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VICE4RAIL

D2.1 Rail user & system requirements

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EXECUTIVE SUMMARY

The railway sector is undergoing significant digital transformation to meet growing demands for safer, more efficient, and sustainable transportation. The integration of Global Navigation Satellite System (GNSS) technology into the European Rail Traffic Management System (ERTMS) can improve safe train localization and bring significantly advantages to the entire sector. Despite the transformative potential of this technology to enhance safety, operational efficiency, and cost-effectiveness in railways, its deployment is hindered by the absence of a standardized and industry-accepted certification methodology tailored to the railway sector's specific requirements. The VICE4RAIL project addresses this critical gap by developing a hybrid virtualized testing and certification framework tailored to EGNSS-based railway localization solutions.

This document defines the rail user and system requirements that will guide the development of the project's hybrid virtualized testing and certification framework. The methodology leverages outcomes from previous and ongoing EU initiatives, particularly the Europe's Rail Joint Undertaking Flagship Project 2 (FP2) R2DATO. Indeed, VICE4RAIL directly supports Europe's Rail, aligning with the Advanced Safe Train Positioning (ASTP) vision, expected to be incorporated into future Technical Specifications for Interoperability (TSIs). An overview of European railway regulations and standards, user needs, functional and non-functional system requirements, and preliminary requirements for a virtual certification platform called HyVICE (Hybrid Virtualized Certification Environment) are provided. The aim is to create a reliable and efficient framework that facilitates the certification of EGNSS-based solutions by adhering to the highest safety and interoperability standards. The HyVICE platform is envisaged as a comprehensive environment combining laboratory simulations and realistic on-field testing to certify GNSS-based train positioning systems according to Safety Integrity Level 4 (SIL4), essential for safety-critical rail applications.

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Acronyms and definitions

Acronym	Meaning
AB	Advisory Board
AoU	Area of Use
APIS	Authorization for Placing in Service
APOM	Authorization for Placing on the Market
AsBo	Assessment Body
ASTP	Advanced Safe Train Positioning
ATO	Automatic Train Operation
ATP	Automatic Train Protection
BTM	Balise Transmission Module
CA	Consortium Agreement
CAB	Conformity Assessment Body
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CER	Community of European Railway and Infrastructure Companies
CCS	Control Command and Signalling
CONOPS	Concept of Operations
COTS	Commercial Off-The-Shelf
CSI	Common Safety Indicator
CSM	Common Safety Method
CSM-RA	Common Safety Method for Risk Evaluation and Assessment
CST	Common Safety Target
DeBo	Designated Body
DG DEFIS	Directorate-General for Defence Industry and Space
DG MOVE	Directorate-General for Mobility and Transport
DGNSS	Differential GNSS
DoA	Description of Action
DUT	Device Under Test
EC	European Commission
EGNOS	European Geostationary Navigation Overlay Service
EGNSS	European Global Navigation Satellite System
EN	European Norm
EoA	End of Authority
ERA	European Union Agency for Railways
ERTMS	European Rail Traffic Management System
ERJU	Europe's Rail Joint Undertaking
ESA	European Space Agency
ETCS	European Train Control System
ETSI	European Telecommunications Standards Institute
EU	European Union
EUCI	EU Classified Information

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EUG	ERTMS Users Group
EU-Rail	Europe's Rail Joint Undertaking
EUSPA	European Union Agency for the Space Programme
EVC	European Vital Computer
FMECA	Failure Mode, Effects, and Criticality Analysis
FP2	Flagship Project 2
FRMCS	Future Railway Mobile Communication System
FRS	Functional Requirements Specification
GA	Grant Agreement
GeA	General Assembly
GDPR	General Data Protection Regulation
GNSS	Global Navigation Satellite System
GSM-R	Global System for Mobile Communications - Railway
GT	Ground Truth
HE	Horizon Europe
HIL	Hardware-in-the-Loop
HyVICE	Hybrid Virtualized Certification Environment
IC	Interoperability Constituent
IM	Infrastructure Manager
IMU	Inertial Measurement Unit
IPR	Intellectual Property Rights
ISA	Independent Safety Assessor
KPIs	Key Performance Indicators
LIDAR	Light Detection and Ranging
LRBG	Last Relevant Balise Group
MIL	Model-in-the-Loop
MoM	Minutes of Meetings
Mxx	Month
NDA	Non-Disclosure Agreement
NoBo	Notified Body
NSA	National Safety Authority
OBU	On-Board Unit
PC	Project Coordinator
PSO	Project Security Officer
PU	Public (deliverable)
QA	Quality Assurance
QAS	Quality Assurance System
R&I	Research & Innovation
RAM	Reliability, Availability, Maintainability
RAMS	Reliability, Availability, Maintainability and Safety
RAP	Risk Acceptance Principle
RBC	Radio Block Center
RTCM	Radio Technical Commission for Maritime Services
RU	Railway Undertaking

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SAB	Security Advisory Board
SBAS	Satellite-Based Augmentation System
SEN	Sensitive (deliverable)
SERA	Single European Railway Area
SCG	Security Classification Guide
SIL	Safety Integrity Level / Software-in-the-Loop
SiS	Signal in Space
SoL	Safety of Life
STIP	Standardization and TSI Input Plan
Txx	Task
THR	Tolerable Hazard Rate
TL	Task Leader
TMT	Technical Management Team
TSI	Technical Specifications for Interoperability
UIC	International Union of Railways
UNIFE	Union of the European Railway Industries
UNISIG	Union Industry of Signalling
UR	User Requirements
V&V	Verification and Validation
VB	Virtual Balise
WP	Work Package
WPL	Work Package Leader

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1 Introduction

1.1 Scope of the document

This document constitutes Deliverable D2.1 “Rail User & System Requirements” as part of the Horizon Europe VICE4RAIL project (Grant Agreement No 101180124). It provides a comprehensive overview of user and system requirements identified during Task 2.1 of Work Package 2 (*“Hybrid Virtualized Testing Certification Environment Requirements/Development of Certification Plan”)*. These requirements reflect the needs of railway users and will guide the project’s development of a hybrid virtualized testing and certification framework tailored specifically for EGNSS-based railway localization solutions.

1.2 Background

The VICE4RAIL project addresses the urgent need for a standardized and efficient certification process for EGNSS-based localization solutions to be used in the framework of the European Rail Traffic Management System (ERTMS). To understand the context and significance of this need, this subsection aims to provide an overview of the current trend in railway digitalization and the role that EGNSS can play in addressing its challenges.

The railway sector is undergoing a significant digital transformation to meet the growing demands for safer, more efficient, and sustainable transportation systems. This evolution will be also characterized by an increasing reliance on advanced on-board sensors and the processing of vast amounts of data they are able to collect. Indeed, a key trend is the reduction of trackside equipment, shifting instead toward leveraging advanced on-board sensors to perform existing and new functionalities, offering a more flexible and cost-effective approach to railway operations [1] [2]. In this context, the Global Navigation Satellite System (GNSS) has emerged as a pivotal technology and innovative train localization systems based on this technology can play a crucial role in the evolution of railway control and signalling systems. A significant number of EU-funded projects on this subject have been undertaken in recent years (e.g., STARS, ERSAT EAV, ERSAT GGC, GATE4RAIL, HELMET, X2RAIL-2, X2RAIL-5, CLUG, VOLIERA, SBS, EGNSS MATE, RAILGAP, R2DATO). It has been demonstrated how EGNSS can offer advanced positioning capabilities by also enhancing the resilience, efficiency, and safety of rail transport systems. The use of GNSS technology for railway signalling is also promoted by ERA, working together with rail and space industry stakeholders. Indeed, GNSS technology has long been recognized as a "Game Changer" for improving the economic sustainability and operational effectiveness of the ERTMS [3]. Furthermore, the European Parliament in its resolution of July 2021 on railway safety and signalling pointed out the need to ensure synergies between the ERTMS and the EGNSS as soon as possible considering that exploitation of EGNSS services do not need equipment deployed along the railway, like the eurobalises, which are rather expensive to deploy and maintain [4]. Potential vulnerability issues should also be noted; indeed, vulnerabilities on the standard balise air-gap interface can be exploited to launch effective and practical attacks, which could lead to catastrophic consequences [5]. The strategic value of integrating GNSS with ERTMS is significantly amplified by the ongoing, large-scale investment in ERTMS deployments all across Europe [6]. This modernization effort encompasses both high-speed

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and regional rail lines, many of which require substantial infrastructure upgrades. While essential for network renewal, the conventional implementation of ERTMS on low-traffic regional lines can present a significant financial burden. GNSS integration offers a cost-effective solution, enabling streamlined ERTMS deployment on these lines. This approach reduces implementation, operational, and maintenance expenses, thereby enhancing overall railway network efficiency and reliability while maintaining a justifiable return on investment.

However, integrating satellite technology into the safety chain of railway operations presents great challenges from both technical and regulatory perspectives. GNSS shall provide safe, reliable data to on-board vital systems, requiring high levels of accuracy, availability, and integrity to meet the stringent safety standards of the railway sector. Indeed, one of the most important aspects of developing a railway localization system based on GNSS technology is compliance with railway safety regulations, which require that every tool or application be rigorously validated and certified. For safety-critical railway applications, it is necessary to ensure that the integrity of the information provided and the railway system that processes such data reach SIL4 (Tolerable Hazard Rate < 10^{-9} failures per hour). Achieving this level of safety demands comprehensive analysis, including identifying major risks that could compromise the integrity of the data provided by the GNSS service. In this regard, it should be noted that the railway environment is particularly challenging for GNSS due to the rapid variability of visibility and signal propagation conditions, which can be negatively influenced by obstructions, reflections, and diffractions caused by the railway infrastructure itself, the morphology of the terrain, and surrounding vegetation. Additionally, the system must be resilient to various threats that may occur during operation, including intentional jamming and signal spoofing or meaconing attacks [7].

Despite a decade of successful experimentation with train control systems integrating GNSS technologies for train localization, the definition of a standard procedure for certifying compliance with the requirements imposed by the highly regulated rail safety-critical applications is still pending in Europe, while in the USA GNSS is part of the PTC system and in China is becoming a standard on the new lines. Currently, the lack of tailored certification procedures for GNSS-based train positioning applications remains a key barrier to their adoption; this limitation has hindered the integration of satellite technology into railway control and signalling systems, despite its transformative potential. This is not due to a lack of innovation or ambition. Rather, the translation of innovation into operational deployment requires an industry-accepted regulatory framework compliant with CENELEC norms and ERTMS standard.

This gap is precisely what VICE4RAIL seeks to address by developing a hybrid virtualized testing and certification framework tailored to the railway sector's unique needs. In this way, the project aims to accelerate the development of a comprehensive, industry-accepted certification methodology for integrating GNSS and IMU technologies into ERTMS, ensuring full compliance with SIL-4 standards. In line with ongoing developments in Europe's Rail Joint Undertaking (EU-Rail), the European partnership on rail research and innovation established under the Horizon Europe programme, this framework will be designed to streamline the development and certification of GNSS-based solutions for applications requiring absolute train positioning. A liaison will be established with the Europe's Rail R2DATO project to complement their on-going activities and to sharing results and assets and with the RTCM SC 134 Special Committee that is completing the standardization process for GNSS receivers for rail applications. This alignment positions VICE4RAIL not as an isolated research initiative, but as

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an integral contributor to the broader European standardization efforts. In conclusion, the project will contribute to the broader objectives of the Horizon Europe program, promoting innovative, interoperable, and competitive railway systems across Europe. The outcomes of VICE4RAIL will pave the way for a global rollout of EGNSS-based ERTMS solutions, fostering the digitalization and modernization of the railway sector.

1.3 Structure of the document

The present document is organized as follows:

- Chapter 1 - Introduction
- Chapter 2 - Overview of European Railway Regulations and Standards
- Chapter 3 - User needs and system requirements
- Chapter 4 - Preliminary requirements for a virtual certification platform
- Chapter 5 - Safety assessment and certification processes
- Chapter 6 - Conclusions

1.4 Relationship to other project outcomes

The main objective of this deliverable is to establish a comprehensive understanding of rail user and system requirements as a foundation for developing a hybrid virtualized testing and certification framework tailored specifically for GNSS-based railway localization solutions within the European Rail Traffic Management System (ERTMS).

The analysis of European railway regulations and standards and the description of safety assessment and certification processes aims to provide a solid foundation for understanding the complex certification landscape that GNSS-based solutions must navigate. These considerations will be complemented within WP2 by Task 2.2 “Development of the certification plan for the VICE4RAIL solution” and Task 2.3 “Synergies between rail, automotive and maritime in the certification process”. The former will consolidate the certification process for the HyVICE test platform by also incorporating the insights and processes identified in this document, while the latter will compare and assess certification procedures in rail, automotive and maritime sectors to identify common elements of the certification schemes to make the certification of multimodal solutions faster and cheaper.

Then, starting from the analysis of the outcomes of WP2, the system requirements and overall architecture of HyVICE test platform will be derived in WP3 “Reference Architecture Design”. Specifically, Task 3.1 "Overall Architecture Design and System Requirements Definition" will deliver D3.1 "Overall Architecture Design Document", and D3.3 "System Requirement Document". The system designed in WP3 will be then actually developed by WP4 “Hybrid Virtualized Testing Certification Environment Development”. Finally, the outcomes of WP2 will also provide the methodological foundation for the validation and assessment strategies (Tasks 5.1, 5.2 and 5.3) to be developed in WP5 “Certification process”.

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The linkages between work packages are depicted in Figure **1**; the sequential workflow ensures a systematic progression from requirements through design and implementation to validation.

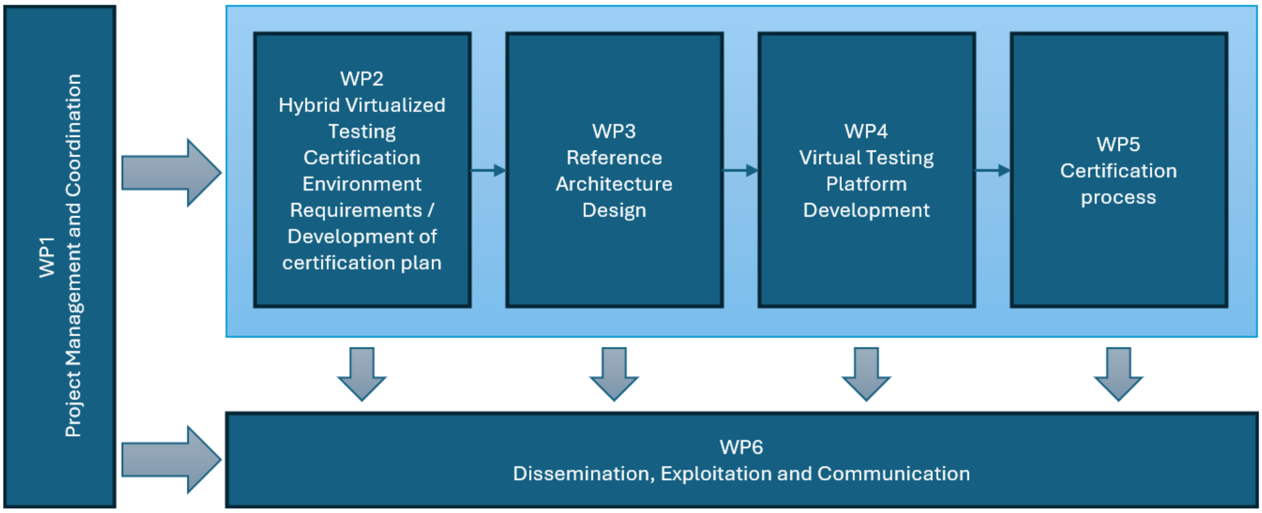

Figure 1: VICE4RAIL Study Logic

Having established the context, objectives, and interdependencies of the VICE4RAIL project within the broader European railway research framework, the subsequent chapter examines the comprehensive regulatory and standardization landscape governing the integration of GNSS technologies for railway signalling. This analysis is essential for understanding the certification challenges that the VICE4RAIL aims to address.

