figure 41 and 42 in D7.1) (Pods4Rail Deliverable D7.1, 2024)	- flush with outer surface in y direction, distance between the centres 2259 mm - in y direction, centres must be 89 mm (lower tolerance: -1.5 mm) indented - in z direction, corner casting as lowest point of TU, ideally protruding a few mm from structure - in the x-direction, the distance between two centre points must be: - 1282 mm (5 ft) - 2787 mm (10 ft) - 5853 mm (20 ft). - In the x-direction, the centre points for the 10 ft and 20 ft TU must be indented by 101.5 mm (lower tolerance: -1.5 mm) on each side. For the 5 ft TU, this value is 122,75 mm - Dimensions L x W x H: 178 x 162 x 118 mm - welded	- Part of the TU structure, no extra load verification except stress verification in the concept phase - All tests (static, dynamic, vibration, impact) initially according to EN 12663, EN 15227, ISO 1161, ISO 1496 are considered in the verification phase BUT: new Standards should be derived specified on the requirements of such a supermodal concept.

Interface	Standardisation	Integration	Load conditions
Twistlock (TU-HS / TU-CU)	- ISO 668 (ISO 668, 2020) - The defined Pattern (Figure 41 and 42 in D7.1) (Pods4Rail Deliverable D7.1, 2024) - for HS: EN 15056+A1 Cranes (EN 15056,2009)	- in the y direction, the distance of the pivot axis must be 2259 mm - in the y direction, the centres must be 89 mm (lower tolerance: -1.5 mm) indented - in x-direction the distance of the pivot axis must be: - 1282 mm (5 ft) - 2787 mm (10 ft) - 5853 mm (20 ft). - In the x-direction, the centre points for the 10 ft and 20 ft TU must be indented by 101.5 mm (lower tolerance: -1.5 mm) on each side. For the 5 ft TU this value is 122,75 mm - In the z-direction, the tenon and bearing surface protrude from the CU surface - Preparatory work for WP14 For the CU, the distances in x-direction between the individual tenon axes are as follows: y: 2259 mm; in x: first and last must be 122,75 mm (plus tolerance to CU structure) away from CU, then 1282 mm and then 279 mm - The entire structure (incl. contact surface) of the twistlocks must be designed to be lowerable - In Rail CU it is also possible to move outwards to reduce complexity - When inactive / lowered, the open area must be sealed against moisture and dust - Fastening with 4 screws (e.g. M20) on or to the side of a support	- Maximum load: fully loaded freight container with 12 t, for UC1 (20 ft) an assumption of 7 t is realistic (D7.1) (Pods4Rail Deliverable D7.1, 2024) - Initially: Accelerations EN12663-1 (category P-III) (EN 12663, 2023) in: - x-direction +-2g, - y-direction +-1g, - z-direction +3 g and -1 g - Lifting load cases based initially on EN12663-1 (one lifting point sags by 10 mm (torsion)) - Standards to be considered in the detailed design: EN 15227, ISO 1161, ISO 1496, but new standards should be derived for such a supermodal system - ISO 3874:2017-10 Series 1 freight containers - Handling and securing
Forklift pockets	- TU Must be equipped with a securing / clamping mechanism, which is why standardisation would be complex due to this special case - Furthermore, there is no direct standardisation, but above all standard market dimensions. These should be adhered to	- Part of the skeleton structure of the subfloor - Opening: 200 x 90 mm - Distance between the fork pockets between 900 (+/- 50) mm and 2050 (+/- 50) mm depending on the TU size. In D7.1, the distance was defined as followed: - 500 mm for the 5 ft TU - 1000 mm for the 10 ft TU - 2050 mm for the 20 ft TU These values changed within the work of this WP. The improved values are: - 920 mm for the 5 ft TU - 920 mm for the 10 ft TU - 2000 mm for the 20 ft TU - Reinforcing plate with 100 mm overhang required in the area of the forklift pockets - Base plate of the forklift pockets should not be completely closed. Openings at least 200 mm away from the outside	- mass of a 20 ft TU: 7 t - mass of a 10 ft TU 3.4 t - Impacts through jamming and damage by the tines - sidewind and accelerations through the HS (assumption: +/- 3g in each direction, according EN 12663-1)

Table 25: Interactions and further restrictions of the mechanical interfaces of the TU

Interface	Influence on other interfaces	Further restrictions	Scalability
Corner casting (TU-CU)	- Positioning in coordination with the twistlocks. However, there is no great variability, as corner castings must be attached to the corners of the TU	- should be equipped with a heating system for defrosting - should be covered when not in use (protection from environmental influences) - Tolerance compensation provided by slotted holes	not required, as it is attached to corners of the TU. At the same time, however, the overall system must be taken into account. 10 and 20 ft TUs are standardised, variability is possible with 5 ft TUs in order to use the same interfaces.
Twistlock (TU-HS / TU-CU)	- same positioning as the corner castings in the TU. This is the only way to ensure that stacking is possible. - Preparatory work for WP14 For the CU, the distances in x-direction between the individual tenon axes are as follows: - y: 2259 mm - x: first and last must be 122,75 mm (plus tolerance (20 mm) to CU structure) away from CU, - x: then alternately 1282 mm and then 279 mm	- should be equipped with a heating system for defrosting - should be covered when not in use (protection from environmental influences) - Fixed locking necessary even if the power supply fails. Manual emergency release must be provided	not required, as it is attached to corners of the TU. At the same time, however, the overall system must be taken into account. 10 and 20 ft TUs are standardised, variability is possible with 5 ft TUs in order to use the same interfaces.
Forklift pockets	- TU must provide gripping / clamping mechanism - No influence on CU	- Fork shoes must be secured / lashed down by the TU mechanism to prevent slipping - Do not position fork lift pockets too close together due to possible imbalance - Clamping mechanism must also ensure safety against crosswinds or impacts (crash). Especially with a light TU that does not generate much friction - Firm locking also necessary if the electrical supply fails. Manual emergency release must be provided	- Easily possible, as there is no interface to the CU, only to the HS. These have adjustable forks, which is why the exact positioning and tolerance compensation have no influence on the functionality of the system

7.2.2 Results of the interface of UC1

In the previous chapter, the mechanical interfaces are explained, as well as their requirements. As mentioned, corner castings are defined in ISO 1161. These will be used for the TUs. Twistlocks on the other hand, are not standardised, but are designed to fit into the corner castings, according to ISO 1161. Additionally, fork pockets are normed by ISO 1496. Handling and securing freight containers during transshipment is declared in ISO 3874. However, moving a container with a forklift is mentioned very briefly. A securing or clamping mechanism between forklift and container is not stated. As a consequence, such a mechanism is to be constructed in order to reach a safe transshipment process for all use cases, especially with passengers. This will be considered later on.

Beforehand, the positioning of the elements is set. In order to guarantee a secure load of the TU on the CU and the TUs on top of each other, the corner castings and twistlocks must

be positioned accurately to one another. Therefore, the interface of the four corner castings must be congruent to each other, as well as the interface of the four twistlocks. Additionally, in each corner, the corner casting must be coaxial to the twistlock, to ensure a vertical stacking. The distances between the two elements, corner casting and twistlock, are given in Figure 41, on the left side for the 5ft TU and on the right side for the 10ft TU.

All lengths declared in that figure are measured off the corner castings centre point of the bottom hole and the centre point of the twistlock's tip. As this figure shows, the distance in x-direction of the elements in the 5ft TU is 1296mm. In the 10ft TU on the other hand, it is 2806mm. The distance in y-direction for the 5ft and 10ft TU is equal with 2259mm. In z-direction, the distance between the bottom of the corner casting and the top surface of the twistlock (retracted), on which the corner casting sits on, is 2588.5mm. This accords with all elements.

Additionally, Figure 41 shows the distance of each pair of fork pockets. The fork pockets are located symmetrically from the centre of the TU. The pockets are set into the y-direction. The width between each pocket pair is measured from the centre of each pocket hole and is defined in the norm ISO 1496. Therefore, the distance for the 5ft and 10ft TU is 900mm with a tolerance of ± 50 mm. For the 20ft TU, the distance is 2050mm and a tolerance of ± 50 mm.

Concept for a securing or clamping mechanism between the Transport Unit and the forklift

As mentioned in the definition of the fork pockets, a securing or clamping mechanism between the fork pockets of the TU and the forks of the forklift is not defined in the norm. As a consequence, a system must be worked out, in order to guarantee a secure transshipment. Therefore, several securing and clamping mechanism are presented and evaluated, following the same method as in Pods4Rail Deliverable D7.1. The evaluation is divided into existing methods and the concept drafts processed in this project.

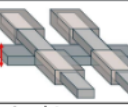
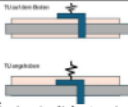
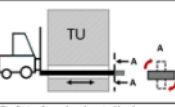
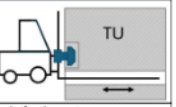
In the first part, existing methods of securing freight onto forks of a forklift were researched. An overview of them is shown in Table 26.

Table 26: Overview of existing securing and clamping methods between container and forklift

Secure mechanism	Method 01 Forklift spreader top	Method 02 Forklift spreader lateral	Method 03 Pipe Stabilising Clamp	Method 04 Tie-Down Clamps
Picture				
Short description	Forklift spreader for container handling Telescoping Top Lift Spreader T192E - For flexible top handling of 10' to 40' ISO / Sealand / special container dimensions - To be slipped onto forks and reversible forks Hook-on Integrated Terminal West Pin Type - Capacity (SWL) from 1.000 kg to 45.000 kg	Forklift spreader for container handling Telescoping Side Lift Spreader T193 - For flexible lateral handling of 10' to 40' ISO / Sealand / special container dimensions - Hook-on Integrated Terminal West Pin Type - Capacity (SWL) from 1.000 kg to 12.000 kg - Optionally available with independent sideshift - Optionally available with hydraulically adjustable bottom support	Pipe Stabilising Clamp - it is designed to be fitted to any large fork lift or telescopic handler to stabilise long loads or long pipes when being transported over uneven ground or when loading and unloading lorries - Rubber edge for secure holding of pipes - Two hydraulic cylinders with flow splitters to ensure the arms travel in sequence - For use on fork lifts from 5 tonnes to 22 tonnes	Forklift Tie-Down Clamps - Uniform Capacity: 4,400 lbs. (2,200 lbs. per clamp/bracket) - Clamps To Fit Forks: 6"W x 2-3/4"H - Steel Construction - Tough Baked In Powder Coated Yellow Finish
Source	https://www.kaup.de/en/material-handling-solutions/forklift-spreader-for-container-handling	https://www.kaup.de/en/material-handling-solutions/forklift-spreader-for-container-handling	https://www.murraymachinery.com/products/pipe-stabilising-clamp	https://www.vestil.com/product.php?FID=1411
Requirements for the TU	Corner Castings on the roof	Corner Castings on the roof	Strong structure on the roof and bottom	Strong structure at edges
Requirements for the forklift	None	None	None	None
Flexibility	high	high	high	very high
Modification on TU	None	None	None	None
Modification on forklift	None	None/ replacement	None	None
Possible degree of automation	High	High	High	Low
Advantages	- flexible use for different container sizes - quick adjust - no modification necessary - independent of TU size - no additional components/ weight on TU - high capacity load (up to 45t)	- flexible use for different container sizes - quick adjust - no modification necessary - independent of TU size - no additional components/ weight on TU - pick up from the side	- flexible use for different container sizes - quick adjust - no modification necessary - independent of TU size - no additional components/ weight on TU	- flexible use for different container sizes - cheap purchase - no adjust at the forklift - independent of TU size - no additional components/ weight on TU
Disadvantages	- expensive purchase - not useable for 5ft TU - spreader is not securely fixed on forklifts	- expensive purchase - not useable for 5ft TU - max. capacity: 12t -> not usable for 20ft TU	- expensive purchase - maybe not usable for TUs (or containers in general) - maybe not enough secured horizontally	- not enough secured for 10ft and 20 ft TU - cannot run automated - low max. capacity (max. 4,400 lbs.)

The research highlights, that there is no ideal system that suits all requirements to move a TU safely. Consequently, a group of experts investigated systems of securing and clamping mechanisms, as well as interface solutions, that suit the requirements of the forklift transshipment. Table 27 shows the results of the concept drafts with possible mechanisms.

Table 27: Overview of concept drafts for securing and clamping mechanisms between container and forklift

Secure mechanism	Idea 01 Secure via magnet	Idea 02 Clamping forks against pockets	Idea 03 Moving plate	Idea 04 Mechanical/electronic clamping of the forks	Idea 05 Safety hooks installed on the forks (rotatable fork tips)	Idea 06 Twistlock system
Picture						
Short description	Secure via magnet - in forklifts - or: at the forklift back	Secure by clamping the forks against the pockets - Forklift fork clamps (when all the way in the TU/ pocket, it clamps the forks together/apart) - Capacity: 2.000 kg	Moving plate - Plate clamps the forks to the TU from below	Mechanical/electronic clamping of the forks Left upper picture: - When the TU is on the ground, the clamp is released Left lower picture: - When the TU is lifted, the spring or an electrical device presses the fork against the underside of the pocket	Safety hooks installed on the forks (rotatable fork tips) - When the forks are completely through the pockets, the tips of the forks rotate 90° vertically. This prevents the forks from being pulled out and secures the TU.	Twistlock system - at the fork carrier, a twistlock is mounted - when loading the TU, the forks enter the pocket and the twistlock enters a corner casting in the TU - Twistlock is automated
Source	https://www.staplerlift.de/en/magnet-lifter-plus/m101A	https://www.impetusforklift.com/de/produkt/gabelstaplerklemmen/turnaforke-aufsatz/				
Requirements for the TU	outer shell must be magnetic	None	Space for system must be available	Space for system must be available	None	Space for the corner casting
Requirements for the forklift	None	None	None	None	System must be able to suit into fork without impact fork or needing more space	Space for the twistlock
Flexibility	high	high	high	high	high	high
Modification on TU	None		System of automated extending bolts/ twistlocks	System of automated extending plate	None	Adding a corner casting on both sides of the TU
Modification on forklift	low	None	None	None	- turnable front of fork - communication system (wireless components or electronic signal from the forklift to the front of fork)	Adjust an automated twistlock system
Possible degree of automation	High	High	High	High	High	High
Advantages	- flexible use for different container sizes - cheap purchase (?) - independent of TU size - no additional components/ weight on TU	- flexible use for different container sizes - one time adjust - quick - no modification necessary - independent of TU size - no additional components/ weight on TU	- independent of forklift - no modification or adjustment at forklift	- independent of forklift - no modification or adjustment at forklift - no el. Energy necessary	- independent of TU size - no additional components/ weight on TU	- flexible use - independent of forklift and TU size - just little modification or adjustment at forklift or TU - TU is fixed in all DOF - cheap purchase - low additional weight - could also be used with unmodified forklift (without people)
Disadvantages	- max. capacity ? - not weather resistant (e.g. ice) - magnet may impact other equipment, signals or people inside/ interior	- expensive purchase - max. capacity is too low (2t)	- expensive purchase - additional costs for TU - more weight for total mass of TU - is needed in every TU - forks are not fixed in x-direction (horizontal)	- Problem: the spring must push the mass of the TU upwards while pressing the forks downwards. - => The system would be better in reverse (with the fork pressed against the TU). - expensive purchase (?) - additional costs for TU - more weight for total mass of TU - is needed in every TU - forks are not fixed in x-direction (horizontal)	- expensive purchase - additional costs for adjustment of forklift - forks are not fixed in x-direction (horizontal)	- weather sensitive (freezing of twistlock)

Subsequently, criteria for the evaluation were defined and described. These comply with the requirements of the mechanism system. Each criterion is weighted to its importance, whereas the value = 1 has a low importance, value = 2 a medium or value = 3 a high importance for the selection process or implementation in the Pods4Rail system. The evaluation criteria, including the weighting, is shown in Table 28.