2 Overview of European Railway Regulations and Standards

Integrating satellite technology into the safety chain of railway operations presents challenges not only from a technical standpoint but also from a regulatory perspective. To allow the integration of EGNSS-based solutions into the rail safety environment, it is indeed essential to meet the required certification and authorization processes, ensuring compliance with relevant standards at both EU and national levels.

This chapter aims to provide a clear overview of the key regulatory frameworks in the railway domain; it is structured as follows:

- Section 2.1 – Actors and roles
- Section 2.2 – Railway Regulations and Standards
- Section 2.3 – Certification and Authorization Processes
- Section 2.4 – Challenges for GNSS Certification in Railway

2.1 Actors and Roles

The integration of the GNSS into railway systems shall be guided by a complex regulatory framework managed by key institutions at European and national levels. These entities ensure compliance with safety, interoperability, and operational standards. Below is an overview of the key stakeholders and their roles.

2.1.1 European Commission (EC)

The European Commission provides the legislative backbone for the European railway system through directives and regulations that promote safety, interoperability, and market harmonization. Central to these efforts are the Interoperability Directive (EU) 2016/797 [8] and the Safety Directive (EU) 2016/798 [9], which establish the principles governing technical compatibility and operational safety. The Commission also oversees the implementation of the Single European Railway Area (SERA), ensuring a unified approach to railway operations across EU member states.

2.1.2 European Union Agency for Railways (ERA)

The role of the European Union Agency for Railways (ERA) is central to the European railway authorisation process. As outlined in Regulation (EU) 2016/796 [10], its key responsibilities include promoting a standardized approach to railway safety, developing technical and legal frameworks to eliminate technical barriers, and serving as the system authority for ERTMS and telematics applications. Under Directive (EU) 2016/797 [8], the ERA is also tasked with drafting Technical Specifications for Interoperability (TSIs) and proposing regulatory amendments to the European Commission. The goal is to establish a fully interoperable Single European Railway Area that prioritizes both safety and competition. With the Fourth EU Railway Package, the ERA's role has expanded to include granting authorizations for placing vehicles and ERTMS/ETCS onboard subsystems into service across designated Areas of Use (AoU). It is also responsible for issuing single safety certificates to railway undertakings and monitoring the effectiveness of National Safety Authorities (NSAs). Furthermore, it provides ERTMS Trackside Approvals for related projects.

Furthermore, ERA actively coordinates with national authorities to harmonize safety and certification requirements across member states.

2.1.3 National Safety Authorities (NSA)

National Safety Authorities NSAs are national bodies tasked with overseeing railway safety in their respective Member States. As defined in Directive (EU) 2016/798 [9] on railway safety, an NSA can either be a single national entity or a collective authority managing safety regulations across multiple countries. To maintain independence, NSAs must operate separately from railway undertakings, infrastructure managers, and other industry stakeholders. Their role is to ensure a transparent, non-discriminatory approach to railway safety by coordinating with the ERA to create a unified European railway area. While some NSAs are integrated into national transport ministries, their operational independence must be preserved. These authorities must have sufficient human and material resources to effectively carry out their duties. Under the Fourth Railway Package, NSAs collaborate with the ERA to review applications and issue authorizations for placing fixed ERTMS installations into service. NSAs have several key responsibilities, including monitoring railway safety, authorizing the entry into service of structural subsystems, ensuring that interoperability constituents meet essential requirements, and granting safety certificates to railway undertakings. They are also responsible for developing safety regulations, supervising compliance, issuing approvals for training centers, and certifying maintenance organizations.

2.1.4 Standards Organizations (CEN, CENELEC, ETSI)

Standardization bodies such as the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC), and the European Telecommunications Standards Institute (ETSI) establish the technical and operational benchmarks necessary for railway interoperability.

CEN, the European Committee for Standardization, supports European economic growth, public welfare, and environmental protection by developing European Standards (ENs) and technical specifications. CEN operates under the legal framework established by Regulation (EU) No 1025/2012 [11] on European standardization, which governs cooperation between the European Standardization Organizations, national authorities, and the European Commission.

CENELEC, the European Committee for Electrotechnical Standardization, was established in 1973. It is one of the three European Standardization Organizations, alongside CEN and ETSI. CENELEC's primary role is to harmonize electrotechnical standards across Europe, supporting the single market and ensuring product safety and environmental protection. It comprises national electrotechnical committees from member countries. CENELEC operates within the legal framework established by Regulation (EU) No 1025/2012 [11] and publishes various standards which are vital for the safety, quality, and interoperability of electrical products in Europe.

ETSI, the European Telecommunications Standards Institute, is officially recognized by the European Union as a European Standardization Organization [11]. It plays a key role in the development of technical standards for telecommunications, for example the telecommunication frameworks like the Future Railway Mobile Communication System (FRMCS).

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These standards complement the TSIs and support the certification processes for railway equipment and systems.

2.1.5 Conformity Assessment Bodies (CABs)

Conformity Assessment Bodies (CABs) are independent entities authorized to evaluate railway systems and subsystems against the requirements of TSIs and other applicable standards. These entities collectively contribute to the comprehensive evaluation and certification of railway systems, ensuring their safe and interoperable operation within the European network.

- Notified Bodies (NoBos): Appointed by member states and responsible for third-party assessment of interoperability constituents and structural subsystems, ensuring compliance with the applicable TSIs. According to Directive (EU) 2016/797 [8], their role includes verifying EC conformity, issuing intermediate statements of verification, and checking the correctness of ETCS system compatibility reports.
- Designated Bodies (DeBos): Operate within the framework of National Technical Rules (NTRs) to ensure subsystems meet specific national requirements not covered by TSIs. They are appointed by Member States to verify conformity against national regulations according to Directive 2012/34/EU [12]. Some DeBos also act as AsBos to avoid redundant assessment processes.
- Assessment Bodies (AsBos): Evaluate the risk management processes required under the Common Safety Methods for Risk Evaluation and Assessment (Regulation (EU) No 402/2013 [13]). AsBos are tasked with evaluating the application of the risk assessment process, ensuring it's conducted in accordance with the CSM RA Regulation. They assess whether risks have been appropriately identified and evaluated, and if adequate mitigation measures are in place. AsBos must be independent from parties involved in the risk assessment and must be accredited or officially recognized to ensure they meet regulatory requirements. Their assessments are broader in scope, covering not only signaling systems but also rolling stock and operational changes.
- Independent Safety Assessors (ISAs): Provide third-party assessments of the safety integrity of railway systems and their compliance with safety standards, including those defined by CENELEC [14, 15, 16, 17]. ISAs ensure the robustness and reliability of EGNSS applications in railways. Although ISAs are not required to be formally accredited, they must be accepted or licensed by a recognized safety authority.

2.1.6 Infrastructure Managers and Railway Undertakings

Infrastructure Managers (IMs) and Railway Undertakings (RUs) are integral to the regulatory framework. IMs are tasked with maintaining and upgrading railway infrastructure to meet interoperability standards, while RUs operate rail services under certified safety management systems.

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2.1.7 Professional organizations and other entities

Professional organizations and other entities play an essential role in advancing railway technology and supporting innovations like GNSS introduction. These organizations foster collaboration, drive research and development, and contribute to the safety, interoperability, and sustainability of the railway sector.

Among the most relevant organizations is the Union of the European Railway Industries (UNIFE). UNIFE represents numerous leading European companies involved in the design, manufacturing, and modernization of railway systems and equipment. Its primary objectives include advocating for policies favorable to rail, promoting an interoperable and efficient railway network, and fostering leadership in the European rail supply industry through innovation and quality.

The Union Industry of Signalling (UNISIG), an Associate Member of UNIFE, is an industrial consortium established to work on the development of ERTMS/ETCS standard. It plays a key role in maintaining and refining these standards and works closely with the European Commission and the European Railway Agency (ERA) to ensure harmonized implementation.

NB-Rail serves as the coordinating group for Notified Bodies. This group collaborates with ERA to gather feedback and propose improvements to the conformity assessment process, ensuring efficiency and consistency.

The International Union of Railways (UIC) operates on a global scale, promoting collaboration among railway operators. It focuses on sharing best practices, enhancing technical and environmental performance, and developing international standards to ensure global rail interoperability.

The ERTMS Users Group, formed by European railway operators, focuses on ensuring the harmonized implementation of ERTMS/ETCS systems. It works closely with ERA and UNISIG to address technical, operational, and commercial challenges, promoting interoperable rail traffic and enhancing competitiveness.

CER (Community of European Railway and Infrastructure Companies) represents railway operators and infrastructure managers across Europe. As a key industry association, CER advocates for the rail sector's interests in EU policymaking. It promotes rail as a backbone of sustainable mobility and works to create favorable conditions for the development and deployment of new technologies. CER actively participates in discussions on ERTMS evolution, providing valuable industry perspective to technical and regulatory developments.

DG MOVE (Directorate-General for Mobility and Transport) is a department of the European Commission responsible for developing and implementing EU policies on mobility and transport. Its mission is to ensure that transport systems across Europe are efficient, safe, secure, and sustainable, benefiting all sectors of society.

DG DEFIS (Directorate-General for Defence Industry and Space) is a European Commission department and plays a pivotal role in the European Union Space Programme. Its activities include assessing current trends, identifying emerging challenges, and ensuring that the objectives of the Space Programme are aligned with broader EU priorities.

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By uniting stakeholders across industry, government, and research institutions, these organizations provide platforms for knowledge sharing and technical collaboration, drive innovation and ensure that railway systems remain aligned with emerging technological and regulatory demands.

2.2 Railway regulations and Standards

The integration of GNSS into railway systems must align with a well-established body of European regulations and standards that govern safety, interoperability, and certification. These regulatory frameworks and technical guidelines are essential for ensuring the seamless and safe operation of railway systems across member states.

2.2.1 EU Directive and Regulations

The regulatory foundation of the European railway system is defined by EU directives and by implementing and delegated that ensure harmonization across member states.

The Directive 2012/34/EU [12] aims to establish a unified European railway area by providing a legal framework that governs the management of railway infrastructure and the activities of railway undertakings within Member States. It also outlines the requirements for issuing, renewing, or amending licenses for railway undertakings in the European Union and specifies procedures for determining and collecting infrastructure charges, as well as allocating railway infrastructure capacity.

The Interoperability Directive (EU) 2016/797 [8] sets the conditions required to achieve interoperability within the EU railway system, working in alignment with the Safety Directive (EU) 2016/798 [9]. Its primary objective is to establish optimal technical harmonization, improve and expand rail transport services both within the Union and with third countries, and support the completion of a single European railway area while advancing the internal market. The directive applies to all aspects of the railway system, including its design, construction, commissioning, upgrades, operation, and maintenance, as well as the qualifications, health, and safety standards required of railway staff.

Complementing this is the Safety Directive (EU) 2016/798 [9], which focuses on enhancing the safety of the European railway system while facilitating better market access for rail transport services. It establishes a harmonized safety framework, clarifies roles and responsibilities, and sets common safety targets (CSTs), common safety methods (CSMs) and common safety indicators (CSIs). Additionally, it provides principles for renewing safety certifications and ensures effective management of railway safety across the Union.

The 2010/713/EU [18] is the Commission decision on modules for the procedures for assessing conformity, determining suitability for use, and conducting EC verification to be used in the technical specifications for interoperability adopted under Directive 2008/57/EC [19].

The Regulation (EU) 402/2013 [13] and amendment is the Commission Implementing Regulation on the Common Safety Method for Risk Evaluation and Assessment (CSM-RA). This regulation is applied whenever changes—whether technical, operational, or organizational—are made to a Member State's railway system. It provides a structured process to evaluate the significance of these changes, identify associated risks, and develop mitigation strategies. Prior to the safety acceptance of the change, fulfilment of the safety requirements resulting from the risk assessment procedure shall be demonstrated.

The Commission Delegated Regulation (EU) 2018/762 [20] establishes common safety methods on safety management system requirements pursuant to Directive (EU) 2016/798 [9] of the European Parliament and of the Council. It defines safety management system requirements both related to railway undertakings and infrastructure managers.

2.2.2 Technical Specifications for Interoperability (TSIs)

The technical specifications of interoperability (TSIs) are defined by Directive (EU) 2016/797 [8] as "a specification adopted in accordance with this Directive by which each subsystem or part of a subsystem is covered in order to meet the essential requirements and ensure the interoperability of the Union rail system". The TSIs are then critical instruments that translate high-level regulatory requirements into detailed technical standards and are updated periodically, to keep up with technical progress or to amend existing deficiencies. The TSIs define the specific conditions that railway systems must satisfy to ensure interoperability across borders, covering areas such as control-command and signaling (CCS), rolling stock, and energy. Of particular relevance to EGNSS integration are the CCS TSIs, which govern the deployment of signaling technologies, including systems that incorporate satellite-based positioning solutions. These TSIs provide guidelines for the implementation of advanced signaling systems such as the European Train Control System (ETCS) and emphasize compatibility between trackside and onboard systems, ensuring seamless operation across borders. The incorporation of satellite-based positioning cannot be done without updating the requirements of the CCS TSI. The TSIs also provide guidelines for assessing the conformity of subsystems and their interoperability constituents. These assessments form the basis for the certification and authorization processes necessary for placing systems into service.

The drafting and adoption process of TSIs can be ideally divided in four stages, involving various actors, among which the ERA and the European Commission assume a key role, as briefly described in the following table.

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STAGE	RESPONSIBLE ENTITY	
Initial stage	European Commission	According to article 50 of Directive 2016/797 [8], the Commission adopts the delegated acts identifying the objectives for the TSIs, which indicates why there is a need for a new TSI or why there is a need for a significant modification of the previous TSI.
Initial stage	European Commission	After the adoption of the delegated act, the European Commission makes a request for the European Railway Agency to elaborate the TSI.
Drafting stage	European Railway Agency	ERA identifies the essential elements of the TSI, the interfaces with the other subsystems and eventual specific cases to consider and regulate differently.
Drafting stage	European Railway Agency	The ERA and its working groups may carry out impact analysis and a cost-benefit analysis.
Drafting stage	European Railway Agency	ERA addresses its recommendation to the Commission, with a description of the consultation process as well as of the impact analysis.
Final stage	European Railway Agency and Committee	According to the applicable procedure, as provided in article 51 paragraph 3 of Directive 2016/797 [8], the European Commission avails itself of a Committee. The Committee votes with a qualified majority and adopts an opinion, which can be either negative or positive.
Final stage	European Commission	The European Commission creates the final act based on the recommendation of the Committee: i) **in case of a positive opinion**, the TSI is adopted. ii) **in case of a negative opinion**, the TSI is not adopted, but it is possible to present a revised project within two months. iii) **in case of no opinion**, the Commission can ordinarily adopt the TSI.

Table 1: Drafting and adoption process of TSIs

This procedure is the one described in the Directive and generally applicable to every TSI. However, for changes to ERTMS specifications the initial phase is regulated differently, with a special procedure known as “Change Control Management” or “CCM”. The ERA is fully responsible for the definition, publication, and implementation of such procedure, as the system authority for ERTMS. Moreover, the ERA has established and is responsible for managing and updating a register of ERTMS specification change requests and their status (it is to be noted that change requests can only be submitted by specific, identified parties). The register also indicates the grounds based on which the request is at a specific step, thus ensuring formal, orderly, and transparent management of all requests.

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The procedure provides for change requests to be submitted to ERA by authorized parties (national safety authorities, Member States and the European Commission are all change requestors, in addition to representative bodies as listed in https://www.era.europa.eu/agency/stakeholder-relations/representative-bodies_en). Change requests must include all the relevant information for the submission, such as the indication of the rationale of the change request as the need to fix an error or generate functional or performances improvement, the detailed description of the problem and its consequences and of the proposed solution.

The change request is then filtered and classified by a "*core team*" formed by ERA staff members and, when needed, ad-hoc sector representatives, and later examined by the "*control group*" formed by external experts. If the "*control group*" does not reject it, the change request is incorporated in a "*package*" of change requests. After the incorporation, a board (formed persons mandated by the representative bodies, representatives of the Network of National Safety Authorities, actors of the sector, and staff from the Agency) determines whether to grant the final acceptance, which means that the package will be submitted to the Commission.