Table 28: Definition of the evaluation criteria for different securing and clamping methods

Evaluation criteria for MCM	Explanation	Importance, Priority of criteria (Multiplication-Factor) 3 = Most important 2 = Medium 1 = Least important
Price/ Costs	Costs for implementation in TU/ forklift system	1
Grade of automation	Possibility for fully autonomous TU/ forklift system	3
Complexity of carrier	Space consumption, weight, moving parts, additional parts, support structures	2
Complexity of TU	Space consumption, weight, moving parts, additional parts, support structures	2
Standardisation	Suitability for all TU 's and forklifts (one solution for the Pod system)	3
Safety	Fulfil safety requirements, emergency solutions	3

Evaluation of securing and clamping mechanism

In the following, every system is evaluated according to the given criteria, as shown in Table 29, for existing methods, and Table 30 for the concept drafts. Every criterion is rated, whereas the value = 1 stands for poor fulfilment or “no possible fulfilment” and the value = 5 stands for the best possible fulfilment. At the end of each solution, each rate number is multiplied with its evaluation number. The products are then added all together. The highest achievable total rate is 70. The solution with the highest score can be seen as the most suitable solution. In this rating, the methods and concepts are rated equally, just as their final score, in order to find the best solution for this system. The rate score of all solutions is between 54 and 67. The scores for the existing methods are in generally lower, compared to the rate of the concept drafts. In further discussion, just the solutions with the two highest scores are considered.

Table 29: Evaluation table of existing securing and clamping methods

Evaluation criteria for MCM	Importance, Priority of criteria (Multiplication-Factor) 3 = Most important 2 = Medium 1 = Least important	Method 01	Method 02	Method 03	Method 04
Price/ Costs	1	2	2	3	4
Grade of automation	3	5	5	5	1
Complexity of forklift	2	3	3	4	5
Complexity of TU	2	5	5	5	5
Standardisation	3	3	2	3	5
Safety	3	4	5	4	4
Total		54	54	57	54

Table 30: Evaluation table of concept drafts

Evaluation criteria for MCM	Importance, Priority of criteria (Multiplication-Factor) 3 = Most important 2 = Medium 1 = Least important	Idea 01	Idea 02	Idea 03	Idea 04	Idea 05	Idea 06
Price/ Costs	1	3	3	4	4	4	4
Grade of automation	3	5	5	5	5	5	5
Complexity of forklift	2	4	4	5	5	3	4
Complexity of TU	2	4	5	4	3	5	5
Standardisation	3	5	2	5	5	5	5
Safety	3	4	4	4	3	4	5
Total		61	54	64	59	62	67

The second highest score reached concept draft 3. In this solution, the forks are not modified. The TU is prepared with an automated plate on the bottom of each fork pocket pair. When the forks have fully entered the pockets, the plate will extend up, pressing the forks onto the top of the pocket. Therefore, the forks are secured against movement. This solution can be operated fully automated. Additionally, it is very flexible, because it can be used by any forklift, without additional parts or previous modifications. As a consequence, the forklift is unrestricted in its use for other duties. On the other hand, this solution may be expensive, because every TU must be provided with an additional system. Furthermore, it adds weight onto the total weight of the TU. Nevertheless, it is secured against movement, but still may vibrate or shake strongly during transshipment, which causes a discomfort for passengers.

The highest score achieved idea 6. This solution provides the forklift with an automated twistlock system, which is mounted onto the load backrest. For the TU, a counterpart is

integrated for the twistlock to enter and lock, similar to a corner casting. This is needed for both sides of the fork pockets, to secure the TU from either side. The position height is to be discussed, but must be at a strong point of the TU's structure. So, when the forks have fully entered the pockets in the TU, the twistlock also has entered the prepared hole in the TU. Then the twistlock locks and the TU is secured. This can be operated fully automated. This solution also allows non-modified forklifts to move TUs without any passengers. Not much space is needed in the TU. Furthermore, the total weight of the TU may not or just slightly rise up. On the TU side, it is a cheap purchase. The forklift on the other hand, must be prepared with an automated twistlock system. This rises the costs of the modification. Also, every forklift in use must be modified. However, once modified, the forklift is able to be used for any TU size.

The final concept for the securing mechanism is idea 6, as described. Therefore, this solution will be considered on further observations. It must be mentioned, that in either way there must be some kind of adaption of the system. Either the TU is adapted or the HS. The chosen solution shows potential for a well working principle with only little adaption of the overall system.

7.3 Electrical and Energy Transfer Interfaces

For both 10 ft TU (Transport Unit) for UC1 and the 5 ft Entrance module, mechanical interfaces are required for Task 10.3. In addition to mechanical connections, both TUs also require interfaces for the energy transfer system.

Due to the boundary conditions, this work had to be carried out in detail in WP7, even though it was originally planned for later stages. The partners involved developed content in WP7 that went beyond the original objectives. This early evaluation was necessary to define the design spaces for subsequent WP8 and WP9. These installation spaces are closely linked to other factors of the energy transfer system, including electrical parameters that influence connections, cable harnesses requirements, and positioning. At the time the Grand Agreement was submitted, this dependency and, therefore, the need for an earlier in-depth evaluation was not known. For this reason, reference is made to Pods4Rail D7.1 to avoid duplication. Only the main results are summarized in the following chapter

7.3.1 Characteristics of the electrical coupling

The most suitable energy transfer system was evaluated based on the work carried out in WP7 and WP12. For the electrical solution, it became clear that a combination of different systems and interfaces was necessary to cover all types of transmission.

As outlined in Deliverable D7.1 (Pods4Rail Deliverable D7.1, 2024), electrical coupling components must meet several key requirements to ensure the safe, reliable, and efficient transfer of energy between the CU and the TU during operation.

Connectors must demonstrate resistance to vibration, ensure safe handling, offer ease of connection and disconnection, and meet specific constraints related to size, weight, power

capacity, and cost. The growing adoption of electric vehicles has driven the need for specialized high-voltage connectors capable of handling voltages ranging from 275 V to over 1,000 V, far beyond the typical 12 V DC used in internal combustion engine vehicles.

These high-voltage connectors must not only support elevated current, and voltage loads but also transmit digital and analog signals in environments subject to high electromagnetic interference (EMI). Furthermore, they must be designed to prevent accidental contact or arcing, while maintaining ease of use.

In fully electric architectures, these connectors are crucial for interconnecting the electric motor, battery pack, charging system, and power electronic converters. In addition to high-voltage interfaces, a variety of low-voltage connectors are also necessary—for sensors, control units, and signal transmission—especially considering the increased power demands of modern electronic systems compared to their predecessors. For the Pods4Rail system a solution for high voltage (HV) transmission should be provided, even though it is not planned that electrical components of the selected use case will require HV power supply. Still, for other use cases it would be needed.

Taking into account the equipment identified within the Transport Unit in Section 5.3 of this document, the electrical coupling must be capable of supplying sufficient energy to ensure the reliable and uninterrupted operation of all onboard systems. These include the HVAC system, charging of the TU's battery, Control Units, and the Passenger Information System—which covers GPS, onboard sensors, and external data feeds.

In addition, the coupling must support all emergency systems, such as alarm and communication systems, emergency door warning devices, fire detectors, and automatic braking responses. Ensuring the continuous power supply to these critical components is essential for the safe and efficient operation of the Transport Unit under all conditions.

The coupling interfaces must operate reliably under a wide range of environmental conditions (Table 31):

Table 31: Design considerations for environmental conditions

Condition	Design Consideration
Winter (snow/ice)	Sealing and heating elements to prevent ice formation in connectors.
Desert (sand/dust)	Dust-proof and IP (Ingress Protection)-rated enclosures (e.g. IP67 or higher).
Rain/humidity	Corrosion-resistant materials and waterproof connectors.
Temperature extremes	Connectors and cables rated for -40°C to $+70^{\circ}\text{C}$ or higher.

For example, this operation under harsh environmental conditions can be demonstrated through the presentation of certificates of compliance with:

- o EN 50155:2017 Electronic equipment used on Rolling Stock

- o EN 50121-3-2:2016 Railway Applications - Electromagnetic Compatibility
- o EN 60068-2-1:2007 Environmental Testing / Cold
- o EN 60068-2-2:2007 Environmental Testing / Dry heat
- o EN 60068-2-11:1999 Environmental Testing / Salt mist
- o EN 60068-2-14:2009 Environmental Testing / Rapid temperature variation
- o EN 60068-2-30:2005 Environmental Testing / Damp heat
- o EN 61373:2010 Mechanical Testing / Shock & Vibration
- o EN 60529:1991+A2:2013 IP68 and IP69 ingress protection
- o EN 45545-2:2013+A1:2015 Railway applications - Fire protection on railway

The connections also must be scalable and modular, allowing plug-and-play compatibility between different TUs and CUs.

In that line, in the following paragraphs, a summary of the two chosen options for electrical coupling are going to be presented.

7.3.1.1 HVIL Connector

When high-voltage energy transfer is needed, the chosen solution is a High Voltage Interlock Loop (HVIL) connector, which provides power transmission and safety monitoring.

As seen in (Pods4Rail Deliverable D7.1, 2024), it is a special electrical connector used in electric vehicles to connect the high-voltage components, including the battery and motor, to the rest of the electrical system. An HVIL connector essentially acts as a switch that can detect when a connection is made or broken. This is important for the connection between TU and CU. When the connection is secure, the HVIL system enables the high-voltage circuits to be activated (e.g. to charge the TU's on-board battery). Conversely, if the connection is interrupted, the HVIL system switches off the high-voltage circuits, preventing the flow of current and minimising the risk of electric shock or other hazards. This is a relevant feature for the autonomous use of TU and CU power supply (RENHOTEC, 2025a). Another advantage is, that it is industry-proved in the automotive sector.

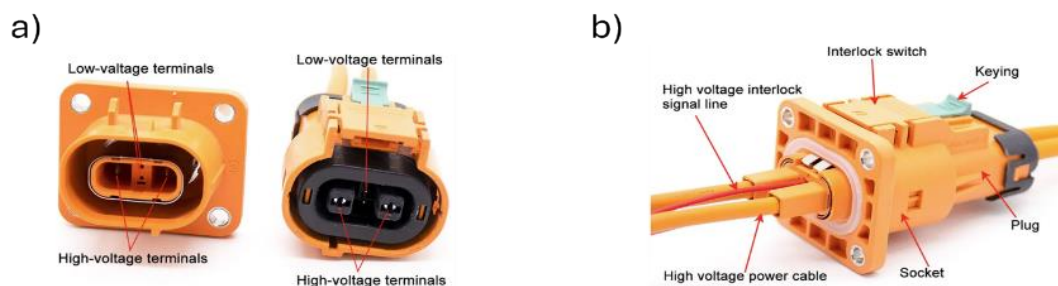


Figure 43: a) Contact Structure of HVIL Connector and
b) Basic implementation of HVIL connectors (RENHOTEC, 2025b)

This connector (Figure 43) is meant to:

- Transfer power from the CU to the TU (e.g. for battery charging, HVAC operation, lighting, and control electronics).
- Ensure safe coupling by monitoring the physical connection. When fully connected, the HVIL loop is closed, enabling high-voltage circuits. If the connection is interrupted, the system automatically cuts the power.
- Support low-voltage terminals, if required, for power distribution to low-consumption systems (e.g. standby electronics).
- Meet safety standards for electric mobility and railway systems (e.g. insulation monitoring, emergency shutdown).

Each TU also includes an onboard auxiliary battery, charged automatically through the electric power connection, allowing at least 15 minutes of autonomous operation in uncoupled or emergency situations. Since not many electric consumers are connected to the HV-line, it is also possible to only provide the HVIL connector to specific TU-variants.

7.3.1.2 Multi-Coupler Solution

The multi coupler is a mechanical adapter that can integrate a wide range of connectors. Within the multi coupler adapter, it is possible to use HV, low voltage and signal connections. Signal communication between the TU and CU can be done wireless, but for some functions it can be better to have a wired communication flow, especially for safety relevant functions. It must be taken into account that different electrical data must be transmitted and systems connected due to the high variability of the UC and different TUs. The results from WP7 were checked again in accordance with the new requirements from WP8 and adjusted accordingly. With hybrid connectors, supply lines and data traffic run side by side without any problems. They also enable automated conversion and set-up processes. Because all connectors are mounted on one base plate, the highest flexibility, also in the terms of individualisation or future updates and upgrades are being reached. All opposite connectors are mounted on an opposite plate. The system has one active component inside the CU, driven by an electric actuator, the other component is fixed to the TU. The space required depending on the specific configuration but can be assumed with approx. 300 x 150 x 350 mm.

a)



b)



Figure 44: Examples for Multi Couplers (Tatje, 2016)

This system is capable of supporting:

- Data exchange for control systems, sensors, diagnostics, and passenger information.
- Emergency signals, including activation of fire suppression systems, emergency doors, alarms, and automatic braking.
- Internal communication between TUs (when multiple units are coupled), particularly relevant in passenger applications.
- Redundant communication paths, using both wired (multi-coupler) and wireless (see Table 32) solutions for increased reliability.

7.3.1.3 Combination of HVIL and Multi-Coupler Interfaces

In the Pods4Rail system, two main types of electrical interfaces are chosen for coupling between the Transport Unit (TU) and the Carrier Unit (CU): the HVIL connector and the multi-coupler interface. While both serve to connect electrical systems between the two units, they have distinct purposes and operate in complementary roles:

- The HVIL connector is used for power transfer, with an integrated safety system.
- The multi-coupler is used for signal and data communication, supporting modularity and automation.

Both systems are essential and work together to ensure a complete and safe electrical interface between the CU and TU. Given the modularity of both the Carrier Units and Transport Units, the use of standardized, scalable interfaces like HVIL and multi-couplers allows for seamless integration regardless of TU size or function. This design supports future system upgrades and simplifies maintenance and replacements.

Both the HVIL and multi-coupler systems are designed for high durability, with a minimum of 10,000 mating cycles, resistance to vibration and environmental stress (IP67/IP69K rated), and support for condition monitoring. This enables predictive maintenance strategies and reduces system downtime. Table 32 shows its main features.

Table 32: Features of HVIL connectors and multi-couplers

Feature	HVIL Connector	Multi-Coupler
Purpose	Power transfer (HV)	Signal & data transfer
Voltage Range	275 V – 1000 V DC	Typically 12–48 V DC
Safety Features	Interlock loop, arc protection	Enclosed modular housing
Automation Support	Yes (actuated connection detection)	Yes (multi-connector docking)
Environmental Rating	IP67 / IP6K9K	IP65+
Modular Use	Yes	Yes
Maintenance	Predictive, sensor-supported	Plug & play design

In order to make the electrical connection more efficient and compact, it is also possible to combine both technologies into one single interface. In this way, the HVIL connector can be integrated into the multi-coupler base plate. It has to be considered, that every connector requires its own space on the baseplate. By combining a high-voltage and low-voltage system together with different signalling options, the most flexibility and highest adaptability can be reached. Also it is possible to reduce the space demand and complexity.

With the approach of the one-in-all multi-coupler, the following example configuration can be proposed, as seen in Figure 45. It has to be noted, that the use of connectors is flexible, but the position always has to be the same for all CU and TU.

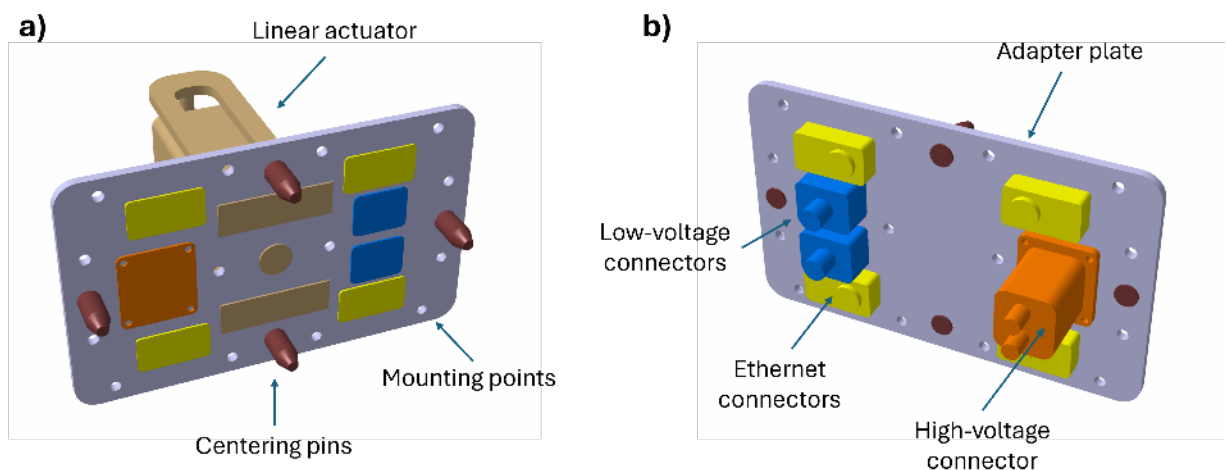


Figure 45: Overview of the schematic electric connection assembly. A) adapter plate with front view of connectors, centering pins and actuator. B) rear view with overview of possible connector types (actuator is not shown here).

The dimensions of the whole system depends on the actual layout, but for this configuration a overall space of 360 x 220 x 300 mm can be reserved, as shown in Figure 46. If communication functions are only done wireless, then the dimensions will be reduced accordingly.

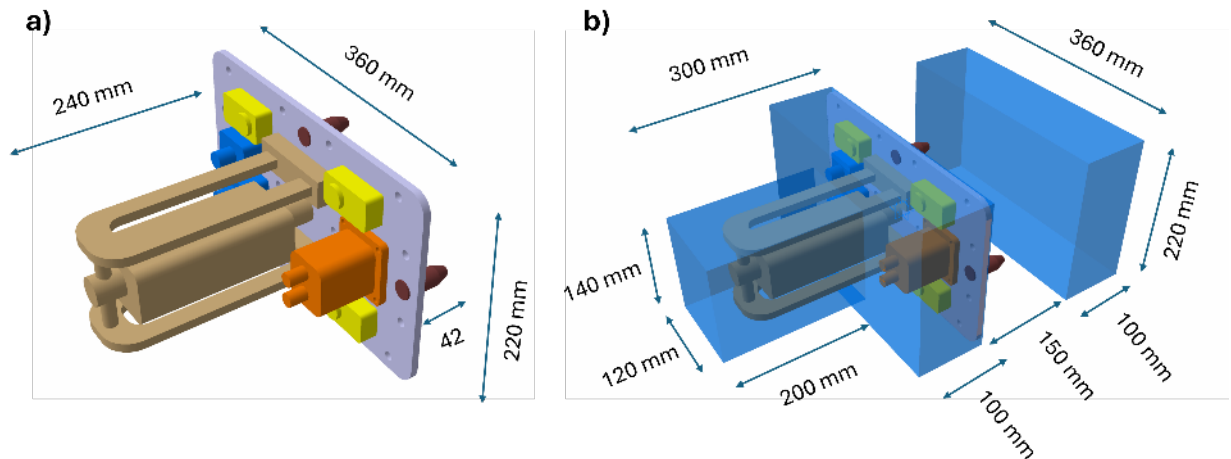


Figure 46: Assembly with dimensions in a) rear view of the component dimensions and b) dimensions of the whole assembly space holder (including space for moving parts and cables).

7.3.2 Control Cabinet and Operation

All the power and control electronics are located in the control cabinet. It is assumed that the Entrance Unit is permanently located on a rail CU. If this is not the case (e.g. storage or transshipment process), it is not envisaged that there will be people in the TU, or that this TU must guarantee 15 minutes of autonomous operation for safety reasons. For the Entrance Unit, it is therefore defined that the necessary control electronics are located in the CU and the other TUs communicate with the Entrance Unit via the CU. This keeps the Entrance module simple.

The 10 ft TU, on the other hand, requires its own control cabinet to guarantee 15 minutes of autonomous operation.

The electrical interface design reflects the modular nature of both the TU and CU:

- CUs must support different TU types (e.g. passenger, freight, entrance).
- TUs must be interoperable, allowing quick exchange between carriers via Handling Systems (HS).
- Interfaces must be standardized, enabling automated connection regardless of TU type or position within the CU.
- Electrical connectors should be positioned uniformly across different TU sizes (5 ft, 10 ft, 20 ft), simplifying system integration.
- The control cabinet configuration reflects this modular approach: For the Entrance Module, the control electronics are located in the CU, since the module is typically fixed in position. For 10 ft TUs, each unit includes a dedicated control cabinet to manage its systems and guarantee autonomous operation when not connected.

7.3.3 Energy flow and workflow operation

The electrical connection process follows a defined cycle: the TU is positioned and lowered into the CU, mechanical locks engage and are verified by sensors, protective covers open, and electrical connectors engage vertically. The High Voltage Interlock Loop (HVIL) connector is then activated to safely enable high-voltage circuits. Any failure in connection is detected immediately, disabling power transfer and alerting the control system.

Under normal operation, the Carrier Unit supplies power to the Transport Unit, while the TU's auxiliary battery supports autonomous operation for up to 15 minutes during handling or emergencies. The following sequence summarizes the electrical coupling process based on WP12's proposed workflow:

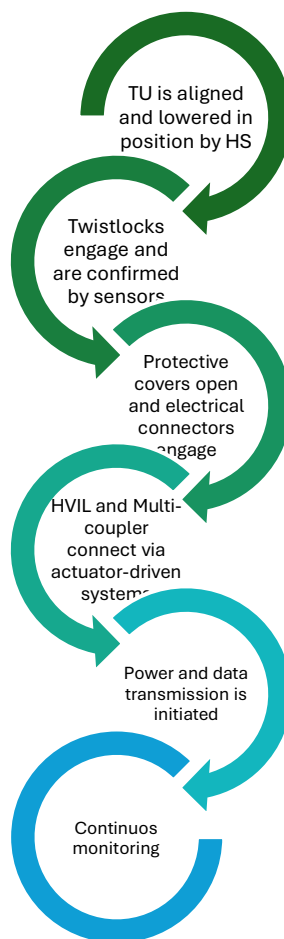


Figure 47: Electrical workflow process

- TU is aligned and lowered into position by the Handling System.
- Mechanical locks (e.g. twist locks) engage and are confirmed by sensors.
- Protective covers on electrical interfaces open automatically.
- HVIL and multi-coupler connections are engaged via actuator-driven systems.

- Power and data transmission is initiated once connection integrity is verified.
- Continuous monitoring of connection status, power flow, and system health is activated.

7.3.4 Safety regulatory and compliance

The electrical coupling system is designed to meet all relevant safety standards and regulations specific to the rail and transport sectors. It incorporates multiple layers of protection to ensure safe operation under all conditions. This includes fail-safe mechanisms that automatically disconnect power in case of faults or improper connections, minimizing the risk of electric shock or fire hazards. Real-time monitoring systems continuously track the status of electrical connections and signal any anomalies immediately. Compliance with international standards such as IEC, EN, and railway-specific norms (e.g., EN 50155, EN 45545) is a priority, guaranteeing that the system operates within the strict safety and environmental requirements mandated by regulatory bodies. Additionally, redundant communication and power circuits are implemented to enhance reliability and prevent operational interruptions.

7.3.5 Energy efficiency and impact

The design of the electrical coupling interfaces prioritizes energy efficiency, minimizing losses during power transfer between the TU and CU. By optimizing connector materials, contact surfaces, and transmission paths, the system reduces resistive losses and heat generation. This is not the focus of our project, but it can be expected, that this contributes to an overall more sustainable operation, reducing the energy consumption of onboard systems such as HVAC, lighting, and control electronics. The coupling system also supports integration with advanced energy management solutions, allowing for smart charging strategies and load balancing between multiple units. Such capabilities are crucial for maximizing battery life and reducing peak power demands, thereby improving the environmental footprint of the Pods4Rail system.

7.3.6 Flexibility and adaptability

The coupling system has been designed with modularity and adaptability in mind to accommodate the wide variety of Transport Unit and Carrier Unit configurations foreseen in the Pods4Rail project. This modular approach allows for easy adaptation to different TU sizes (e.g., 5, 10, 20 ft), payload types, and operational requirements without major redesigns. The positioning of the interface is therefore centred to every 5ft unit, in that way every possible combination can be managed. The electrical interfaces can be configured to support different voltage levels, data protocols, and power capacities, ensuring compatibility with future technologies and upgrades. This flexibility also facilitates integration across multiple transport modes and infrastructure types, aligning with the project's goal of a fully interoperable, supermodal transport system. Furthermore, the modular coupling design simplifies maintenance and future expansions, reducing downtime and lifecycle costs.

7.3.7 Maintenance and diagnosis

To ensure long-term reliability and safety, the coupling system is designed to facilitate easy maintenance and diagnostic procedures. Integrated sensors can monitor the health and status of both mechanical and electrical connections in real-time, detecting issues such as connection wear, insulation degradation, or contact resistance anomalies. This enables predictive maintenance and timely interventions, minimizing downtime and enhancing operational efficiency. Additionally, remote diagnostic capabilities support quick fault identification and troubleshooting without the need for physical inspection, which is especially valuable in automated and modular transport systems.

7.3.8 Conclusions and recommendations

The selected interface solutions - HVIL for power and multi-coupler for data and control - or a combination of both of it within one unit - offer:

- High safety through automated connection detection and shutdown features.
- Compatibility with modular and scalable transport configurations.
- Integration potential for both passenger and freight use cases.
- Compliance with international standards (ISO 1161, EN 50155, EN 15227, etc.).
- Readiness for automation and real-time monitoring, essential for future autonomous systems.

In terms of technical, integrational and operative recommendations, some of them can be listed below:

- Conduct further validation under operational conditions to confirm long-term reliability of the HVIL and multi-coupler systems in dynamic environments (e.g., vibration, temperature, humidity).
- Implement redundancy in monitoring sensors (for mechanical locks and HVIL status) to ensure fault tolerance and maintain system safety in case of single-point failures.
- Standardize connector layouts and dimensions across Transport Units (TUs) and Carrier Units (CUs) to facilitate interchangeability and simplify maintenance.
- Integrate self-diagnosis and predictive maintenance algorithms to detect connector wear, contamination, or misalignment before failure occurs.
- Develop a unified communication protocol for power, data, and diagnostic signals to ensure interoperability with different control systems.
- Perform electromagnetic compatibility (EMC) testing to guarantee stable data transmission alongside high-voltage power lines.
- Define clear maintenance and inspection intervals for couplers and locking systems, based on usage cycles and environmental exposure.
- Evaluate integration with autonomous coupling systems, enabling fully automated loading and unloading without human intervention.