In the context of CCM procedures and TSI modifications, Europe's Rail Joint Undertaking (EU-Rail) plays a crucial role. Established in 2021 under the Horizon Europe framework program for research and innovation, EU-Rail is the successor to Shift2Rail, the joint undertaking created in 2014 to manage railway research and development activities.

EU-Rail's structure is based on two main pillars: the System Pillar and the Innovation Pillar. The System Pillar focuses on all activities aimed at providing a functional and safe system architecture for the railway network, as well as unified and common operational concepts, with particular attention to the protection of interoperability. The Innovation Pillar is dedicated to research and development activities, demonstrating the technical feasibility of innovative solutions.

The System Pillar plays a fundamental role for the evolution of TSIs. Among its activities, is the development of a Standardization and TSI Input Plan (STIP), which encompasses the main changes to be introduced in future TSIs and the Commission's standardization requests. This plan is updated annually following approval by the System Pillar steering group. Within the plan, the various segments are organized by technical sector and described according to the harmonization channel through which they should be introduced, the implementation timeframe, and the connections and dependencies with regulations, other standards, and ongoing R&D activities.

The first version of STIP, approved in 2024, was conceived with the intention of facilitating the circulation of EU-Rail information for use in regulatory and standardization activities, as this circulation had proven difficult in the past. The plan aims to ensure the transfer of research results to the EU standardization and regulatory process, ensuring coordination between change requests from the European Commission and the outcomes of EU-Rail activities.

The introduction of the STIP also supports the creation of a clear and agreed timeline for the evolution of the systems concerned. Through this defined process, the System Pillar activities are positioned to become the center for coordinating, specifying, and creating agreements regarding any changes related to TSIs and standards that will support interoperability, harmonization, and implementation of the Single European Railway Area.

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This structured approach is particularly relevant for the integration of GNSS-based solutions in the ERTMS framework, as it provides a clear pathway for innovative technologies to be incorporated into the regulatory and standardization process.

2.2.3 Railway standards

European standards, developed by CENELEC, provide detailed technical specifications that complement TSIs. These standards ensure safety, reliability, and interoperability within the European railway network. They address various aspects of railway systems, from environmental conditions to software and system safety, and support compliance with EU legislation such as Directive (EU) 2016/797 on railway interoperability.

2.2.3.1 EN 50126: RAMS Requirements

EN 50126, comprising of EN 50126-1 [14] and EN 50126-2 [15], defines the processes for achieving and demonstrating Reliability, Availability, Maintainability, and Safety (RAMS) throughout the entire lifecycle of railway systems. This includes concept, design, implementation, operation, maintenance, and decommissioning. It ensures systematic identification, assessment, and mitigation of risks. It applies to railway applications, including CCS applications, rolling stock, and fixed installations, covering new systems, modifications to existing systems, and integration of new functionalities.

2.2.3.2 EN 50716:2023: Railway Applications - Requirements for software development

EN 50716:2023 [16], titled "Railway applications – Requirements for software development", specifies process and technical requirements for the development of software used in programmable electronic systems for railway CCS applications, as well as onboard rolling stock systems. This standard replaces EN 50128:2011 [21] and EN 50657:2017 [22], consolidating guidelines for software development in the railway sector and aligning with EN 50126 [14, 15] and EN 50129 [17].

2.2.3.3 EN 50129: System Safety Certification

EN 50129:2018 [17] defines requirements for certifying safety-related electronic systems used in railway signaling, including development of a safety case to demonstrate compliance with required Safety Integrity Levels (SILs). The standard emphasizes traceability, evidence-based safety claims, and robust documentation, supporting system certification. It applies to new and modified systems, as well as Commercial Off-The-Shelf (COTS) equipment integrated into signaling systems.

2.2.3.4 EN 50159: Safety in Communications

EN 50159:2010 [23] applies to safety-related electronic systems using digital communication. It defines requirements to ensure safe communication between connected safety-related equipment, considering hazards such as message alteration, delay, or loss. The standard addresses communication in both closed and open transmission systems but does not cover general IT security issues. Its focus is on intentional, message-based attacks affecting the integrity of safety-related systems.

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2.2.3.5 EN 50125: Environmental Conditions

EN 50125-1 [24] specifies the environmental conditions that railway equipment, including rolling stock and onboard systems, must withstand during operation. This includes factors such as temperature, humidity, vibration, altitude, and pollution. While the standard primarily addresses normal service conditions, it also provides guidance for designing systems that can endure severe environmental conditions but excludes extreme events like natural disasters.

2.3 Certification and Authorization Processes

The certification and authorization processes are needed to ensure compliance with European safety, interoperability, and operational standards. This section is only intended to provide a brief and high-level overview; more details will be provided in Chapter 5 and in subsequent VICE4RAIL deliverables.

Certification verifies that railway subsystems and components meet the essential requirements of interoperability, safety, and reliability as defined by European directives and TSIs. The process involves Conformity Assessment Bodies, which evaluate the design, production, and performance of subsystems against relevant standards. A key element of certification is EC verification, a structured process that assesses technical documentation, production methods, and operational tests. CABs are authorized to inspect and validate that the subsystem's performance aligns with the applicable TSIs and European standards. Upon successful completion, an EC Declaration of Conformity or EC Declaration of Verification is issued, demonstrating the readiness of the subsystem for integration into the railway system.

Authorization ensures that certified subsystems and vehicles are safe and compatible with the railway network. This process, governed by the ERA and NSAs, involves detailed assessments of technical documentation and compliance with safety and interoperability requirements. Subsystems such as CCS and trackside infrastructure require an Authorization for Placing in Service (APIS) before deployment. This includes a review of the EC Declarations, safety documentation, and operational testing results. Similarly, vehicles must undergo an Authorization for Placing on the Market (APOM), confirming their compatibility with infrastructure and compliance with rolling stock TSIs. These authorizations are essential steps in achieving a fully interoperable and safe railway system.

2.4 Challenges for the use of GNSS-based solution in Railway

The existing railway regulatory framework, centered on the Technical Specifications for Interoperability (TSIs), was not originally designed to accommodate satellite-based positioning systems. The GNSS into railway operations requires a comprehensive revision of technical specifications to include satellite-based technologies. This alignment must define clear, standardized requirements for accuracy, reliability, safety, and interoperability, while also establishing robust validation methodologies for assessing GNSS performance under real-world railway conditions.

A critical challenge in GNSS-based railway solutions is meeting the highest safety integrity requirements. The enhanced train positioning function must ensure compliance with Safety Integrity Level 4 (SIL4), the most stringent safety standard in rail signaling applications. Demonstrating certifiable SIL4 compliance requires:

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- Rigorous testing and validation methodologies tailored to railway operational conditions.
- GNSS augmentation systems designed to support safety-critical applications, mitigating risks associated with signal interference, multipath effects, and integrity failures.
- Development of advanced fault detection and mitigation strategies to prevent positioning errors that could impact train operations and passenger safety.

The successful deployment of GNSS-enabled systems for SoL train localization also depends on seamless interoperability with existing railway system, particularly the ERTMS. However, enhanced train positioning solutions require additional enablers to be standardized, such as GNSS augmentation and digital maps. Key challenges include:

- Defining a standardized GNSS augmentation framework that ensures consistent and reliable performance across different railway environments.
- Establishing standard digital maps with a uniform format, ensuring compatibility across rail networks and signaling technologies.
- Developing standardized interfaces and protocols to facilitate integration with legacy systems.

Finally, the certification of GNSS-based railway positioning solutions presents unique challenges, particularly when relying on services provided by external entities outside the railway domain. Certification requires addressing multi-technology sensor fusion, ensuring that GNSS data can be reliably combined with Inertial Measurement Units (IMUs), odometry, and other onboard sensors to achieve a robust positioning solution. Furthermore, liability and regulatory clarity regarding the use of GNSS augmentation services, must be established, as these services are provided by third-party organizations, raising concerns about accountability in case of system failures or inaccuracies. The role of ERA (European Union Agency for Railways) and EUSPA (European Union Agency for the Space Programme) in the authorization process needs to be clearly defined.

The certification process for EGNSS in railways can leverage experience from other domains, such as aviation, where Satellite-Based Augmentation Systems (SBAS) like EGNOS have been widely implemented. However, direct adoption of aviation standards is not feasible due to differences in operational environments, safety requirements, and stakeholder roles. To facilitate a cross-domain certification framework, efforts should focus on adapting best practices from aviation while addressing the unique requirements of the railway sector, as well as establishing clear certification pathways that consider both GNSS-specific challenges and railway-specific operational constraints. Addressing these challenges requires a multi-stakeholder approach, involving railway operators, regulatory bodies, technology providers, and certification agencies. Establishing standardized methodologies for safety validation, interoperability, and certifiability will be essential to ensure the successful integration of GNSS-based positioning solutions into railway operations.

This chapter has outlined the complex regulatory ecosystem and the roles of key stakeholders in railway standardization and certification processes. Building upon this foundation, Chapter 3 focuses on the specific user and system requirements that will inform the development of the VICE4RAIL virtualized testing and certification environment, ensuring alignment with both regulatory constraints and operational needs of the European railway sector.

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3 User needs and system requirements

The objective of this section is to define the rail user and system requirements which are instrumental in supporting the development of a hybrid virtualized testing and certification framework tailored specifically for EGNSS-based train localization solutions.

3.1 Background

In the ERTMS, accurate train positioning is essential for ensuring proper spacing between trains and thus allow a safe circulation. Train positioning refers to the process of determining the location and orientation of the train front end along the track. This information, combined with other inputs from the train and/or trackside, is needed to identify the section of track occupied by the entire train. While the train provides Train Position data, this alone is not sufficient. Additional parameters, such as train length (both behind and ahead of the active cab) and train integrity status, are also required. These can be supplied by the train itself or determined from trackside systems. Together, these data ensure the safe monitoring and control of railway traffic.

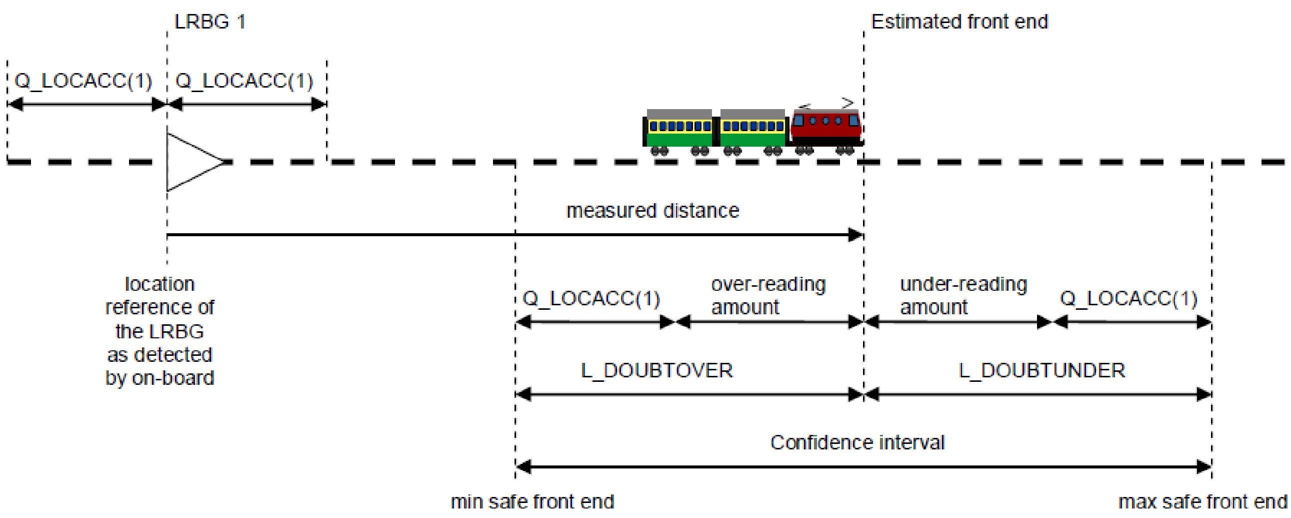

Figure 2: ETCS train positioning principles (Subset 026) [25]

According to ETCS principles, train position information is determined by measuring the distance traveled from fixed reference points known as Eurobalises. Specifically, localization relies on:

- Groups of balises installed at regular intervals along the track, whose positions are georeferenced.
- The on-board odometry system, which estimates the train’s movement based on wheel rotations and other sensor inputs.

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The detection of a balise group by the on-board reader, known as the Balise Transmission Module (BTM), allows the determination of the train's absolute position[1], while the odometer provides a continuous estimate of the distance traveled since the last successfully detected balise group. With the measurement of the distance traveled, the train also provides the corresponding confidence interval, a parameter indicating the reliability of the position estimate. The confidence interval is reset whenever the BTM detects a balise group (whose position is georeferenced during the installation phase), while increases over distance between one balise group and the next one (this behavior is depicted in Figure **3** and it is dictated by the typical error model of the legacy odometric system).

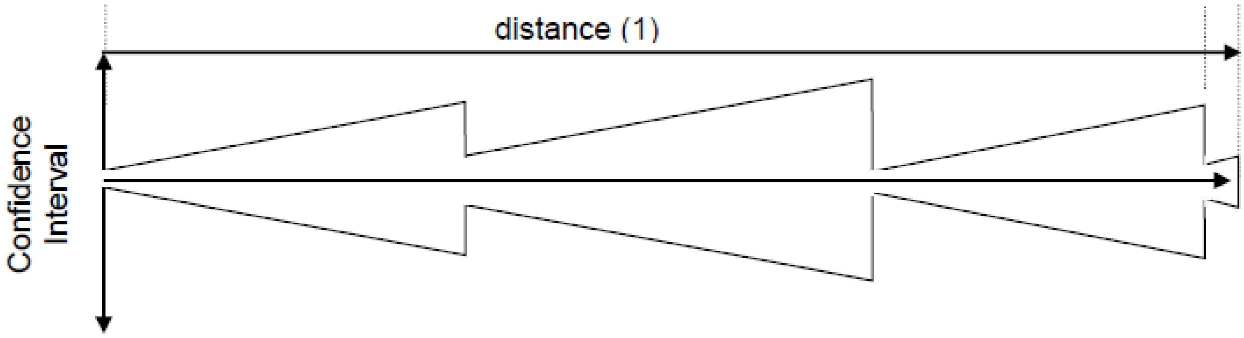

Figure 3: Confidence interval over distance (Subset 026) [25]

Although effective, this system has several disadvantages: balises are expensive to install and maintain, and the odometric systems currently in use have several limitations. More specifically, the accuracy of these systems can be influenced by:

- Skidding and slipping phenomena due to the imperfect wheel-rail coupling (this phenomenon occurs mainly under low adhesion conditions, such as rain or ice).
- Wheel wear and diameter variation, which, if uncorrected, leads to progressively larger estimation errors.
- Initial calibration errors, where incorrect settings (e.g., wheel diameter, sensor sensitivity) cause systematic position errors).

These factors can result in significant localization errors and widening confidence intervals, which, in turn, limit railway capacity and operational efficiency.

To compensate for these limitations, new technologies are being explored to reduce operational costs associated with ground components, minimize confidence intervals, and increase line capacity. Emerging approach should enable the transition from the current system to one that performs the localization function by leveraging the use of new technologies such as GNSS, Digital Maps, inertial sensors, and/or visual sensors (cameras and LIDAR). Among these, GNSS is considered a key "Game Changer" technology due to its potential to improve overall accuracy while reducing infrastructure costs. However, GNSS alone is not a complete solution—challenges such as signal interference, multipath errors (e.g., in urban areas), and cybersecurity concerns must be addressed through hybrid approaches combining multiple sensors and technologies.

[1] The determination of the train's absolute position means a position referred to a georeferenced reference position point known to the trackside subsystem.

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Recognizing the potential of satellite-based localization, the EU has funded several initiatives to explore and validate GNSS performance in railway operations. Notable projects include STARS, 3inSAT, ERSAT EAV, ERSAT GGC, GATE4RAIL, DB4RAIL, SBS, HELMET, X2RAIL-2, X2RAIL-5, CLUG, EGNSS MATE, RAILGAP, and R2DATO (the latter still on-going).