- Collaborate with standardization bodies (e.g., CENELEC, ISO, IEC) to contribute to the evolution of modular transport interface standards.
- Assess cybersecurity implications of data coupling, ensuring secure communication channels between TU and CU systems.

7.4 Specific Interfaces for the HVAC system

There are three interfaces which must be considered for the air conditioning unit. These are:

- the mechanical connection between the HVAC system and the TU,
- the air ducts for distributing the conditioned air and
- electrical/miscellaneous connections (e.g. data transmission cables).

The air conditioning unit must be installed on the roof of the TU as specified in D4.4 (see Table 20). This can be done using bolted joints. If necessary, the air conditioning unit can be mounted using damping elements to prevent vibrations from being transmitted from the HVAC unit to the TU and vice versa.

In order to distribute the conditioned air inside the passenger compartment, it may be necessary to install air ducts alongside the TU walls, especially in the larger TUs (10/20 ft). This is particularly necessary if heating is integrated in the rooftop unit, as the heated air must be blown into the lower area of the passenger compartment. The different air routing in heating and cooling mode is shown in principle in Figure 48.

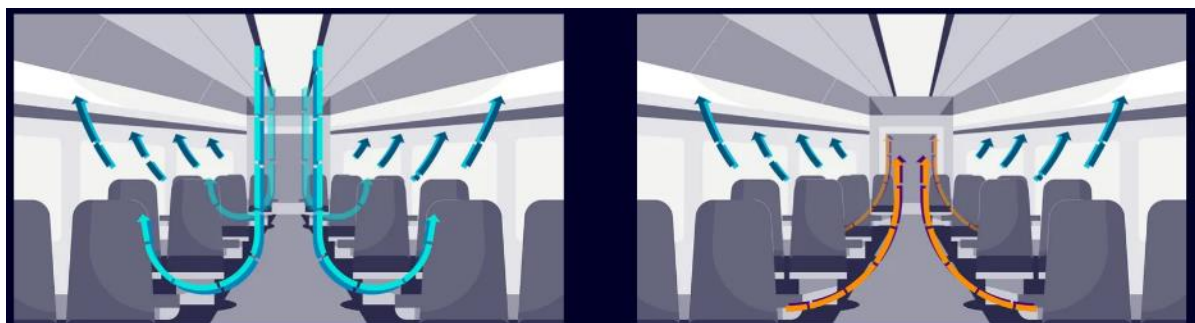


Figure 48: Air movement in the passenger compartment during cooling (left) and heating (right) (Siemens, 2025)

The HVAC system can be supplied with electrical energy via the TU's central power supply. This means that no separate connection is needed between the TU and CU. Converters may need to be provided in order to obtain the correct form of electrical energy.

Typically, a VCRS (heating unit, fans and compressor) is to be supplied with 3x400 V at 50 Hz. However, there are also systems which must be supplied with 600/750 V DC for heating (Konvekta, 2020), (Liebherr, 2025).

Depending on the model, the control unit of the system requires between 24 to 110 V DC. As the control unit can be installed in the housing of the HVAC unit or externally, additional connections may also be needed (e.g. CAN bus or Ethernet) (Konvekta, 2020), (Liebherr, 2025).

7.5 Telecommunication interface

According to the analysis carried out in WP7, complemented by the detailed comparison studied in Chapter 8 of this document, several technological solutions can be considered for communication interfaces assuring reliability and precision during signalling and connection among involved elements. In particular, new standards and techniques for vehicle to Everything (V2X) can be taken into consideration. The IEEE 802.11p and the successor IEEE 802.11bd has been developed for wireless access in vehicular environment, where short response in highly dynamic contexts is tacked.

A wireless access for vehicular environment with IEEE 802.11p and .11bd is suitable for highly dynamic vehicle to everything environments, without the need of specific infrastructure, and with self-configurable devices. It is based on the Physical and MAC layers of the IEEE 802.11 adapted to vehicular communications, including enhanced capabilities for reliable authentication and connections in dynamic and timely critical contexts.

Sidelink for direct device-to-device and V2X communication over 3GPP 5G NR (5G Sidelink), is based on 3GPP technology to establish direct communication but without cellular infrastructure. This approach provides high versatility and flexibility for dynamic communications with a robust and secure device-to-device data exchange. It allows different spectrum configurations, from license to non-license bands, bringing adaptability to a high range of devices. This will ultimately provide benefits in terms of interoperability and scalability.

The former one has the advantage of high testing and practical evaluations, so it can be a strong candidate for real implementation in the near future, while 3GPP 5G NR and it's successor 3GPP 6G can be candidates for long-term deployments. A comprehensive comparison can be found in 8.4.1.

7.6 Cybersecurity considerations

Autonomous pods rely heavily on wireless communication networks to ensure safe navigation, coordination, and interaction with passengers, infrastructure, and cloud-based control systems. However, this growing dependence on connectivity introduces a range of technical and security challenges that must be addressed to guarantee system reliability, data protection, and user trust.

A major issue lies in the complex communication environment in which these pods operate. High-speed movement, dense urban deployment, and heterogeneous networking technologies such as 5G, Wi-Fi 6E and V2X create demanding requirements for latency, coverage, and handover performance. The continuous exchange of control and sensor data between pods, roadside units, and central management systems must be achieved with

ultra-low latency and high reliability in order to avoid service disruptions or collisions. Furthermore, interoperability across different communication standards and operators presents additional integration challenges.

From a security perspective, the pod ecosystem introduces multiple attack surfaces that include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and cloud communication channels. Specifically, there is also a specific point related to communications between the pod and the carrier. Potential threats such as spoofing, jamming, data interception, or unauthorized access could compromise not only service continuity but also passenger safety and privacy. The integration of artificial intelligence and edge computing further expands the attack landscape, making cybersecurity a central design priority.

Several solutions and research directions are being explored to address these challenges. On the connectivity side, the adoption of multi-access edge computing (MEC) and network slicing in 5G and 6G architectures can provide adaptive, low-latency communication tailored to each pod's operational context. Hybrid communication frameworks that combine cellular, short-range (Dedicated Short-Range Communications (DSRC) or Wi-Fi), and satellite networks can enhance coverage and redundancy. At the same time, the application of security-by-design principles such as mutual authentication, end-to-end encryption, intrusion detection, and secure key management is essential to ensure trust and resilience. Emerging technologies including blockchain-based identity management and quantum-resistant cryptography also offer promising protection mechanisms for future deployments.

Post-Quantum Cryptography for Future-Proof Security

As pod-based transport systems and the communications between the pod and the carrier evolve toward large-scale deployment, their communication and control infrastructures will rely increasingly on cryptographic mechanisms to ensure confidentiality, integrity, and authentication. Current security protocols are largely based on public key algorithms such as RSA (Rivest, Shamir, Adleman) and elliptic curve cryptography (ECC). While these methods are considered secure against classical computing attacks, they are vulnerable to the computational capabilities of quantum computers. A sufficiently powerful quantum computer could solve the mathematical problems on which these algorithms are based, making current security systems ineffective.

To mitigate this emerging risk, the research community and standardization bodies are actively developing post-quantum cryptography (PQC) algorithms. PQC refers to cryptographic techniques designed to resist both classical and quantum computational attacks. These algorithms rely on hard mathematical problems unrelated to integer factorization or discrete logarithms, such as lattice-based, hash-based, code-based, and multivariate polynomial problems.

In the context of pod-based transport systems, PQC can play a crucial role in several areas. First, it can secure vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications by providing quantum-resistant authentication and key exchange mechanisms. This ensures that messages exchanged between pods and control centres remain confidential and tamper-proof even in a post-quantum era. Second, PQC can protect the software update processes of autonomous pods, preventing malicious entities from injecting unauthorized code through digital signature forgeries. Third, PQC can strengthen

data storage and cloud connectivity, particularly where long-term confidentiality is required for mobility records, passenger data, or operational analytics.

To implement PQC efficiently, system designers must address several practical considerations. Post-quantum algorithms typically require larger key sizes and higher computational resources compared to conventional cryptography. Therefore, hybrid schemes that combine classical and quantum-resistant algorithms are recommended during the transition period. These schemes preserve compatibility with existing infrastructure while progressively enhancing security. Hardware acceleration optimized cryptographic libraries, and integration at the network edge can also help to minimize latency and energy overhead.

The European Union and global standardization organizations such as NIST and ETSI are currently defining and validating PQC standards to support their adoption in future communication systems. Integrating these standards within the design of pod-based mobility platforms will ensure that European transport networks remain secure and resilient in the face of technological change.

Table 33: Overview of Cryptography algorithms

Algorithm Family	Underlying Principle	Main Advantages	Typical Limitations	Potential Applications in Pod Transport Systems
Lattice-Based Cryptography	Based on the hardness of lattice problems such as Learning With Errors (LWE)	High efficiency, strong security proofs, suitable for key exchange and encryption	Larger key sizes compared to ECC or RSA	Secure V2V and V2I communication, quantum-resistant key exchange, authentication protocols
Hash-Based Cryptography	Relies on one-way hash functions and Merkle trees	Well-understood security, efficient signature verification	Limited use for encryption, larger signature sizes	Secure firmware and software updates, digital signatures for system integrity
Code-Based Cryptography	Based on the difficulty of decoding random linear codes	Proven security, long history of study, resistant to both classical and quantum attacks	Very large public keys	Secure cloud communication, data confidentiality for fleet management systems
Multivariate Polynomial Cryptography	Uses systems of multivariate quadratic equations over finite fields	Fast operations, suitable for embedded systems	Key generation can be complex, signature size may be large	Lightweight authentication for onboard sensors and embedded controllers
Isogeny-Based Cryptography	Relies on the difficulty of finding isogenies between elliptic curves	Small key sizes, suitable for constrained environments	Computationally slower, relatively new field	Lightweight key exchange in edge devices and low-power communication nodes

The cybersecurity challenges identified for autonomous pod-based transport systems closely replicate those observed in other highly automated and connected rail and mobility concepts, such as Virtually Coupled Train Sets (VCTS) (EU-Rail Flagship Area 2) (Kumar, 2020). Similar to autonomous pods, VCTS architectures rely on continuous, low-latency wireless communication between mobile units, infrastructure elements, and central control systems to maintain safe and efficient operations. As demonstrated in the VCTS cybersecurity risk assessment, increased

connectivity and system integration significantly expand the attack surface, making cybersecurity a critical enabler rather than a secondary concern.

In particular, the VCTS study highlights how wireless communication channels introduce vulnerabilities related to spoofing, tampering, denial-of-service, and unauthorized access—threats that are equally relevant to pod-based ecosystems operating in dense, heterogeneous communication environments. The division of VCTS into onboard and trackside security zones and the systematic evaluation of risks using the this threat model underlines the importance of structured, standards-based risk assessment approaches. These findings reinforce the need for autonomous pods to adopt similar security-by-design principles, ensuring that communication between pods, infrastructure, cloud services, and carriers is protected against both accidental failures and deliberate cyberattacks.

The long operational lifetimes expected for both railway systems and autonomous pods make future-proof security a strategic necessity. The transition toward post-quantum cryptography, aligns with the innovative approach represented by VCTS, where long-term confidentiality, integrity, and compliance are key drivers of cybersecurity requirements. Integrating quantum-resistant cryptographic mechanisms into pod-based transport systems can therefore be seen as a natural extension of established cybersecurity practices in safety-critical transport domains, ensuring resilience against emerging technological threats while supporting scalable and interoperable mobility solutions.

8 Concept proposals for localisation and communication

The objective of this task is to analyse advanced sensing and communication technologies to enable precise localization, tracking, and trajectory prediction of the Transport Unit (TU) and between TU and Carrier Unit (CU). To achieve this, various types of sensing devices are identified and evaluated, ensuring accurate positioning even in complex environments. The localization subsection is specifically oriented to the transport unit.

Another key goal is to assess and integrate modern communication technologies such as 5G and Ultra-Wideband (UWB), while also addressing cybersecurity requirements. These technologies are essential for enabling real-time data exchange and secure operation within an automated and connected transport system.

Different types of sensing devices are defined to locate and track the pod to detect the location of the pod and predict the trajectory. Communications standards such as 3GPP 4G LTE, 3GPP 5G NR, IEEE802.11, ETSI ITS-G5 or IEEE802.15.4 are also considered here.

8.1 Introduction

Building on the outcomes of WP4.4 and WP7, different technical concepts are being analysed to support different TU use cases as core components of the automation strategy:

- For localization:
 - o Magnetic field-aided TU localization and identification: This concept forms part of a multi-sensor localization approach that includes Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU). It is designed to ensure reliable positioning in GNSS-degraded or denied environments, such as indoor or underground hubs. Additionally, it enables the identification of different TUs or carriers by leveraging their unique magnetic signatures.
 - o To consider the diversity of environments crossed by the Pod and of dynamics of the CU, an adaptive GNSS-based localization solution is proposed that relies on machine learning models for context detection and adaptive position estimators.
- For communication
 - o Direct V2X communications between CU and transport unit TU considering different frequency range for short and long range communications but also Software Define Network (SDN) capabilities.
 - o Short-range communication and ranging between pods or between CU and TU: This concept will provide a direct wireless Ultrareliable Low Latency Communication (URLLC) between a CU and TU or between nearby units. URLLC enables cooperative, connected, and automated mobility of pods by exchanging in real-time control and sensor information for situational awareness and decision making. Furthermore, communication and ranging enables redundant relative localization augmenting the magnetic field aided pod localization.

8.2 Requirements and Performance criteria for communication and localisation

8.2.1 Communications

Communication requirements will induce system performance criteria that are more or less constraining. They will impact the choice of the communication standard, related technologies and the system architecture. It is important here to remind that in the transport domain, data exchange applications can be classified into two main families: safety critical applications, and non-safety critical applications addressing passenger or maintenance purposes. Generally, when safety is involved, a safety layer is added at the application level to guaranty the System Integrity Level (SIL). Safety related applications concern generally SIL4 systems. They generally require the following aspects:

- Availability: high availability of the connectivity system is key for transferring the data from the pod to the control units. The coverage of certain distance is necessary for communication between the pods to guaranty continuity of service.
- Reliability: very low message error rate, very low age of information and high resistance to interference is required for safety critical applications. These requirements are even more stringent for V2X communication and the control of moving pods.
- Low Latency: The latency requirements vary strongly for different applications. The control of moving vehicles or of a platoon of moving vehicles result in the most demanding latency requirements with very low or ultra-low latency.
- Data rate: data rates need to be adjusted to the corresponding application. Not all applications require high data rates. Due to the limited channel capacity, a trade of between data rate and latency requirements need to be achieved for each application. High data rate capability can allow message repetition to guaranty robustness (very low message loss rate) that is required for safety related applications.

New challenging applications such as remote control of trains will require very high data rate (e.g. for video surveillance) and low latency (e.g. for control). Example of communication requirements for V2X applications in the automotive and rail domain are given in D11.1.

8.2.2 Localisation

According to D2.1 deliverable, transport unit and autonomous driven transport vehicle are separated and it is possible to use both individual pods that travel and move from one means of transport to another, as well as combined units for public transport or simple freight containers. Both are managed by a Mobility Management System (MMS), which is responsible for all aspects of the general operation of the system in its environment. We must then consider that both will then require to be located: the pod and the carrier vehicle,

and that use cases will cover autonomous vehicle cases as well as public transport, rail operations etc.

The main operational requirements for localization in the scope of the pods concept are:

- Along-track localization: determination of the absolute position of a vehicle on a track.
- Track selectivity (cross-track localization): determination of the track on which the vehicle is, in particular in the case of neighbouring parallel tracks and after switches.
- Ubiquitous availability: the availability of the localization in different environments (e.g. in open-sky conditions, in tunnels)
- Multimodal availability: the availability of the localization for different modes of transport (e. g. rail, road, cable car).

Localisation performance is mainly defined by the following criteria:

- Availability: is the percentage of time the position, navigation or timing solution can be computed by the user. System availability: the percentage of time the system allows the user to compute a position. Overall availability considers the receiver performance and the user's environment.
- Accuracy is the difference between true and computed solution (position or time).
- Continuity is the ability of a system to perform its function (deliver PNT services with the required performance levels) without interruption once the operation has started. It is usually expressed as the risk of discontinuity and depends entirely on the time frame of the application.
- Integrity is a term used to express the ability of the system to provide warnings to users when it should not be used. It is the probability of a user being exposed to an error larger than the alert limits without timely warning.

The performance requirements and the use cases will clearly dimension the choice of the sensor(s) and their combination.

If the MMS is responsible for pods tracking, requirements will follow typical non-safety critical requirements, but in case the Pod system is using standardised autonomous driven transport or rail, the transport system will follow safety-critical requirements.

8.3 Overview of relevant results from other WPs

Work Package 7 established in D7.1 the initial technical concepts and design constraints for the Pods System. These findings formed the foundation for Work Package 12, which refined and formalized the system requirements and developed a detailed mechanical coupling concept between the TU and the CU. Work Packages 10 and 11 complement these efforts by addressing data communication.

Additionally, the work carried out in WP4 and detailed in the deliverable D4.4 defines the high-level functional requirements for the overall Pods System. Deliverable D4.4 defines several key requirements related to the communication systems of the Pods4Rail carrier unit. The carrier must be capable of operating with short-range communication

technologies, which are expected to provide high-bandwidth and low-latency connectivity suitable for inter-unit coordination. In addition, the short-range communication system shall enable redundant relative localization between the TU and the CU, thereby improving positional accuracy and ensuring operational safety. Candidates for short-range communication and ranging are e.g. 3GPP 5G NR V2X, IEEE802.11bd or IEEE802.15.4 UWB as listed in Table 34. The communications need to be secured by cybersecurity mechanisms to safeguard communication interfaces and data exchange within the overall Pods System. These combined requirements establish the foundation for a robust, secure, and high-performance communication architecture to support full system integration.

8.4 Communications

8.4.1 Wireless technologies candidates

Based on existing works, different technologies can be considered namely IEEE802.11, ETSI ITS-G5, 3GPP 4G LTE, 3GPP 5G NR, IEEE 802.15.4 UWB, LEO satellite systems. Future technologies for wireless communication like the hybridization of several radio access technologies, the Integration of Sensing and Communications (ISAC) in the same device and Reconfigurable Intelligent Surfaces (RIS) may be of interest. For more flexibility the development of adaptive communication system inspired from cognitive radio technology could be appropriate. The following Table 34 presents a comparison of different wireless technologies candidates and communication standards.

Table 34: Comparison of communication Standards

Technology	Frequency ranges or bands	Frequency (GHz)	Bandwidth (MHz)	Data Rate	Range	Latency (ms)	Tx Power (dBm)	Mobility	Protocol / Standards	Supported V2X modes
4G LTE		0.45-5.9	1.4-20						3GPP Rel. 12/13	V2I
4G LTE-V2X	ITS	5.9	10, 20	27 Mbps	1 km	15	23	Yes	3GPP Rel. 14/15	V2X
5G NR	FR1	0.4-7	5-100		400 m			Yes	3GPP Rel. 15	V2I
5G NR	FR2	24-100	50-2000	10 Gbps	100 m	1		Limited	3GPP Rel. 16/17	V2I, TU-to-CU
5G NR V2X	ITS	5.9	10, 20, 40		2 km		23	Yes	3GPP Rel. 16/17	V2X
5G NR V2X	FR2	24-100	50-2000		100 m	1		Limited	3GPP Rel. 18	V2X
6G	FR1	0.4-7	5-100			0.1		Yes	3GPP Rel. 21	V2I
6G	FR2	24-100	50-2000	100 Gbps	100 m	0.1		Limited		V2I, TU-to-CU
6G	FR3	7-24			1 km	0.1		Yes		V2I

Technology	Frequency ranges or bands	Frequency (GHz)	Bandwidth (MHz)	Data Rate	Range	Latency (ms)	Tx Power (dBm)	Mobility	Protocol / Standards	Supported V2X modes
6G	THz	100-3000		1 Tbps	10 m	0.1	-	No	IEEE 802.15.3d	TU-2-CU
6G V2X	ITS	5.9						Yes		V2X
6G V2X	FR2	24-100	50-2000					Yes		V2X
Wi-Fi 6		2.4, 5	160	9.6 Gbps	150			Limited	IEEE 802.11ax	V2I, TU-to-CU
Wi-Fi 6E		2.4, 5	160	9.6 Gbps	150			Limited	IEEE 802.11ax	V2I, TU-to-CU
Wi-Fi 7		2.4, 5, 6	320	46 Gbps	150			Limited	IEEE 802.11be	V2I, TU-to-CU
Wi-Fi 8		2.4, 5, 6	320					Limited	IEEE 802.11bn	V2I, TU-to-CU
ITS-G5 rel 1	ITS	5.9	10	27 Mbps	1 km	10	23	Yes	IEEE802.11p	V2X
ITS-G5 rel 2	ITS	5.9	10- 20		2 km	1	23	Yes	IEEE802.11b d	V2X
ITS-G5 rel 2	ITS	65	2000					Yes	IEEE802.11b d	V2X
UWB		3-10	500, 1000	1 Gbps	100 m	1	-41.3	Yes	IEEE802.15.4	V2X
RFID		0.125-0.96	-	Up to 640 kbps	~10 m	1	-	Limited	ISO/IEC 18000	V2X
NB-IoT (Cat-NB1/2)		0.9, 1800	0.2	26 kbps(DL), 62kbps(UL) / 127kbps(DL) 159kbps (UL)	Rural: 35 km; Urban: 8 km	1000	20, 23	limited	3GPP Rel. 13/14(NB-IoT)	-
LoRa		0.433, 0.868 (EU)	0.125, 0.25, 0.5	50 kbps	Urban: 5 km; Rural: 35 km	1000	14-20	Yes	LoRaWAN 1.0/1.1	V2I
ETSI TETRA								Yes		V2X
LEO Satellite Com			5-400	1 Gbps	-	20-100	-	Yes	Starlink, IRIS ² , OneWeb	V2I, V2N

The technical parameters in this table are based on the pods system, the following are notes for the symbols used in the table.

Note I

The technical parameters in this context are based on the Pods system configuration. 6G is expected to operate in addition to Frequency Range (FR) 1 and FR2 in FR3 and in THz frequency range. In the future, it may support V2S (Vehicle-to-Satellite Communication) and ISAC (Integrated Sensing and Communication). Communication in the FR2 (24-100 GHz) and in the ITS band at 65 GHz, is used for short-range, high-speed vehicle-to-everything (V2X) communication (V2V, V2I, Vehicle to Network(V2N)), and may support high-precision positioning and environmental sensing. Wi-Fi 6E (IEEE802.11ax) has a maximum rate of 9.6 Gbps, while Wi-Fi 7 (IEEE802.11be) is expected to reach 46 Gbps, depending on channel aggregation and spectrum utilization. The THz band (0.1-3 THz) has a limited communication range and could be used in the Pods system for in-vehicle sensor communication, such as high-resolution radar and ultra-high-speed data exchange.

The communication range values in the table are based on typical usage scenarios (urban/rural), antenna gain, and channel models (LOS/NLOS). The actual values may be affected by the environment, power, obstacles, and spectrum scheduling strategies.

The latency values in the table are “nominal” values. The actual latency may fluctuate due to factors such as network load, interference, and scheduling strategies. The values are based on 3GPP/IEEE specifications and experimental data.

The general term of V2X modes include the following terms from the road and rail domain, and specific pod communication links:

- vehicle-to-infrastructure (V2I), train-to-ground (T2G), Pod-to-infrastructure
- vehicle-to-vehicle (V2V), train-to-train (T2T), Pod-to-Pod
- vehicle-to-pedestrian (V2P), train-to-trackside, Pod-to-pedestrian, pod-to-trackside
- TU-to-CU

The wireless communication technologies in the table can be divided in four categories:

i. High-performance main communication (Primary operational link)

Supports high-speed, highly reliable communication between Pods and between Pods and infrastructure, and handles scheduling, coordination, and control tasks.

- 4G LTE-V2X: Current commercial mainstay, supporting platooning, obstacle avoidance, and lane changing
- 5G NR-V2X: Core standard for future Pods networks, featuring low latency and high reliability
- ITS-G56G: Future-oriented ultra-high-speed, intelligent sensing communication platform
- ITS-G5 rel 1: Widely deployed in Europe
- ITS-G5-rel 2: high performance for V2X communication

ii. High-precision sensing and auxiliary positioning (Positioning and docking support)

Achieve centimetre-level or higher precision positioning in scenarios such as pod docking, formation, docking, and precise transfer.

- UWB: High accuracy (centimetre-level), interference-resistant, suitable for spacecraft docking and parking positioning
- ITS-G4 rel 2 65 GHz, 5G NR V2X FR2: high data rate communication and high-precision ranging
- 6G V2X FR2: high data rate communication + high-precision sensing (supports ISAC)
- 6G THz: Ultra-short range, very high data rate, high positioning accuracy (experimental)

iii. Supplementary and emergency communications (Back up)

Used for status feedback, resending scheduling signals, or environmental monitoring in the event of a main link disconnection or blind spot.

- NB-IoT: Widely deployed in Europe, suitable for low-frequency remote heartbeat and status uploads
- LoRa: Can be deployed in rural areas for low-speed Pod status monitoring
- LEO Satellite Communication: Maintains minimum communication capability in extreme blind spots (e.g., mountainous areas, suburbs)

iv. Transshipment centre / Static platform connection (Station/Cloud Link)

High-speed communication and data synchronization between static areas (such as transfer centres and railway platforms).

- Wi-Fi 6, 6E, 7, 8: High bandwidth, low latency, suitable for data synchronization and control in hotspot areas
- 5G NR FR2, 6G FR3, 6G FR2, 6G THz: Can be used for platform-side data push, high-speed video/map downloads
- RFID, UWB: Platform management, automatic positioning and identity recognition of pods when docking.

The technologies mentioned in Table 35 are not necessarily all applicable to Pods; they represent potential applications across various aspects of communication. This provides a reference for selecting technologies.

Table 35: Communications technologies

	User Disptach Center	MEC /Infrastruct ure TU/CU/Pod	TU - CU, Docking	TU - CU, Running	Pod - Pod Rail	Pod - Pod Road
4G LTE						
4G LTE-V2X, 5.9 GHz						
5G NR, FR1						
5G NR, FR2						
5G NR V2X, 5.9 GHz						
5G NR V2X, FR2						
6G, FR1						
6G, FR2						
6G, FR3						
6G, THz						
6G V2X, 5.9 GHz						
6G V2X, FR2						
Wi-Fi 6/6E/7						
ITS-G5 rel 1, 5.9 GHz						
ITS-G5 rel 2, 5.9 GHz						
ITS-G5 rel 2, 65 GHz						
IEEE.15.4 UWB						
RFID						
NB-IoT (Cat-NB1/2)						
LoRa						
TETRA						
LEO Satellite Comm.						

not applicable

average applicable

good applicable

8.4.2 Proposed SDN framework

Pods, CU and TU need to communicate and coordinate not only between them, but also with other traditional moving and fixed nodes including vehicles, passengers, road/railway side infrastructures, etc. Such system requires to have a communication architecture that integrate with other existing communication infrastructure such as vehicular communication, cellular networks, communication in the railway infrastructure, etc. On this

regard, the designed communication architecture necessitates programmability, low-latency, and flexibility in deployment. These features can be particularly enabled by incorporating one or more of the emerging technologies such as Software Defined Networking (SDN), Network Functions Virtualization (NFV), Network Slicing, Multi-Access Edge Computing (MEC), *etc.* (Taleb, 2017).