Shift2Rail (S2R), established under the Horizon 2020 program, was the EU's first dedicated joint undertaking for railway innovation, aiming to transform the sector's efficiency, reliability, and sustainability through coordinated research. The S2R Joint Undertaking was established by Council Regulation (EU) No 642/2014 [26] and commenced operations on July 7, 2014, with a mandate that extended until December 31, 2024. Recognizing satellite-based localization's strategic importance, as a result of the work carried out in X2RAIL-5 within S2R, two solutions emerged, known as Stream 1 and Stream 2. These two streams are relevant because reflect the approaches proposed and validated in most of the previous projects mentioned before. A comparative analysis of Stream 1 and Stream 2 is provided below.

Stream 1 adopts the so-called "Virtual Balise" approach that essentially maintains compatibility with existing ETCS principles. At its core, this solution virtualizes physical balises by emulating traditional BTM (Balise Transmission Module) behavior. The Virtual Balise Detection function uses multi-sensor technology to determine train position and evaluate when the train crosses virtual balise locations stored in a Digital Map. This approach effectively translates satellite-based positioning into the "language" of legacy ETCS principles without modifying the actual ETCS architecture.

In contrast, Stream 2 takes a different absolute positioning approach. Rather than working within the balise paradigm, it provides continuous absolute train positioning in three-dimensional coordinates. The system projects this 3D position onto the correct track (converting to 1D with orientation) and defines distances relative to reference points. Stream 2 relies on a Safe Sensor Fusion Algorithm that combines inputs from multiple sensors including GNSS, IMU, speed sensors, balises, and digital map information.

The position reference mechanism differs significantly between the two solutions. Stream 1 continues to use balises (including virtual ones) as reference points, maintaining the established ETCS paradigm. Stream 2, however, is more flexible in its reference system, capable of using any point from the Digital Map, the Last Relevant Balise Group, or an initialization point established since train startup.

Regarding architectural impact, Stream 1 represents a more conservative evolution to existing ETCS systems. It complements the BTM with virtual balise management capabilities, resulting in relatively smaller effects on the European Vital Computer (EVC). Stream 2 introduces more substantial changes to the actual ETCS aiming at replacing the embedded odometry platform within the EVC itself with an external self-standing unit.

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With respect to Stream 2, Stream 1 explicitly addresses backward compatibility, noting that trains equipped with this solution can run on legacy lines. Furthermore, the GNSS positioning is required only at the Virtual Balise locations that can be chosen in a way to maximise the visibility of the satellites [27]. As for the required inputs, both solutions need Digital Maps and GNSS Augmentation signals.

A comparative analysis of the two streams is summarized in the table below:

	Stream 1: Virtual Balise	**Stream 2: Absolute Positioning**
Core concept	The Virtual Balise (VB) detection system emulates traditional BTM (Balise Transmission Module) behavior.	Provides continuous absolute train positioning in 3D coordinates.
Core function	Virtual Balise Detection (VBD) using multi-sensor technology to identify when train crosses predefined position (Virtual Balise) on a digital map.	Safe Sensor Fusion Algorithm (SFA) combining multiple sensor inputs (GNSS, IMU, speed sensors).
Output	Virtual Balise detection and transmission to ETCS Kernel.	Absolute train position (3D coordinates), longitudinal speed, and relative distance from a reference point.
Integration with ETCS	Maintains ETCS location principles by translating satellite positioning into "balise language".	Projects 3D position onto track and compute the distance from a given reference point (1D with orientation).
Position Reference	Uses Virtual Balises as reference points (maintains ETCS paradigm).	Can use any reference point from Digital Map, Last Relevant Balise Group, or initialization point.
Impact on ETCS Architecture	Lower impact - complements BTM with VB management, smaller effect on EVC.	Higher impact - replaces embedded odometry platform in EVC by an external self-standing device

Table 2: “Virtual Balise” vs “Absolute Positioning”

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In summary, Stream 1 represents a more conservative approach that maintains compatibility with existing ETCS paradigms by translating satellite positioning into the legacy balise detection model. Stream 2 offers a more revolutionary approach, replacing core positioning components with a comprehensive absolute positioning system. While Stream 1 potentially offers an easier migration path, Stream 2 provides potentially more advanced capabilities but with greater architectural impact and integration complexity into the actual ETCS architecture and challenging safety requirements.

Building on S2R's achievements, Europe's Rail Joint Undertaking (EU-Rail) was launched in 2021 to accelerate the technological transformation of Europe's railways and bridge the gap between research and standardization. Based on the analysis and the work carried out within S2R, the solution currently under discussion within the Europe’s Rail Joint Undertaking - and therefore a strong candidate for standardization - is the so-called Advanced Safe Train Positioning (ASTP).

3.2 Advanced Safe Train Positioning (ASTP)

The Advanced Safe Train Positioning (ASTP) system has been defined in the context of ERJU as a modular, scalable component within the CCS-OB architecture that provides localization information to multiple on-board users (e.g., ETCS-OB, ATO-OB) through standardized interfaces. This concept can be seen as a direct evolution of Stream 2. ASTP will not provide the train position report to trackside however it will provide the information the ETCS on-board (and possible other on-board consumers) uses to build the train position report according to the ETCS standard.

A fundamental architectural choice (currently under discussion and to be validated) establishes that ASTP provides localization data via a fixed reference frame attached to the vehicle where ASTP is installed. This reference frame utilizes the ASTP reference point (e.g., a bogie pin) as origin, with axes defined relative to the carriage structure. The system thus avoids transforming data to the train front end reference frame, as this would introduce dependencies on train configuration and dynamic operational states. Instead, transformation responsibility is allocated to consumers of localization information (such as ETCS-OB and ATO-OB), who must apply appropriate offsets and rotations based on train configuration parameters. This architectural decision delivers advantages in terms of modularity and independence from specific train configurations. This approach is still being evaluated and has not yet been formally approved.

ASTP uses several reference frames to express different types of localization information to different users:

- **ASTP Reference Point**: A fixed point located on the carriage floor, along the longitudinal axis of the vehicle where the ASTP is installed. This point doesn't depend on train configuration and is a static parameter. Preferably, this should be on a bogie pin.
- **ASTP 1D Reference Frame**: A one-dimensional reference frame attached to the vehicle, defined by the ASTP reference point as origin and the x-axis following the track centerline. This reference frame is fixed and doesn't change with train configuration or movement, and is used to express position, speed, and acceleration along the track centerline.
- **ASTP 3D Reference Frame**: A three-dimensional reference frame defined as a right trihedron. The origin is the ASTP reference point, with the x-axis aligned with the carriage longitudinal axis, y-axis orthogonal to it (to the left), and z-axis orthogonal to the carriage floor (upward).

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- **ASTP Absolute Position Reference Frame**: A geocoordinate system (e.g., WGS84) used to express absolute position of the ASTP reference point.
- **ASTP Attitude Reference Frame**: Describes orientation of the vehicle using rotational angles (yaw, pitch, roll).

ASTP can utilize various supporting information to achieve performance requirements:

- **Map Data**: Digital representation of track layout and topological information, used for sensor fusion and absolute positioning.
- **Augmentation Data**: GNSS augmentation data (e.g., EGNOS) to improve accuracy and integrity of positioning information. The augmentation data may be provided to the ASTP through Signal in Space (SiS) or by the trackside augmentation system.
- **Routing Information**: Point status according to the safe train path uniquely assigned to a train/vehicle, useful for track selectivity determination.
- **Eurobalise Telegram**: Information from physical balises on the track, serving as reference points. This information is provided from the ETCS.
- **Last Relevant Reference Location**: Reference point information (LRBG or virtual reference point) for establishing relative positions.
- **Cold Movement Status**: Information about whether a train has moved during power-off conditions.

ASTP should be able to meet the new localization user requirements which are currently under discussion. According to the current specification [28], the performance requirement of the odometry is defined as a linear model of the measured distance from the reference balise group (LRBG). Specifically, for every measured distance *s*, the accuracy of distances measured on-board shall be better or equal to ±*(5m+5%s)*, i.e. the over reading amount and the under reading amount (which directly impact the confidence interval, see Figure **2**) shall be equal to or lower than *(5m+5%s)* [28].

The principle for limiting the upper limit of the confidence interval is detailed in [25] and involves resetting it to a minimum value whenever the train crosses a reference point, e.g. physical balise. Consequently, the maximum value of the confidence interval is determined by the distance between LRBGs. The engineering rules for placing balises are thus essential to meet the operational performance targets of a line.

Activities to review train localization user requirements are in the scope of R2DATO within the ASTP activities, where a fixed values model for the confidence interval limits has been proposed [29]. This model is based on the Max Accepted Position Underestimation (MAPU) and the Max Accepted Position Overestimation (MAPO). The former is a limit to the underestimation (L_DOUBTUNDER) of the estimated train front end position, while the latter is a limit to the overestimation (L_DOUBTOVER).

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The fixed values for MAPO and MAPU of the model proposed in [29] have been defined for two types of areas and are listed in Table **3**.

Type of areas	MAPO, MAPU
Area with negligible constraints *(mainline, dense traffic line, track section between two areas with constraints)*	**60 m**
Area with constraints *(station area (platform), traffic node (specific point), stopping point (EoA), limit of authority (LoA))*	**10 m**

Table 3: Fixed values confidence interval model

The development of an independent GNSS-based train positioning system able to satisfy the revised localization user requirements aims to achieve the following main objectives:

1. Reducing the train confidence interval, improving both safety and performance by preventing confidence intervals from increasing indefinitely with distance traveled.
2. Mitigating skidding and slipping effects, which are common issues affecting legacy odometry accuracy, particularly in adverse weather conditions.
3. Significantly reducing systematic errors, such as those caused by incorrect wheel diameter calibration.
4. Reducing the need for physical repositioning reference points, thereby reducing infrastructure costs.
5. Supporting the transition to an on-board-centric approach by enabling the migration of track occupancy functions from trackside to onboard systems.
6. Facilitating the integration of future technologies through a modular safety architecture.
7. Reducing the distance that trains operate in ETCS mode with restricted supervision when a valid and unambiguous train position cannot be ensured, either after Start of Mission or following a recovery from a failure, thereby improving train operation efficiency.

The ASTP has been incorporated into the first version of the STIP (the indications that EC and ERA should adopted to define priorities for the evolution of TSIs), developed by the System Pillar of Europe's Rail Joint Undertaking. ASTP deployment has been structured in two-phase incremental phase ("Standardization and TSI Input Plan" presentation at ERTMS 2024 Conference [30]):

- **Phase 1 (Basic ASTP)** – Targeted for TSI 2027, this phase focuses on enhancing odometry performance and robustness while defining the interface between ASTP and the EVC. However, it does not include the standardization of GNSS augmentation or Digital Maps, meaning that the use of virtual reference points is not yet possible.

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- **Phase 2 (Full ASTP)** – Planned for TSI 2032, this phase aims for a more comprehensive implementation, incorporating absolute positioning capabilities and the potential use of GNSS augmentation, including EGNOS. This phase may allow for the use virtual reference points. However, it should be noted that, compared to the Stream 1 "Virtual Balise" approach (which retains the current ETCS odometry), ASTP seems to pose greater challenges, similarly to Stream 2, particularly regarding its potential integration and certifiability.

The integration of ASTP within the STIP framework, developed by the System Pillar of Europe's Rail Joint Undertaking, represents a significant institutional endorsement for GNSS-based train positioning in the European railway ecosystem. This inclusion establishes ASTP as the officially recognized pathway toward standardization and incorporation of GNSS-based solutions into future TSIs by 2032. The structured approach provided by the STIP offers a clear timeline for the evolution of ASTP from its initial conceptual phase to full standardization.

According to STIP, Full ASTP - with GNSS Augmentation and Digital Maps - is the satellite-based positioning solution under consideration for inclusion in the future TSI (2032). Consequently, VICE4RAIL strategically aligns with this European standardization trajectory by adopting the Full ASTP requirements as its developmental baseline. This alignment positions VICE4RAIL not as an isolated research initiative, but as an integral contributor to the broader European standardization efforts. By developing its hybrid virtualized testing and certification environment in accordance with the ASTP framework, VICE4RAIL aims to facilitate the critical certification processes that will ultimately enable the widespread adoption of GNSS technologies in safety-critical railway applications across Europe.

3.3 Methodology for requirements derivation

The derivation of system requirements for technical safety systems typically begins with high-level user requirements and operational concepts. These initial requirements are informed by a Concept of Operations (CONOPS), a document that articulates the operational needs, expectations, and views of user groups without delving into technical implementation details. Written in user language, the CONOPS serves as a foundational reference for extracting high-level user requirements and performance objectives.

The CONOPS document generally includes the following elements, grouped into broader categories:

- Identification of different operational modes/ scenarios for safety applications;
- Identification of various operational environments and constrains;
- Derivation of high-level user requirements for system solutions;
- Summary of high-level user requirements for the system;
- Specification of functional user requirements - to show how user requirements are realised (by which functions);
- Specification of high-level reliability and availability requirements;
- Description of high-level safety concepts;
- Derivation of high-level safety requirements;
- Overview of high-level user safety requirements;
- Regulatory requirements for safety assessment, certification and authorization process.

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This structure ensures that the CONOPS provides a comprehensive and user-focused foundation for the development of high-level functional and safety requirements, as well as system-level technical specifications. Once the CONOPS and preliminary system architecture are established, system requirements can be derived. These requirements, intended for system developers and certification bodies, include the necessary technical details and align closely with the results of the CONOPS. According to EN 50126 [14], system requirements are divided into:

- Functional Requirements: Defining the specific functions the system must perform.
- Non-Functional Requirements: Covering performance, reliability, safety, environmental protection, security, electromagnetic interference (EMI), electrical standards, maintainability, installation constraints, robustness to casual and systematic faults, and more.

In the VICE4RAIL project, the methodology for deriving system requirements builds upon the outcomes of previous and ongoing EU initiatives, streamlining the process by refining existing results rather than starting from scratch. Research initiatives performed under Shift2Rail, EU-Rail or any other EU-funded projects, such as STARS, ERSAT, HELMET, and CLUG, have already established user and system requirements for GNSS-based train positioning for the context of ERTMS.

Specifically, user and system requirements derivation has been performed by taking as inputs the following sources:

- Europe's Rail Joint Undertaking Flagship Project 2 (FP2) R2DATO: Specifically, the deliverables D21.1 [29] and D21.2 [31] from R2DATO Work Package 21. These documents provide essential information and insights on ASTP. It is worth noting that these deliverables represent the result of collaborative efforts involving multiple stakeholders from across the European railway sector, incorporating lessons learned from previous projects and initiatives. They are the result of an extensive review and synthesis process which also involved the European space agencies (ESA and EUSPA), ensuring their relevance and technical validity for the ASTP development.

- Europe's Rail System Pillar activities: VICE4RAIL benefits from connections with the relevant System Pillar activities, providing awareness of ongoing standardization discussions and emerging concepts on GNSS-based localization for ERTMS. This engagement helps ensure the project maintains alignment with the evolving European railway standardization landscape, particularly regarding train positioning solutions. As part of its connection with Europe's Rail System Pillar activities, VICE4RAIL considers the ASTP Functional Requirements Specification (ASTP FRS) [32] as a key reference. Currently in draft status, this document outlines a structured set of requirements for ASTP, developed through a systematic methodology that consolidates inputs from R2DATO WP21 deliverables, previous projects results, and standardization discussions. Its approach ensures alignment with the broader ASTP framework, making it a valuable resource for requirement definition. The ASTP FRS is expected to be publicly released in the coming months.

- Shift2Rail and previous projects deliverables: Results have been consulted to provide context and background information in the previous sections of this chapter and have been indirectly considered trough ASTP FRS [32].

This approach leverages the synthesis work already performed in the Europe's Rail, which incorporate findings from earlier EU-funded initiatives, and aims to maximize synergies with ongoing projects (particularly FP2-R2DATO), ensuring a comprehensive approach to requirements derivation. The alignment with the ASTP vision and ongoing standardization efforts provides assurance that the requirements adopted for VICE4RAIL cover the essential aspects needed for the development of a hybrid virtualized testing and certification framework that will support the entire European railway community and will complement the on-going efforts being pursued in other European initiatives. Indeed, VICE4RAIL strategically aligns with the evolving European standardization trajectory, recognising the prominent role of the STIP developed by Europe's Rail System Pillar and thus adopting the Full ASTP requirements as a baseline.

However, it should be noted that, as ASTP is still under discussion within Europe's Rail, the requirements outlined below should not be considered as finalized or universally agreed upon by the entire railway sector. Discussions are still ongoing and full consensus on ASTP scope, technical implementation, and integration strategy has not yet been reached. This is why a high-level approach has been maintained, providing necessary flexibility to accommodate evolving specifications while ensuring alignment with the fundamental principles and objectives of ASTP. Once new ASTP requirements are consolidated and made publicly available, they may be taken into consideration for the implementation of the project, provided that developments and timelines allow it.

This approach ensures that VICE4RAIL not only builds upon technical achievements of previous initiatives but also contributes directly to the official standardization pathway for GNSS-based positioning in European railways. The project timeline, with completion scheduled for the end of 2027, positions VICE4RAIL to contribute to the standardization processes leading toward the Full ASTP implementation targeted for TSI 2032. For all this reasons, VICE4RAIL aims to position itself as a facilitator for the broader European vision of GNSS integration in railway safety systems.

3.4 User needs

The following table details the rail user needs.

ID	DESCRIPTION
UN-01	IMs need to increase the capacity of railway lines by optimizing headway and enabling denser train operations.
UN-02	IMs need to reduce reliance on physical reference/repositioning points (balises) compared to current ETCS specifications, thereby lowering the infrastructure costs associated with installation and maintenance.
UN-03	IMs need to improve accuracy and reduce confidence interval associated to train position data.
UN-04	IM needs a train localization system that minimizes or eliminates the impact of slipping and sliding phenomena on localization accuracy.

UN-05	IM needs a train localization system that allows to reduce/eliminate the dependency from systematic error (such as inaccuracies caused by wheel diameter variations).
UN-06	IMs need a train localization system that performs effectively under all physical rail environments such as station areas, urban areas surrounded with high buildings, forests, deep valleys, etc.
UN-07	IMs need a train localization system that performs effectively across diverse rail infrastructures, such as metallic bridges, concrete bridges, slab tracks, ballasted tracks, and varied sleeper and point configurations.
UN-08	IMs need a train localization system that is robust with respect to cybersecurity requirements, ensuring secure and resilient operations.
UN-09	IMs aim to improve odometry performance compared to current ETCS specifications, particularly by considering error model profiles that should not necessarily increase with distance run.
UN-10	IMs need localization systems to serve as enablers (albeit not solely sufficient) for transitioning track occupancy functions from trackside to on-board, fostering an on-board-centric approach.
UN-11	IMs need localization systems that facilitate the adoption of new and future technologies through modular safety designs, making upgrades more flexible and faster with minimum effort and no impact on the other CCS-OB equipment.
UN-12	IMs aim to reduce the distance that trains operate in ETCS mode with restricted supervision when a valid and unambiguous train position cannot be ensured, either after Start of Mission or following a recovery from a failure, without relying on physical balises.

Table 4: Rail user needs

3.5 System requirements specification

According to EN 50126 [14], system requirements are categorized into functional requirements, which define the system's intended behaviour, and non-functional requirements, which encompass aspects like reliability, availability, maintainability, safety, security, performance, and more.

For the reasons explained before, the following requirements are extracted from the draft version of the Europe's Rail System Pillar ASTP Functional Requirements Specification (ASTP FRS) [32], which represents the most up-to-date synthesis of prior work, integrating inputs from R2DATO WP21, previous EU-funded projects, and ongoing standardization discussions.

These requirements are referenced as they appear in the latest available ASTP FRS draft (Version 1.0, Revision 452312, Last Change Date 16.12.2024) [32], and their final version may be subject to modifications upon official publication by Europe's Rail.

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Requirements classified as [UN] (Unstable), which are linked to ongoing decisions and not yet consolidated, have been intentionally excluded from this document to ensure alignment with the most stable and validated ASTP requirements. Once new ASTP requirements are consolidated and made publicly available, they may be taken into consideration for the implementation of the project, provided that developments and timelines allow it.

3.5.1 Functional requirements

ID	DESCRIPTION
FR-01	[SPT2ARC-2622] - ASTP shall provide position, speed, acceleration and other data such as heading, attitude (pitch, roll, yaw) with the relative confidence interval and with different SIL levels to multiple users simultaneously. Note: the need to make available other data will be duly demonstrated through a survey aiming to identify all ASTP consumers and their requirements.
FR-02	[SPT2ARC-2621] - ASTP shall provide train 1D position relative to a physical balise reference location or the travelled distance from the last power on, according to 1D reference frame.
FR-03	[SPT2ARC-2836] - ASTP shall provide train 1D speed according to 1D reference frame.
FR-04	[SPT2ARC-2835] - ASTP shall provide train 1D acceleration according to 1D reference frame.
FR-05	[SPT2ARC-2083] - ASTP shall provide train 3D position.
FR-06	[SPT2ARC-2804] - ASTP shall provide train 3D velocity, according to 3D reference frame.
FR-07	[SPT2ARC-2805] - ASTP shall provide train 3D acceleration, according to 3D reference frame.
FR-08	[SPT2ARC-2806] - ASTP shall provide train 3D attitude (rotational angles) according to the attitude reference frame.
FR-09	[SPT2ARC-2649] - ASTP, from the train power on, shall initialise itself and provide the outputs with no human supervision. Note: Manual procedures are only admitted at the first power-on or during maintenance activities.
FR-10	[SPT2ARC-2604] - ASTP shall always provide train speed and travelled distance after an ASTP initialisation independently if the position is valid or not for ETCS.
FR-11	[SPT2ARC-2802] - ASTP shall exchange data with Time control unit, Control cybersecurity access, Maintenance and diagnostic monitoring unit and juridical recorder.

FR-12	[SPT2ARC-2839] - ASTP shall use a common time synchronisation technique compatible with the safety requirements in accordance with the EN50159 standard. Note: If available, the chosen technique shall be the one defined in the future TSI.
FR-13	[SPT2ARC-2877] - ASTP shall be able to operate in LNTC, ETCS Level 1, ETCS Level 2. Note: the full ASTP performance shall be achieved in ETCS Level 2.
FR-14	[SPT2ARC-2632] - ASTP shall ensure the fulfilment of functional and non-functional requirements without the need for human intervention (unless for maintenance purposes).
FR-15	[SPT2ARC-2648] - ASTP shall not be sensitive to train track adherence phenomenon (e.g. slip/slide). Note: a release of the constraints for the maximum distance between BGs is expected.
FR-16	[SPT2ARC-2842] - ASTP shall manage a time stamped event memory.

3.5.2 Non-functional requirement

3.5.2.1 Environmental requirements

ID	DESCRIPTION
ENV-01	ASTP shall ensure the fulfilment of functional and non-functional requirements in an onboard vehicle, fitted for a SERA area, whose characteristics (traction system, temperature, pressure, EMC, pollutions, pressure, water proofing, vibration and shock, chemical, fire prevention, etc.) shall be considered during the design phase. Note: The traction system has an impact on the adhesion factor between wheel and rail; exceptions can be accepted for vehicle not in commercial operation.
ENV-02	ASTP shall ensure the fulfilment of functional and non-functional requirements in severe weather condition (temperature, altitude, rain, snow, fog, wind, etc.) which allow train operations in Europe (SERA). Note: in case GNSS technology is envisaged (only for full ASTP [FA]), also space weather conditions should be considered.
ENV-03	The ASTP system shall function under the environmental conditions defined in document EUG 97S066 [33] environmental constraints.
ENV-04	ASTP shall ensure the fulfilment of functional and non-functional requirements in all physical SERA rail environments and type of infrastructure such as station areas, urban areas surrounded with high buildings, forests, deep valley, tunnel bridges, with or without catenary, concrete track, ballast, etc..
ENV-05	ASTP technology and installation choices shall not interfere with the correct working of all other subsystems present into the vehicle environment.

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ENV-06	ASTP shall ensure the fulfilment of functional and non-functional requirements from standstill to the maximum speed allowed by ETCS (500 km/h).
ENV-07	ASTP shall ensure the fulfilment of functional and non-functional requirement when performing under all light environmental conditions (e.g., night, darkness, sunlight...).

3.5.2.2 Performance requirements

ID	DESCRIPTION
PER-01	[SPT2ARC-2643] - ASTP shall improve the positioning/speed accuracy model (error profile and over/under reading amount) compared to the existing on-board odometry solutions used in the ETCS domain (see Subset 041).
PER-02	[SPT2ARC-2851] - ASTP shall provide the train estimated acceleration with a computed confidence interval better than 0.2 m/s2.
PER-03	[SPT2ARC-2641] - ASTP shall allow to determine a safe track selective positioning in a short time and minimising the distance to be run. Note: This will make safer and more efficient the operation at Start of Mission, when other subsystems cannot ensure an un-ambiguous train position and after passing a switch point.
PER-04	[SPT2ARC-2602] - ASTP shall ensure a start-up time compatible with common rail starting up operational procedures (order of 60 seconds).
PER-05	[SPT2ARC-2843] - ASTP could be scalable if reduced costs can be expected when lower performance is required.
PER-06	[SPT2ARC-2844] - ASTP dataset time validity shall not exceed 200 ms when transferred to users.
PER-07	[SPT2ARC-2858] - ASTP shall provide the estimated distance travelled since power-on according to subset 035.
PER-08	[SPT2ARC-2876] - ASTP shall fulfil the specified performance requirements even in case of degraded visual environment. Note: Some sensors may struggle in degraded visual environment (e.g., camera, lidar, etc). ASTP design must consider the specific weak point of each sensor to avoid loss of performance under conditions considered probable.

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3.5.2.3 Reliability requirements

ID	DESCRIPTION
REL-01	[SPT2ARC-2601] - ASTP shall ensure at least the same reliability target (MTBF) compared to the existing on-board odometry solutions used in the ETCS domain.
REL-02	[SPT2ARC-2600] - ASTP reliability target (MTBF) shall be defined according to the impact on operation of the failure: minor (no impact), reduced service, immobility.
REL-03	[SPT2ARC-2834] - ASTP life cycle shall be at least 30 years.

3.5.2.4 Availability and Robustness Requirements

ID	DESCRIPTION
AR-01	[SPT2ARC-2599] - ASTP shall ensure at least the same availability target compared to the existing on-board odometry solutions used in the ETCS domain. Note: Availability needs to be correlated to the kind of failure (minor, reduced service, immobility - see MTBF).
AR-02	[SPT2ARC-2814] - If the ASTP is not providing data at the defined frequency, the ASTP is considered as unavailable during this time.

3.5.2.5 Maintainability Requirements

ID	DESCRIPTION
MAN-01	[SPT2ARC-2597] - ASTP shall be able to self-diagnose hardware temporary and permanent failures and systematic errors from individual sensors, allowing a possible degraded working mode before considering the entire ASTP out of order.
MAN-02	[SPT2ARC-2808] - The results of the self-diagnose shall be able to determine the replaceable unit to be replaced.
MAN-03	[SPT2ARC-2596] - ASTP shall make available maintenance-relevant information for recording to determine possible predictive and corrective maintenance interventions. Note: Predictive and corrective maintenance analysis can be performed offline and outside ASTP.
MAN-04	[SPT2ARC-2595] - Preventive maintenance and periodic workshop sensor calibration period of the overall ASTP shall exceed 2 years.
MAN-05	[SPT2ARC-2859] - If a periodic workshop sensor calibration is needed, the procedure shall not exceed two hours for the whole ASTP sensors and shall be done without the use of complex calibration benches.

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MAN-06	[SPT2ARC-2860] - Calibration procedure(s) operated during the train operation shall avoid the use of specific trackside equipment.
MAN-07	[SPT2ARC-2861] - Following the installation of a new set of on-board equipment (line replaceable unit of the ASTP), ASTP shall reach full operational capability at switch-on in less than 20 minutes with no human intervention.
MAN-08	[SPT2ARC-2810] - The Mean Repair Time (MRT) shall be less than 15 minutes as per EN50126.
MAN-09	[SPT2ARC-2809] - The ASTP's design and maintenance concept shall meet a Mean Time To Restore (MTTR) ≤ 1h. The Mean Time to Restore (MTTR) is defined in EN50126. The time elapsed to restore starts when the failure occurs and ends when the ASTP is ready for service. The administrative delay (MAD), Logistic Delay (MLD) shall not be counted into the MTTR.
MAN-10	[SPT2ARC-2593] - ASTP shall include monitoring and diagnosis interface locally.
MAN-11	[SPT2ARC-2811] - Maintenance optimization shall also be considered minimizing calibration operations in case of a component replacement.
MAN-12	[SPT2ARC-2812] - The long-term maintenance strategy shall include damage-dependent (past) and preventive (forward-looking) measures.
MAN-13	[SPT2ARC-2880] - It shall be ensured that spare parts are available for the entire ASTP life cycle.
MAN-14	[SPT2ARC-2881] - Maintenance measures shall be carried out in such a way that the system can be operated within the defined RAMS requirements for the entire system life cycle.

3.5.2.6 Safety requirements

ID	DESCRIPTION
SAF-01	[SPT2ARC-2625] - ASTP shall serve users with different safety integrity requirements (e.g. ETCS, ATO, traffic management, maintenance and diagnostic, asset management, passenger info, etc.).
SAF-02	[SPT2ARC-2807] - For the safety relevant data, if safety requirements cannot be achieved the data shall not be provided
SAF-03	[SPT2ARC-2862] - The safety of the ASTP shall be ensured and demonstrated according to the Common Safety Methods [ERA_CSM] and the [EN 50126] standard.
SAF-04	[SPT2ARC-2863] - The front-end true position shall be included in ASTP computed confidence interval within the most constraining THR.

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SAF-05	[SPT2ARC-2864] - The train true speed shall be included in ASTP computed confidence interval within the most constraining THR.
SAF-06	[SPT2ARC-2865] - The train true acceleration shall be included in ASTP computed confidence interval within the most constraining THR.
SAF-07	[SPT2ARC-2866] - If needed, calibration procedure(s) shall comply with the safety requirements.

3.5.2.7 Security Requirements

ID	**DESCRIPTION**
SEC-01	[SPT2ARC-2618] - ASTP and its interfaces shall be designed considering the security detections and mitigation measures identified adopting a systematic procedure performed according to recognised standards, aiming to identify all the possible security threats and risks.
SEC-02	[SPT2ARC-2867] - ASTP shall fulfil requirements and recommendations for cybersecurity as specified in CLC/TS 50701 with the purpose to demonstrate that the system is up to date from a cybersecurity perspective and that it meets and maintains the target level of security for the entire system life cycle.
SEC-03	[SPT2ARC-2868] - ASTP security shall be ensured by using means and technologies in accordance with project security plan.
SEC-04	[SPT2ARC-2869] - ASTP shall be resilient to signal spoofing, jamming (e.g. GNSS, Balise signals...) attacks. Appropriate detection measures of such conditions and mitigation measure to counter such attacks shall be addressed to keep the integrity of the ASTP.

3.5.2.8 Installation Requirements

ID	**DESCRIPTION**
INS-01	[SPT2ARC-2870] - ASTP can be installed on any wagon/carriage of the train. Note: ASTP may not be a monolithic module, embedding several types of sensors in different locations in the train.
INS-02	[SPT2ARC-2872] - ASTP design shall be ease to install on new trains and in refurbished trains.
INS-03	[SPT2ARC-2874] - ASTP components shall comply with the EN 45545 [34] standard: Railway applications - Fire protection on railway vehicles. The latest edition shall apply.
INS-04	[SPT2ARC-2875] - ASTP components shall comply with the REACH and RoHS2. The latest edition shall apply.

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3.5.2.9 Interoperability Requirements

At the stage of this document, the functional and physical architecture is not defined yet therefore it is not possible to provide precise interface requirements.