As in a conventional communication architecture, the Pods/Pod-Carriers and other elements are interconnected using wireless links to form a communication network. Integrating SDN, both network and nodes could be managed dynamically by (re)configuring routing policies and controlling data traffics. SDN could provide a centralized management of control logic, decoupling the control plane from the data plane, enabling more flexible and efficient network path scheduling, resource allocation, and traffic control (Taleb, 2017). However, to support advanced mobility services such as those envisioned in the Pods4Rail system—characterized by high dynamism, real-time responsiveness, and multi-node coordination. Conventional centralized SDN solutions may face limitations, these include potential bottlenecks, single points of failure, and delayed responsiveness under highly dynamic wireless conditions (Assegie, 2019).

To address these challenges and further enhance the system's adaptability and responsiveness, we explore a distributed SDN architecture that shifts part of the control intelligence toward the edge (Figure 49). The programmability of SDN can be extended by incorporating NFV, which decouples network functions from dedicated hardware and supports dynamic orchestration (Taleb, 2017). Moreover, with the advancement of embedded computing, edge nodes (e.g., roadside and trackside units) are evolving beyond passive relays, gaining computing, storage, and decision-making capabilities (Liu, 2021b). By integrating MEC, these nodes can perform local control and real-time processing, enabling ultra-low latency services and robust operation under complex, real-world conditions.

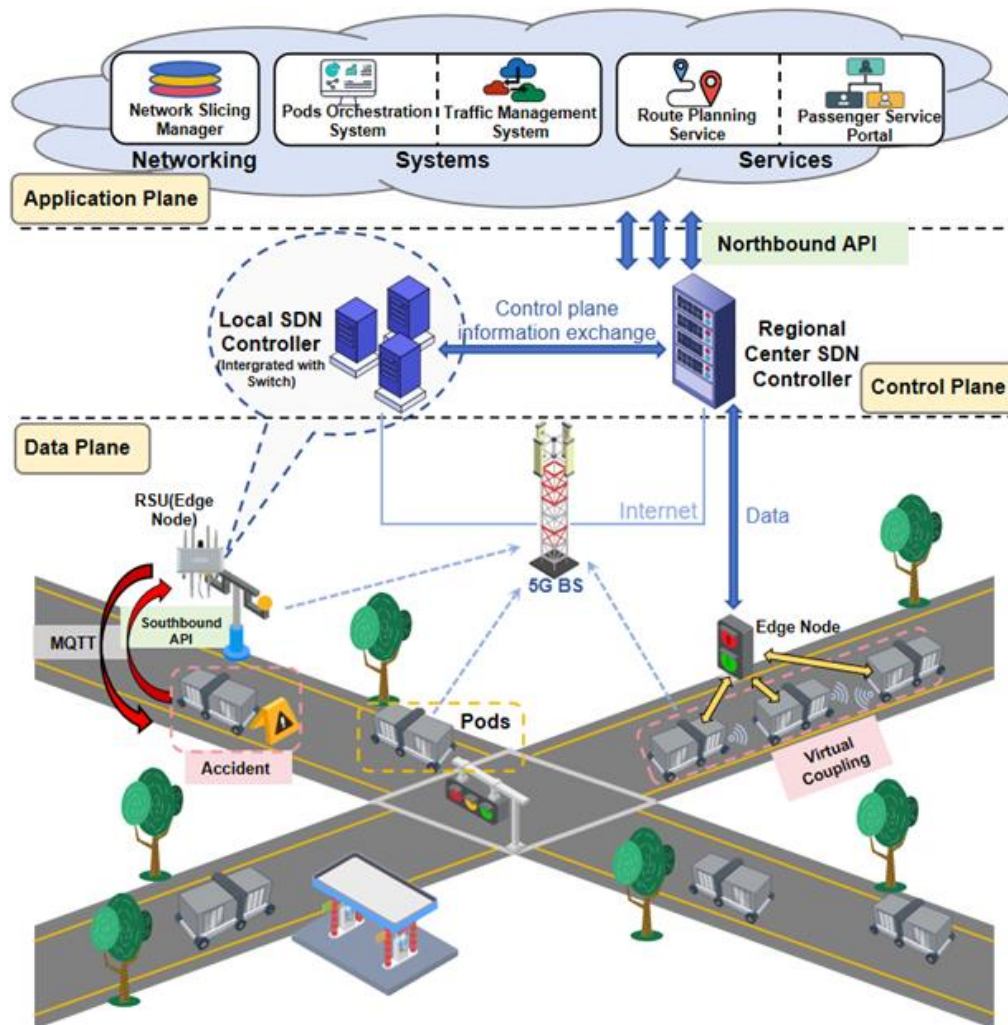


Figure 49: System-Level SDN Enabled Distributed Architecture

This layered SDN control architecture integrates regional centre controllers and local edge controllers to build an autonomous driving pod communication control system with layered decision-making, dynamic perception, and flexible scheduling capabilities.

From a top-down perspective, various service modules in the application plane (such as route planning, passenger services, and traffic management) formulate global control strategies based on different business scenarios. These strategies are managed and distributed by the regional centre controller in the control plane, which then sends them to local edge controllers (deployed at key nodes such as traffic lights, cameras, and RSUs) to execute local operations on Pod nodes, such as dynamic switching of communication interfaces, low-latency data forwarding, signal intervention, and cooperative formation management (such as virtual formation).

From a bottom-up perspective, Pod nodes in the data plane continuously monitor and report critical data such as communication quality (QoS), travel speed, location coordinates, congestion status, and potential safety risks to edge controllers. The edge controller can calculate and quickly formulate scheduling strategies in real time based on the local

environment, directly control the behaviour of relevant Pods, and synchronously feedback important status information and strategies to the regional centre controller, achieving global consistency and closed-loop feedback of the system state.

As a result, this architecture significantly reduces the computational and communication pressure on the central controller, achieves control and decision-making logic offloading to edge nodes, and possesses excellent scalability and fault tolerance. In certain emergency or extreme situations (such as communication interruptions or accident handling), the system even allows Pod nodes to make autonomous decisions, achieving partial autonomy, thereby constructing an intelligent, autonomous, and resilient cooperative traffic communication system. The performance of this architecture is under study with different wireless technologies.

8.5 Localisation

8.5.1 Localisation solutions

Over the last two decades, most of the solutions developed and deployed for localisation rely on satellite signals thanks to the American GPS (Global Positioning System) or more generally to GNSS (Global Navigation Satellite Systems) including Galileo, Glonass and Beidou satellites. However, in land transport environments, satellite signals may not be received because of blocking obstacles such as tunnels or deep indoor environments for example or signal propagation may be degraded with reflections or diffractions on these obstacles that will degrade GNSS performance. Some complementary sensors can then be deployed to compensate in GNSS-denied environments or to enhance performance in a fusion scheme.

As an example, to ensure a high level of accuracy as well as integrity for signalling applications (but not only), the ERTMS User group structures a train locator based on the following sensor: Eurobalise, GNSS, IMU, optical sensors, digital map... (figure 3). This use case is certainly the most stringent one in the list of the railway applications and may be not necessary for Pods4rail.

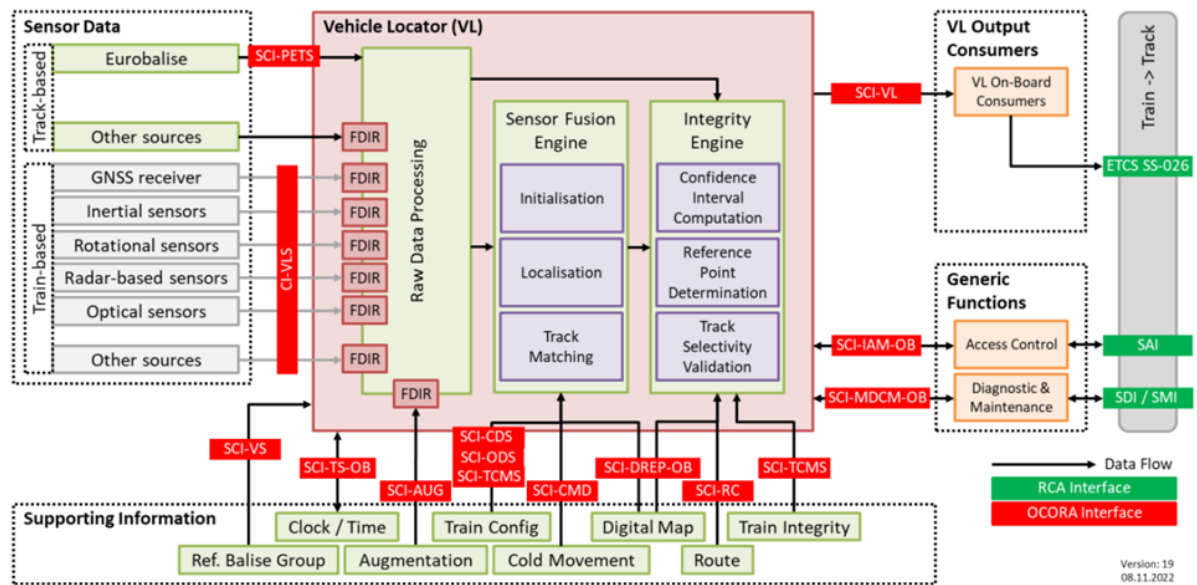


Figure 50: Informative preliminary visualisation of Localization on Board (LOC-OB) insights
(Source: (EUG WG, 2023))

8.5.2 Adaptative GNSS-based solution

Depending on the vehicle (rail, road, cable car/funicular...) with different dynamic models, the localisation unit will benefit from an adaptive solution. Using diverse transport modes as the Pods will, an onboard GNSS-based system will have to answer different requirements and will face various constraints as signal reception conditions. In order to answer all these requirements and offer optimal performances in every condition, the capacity of the system to adapt to the conditions is of main interest. Context-aware localization has emerged as a promising solution for adjusting positioning systems to dynamic environmental conditions. By analyzing GNSS data, including Carrier-to-Noise Ratio (C/N0), pseudo ranges, satellite elevations, and Dilution of Precision (DOP), commonly used in some literature (Zhu 2024), (Liu 2021a), and (Ding, 2023), along with contextual information such as the environment type, positioning solutions can be dynamically adjusted to improve accuracy under various conditions. Machine learning (ML) has emerged as a powerful tool, providing accurate classification and real-time adaptability, thereby significantly improving context detection and the dynamic adjustment of positioning systems. The approach focuses on leveraging GNSS and image data (when available), with machine learning algorithms for environmental context detection, aiming to enhance positioning performance, particularly in challenging environments where traditional positioning systems may not perform optimally. This context information can be used to select the optimal navigation estimator considering satellite state of receptions. Regarding this state of the art, the concept proposed aims to provide a smart adaptation and mitigation of these effects, merging work performed for context detection and classification and different weighted least squares for position estimation.

In (Chaiben, 2025) we propose a GNSS/vision-based environmental context detection system using Multi-Layer Perceptrons (MLP), Support Vector Machines (SVM), K-Nearest Neighbors (KNN) and Random Forest (RF) machine learning models to identify contexts as Open-sky, Urban, Canyon and Trees. The models are trained and evaluated using GNSS signal data collected from a public database. The evaluation shows that the considered models performed well, especially MLP and RF, for both distinguishing Mix/Non-Mix and primary classes environments. The evaluation of the models showed improvements in classification performance, with the MLP model achieving an accuracy of 96.5%, KNN reaching 95%, and RF achieving 99.9% as the best-performing model in the first classification stage, while the SVM model achieved 79.2%. Similarly, in multi-class classification, MLP, KNN, and Random Forest consistently outperformed the SVM.

A second step is to provide an optimal Weighted Least Square solution that optimally fits the context or conditions of receptions. In the literature, the implementation of Weighted Least Squares (WLS) has been investigated to mitigate local errors and enhance reliability of GNSS-based solutions. Considering GNSS observations, literature proposes different weighting schemes relying either on C/N0 or satellite elevation considering that the C/N0 will vary with the elevation of the arriving signal and that lowest elevated satellites are more likely to be affected by propagation errors. Most investigated ones with the elevation are the model published by (Groves, 2013) based on an exponential elevation based weighting scheme or the model used in (Medina, 2018). As C/N0 reflects both satellite elevation and propagation conditions, the model introduced by (Hartinger, 1999) (Kuusniemi, 2007) links variance to C/N0. (Marais, 2025a) adds some new models based on experimental datasets and compares performance with different weighting schemes and depending on the reception context.

The complete concept will then combine context detection and optimal WLS to propose an adaptive positioning solution as developed in (Marais 2025b).

8.5.3 Magnetic field-based localization

Magnetic field-based localization can be used as a supplement to GNSS as it works completely independent from GNSS. It is based on the observation that the magnetic field along a railway line is subject to time-persistent but position-dependent distortions which are caused by ferromagnetic material in and next to the track (see Figure 51).

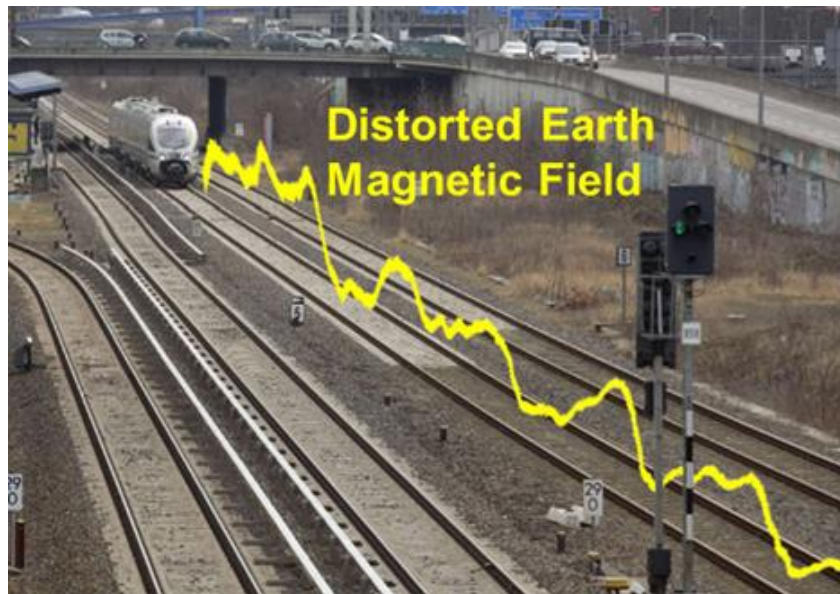


Figure 51: Magnetic field dependence on the position along a railway line

As can be seen in Figure 51, the earth magnetic field depends on the position along a railway line due to magnetic distortions caused by ferromagnetic material in and next to the track.