ID	DESCRIPTION
INT-01	[SPT2ARC-2616] - The functions, performance figures, interfaces, testing and certification of the ASTP having an impact on interoperability shall be standardised (this also implies modification to possible already existing interfaces). Note: functions allocation, architecture and interface definition are in the scope of next steps of the process.

3.5.2.10 Upgradability Requirements

ID	DESCRIPTION
UPG-01	[SPT2ARC-2612] - ASTP software upgrade shall be possible remotely.
UPG-02	[SPT2ARC-2610] - ASTP hardware shall have enough hardware spare resources available (e.g. wired inputs/outputs, memory, cpu load…) for future upgrade, additional features.

3.5.2.11 Migration Requirements

If solutions are being standardised which require trackside support, such as the provision of a map or of GNSS augmentation through radio, these will have to be provided by every infrastructure manager for interoperability reasons. For interoperability with lines not implemented according to the target system, odometry information has to be provided to ETCS anyway.

ID	DESCRIPTION
MIG-01	[SPT2ARC-2628] - ASTP shall ensure on-board and trackside backward compatibility to facilitate migration strategies. Note: different migration rules could apply, once agreed by IM and RUs under standard provisions, when trackside is implementing ASTP interfaces and vehicles without full or basic ASTP could frustrate the increase of operational performances of the line.
MIG-02	[SPT2ARC-2608] - In case of trains equipped with the full ASTP running on a trackside without full ASTP interfaces, ASTP shall ensure the fulfilment of the performance requirements valid for basic ASTP without exporting condition to the trackside subsystem. Note: This also includes the scenario of a non-radio-based signalling system.
MIG-03	[SPT2ARC-2634] - Trackside backward compatibility (i.e. making possible the train operation without full or basic ASTP over a trackside equipped with full ASTP interfaces) should be technically possible in order to facilitate migration strategy. Note: an impact analysis (including possible safety aspect) against a train without full or basic ASTP will be necessary anyway due to the reduction of the physical relocation balises.

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4 Preliminary requirements for a virtual certification platform

Currently, integrated railway systems consist of different products (mostly provided by one supplier). To ensure proper system assembly, all functions and communication must be thoroughly tested. Testing plays a crucial role in ensuring functionality, safety, and interoperability. Traditionally, validation has been conducted through field tests, where real trains operate in real environments to assess performance under actual conditions. However, due to high costs, operational constraints and scalability limitations, laboratory tests and simulations have become increasingly common. These rely on real hardware in controlled settings, allowing for more repeatable and structured testing processes.

As railway systems become more complex, virtual testing is emerging as a key approach to complement and, in some cases, replace traditional field and laboratory tests. Virtualization allows engineers to simulate components, communication protocols, and environmental conditions without relying on physical infrastructure. This shift enables earlier detection of design flaws, faster iteration cycles, and reduced dependency on costly and time-consuming physical tests. Communication testing in virtual environments is already a standard practice, and the goal is to expand this approach to broader system validation.

However, virtual testing cannot entirely replace real-world tests. Certain complex scenarios, such as GNSS multipath effects and signal obstructions remain challenging to simulate with high fidelity. In these cases, real-world testing remains essential to feed, validate and refine simulation models. By integrating both virtual and real-world tests, railway operators and manufacturers can ensure that digital models provide accurate and reliable results, improving the overall efficiency of system validation.

Virtual testing also plays a key role in enabling interoperability across multiple manufacturers. Currently, railway operators are highly dependent on single suppliers for both vehicles and infrastructure, which limits flexibility and increases long-term costs. Standardizing interfaces, testing methodologies, and certification frameworks would enable operators to integrate components from different suppliers while maintaining system reliability and safety.

However, this transition poses challenges. With multiple suppliers involved, there is no longer a single manufacturer responsible for the entire system, which increases the complexity of certification. To address this, industry-wide standards must be developed to establish trust in virtual testing and certification. Defining standardized test procedures, validation requirements, and certification frameworks is essential to ensure the reliability of multi-vendor railway systems. However, achieving consensus on common standards requires time, resources, and coordinated efforts from manufacturers, railway operators, and regulatory authorities.

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Additionally, the shift toward a unified European railway architecture, as envisioned for the future Control, Command, and Signaling (CCS) system, provides an opportunity to streamline approval processes. Aligning virtual testing with CENELEC safety procedures and ongoing standardization efforts will be crucial in ensuring a cost-efficient and interoperable railway system.

A structured approach to virtual certification must involve all key stakeholders, including manufacturers, railway operators, certification bodies, and regulatory authorities. This requires defining clear guidelines, standardized validation protocols, and compliance mechanisms. By ensuring alignment with existing safety frameworks, such as CENELEC standards, virtual certification can accelerate approval processes while maintaining safety and reliability.

The following strategic high-level requirements guide the definition of the simulation platform/laboratory architecture for virtual certification:

- Zero on-site testing objective: which implies that the simulation tools and procedures have to support full laboratory end-to-end test processes;
- Sub-components from different suppliers: which implies a clear definition (standardization) of the functions and interfaces of the simulation platform;
- Remote connection of different components: which reinforces the importance of the virtual lab approach;
- Costs reduction and efficiency increase for testing technologies and their evolutions: a dedicated process that can be upgraded to stay up to date increases the efficiency of test resources management and reduce the need of real lab equipment due to acquisition, maintenance etc.
- Contribution to the required safety integrity level: a laboratory test allows simulating rare events as well as various configurations encountered in the railway operational environment and thus characterizing the safety level of a solution with large data sets that could not be obtained by experimentation.

As for ASTP, the virtual certification should focus on testing activities at three primary levels:

- Component level: Testing of the ASTP as an individual component, including integration tests to verify proper communication between the test platform and ASTP, verification tests to demonstrate correct implementation of requirements, functional validation tests, performance tests, and RAMS tests.
- Subsystem level: Testing ASTP integrated with other key components, particularly the ETCS-OB, which are essential for system operation. This includes functional tests that may comprise a subset of certification tests defined in the Subset-076 [35] of the CCS TSI.
- System level: Full integration of ASTP within the complete CCS on-board and trackside environment to validate behavior across operational scenarios that involve interaction between ERTMS and GNSS.

The virtual certification process must provide equivalent assurance as traditional certification methods while offering advantages in terms of cost, time, and comprehensiveness of testing scenarios. This approach aligns with the "zero on-site testing" objective, which requires simulation tools and procedures that support full laboratory end-to-end test processes.

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For ASTP specifically, virtual testing environments must be capable of simulating various environmental conditions that affect GNSS performance, including signal obstruction in tunnels, multipath effects in any constrained environments, and interference scenarios. The test facilities must also support the injection of simulated faults to validate system behavior under degraded conditions.

As identified in the R2DATO project, the certification process for ASTP should follow the standard procedures for conformity assessment of ASTP as an interoperability constituent, as defined in Commission Decision 2010/713/EU [18].

The validation testing framework for ASTP requires particular attention to its integration with other railway safety systems. Functional testing must verify the ASTP's ability to provide accurate position data with appropriate confidence intervals. Performance testing must compare ASTP outputs with reference trajectories to validate the system's ability to maintain required accuracy levels across different operational environments.

A particularly important aspect of ASTP certification is the verification of safety requirements. The system must demonstrate compliance with SIL4 requirements for safety-related functions as defined in CENELEC EN 50129 [17], providing evidence that both random and systematic failures have been adequately addressed. This requires the development of a comprehensive Safety Case, including:

- Definition of the system
- Quality management report
- Safety management report
- Technical safety report
- Conclusion

The independent safety assessment must be conducted by a recognized Assessment Body (AsBo) to validate that the ASTP complies with the Common Safety Method for Risk Evaluation and Assessment (CSM-RA) as specified in Regulation (EU) 402/2013 .

To ensure that the virtual certification process meets all regulatory and safety standards, the following high-level certification requirements for ASTP are defined. These requirements address functional safety, systematic failure elimination, security threats specific to GNSS, and validation of virtual testing environments to ensure their equivalence to real-world scenarios.

ID	DESCRIPTION
CER-01	ASTP certification must demonstrate compliance with SIL4 requirements as defined in CENELEC EN 50129 for safety-related functions used by ATP.
CER-02	The certification process must include evidence that systematic failures have been eliminated through appropriate design and development techniques.
CER-03	A complete Safety Case must be developed according to EN 50129 [17] structure, including definition of the system, quality management report, safety management report, technical safety report, and conclusion.

CER-04	Independent safety assessment by a recognized Assessment Body (AsBo) must confirm that the risk management process according to CSM-RA regarding integration of ASTP with ERTMS was correctly applied by the proposer of this change.
CER-05	Certification must address GNSS-specific vulnerabilities including signal interference, multipath effects, and spoofing through appropriate detection and mitigation measures.
CER-06	Virtual validation environments for ASTP certification must demonstrate equivalence to real-world testing through appropriate validation of simulation models.
CER-07	The certification process must evaluate ASTP performance across all relevant physical rail environments (urban areas, tunnels, deep valleys, forests) and infrastructure types (metallic bridges, slab tracks, etc.).
CER-08	Certification must validate ASTP behavior under degraded conditions, including partial or complete GNSS signal loss.
CER-09	Certification must demonstrate compliance with all relevant requirements of CCS TSI, including Subset-026 [25] and Subset-076 [35], ensuring full interoperability with existing ETCS components.
CER-10	The certification process must include a structured Validation and Verification (V&V) process, documenting all testing activities and ensuring traceability from requirements to test cases and results, in compliance with EN 50716 [16] and EN 50129 [17].
CER-11	The certification process must include a co-engineering approach for cybersecurity and safety, ensuring that cybersecurity measures (e.g., spoofing and jamming mitigation) do not negatively impact the functional safety requirements of the ASTP, in compliance with CLC/TS 50701 [36] and EN 50129 [17].
CER-12	The certification process must support modular certification and allow for software updates and patches while ensuring continued compliance with safety and interoperability requirements, in accordance with EN 50716 [16] and EN 50129 [17].
CER-13	Certification must include robustness and stress testing to validate the ASTP's performance under extreme operational conditions, including electromagnetic interference, temperature extremes, and power supply variations, ensuring compliance with RAMS requirements defined in EN 50126 [14].
CER-14	All ASTP certification tests must be performed by an independent, accredited laboratory in line with the certification practices for Subset-076 [35].

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4.1 HyVICE: User Requirements

In VICE4RAIL two important and interlinked aspects are considered:

1. the identification of the most viable preliminary paths for certification procedures to allow the use of GNSS in train positioning;
2. the construction of a dedicated reference testing environment (HyVICE) based on the near zero-on-site testing paradigm to support the validation and certification process.

The following preliminary User Requirements (URs) have been identified for the HyVICE platform. These requirements reflect the expectations of end-users (railway operators, safety assessment and certification bodies) and provide a foundational basis for the design of a flexible and scalable architecture that supports virtual certification while ensuring compliance with all regulatory and safety standards.

ID	DESCRIPTION
HV-UR-01	HyVICE shall enable cost-efficient and comprehensive virtual certification for EGNSS-based localization solutions, minimizing the need for on-site testing.
HV-UR-02	The simulation environment shall accurately model GNSS signal characteristics, propagation effects, local/global error sources, and interference mechanisms, ensuring high-fidelity replication of real-world conditions.
HV-UR-03	HyVICE shall provide standardized and modular testing methodologies with comprehensive documentation to support validation and certification, facilitating acceptance by NoBos and AsBos.
HV-UR-04	HyVICE shall enable the simulation of complex operational scenarios, including urban canyons, tunnels, and multipath effects, to accurately validate GNSS performance.
HV-UR-05	HyVICE platform shall facilitate remote connection and integration of sub-components from different suppliers to enhance interoperability and reduce dependency on single vendors.
HV-UR-06	HyVICE shall support the simulation and validation of performance under degraded and extreme operational conditions, including partial or complete GNSS signal loss, hardware malfunctions, and electromagnetic interference.
HV-UR-07	The environment shall support simulation of multiple scenarios across various geographical areas, train speeds, and operational conditions simultaneously.
HV-UR-08	The simulation platform shall provide interfaces for integration with actual ERTMS hardware components (HIL - Hardware-in-the-Loop) to test real equipment responses.

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HV-UR-09	Test conditions shall be precisely reproducible across multiple tests runs to ensure consistent and comparable results.
HV-UR-10	The simulation architecture shall be modular to allow independent updating of individual components (GNSS models, train dynamics, track infrastructure, etc.).
HV-UR-11	The system shall enable replay of recorded real-world scenarios with the ability to inject faults or variations for robustness testing, including intentional GNSS interferences such as jamming and spoofing.
HV-UR-12	Test scenarios shall cover the full range of operational conditions including: • Normal operation in various environments (open sky, urban canyons, tunnels, etc.) • Degraded GNSS conditions (multipath, interference, atmospheric effects) • System failure modes and recovery procedures • Edge cases and boundary conditions
HV-UR-13	HyVICE shall include real-time synchronization mechanisms to ensure coherence between GNSS signal generation, IMU sensor data, and train motion dynamics.

4.2 HyVICE: Preliminary High-Level System Architecture

The certification of GNSS-based train localization technologies within the European Rail Traffic Management System (ERTMS) presents significant challenges due to the absence of standardized methodologies for evaluating system performance in safety-critical applications. As stated before, current certification frameworks primarily rely on empirical field testing, which entails high costs, extended validation timelines, and dependency on real-world infrastructure availability. The lack of repeatability in field tests further complicates the process, making it difficult to isolate and analyze specific environmental variables affecting GNSS-based localization.

To overcome these limitations, VICE4RAIL introduces a hybrid virtualized certification framework, known as HyVICE, which aims to significantly reduce on-site testing while maintaining compliance with regulatory and interoperability standards. By replicating real-world operational conditions in a controlled environment, HyVICE will ensures a cost-effective, repeatable, and comprehensive approach to the assessment and certification of train localization technologies.

At the heart of VICE4RAIL is the HyVICE testing environment, designed to replicate real-world operational conditions through a hybrid approach integrating Model-in-the-Loop (MIL), Hardware-in-the-Loop (HIL), and Software-in-the-Loop (SIL) methodologies. The objective of the HyVICE architecture is to allow testing, in one single place, the behaviour of an ERTMS signalling system integrating any GNSS-based localization solution, under different scenarios and operational conditions, as if it was deployed in different railway contexts across the globe. Although the objective is to maximize virtualization and achieve zero on-site testing for most scenarios, the HyVICE platform will adopt a hybrid approach. This includes real-world testing in specific cases where virtual models

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cannot fully replicate complex environmental conditions. The hybrid approach ensures the reliability and validity of the virtual certification process by complementing simulations with real-world validation when necessary.

HyVICE is structured around two complementary platforms:

- the Laboratory Testing Platform, hosted at the CEDEX ERTMS Simulation Lab,
- the On-Field/Mixed Reality Testing Platform, implemented at the RFI Bologna San Donato Test Circuit.

This architecture – virtualized and scalable - will allow to independently assess the global ERTMS chain equipped with any GNSS-based localisation unit and to generate the standard documentation for sustaining the certification process. It will be flexible in order to evolve to perform tests, validations and certification of innovative products and services when new EGNSS features are introduced by EUSPA and new ERTMS specifications and functionalities are established by the rail community.

The two pillars of the HyVICE architecture (lab and testing platforms) intends to be complementary with a comprehensive approach utilizing Model-in-the-Loop (MIL), Hardware-in-the-Loop (HIL), and Software-in-the-Loop (SIL) techniques. MIL is employed for signal synthesis at the antenna level, while HIL focuses on testing the real system within a virtualized electromagnetic environment, ensuring equivalence to a physical circuit anywhere on earth. This approach is particularly crucial for addressing the challenges associated with testing Inertial Measurement Units (IMUs) through virtualized accelerations, especially in systems with multiple positioning sources. At this aim, HyVICE allows to:

- Jointly test and certify GNSS + IMUs, through procedures for which GNSS receiver can receive either real or synthetic data, or a blend of them, while IMUs experience real train dynamics.
- Add interferences (jamming and spoofing) to real GNSS signals, to test vulnerability/resilience of both signal and data processing stages.