These disturbances of the magnetic field create a signal over the course of the track which is called magnetic signature. Using a map of the magnetic field recorded in prior, it is therefore possible to localize a rail vehicle with measurements from a smartphone-grade passive magnetic field sensor mounted on the vehicle. The current position of the vehicle is calculated by comparing the current measurements with the map using a signature similarity approach in combination with an odometer (Heirich, 2017) or a particle filter approach relying only on magnetic field measurements (Siebler, 2018a). The magnetic map can be generated e.g. by using a Simultaneous Localization and Mapping (SLAM) approach with an odometer only but without the need of knowing the absolute position along the railway line while the map is recorded (Siebler, 2024). One specific advantage of magnetic field-based localization for the usage in the pods concept is its availability in a wide range of environments. Firstly, it provides continuous Absolute positioning also in GNSS-denied environments such as tunnels or indoor hubs (ubiquitous availability) as well as in case GNSS does not provide reliable position information due to jamming or spoofing. Secondly, it is also independent of track-side infrastructure (e. g. balises) and the type of transport mode. Thus it can not only be used on railway lines but also e. g. on the road, in indoor facilities and on cable cars (multimodal availability). The feasibility of magnetic field-based localization has already been shown for indoor navigation (Frassl, 2013, Siebler 2023) and on the road (Shockley, 2014). Concerning the feasibility on cable cars, the validity of the aforementioned underlying principle of time-persistent magnetic signature for has been shown in the scope of the Pods4Rail project (see Figure 52).

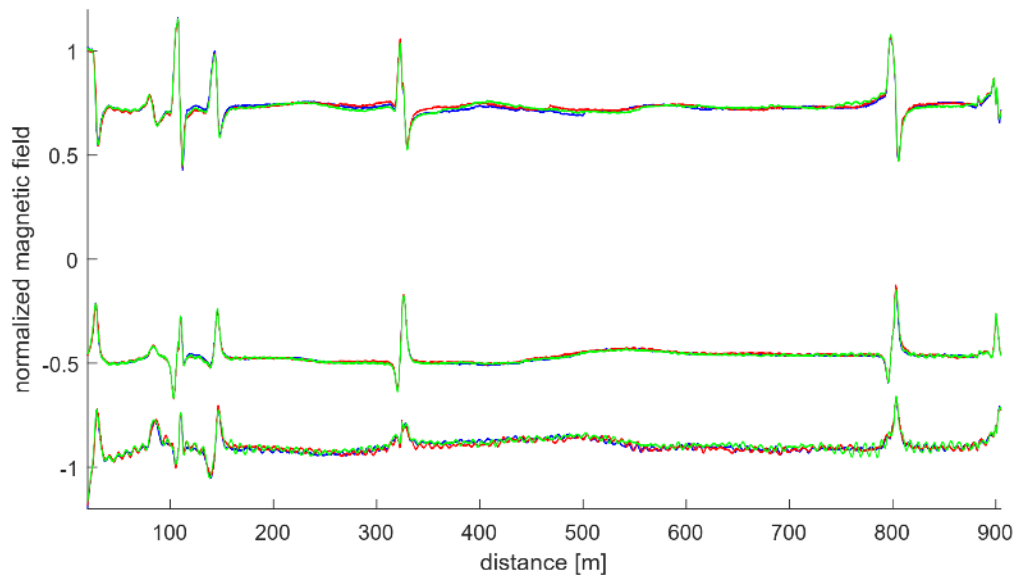


Figure 52: Magnetic field components as a function of the distance to the starting point

Figure 52 shows the magnetic field components as a function of the distance to the starting point for three different runs (blue: first run, red: second run, green: third run) on a cable car. The data have been collected during a measurement campaign carried out by DLR in the scope of the Pods4Rail project on a cabin of Kölner Seilbahn GmbH in Cologne. The upper three graphs represent the component in the direction of travel (horizontal component) while the graphs in the middle represent the vertical component and the lower graphs represent the lateral component of the magnetic field.

The magnetic signature on the cable car is strongest near buildings and near the support masts which carry the cable car due to the magnetic field caused by the buildings and the masts. In contrast to the magnetic signature for other means of transport, this signature is superimposed by time-dependent sinusoidal variations due to small variations in the orientation of the cabin. However, this effect is negligible for the horizontal and vertical component of the magnetic field. Even for the lateral component, these variations are small compared to the magnetic signature near the support masts (around 100m and around 800m in Figure 52).

Besides serving as a standalone solution, magnetic field-based localization can also be used in combination with GNSS to enhance localization performance and robustness if GNSS is available. Fusion of magnetic field-based localization with GNSS as well as IMU and speed sensors is covered in detail in the project FP2 R2DATO, WP 22 (see Figure 53)(R2DATO1 2026).

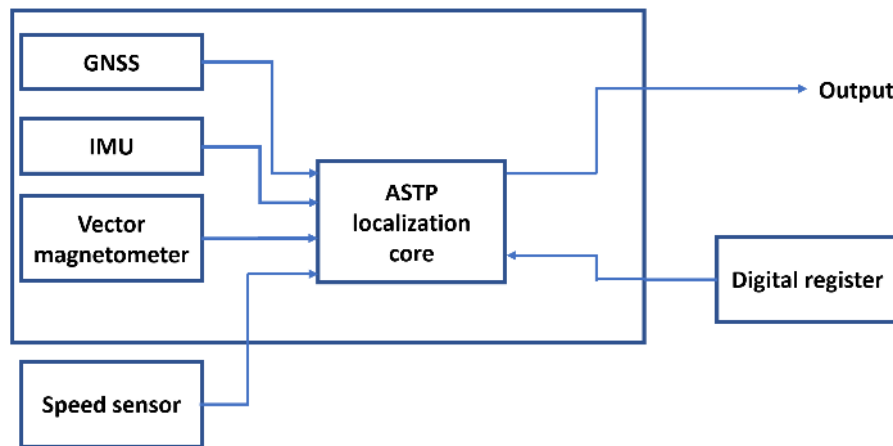


Figure 53: Proposal for sensor fusion concept by DLR in the project FP2 R2DATO.

Figure 53 shows the proposal for sensor fusion concept by DLR in the project FP2 R2DATO, WP 22 (R2DATO1 2026). ASTP is short for Absolute Safe Train Positioning. The digital register is used to store a map of the magnetic field and a track map.

Unlike other concepts proposed for multi-sensor localization in FP2 R2DATO, WP 22, this concept does not rely on infrastructure on the track (e. g. balises). It is therefore particularly suitable for the pods concept as robust localization can not only be provided on railways but also e. g. on streets and on cable cars. There also exists an extended version of this sensor fusion concept which includes a Fault Detection and Exclusion (FDE) stage to check the validity of the sensor data and exclude data which are classified as faulty. As multiple independent sensors are used, it is still possible to estimate the position even if the data from one sensor is faulty.

In an evaluation over three exemplary railway tracks an overall along-track localization RMSE of less than 4 m was achieved and the 95% quantile of the along-track error was below 5.2 m using only one magnetometer measuring the magnetic field in all three spatial directions (see Figure 54, Siebler 2018a).

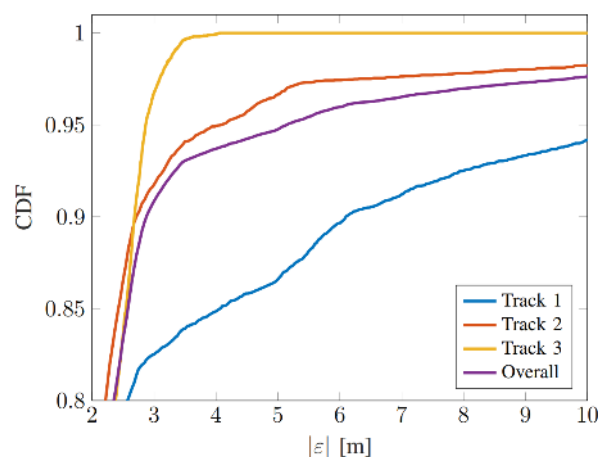


Figure 54: CDF of the absolute along-track position error for the different tracks and the overall dataset (Siebler, 2018a)

The accuracy of magnetic field-based localization is in the same range as for GNSS- based localization and is usually sufficient for localization on an open track. However, more accurate positioning might be required if other vehicles are nearby (e. g. in a virtual coupling scenario) or next to operational facilities. In these cases, more accurate information about the position relative to other vehicles or operational facilities can be achieved by information fusion with radio-based short-range communication and ranging (see the following subsection for more details).

It has been shown that changing the type of rail vehicle on which the sensors are mounted results in an affine linear transformation of the measured magnetic field which can be interpreted as a change in the calibration parameters and localization is still possible in this case by using a Simultaneous Localization and Calibration (SLAC) algorithm (Siebler, 2021). Exemplary evaluations on the along-track localization accuracy show that the performance of the SLAC algorithm with an uncalibrated sensor and a magnetic map recorded with a different kind of vehicle is close to that of the pre-calibrated sensor case after a short initialization phase (Siebler, 2021). Changing the carrier unit or the transport unit is expected to have the same effect as mounting the sensor on another type of rail vehicle. Therefore, magnetic field-based localization of the carrier unit respectively the transport unit on which the sensor is mounted is still possible even if the corresponding unit has been exchanged. Additionally, this effect of changing calibration parameters enables identification of the type of corresponding unit by estimating these calibration parameters with the SLAC algorithm as different carrier/transport units usually result in different calibration parameters. Therefore, it is sufficient to use a magnetic field sensor either on the carrier unit or on the transport unit in order to localize this unit and to identify the type of the other unit without the need of establishing a communication link between the units or of mounting any sensors on the other unit. While the described method to identify the type of carrier/transport unit requires a magnetic map, it is also possible to detect the mode of transport using magnetic field measurements without the need of a map. This works by exploiting different characteristics of the magnetic field for different transport modes. A machine learning algorithm for this has already been developed and its ability to distinguishing between different transport modes including railway and subway solely using magnetic field measurements has been shown (Karite, 2025). The cable car and road transport modes also each have characteristic properties in the magnetic field (see Figure 55).

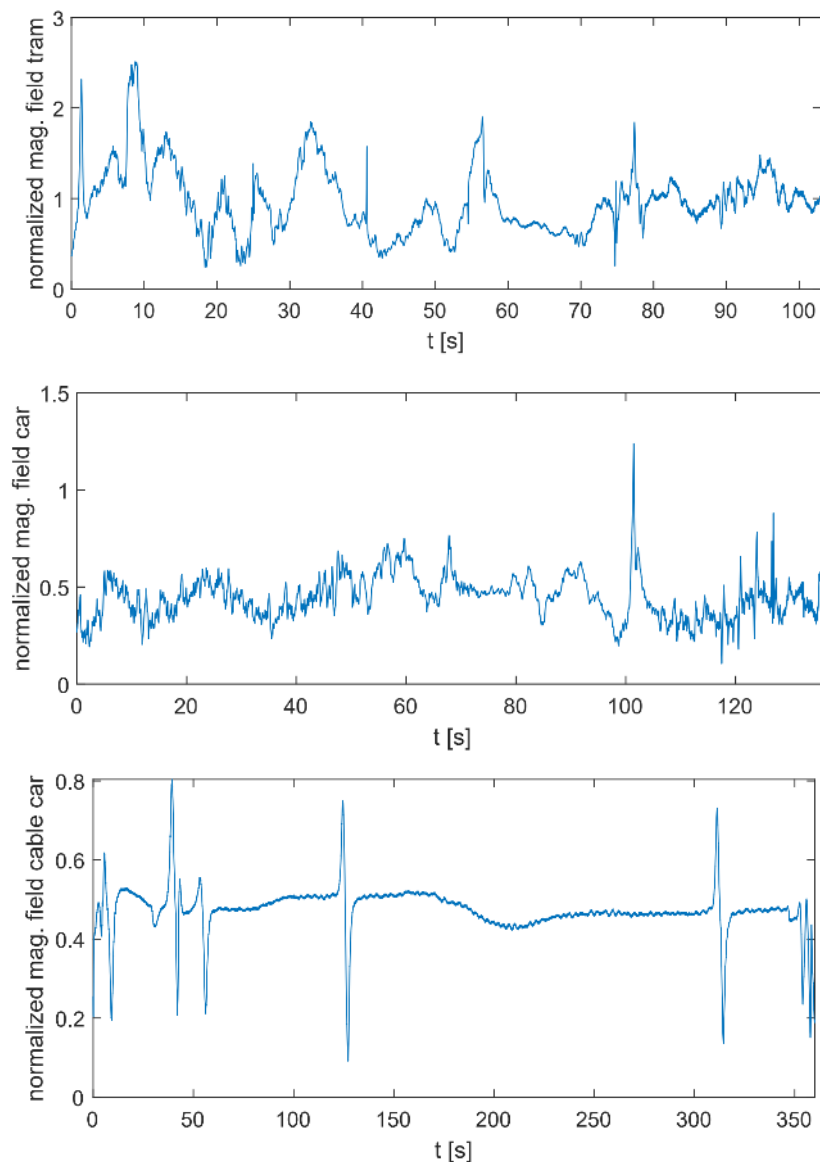


Figure 55: Normalized absolute value of the magnetic field (example) for different transport modes.

The data in Figure 55 have been collected over and next to the river Rhine in Cologne during a measurement campaign carried out by DLR in the scope of the Pods4Rail project.

Evaluations on the sensor placement show that using magnetic sensors mounted outside on the underside of a vehicle measure a magnetic signature with greater energy than magnetic field sensors mounted inside the vehicle on the floor. This results in a better localization performance, i. e. the 95% quantile of the along track error is approximately 20% lower with a sensor mounted outside (see Figure 56, Strang 2024).