HyVICE will also include the generation of Augmentation and Integrity Monitoring data as if they were provided by current and future SBASs (e.g., EGNOS V2) as well as by local augmentation networks, focusing on DGNSS and RTK.

By incorporating these testing methodologies, the project aims to establish a robust test bench solution that encompasses the entire spectrum of testing requirements, from individual components to the complete system. The integration of MIL, HIL, and SIL enables a thorough examination of the entire system, aligning with subset 76 for European Train Control System (ETCS) standards.

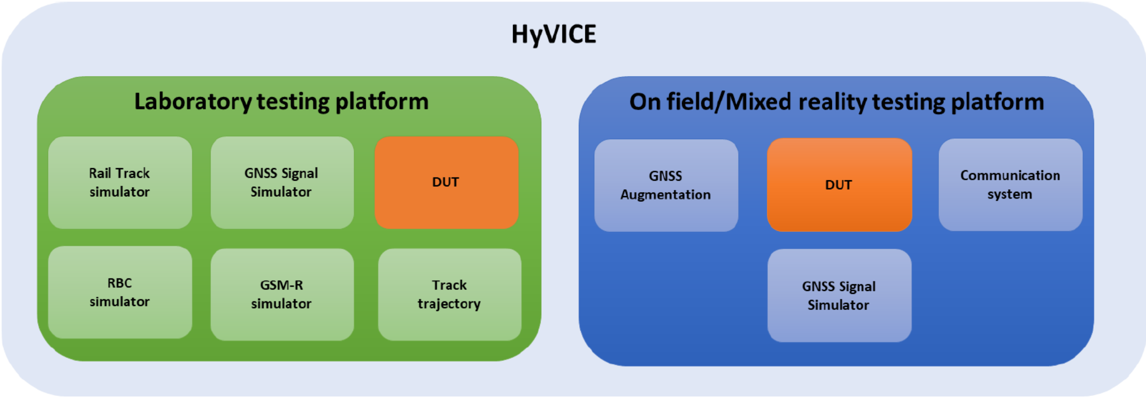

Figure 4: Functional Blocks of the HyVICE platform

The laboratory testing platform will support simulation of the core challenge in real-time modelling of the electromagnetic environment, in particular caused by multipath. Global errors, influenced by atmospheric and system causes, are addressed through existing models. Local effects, shaped by the immediate electromagnetic surroundings of the receiver antenna, pose a unique challenge. They will be considered thanks to state-of-the-art error models and tools but a deep analysis of the reliability and representativity of 3D models and raytracing for a railway application will also be conducted to analyse if it can extend representativity of local effects.

Real experiments with the Device Under Test (DUT) installed on board of a test train will be performed on the Bologna San Donato Test Circuit, creating a real-world testing ground for GNSS and IMU technologies. While the GNSS receiver is fed by RF signals produced by a GNSS RF signal generator, like in the zero on-site test approach, the IMU sensor package experiences real accelerations and angular velocities. Specifically, the field testing in Bologna aims to:

- Create and validate virtual models for the GNSS electromagnetic environment.
- Jointly test and certify GNSS + IMUs, through procedures for which GNSS receiver can receives either real or synthetic data, or a blend of them, while IMUs experience real train dynamics.
- Add interferences (jamming and spoofing) to real GNSS signals, to test vulnerability/resilience of both signal and data processing stages.

This architecture – virtualized and scalable - will allow to independently assess the global ERTMS chain equipped with any GNSS based localisation unit and to generate the standard documentation for sustaining the certification process.

4.2.1 Laboratory Testing Platform - CEDEX ERTMS SIMULATION LAB

CEDEX ETCS/ERTMS laboratory is an accredited lab for functional verification testing ERTMS components, such as EVCs (Euro Vital Computers) and Eurobalises and collects a deep experience on testing ETCS trackside implementations and onboard integration into the line at operational level. CEDEX lab had in the past an important role testing Spanish real lines before authorization to put into service, which can allow a significant reduction of on-site testing time and resources, as the real lines can be debugged in advance in the laboratory environment. Real ETCS trackside equipment (RBC) configured with corresponding project data associated to the line is connected to the lab, allowing testing it by using ETCS on-board equipment of different suppliers.

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The lab is, thus, composed by two test benches connected to main additional modules, as Track Simulation Tool (TST) and the GSM-R network simulator. The current lab architecture is shown in Figure **5**.

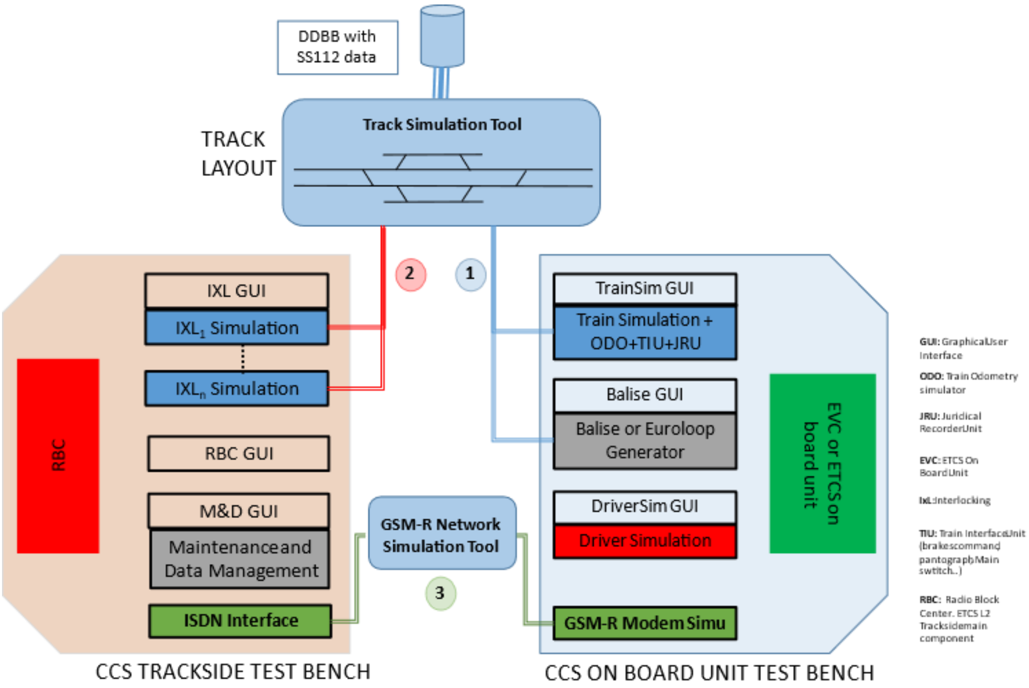

Figure 5: Cedex ERTMS test lab (current architecture)

The main functions of each block are the following:

- OBU test Bench where a real (or simulated) ETCS OBU is connected to be tested. It simulates the train movement, the interfaces between the OBU and the simulated train. It also generates the balise telegrams and connect the EVC to the GSM-R network simulator
- A Trackside test Bench where a real (or simulated) RBC is connected for the tests. It can simulate the interlocking (IXL) or, alternately, in case of using a real IXL, this one relates to the local operation post to set the routes. The IXL is connected to the Track Simulation Tool (interface 2) to reproduce track circuits occupation, switches status and signals aspects. It also connects the RBC radio channel to the GSM-R network simulator to send/receive radio messages to/from the ETCS onboard.
- GSM-R Network Simulator (3): This module simulates the GSM-R network and is the way of exchanging L2 messages between the RBC and the EVC.
- Track Simulation Tool simulates the real trackside. It is customized with the real track layout as well as all involved infrastructure and signalling elements. This tool provides the lab the functionality of moving the trains over the real track. The interface with the trackside (2) test bench is mainly the status of track circuits, switches, and signals aspects. The interface with the On-Board unit test bench (1) is bidirectional, exchanging balise telegrams and locations, and the train speed to allow the train moving over the simulated track. The simulation has the possibility of adding more trains to simulate several trains running over the line.

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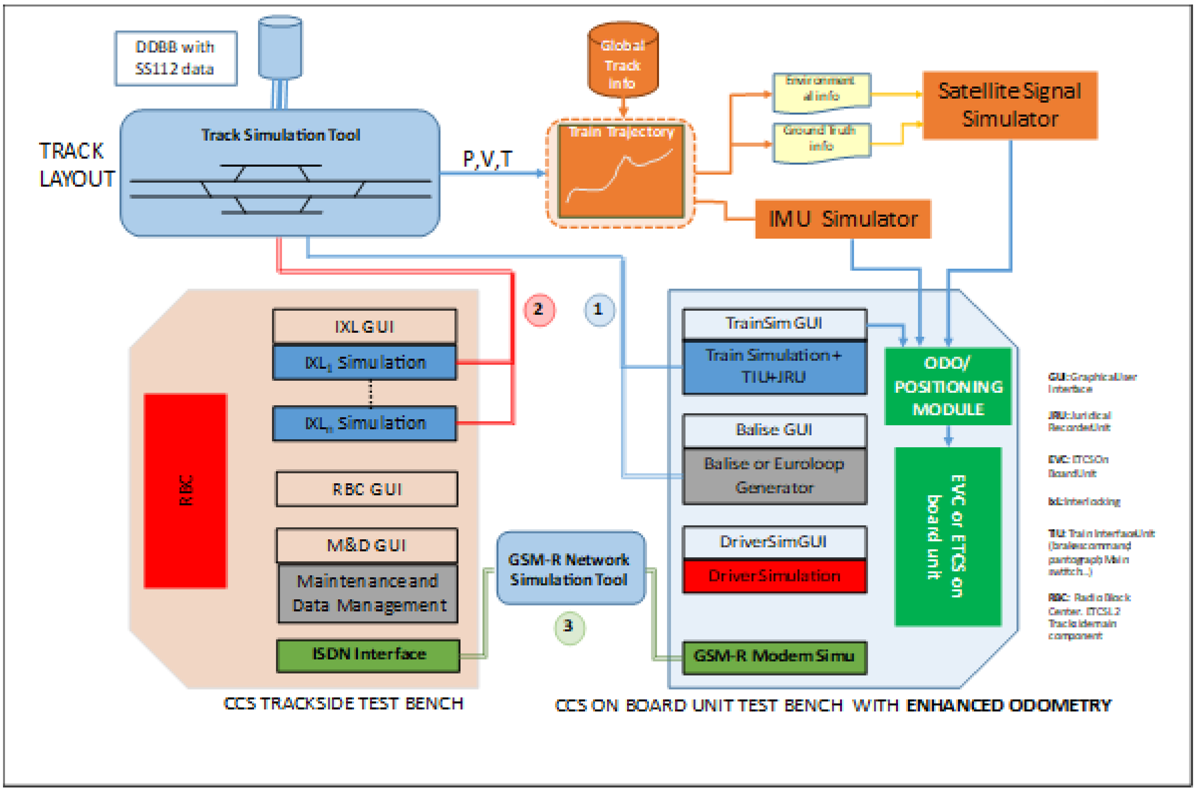

Figure 6: Cedex ERTMS test lab (VICE4RAIL architecture)

To enhance its capabilities for supporting the certification of GNSS+IMU-based localization solutions, the CEDEX laboratory will be expanded with additional components. Figure **6** shows the proposed testing architecture for testing ETCS Onboard Units with a positioning module that uses GNSS and IMU sensors.

The Ground Truth and the Environmental Information modules have been introduced to provide high-resolution terrain and railway infrastructure data, ensuring that simulations accurately reflect real-world conditions. A Satellite Signal Simulator has been integrated to generate synthetic GNSS signals, allowing for precise testing of onboard receivers under both nominal and degraded conditions. Finally, an IMU Signal Simulator will be incorporated to replicate train dynamics, including accelerations, velocity changes, and angular rates, thereby enabling a comprehensive evaluation of hybrid localization solutions that integrate GNSS and inertial sensors. These enhancements will enable the CEDEX lab to perform closed-loop testing that accurately reproduces real-world railway environments.

4.2.2 On-Field/Mixed Reality Testing Platform: Bologna San Donato Test Circuit

The Bologna San Donato Test Circuit serves as the primary field-testing facility within the HyVICE framework, providing a real-world railway environment for the validation of GNSS-based localization systems. Originally a freight yard, the site was converted into a 6 km closed-loop railway test circuit, offering a controlled yet operationally realistic setting for the experimentation of new railway technologies.

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Figure 7: Bologna San Donato test circuit

The test circuit is characterized by a single-track length of 5,749 meters, electrified at 3 kV DC. The maximum achievable speed for rolling stock is 120 km/h. By the end of 2025, the circuit will be equipped with an ERTMS Level 2 system. This configuration makes the circuit an ideal environment for testing rolling stock, signaling systems, and GNSS-based localization technologies, as well as for conducting homologation and certification trials for new railway components.

In Figure **8** the functional architecture of the On field/Mixed reality testing platform that will be developed in VICE4RAIL and deployed in the RFI Bologna San Donato Testing Circuit is presented.

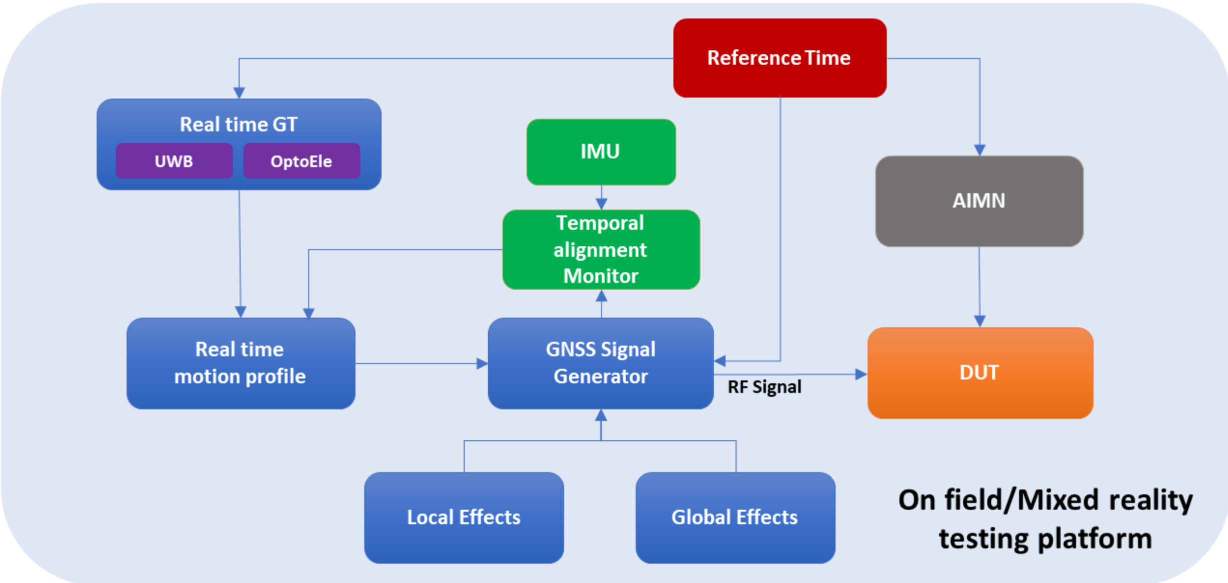

Figure 8: On field/Mixed reality testing platform

To guarantee the coherence between accelerations and angular rates sensed by the IMU package of the DUT and the SISs injected into the GNSS receiver chain, a real time GT (Ground Truth) will be realized by using terrestrial ultra-wideband radio transmitters integrated with optoelectronics devices. To assure synchronization among all components, the platform will be equipped with a Reference Time distribution subsystem based on an atomic clock providing high short-term temporal coherence complemented with a GNSS receiver, for longer, stable, temporal coherence. Latencies and delays between the Real Time GT and the GNSS Signal Generator output will be continuously monitored by the Temporal Alignment Monitor. At this aim a high (e.g. tactical) grade IMU accurately sensing the train dynamics will be employed. The measured latencies and delays will then be compensated through a short time train motion prediction performed by the real Time motion profile block. This block will provide real-time train dynamics profile including position, velocity, acceleration and timing

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to the GNSS Signal Generator block, that exploit the knowledge of the georeferenced circuit geometry. The GNSS Signal Generator will be responsible for the generation of synthetic GNSS signals both in nominal and faulty conditions by accounting for both global and/or local hazards (multipath, GNSS signal blockage, unintentional and intentional interferences). These faults will be made available to the GNSS RF signal generator by the Local and Global effects blocks and will be injected to test vulnerability/resilience of both signal and data processing stages.