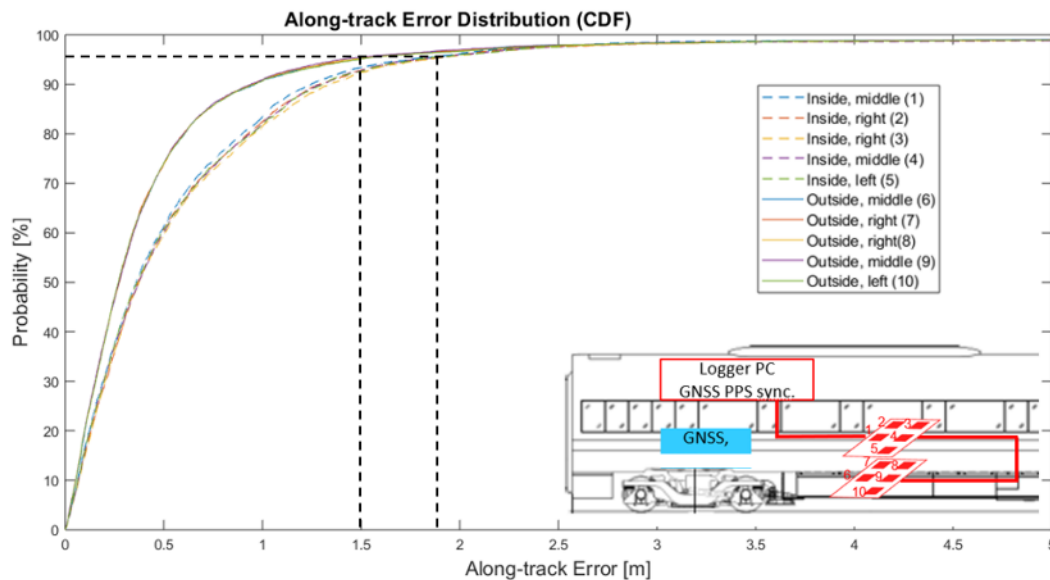


Figure 56: Accuracy of the longitudinal positioning

The 95%-accuracy of the longitudinal positioning is 1.8 m for the sensors mounted, and 1.5 m for the sensors mounted outside. GNSS-based positioning from a geodetic receiver was used as reference.

For the pods concept this fact implies to mount the magnetic sensors at the underside of the carrier unit if possible. Nevertheless, the aforementioned evaluations suggest that localization is also possible with magnetic field sensors mounted inside on the floor of the transport unit, although with a slightly lower performance. For mounting the magnetic sensors at a larger vertical distance to the track, it is expected that the performance is even more degraded but magnetic localization still works. Data from magnetic sensors mounted inside a train at a relatively large distance to the track up to approximately 2 m above the floor of the train have been collected in the frame of the project Impact (IMPACT, 2025). In this case, the magnetic signature can still be recognized in this data although it is less strong. On the contrary, the lateral position of a magnetic sensor hardly effects the localization performance. In order to minimize disturbances from the magnetic field of electric drives and DC power lines, it is advantageous to mount magnetic field sensors not too close to electric drives or DC power lines with high electric current. Passive magnetic sensors only need interfaces for data transfer to a signal processing unit at a rate in the order of 100 Hz and for low-voltage power supply. The power consumption is very low due to the passiveness of the sensors. For example, the USB 3.0 standard could be used for both data transfer and power supply. CAN bus has also been proven to be an option for data transfer, e. g. in the Impact project (IMPACT, 2025).

In addition to along-track localization, magnetic field sensors can also be used to identify the track on which a rail vehicle is driving (track selectivity) (Siebler 2020). Besides localization using a map, there also exist approaches to determine the relative along-track positions between two rail vehicles equipped with one magnetic sensor each (Siebler 2018b) and for velocity estimation of a vehicle using two longitudinally arranged sensors (Siebler 2017).

8.5.4 Short range communication and ranging

Short range communication (SRC) and relative localization (RL) combine communication and measuring the distance (ranging) between two vehicles for short distances by exchanging radio signals. In terms of the pods concept it can be used for TU and CU distance and orientation estimation. One common technology for SRC and RL is UWB technology. UWB can provide centimetre-level accuracy in theory under the presence of disturbances as well as data exchange up to a distance of at least 250 m. UWB ranging is usually based on time-based estimation. In FP2R2DATO WP 48, the use of Round Trip Time (RTT) (see Figure 57) measurements were proposed as no clock synchronization is needed (R2DATO2, 2026).

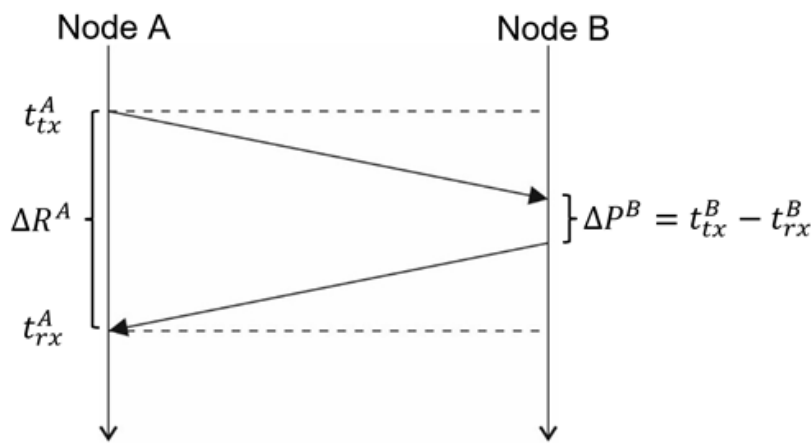


Figure 57: Round trip time measurement procedure

More details on UWB technology in the railway environment can be found in the project FP2 R2DATO, WP 48. Use cases for SRC and RL in the pods system are communication between different pods or between different TU and CU, e. g. for pod docking. To enable communication and ranging in the latter case, a Line of Sight (LOS) connection between the UWB antenna on the CU and the one on the TU is needed. Both directional and omni-directional antennas can potentially be used. While directional antennas outperform omnidirectional ones in terms of achievable distance and power efficiency, omni-directional antennas offer more flexibility concerning the direction of the other communication and ranging participant. A typical value for the gain of an omni-directional could be 1.9 dBi (see e. g. (West, 2023)), whereas for a directional antenna a typical value could be e.g. 16 dBi with an opening angle of 17° for the main lobe (see e. g. (Yeung, 2019)). On the contrary using a omni-directional antenna, the same antenna can be used both for SRC and RL between different CUs as well as for SRC and RL between CU and TU for pods docking.

To obtain a 2D/3D-estimate of the position of a pod relative to the carrier unit, two or more UWB antennas are necessary for each communication node.

As similar bandwidth as for UWB can be achieved by communication systems based on mm-Wave.

8.6 Outputs for other WPs

Advanced localisation approaches, including magnetic field based positioning, adaptive GNSS, UWB ranging and multi-sensor fusion architectures, provide WP11 with realistic options for achieving the high accuracy, high integrity positioning required for autonomous pod operation, virtual coupling, and safe traffic coordination. These localisation concepts directly contribute to this work package by informing the system requirement specification for vessel and pod identification, positioning granularity and infrastructure interface points. They also enable modelling activities, where routing and automation behaviours rely on reliable positioning and vessel state information across different operational environments.

Short-range communication provide technical guidance for designing the communication layers between pods, infrastructure and backend coordination systems. At the same time, the SDN-based distributed communication architecture offers a flexible and scalable approach for managing these heterogeneous communication channels. This becomes particularly relevant for multi-modal interactions, mixed passenger and freight operations and planning, where the system must dynamically allocate information flows and maintain quality of service. The achievements will be transferred to WP11 and integrated in the concept design of the traffic coordination.

9 Conclusions

Deliverable D10.1 provides a comprehensive and integrated concept for the technical equipment, power supply, interfaces and enabling technologies of the Pods4Rail TU. The work demonstrates that a modular, lightweight and interoperable TU is technically feasible when the equipment is carefully allocated between the TU and the CU, and when all subsystems are developed within a coherent framework of standards, use-case requirements and cross-work-package dependencies. By focusing on the representative Use Case UC1 – Basic Public Transport – the deliverable establishes a concrete reference configuration that can be scaled and adapted to other passenger and freight applications without changing the fundamental architectural principles.

From the equipment and power-supply perspective, the analysis confirms that the TU can be designed as a passenger-oriented module containing only those systems which must remain operational during detached phases, such as HVAC, lighting, door actuation, the Passenger Information System, sensors, control electronics and emergency equipment, while heavier, more complex or traction-related systems are deliberately assigned to the CU. This clear division reduces TU mass and complexity whilst still enabling at least fifteen minutes of autonomous operation through a dedicated underfloor battery system. The proposed battery concept, located within the floor structure, improves stability by lowering the centre of gravity, uses space efficiently, and complies with safety and ventilation requirements. Furthermore, the modular nature of the battery solution supports scaling to different TU lengths without altering the fundamental interface or layout logic, thereby reinforcing the modularity principle that underpins the Pods4Rail concept.

The work on layout and interior equipment shows that the combination of a structured Work Breakdown Structure, aligned with EN 15380, and a use-case-driven selection of components enables a robust methodology for interior design. The WBS not only supports traceability, standardisation and digital integration for maintenance and configuration management, but also underpins modularity: seats, luggage storage elements, handrails, lighting devices, PIS components, control cabinets and emergency equipment are all treated as modular building blocks. Different seating arrangements (for example, lateral versus medial layouts), luggage solutions (under-seat compartments versus dedicated racks) and PIS concepts (from conventional displays to more experience-oriented or hybrid solutions) can be applied to match demand profiles and quality-of-service objectives without compromising the overall structural envelope or regulatory compliance. This approach offers operators significant flexibility to adapt the TU interior over time and across use cases while maintaining a consistent technical backbone.

A key outcome of D10.1 is the consolidation of HVAC concepts for the TU. The deliverable shows that, within the limited installation space and under the combined constraints of rail and road standards, a vapour-compression refrigeration system using a natural refrigerant such as R290 is currently the most suitable option. It satisfies the stringent requirement for a very low Global Warming Potential, matches or exceeds the performance of R134a-based systems, and is already available at appropriate Technology Readiness Levels for rail applications. The analysis concludes that heating should primarily be provided by a heat pump operating with the same refrigerant, complemented where necessary by resistance heaters for rapid warm-up or

defrosting. At mechanical level, two competing integration strategies—HVAC at ceiling level and HVAC above the ceiling—are examined in detail, each presenting specific trade-offs in terms of interior headroom, compatibility with ISO container geometry, maintenance access, airflow quality and dynamic behaviour. The work therefore provides a clear decision framework and well-defined design envelopes for subsequent detailed design and structural integration in later work packages.

With regard to the interfaces between TU and CU, D10.1 synthesises the findings of related work into a coherent mechanical and electrical interface concept tailored to UC1 but conceived for generalisation. On the mechanical side, the combination of ISO 1161 corner castings, automatic twistlocks and forklift pockets delivers a robust, standardised and multimodal interface that supports rail, road and storage scenarios, including stacking. The TU can be securely fixed to the CU under demanding load cases while remaining compatible with standard intermodal handling equipment. A significant contribution of the deliverable is the systematic analysis of securing and clamping mechanisms for forklift operations, which culminates in a preferred concept wherein the forklift is equipped with an automated twistlock system engaging with counterparts integrated in the TU. This solution improves safety and comfort during transshipment, particularly when passengers are present, while preserving flexibility for operations involving non-modified forklifts in non-passenger contexts.

On the electrical side, the deliverable confirms that a dual-layer interface architecture, combining a High Voltage Interlock Loop connector for power transfer with a multi-coupler baseplate for low-voltage and data connections, is the most suitable solution for the Pods4Rail concept. This arrangement supports safe high-voltage operation, modular low-voltage and signal interfaces, automated coupling and high levels of environmental protection. The concept can be further compacted by integrating the high-voltage connector into the multi-coupler plate, enabling an “all-in-one” interface that simplifies installation and operation. The design is explicitly modular and scalable, allowing straightforward adaptation to different TU sizes and functions and to various CU platforms, whilst offering a clear pathway towards predictive maintenance and standardisation of connector geometries across the system.

D10.1 also contributes substantially to the definition of localisation and communication concepts that are essential to achieving the desired levels of automation and autonomy in Pods4Rail. The deliverable proposes an advanced multi-sensor localisation strategy combining adaptive GNSS, inertial measurements, magnetic-field-based localisation and short-range ultra-wideband ranging. This approach addresses the challenges of GNSS-degraded or GNSS-denied environments and enables high-integrity, ubiquitous positioning across different modes and infrastructures. In parallel, the communication architecture leverages a heterogeneous mix of vehicle-to-everything technologies, including 5G and 6G New Radio, IEEE 802.11bd, UWB and advanced Wi-Fi generations, structured through a distributed software-defined networking framework with edge-computing capabilities. This combination supports low-latency, resilient and programmable networking, which is essential for safety-related control, traffic coordination and real-time passenger and operational data services. Cybersecurity is treated as a first-class requirement, with explicit consideration of security-by-design principles and future-proofing through the adoption of post-quantum cryptography to protect the system over its full life cycle.

Taken together, these results confirm that the TU can be designed as a modular, interoperable and future-ready subsystem within the wider Pods4Rail ecosystem. The deliverable demonstrates that key subsystems—equipment, power supply, HVAC, mechanical and electrical interfaces, localisation and communication—can be integrated within realistic spatial, regulatory and operational constraints. It shows that the concept is scalable across different TU sizes and flexible enough to cover multiple use cases beyond UC1, including premium passenger and freight services, and that the chosen solutions are compatible with current European regulatory frameworks and industry standards while also providing a clear basis for contributing to new “supermodal” standards in the longer term.

Finally, D10.1 establishes a solid bridge towards subsequent and parallel work packages. The defined WBS, equipment layouts, HVAC envelopes, interface geometries, communication requirements and localisation concepts form critical inputs for future work on design variants, detailed TU design, traffic coordination and virtual coupling, handling systems and carrier development. The deliverable therefore not only fulfils its immediate objective of concept development for the sample vessel but also acts as a key architectural reference for the technical and operational maturation of the Pods4Rail system as a whole.

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