The hybrid approach of the HyVICE architecture has been designed to satisfy the high-level certification requirements outlined in the previous section. Through this integrated approach, the HyVICE platform is expected to provide a robust, reliable, and compliant framework for virtual certification, addressing all regulatory and safety standards.

While the HyVICE platform provides the technical infrastructure for virtual certification, it must operate within a comprehensive methodological framework that adheres to established safety assessment and certification processes. Chapter 5 delineates these processes in detail, thereby completing the conceptual framework necessary for developing a compliant virtualized certification environment for GNSS-based railway localization solutions.

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5 Safety assessment and certification processes

5.1 Purpose

This chapter describes the basic methodology for the assessment and certification processes for safety-critical railway systems that must be applied to demonstrate the safety and interoperability of large-scale solutions such as ERTMS/ETCS [9] [8] [37]. The same processes for demonstrating safety and interoperability must also be followed for the ERTMS with GNSS-based localization solutions. In the VICE4RAIL project, the methodology will be used as a stepping stone for the safety assessment and certification of the HyVICE solution. This section is an introduction to safety assessment and certification. A more detailed description of the methodology will be contained in deliverables D2.2 (Risk Analysis Evaluation Report) and D2.3 (Certification Plan).

5.2 Basic framework for safety assessment and certification of ERTMS

In order to apply the GNSS-based solution for safe train positioning in the EU member states, it is necessary to develop and authorise it according to the relevant European and national standards and regulations. It means that a new subsystem to be integrated into the Interoperability Constituent (IC) within ERTMS/ETCS and also incorporated into the ERTMS Technical Specifications for Interoperability (TSI) [8, 37] must pass through all phases of the development cycle according to CENELEC standards [14, 15, 16, 17] including the safety and conformity assessment processes [8].

Although innovation is encouraged, especially if it improves the operational efficiency of ERTMS, a risk analysis is mandatory to evaluate eventual additional risks brought by the new technologies and the proper mitigation solutions. Each intended change in railway signalling represents a risk, which could endanger safety. In order to manage risks at an acceptable level, tools called Common Safety Targets (CSTs) and Common Safety Methods (CSMs) have been originally introduced in the Railway Safety Directive (EU) 2004/49/EC [38] and also in its recast within Directive 2016/798 [9]. Currently, seven CSMs are available. They are fully described on the EU website www.era.europa.eu.

One of these methods is the Common Safety Method for Risk Evaluation and Assessment (CSM-RA) specified in Regulation (EU) 402/2013 [13], which aims to harmonise the risk assessment process for the European rail industry. CSM-RA is the most appropriate common method for risk management and for setting safety requirements in case of a change in the system from a safety perspective. It therefore represents a starting point and the basic framework for assessing the integration of GNSS with ERTMS. – see Figure **9**.

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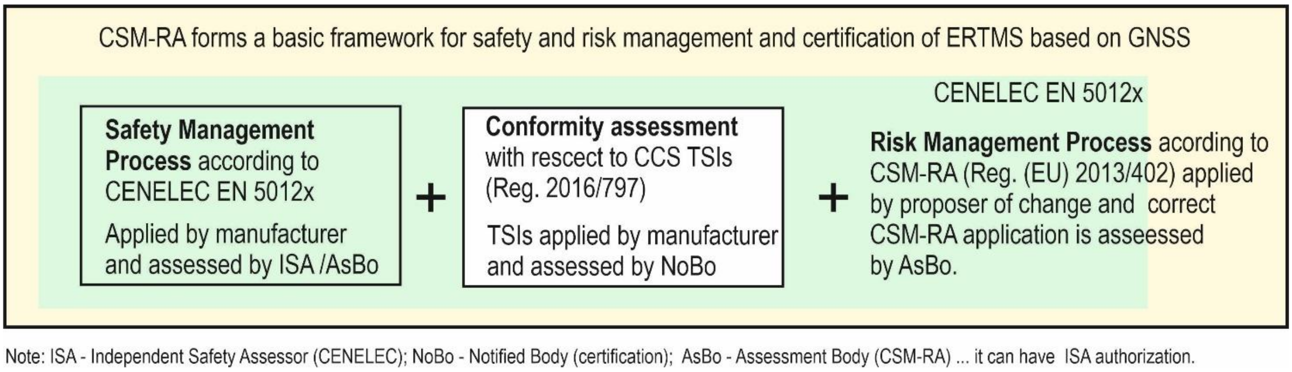

Figure 9: Basic framework for safety assessment and certification of ERTMS based on GNSS.

Other common methods are applicable at later stages of the life cycle and are used by railway stakeholders such as national safety authorities, infrastructure managers, railway undertakings and maintenance entities.

The application of the CSM-RA to a change in the safety system can be seen as a 'risk management process' associated with that change. The risk management process follows the 'safety management process' according to CENELEC standards. Similarly, the safety management is linked to certification process according to the TSI in the sense of Reg. (EU) 2016/797 [8] because list of mandatory standards [14, 15, 16, 17] are referred in Reg. 2023/1695 (CCS TSI) [37]. Both essential links are outlined in Figure **9**.

The individual elements of this framework for the safety/risk assessment process and certification process are described in sections below.

5.3 Common Safety Method for risk evaluation and assessment (CSM-RA)

The CSM-RA (Regulation (EU) 402/2013) [13] and its amendment 1136/2015 sets out a harmonised framework to be applied by the proposer (defined in Article 3(11) [13]) when making any change, significant or not significant (Article 4 [13]), to the railway system in a Member state. Depending on the classification of the change the process could be justified with an adequate documentation for a not significant change up to a specific process set out in Article 5 for a significant change.

This regulation shall facilitate the access to the market for rail transport services through harmonisation of [13]:

- The risk management processes used to assess the impact of changes on safety levels and compliance with safety requirements;
- The exchange of safety-relevant information between different actors within the rail sector in order to manage safety across the different interfaces which may exist within this sector;
- The evidence resulting from the application of a risk management process.

The CSM-RA shall be applied by the person in charge of implementing the change under assessment. This person, referred to as the “proposer”, can be one of the following actors:

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- The railway undertakings (RUs) and infrastructure managers (IMs) which implement risk control measures in accordance with Article 4 of the safety directive 2004/49/EC [38] and its revision 2016/798 [9];
- An entity in charge of maintenance (of vehicles) which implements measures in accordance with the directive 2016/798 [9];
- The contracting entities and the manufacturers, when they invite a conformity assessment body to apply the "EC" verification procedure in accordance with Article 15(1), of the interoperability directive 2016/797 [8];
- The applicant of an authorisation for placing in service of vehicles.

If the proposer is an infrastructure manager or a railway undertaking, sometimes it may be necessary to involve other actors in the process. In some cases, the infrastructure manager or the railway undertaking might sub-contract, partly or completely, the risk assessment activities. The CSM on risk assessment shall apply to any change of the railway system (technical, operational or organisational nature) which is considered to be significant. It is e.g. introduction of GNSS into ETCS. If the change in signalling system is significant, then the proposer has to evaluate the associated risk according to the six criteria [13]:

- Failure consequence: credible worst-case scenario;
- Novelty: innovative or new to organization;
- Complexity: the complexity of the change;
- Monitoring: the inability to monitor the implemented change throughout the system life cycle & intervene appropriately;
- Reversibility: the inability to revert to the original system;
- Additionality: assessment of the significance of the change taking into account all recent safety-related changes which were not judged to be significant.

The analysis should consider worst cases, not just the likely or expected case. When the change is significant, a CSM Assessment Body (AsBo) must be appointed by the Proposer.

5.4 Railway Safety Management and the CENELEC Standards

5.4.1 EN 50126, EN 50129 and EN 50716

The basic framework for ensuring the safety and dependability of railway systems is defined in CENELEC standard EN 50126 [14] [15] on the specification and demonstration of RAMS (Reliability, Availability, Maintainability and Safety). EN 50126 considers the railway system in a given physical and operational environment, i.e., including human operators, as well as the factors that influence the railway RAMS - in particular the technical system and the operational and maintenance conditions. The standard specifies in detail the different phases of the system life cycle, i.e. including the role of the human factor in them and also prescribes methods for managing the RAMS within the system life cycle. Safety shall be demonstrated by means of safety case and independent third-party assessment. The basic framework defined through RAMS can be imagined as an umbrella (Figure **10**) under which a safety-related system is subsequently developed and implemented according to the downstream standards EN 50129 [17] (safety-related system), EN 50716 [16] (software for safety-related system), and others.

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A safety case and its independent assessment alone is still not enough to ensure safety on European railways. Technical interoperability must also be ensured (Figure **10**). In the case of ERTMS, e.g., this means that one manufacturer's on-board equipment works correctly with another manufacturer's track-side equipment. Therefore, certification according to the Technical Specifications for Interoperability (TSI) must be carried out.

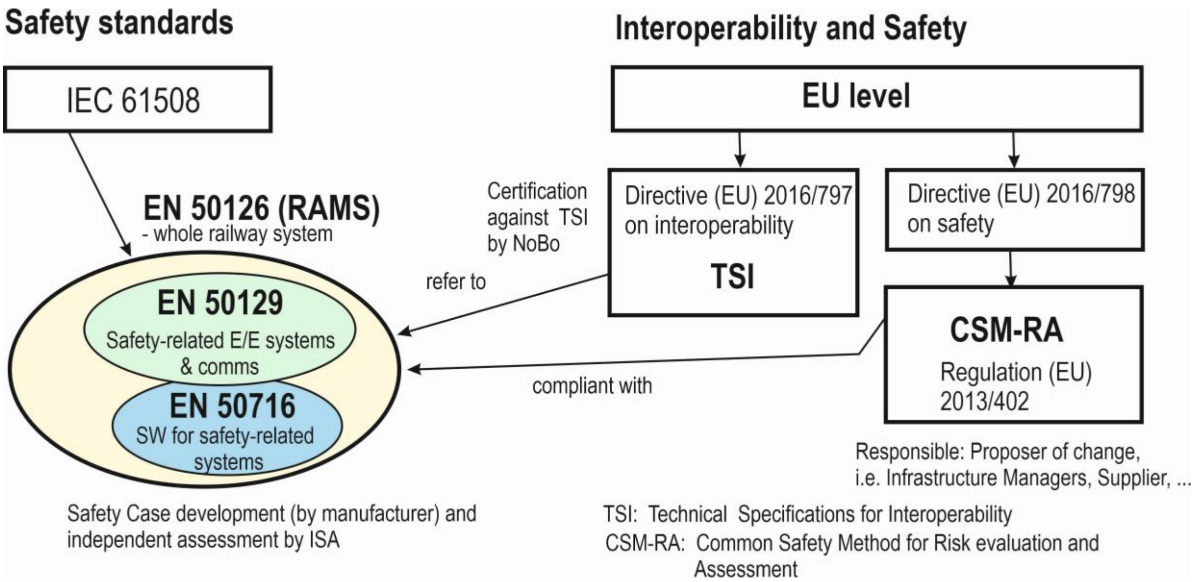

Figure 10: Railway safety standards, interoperability and common safety method.

The certification process is the conformity assessment activities performed by a Notified Body (NoBo)/ Designated Body (DeBo) based on the requirements set out in applicable Technical Specifications for Interoperability (TSI). The TSI define the technical and operational standards which must be met by each subsystem or part of subsystem in order to meet the essential requirements and ensure the interoperability of the railway system of the European Union.

But even this may not be enough to ensure safety. In the case of a change in the railway system from a safety point of view, the so-called Common Safety Method for Risk Evaluation and Assessment (CSM-RA) according to the Regulation (EU) 402/2013 [13], which harmonises the risk assessment process and safety requirements, must be applied. The safety concept of EN 50129 [17], as well as IEC 61508 [39], is based on the predictable (safe) behaviour of the system in the event of a failure. A causal analysis, i.e. an analysis of the reasons how and why a particular hazard can come into existence, is therefore important part of hazard analysis.

EN 50129 [17] defines the conditions that shall be satisfied in order that a safety-related electronic railway system/sub-system/equipment can be accepted as adequately safe for its intended application. The conditions for safety acceptance are the following:

- Evidence of quality management;
- Evidence of safety management;
- Evidence of functional and technical safety.

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All these conditions shall be satisfied, at equipment, sub-system and system levels, before the safety-related system can be accepted as adequately safe. The documentary evidence that these conditions have been satisfied shall be included in a structured safety justification document, known as the Safety Case. The Safety Case forms part of the overall documentary evidence to be submitted to the relevant safety authority to obtain safety approval for a generic product, a class of application or a specific application.

5.4.2 Purpose of Safety Management Process

Safety management process is that part of the RAMS management process which deals specifically with safety aspects (EN50126-1) [14]. The above-mentioned evidence of safety management represents one of three basic conditions for safety acceptance of the railway safety-related system.

The use of this safety management process is mandatory for Safety Integrity Levels (SIL) 1 to 4 inclusive. However, the depth of the evidence presented and the extent of the supporting documentation should be appropriate to the Safety Integrity Level of the system/sub-system/ equipment under scrutiny.

The documentary evidence to demonstrate compliance with all elements of the safety management process throughout the life cycle shall be provided in the Safety Management Report, which forms Part 3 of the Safety Case – see EN 50129 §7 [17]. The purpose of this process is to further reduce the incidence of safety-related human errors throughout the life cycle, and thus minimise the residual risk of safety-related systematic faults.

5.4.3 Safety life cycle (EN 50129 § 5.3.3)

The safety management process shall consist of a number of phases and activities, which are linked to form the safety life cycle; this should be consistent with the system life cycle defined in EN 50126-1 [14] and in EN50129 [17]. The design part of the system life cycle can be viewed as a "top-down" sequence of phases followed by integration and validation part as "bottom-up" phases: this is called a "V"- diagram. The "top-down" part represents what we want to get and the "bottom-up" means what is achieved.

5.4.4 Safety organization (EN50126-1 and EN50126-2, EN50129 §5.3.4)

The safety management process shall be implemented under the control of an appropriate safety organisation, using competent personnel assigned to specific roles. Assessment and documentation of personnel competence, including technical knowledge, qualifications, relevant experience and appropriate training, shall be carried out in accordance with recognised standards. An appropriate degree of independence shall be provided between different roles, depending on the required SIL.

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5.4.5 Safety Plan (EN50129 §5.3.5)

A Safety Plan shall be drawn up at the start of the life cycle. This plan shall identify the safety management structure, safety-related activities and approval milestones throughout the life cycle and shall include the requirements for review of the Safety Plan at appropriate intervals. The Safety Plan shall be updated and reviewed if subsequent alterations or additions are made to the original system/sub-system/ equipment. If any such change is made, the effect on safety shall be assessed, starting at the appropriate point in the life cycle. See Table E.1 in EN 50129 [17] for guidance on Safety Plans for each Safety Integrity Level. The Safety Plan shall deal with all aspects of the system/sub-system/equipment, including both hardware and software. EN50716 [16] shall be referenced for Software aspects. The Safety Plan should include a Safety Case Plan, which identifies the intended structure and principal components of the final Safety Case.

5.4.6 Safety approval process (EN50129 §8)

Before an application for Safety approval according to EN 50129 [17] can be considered, an independent safety assessment of the system/sub-system/equipment and its Safety Case shall be carried out, to provide additional assurance that the necessary level of safety has been achieved. Its results should be presented in a Safety Assessment Report – see Figure **11**. The report should explain the activities carried out by the safety assessor to determine how the system/sub-system/equipment, (hardware and software) has been designed to meet its specified requirements, and possibly specify some additional conditions for the operation of the system/sub-system/equipment.

The overall documentary evidence according to EN50129 [17] shall consist of:

- the System (or sub-system/equipment) Requirements Specification,
- the Safety Requirements Specification,
- the Safety Case, and
- the Safety Assessment Report.

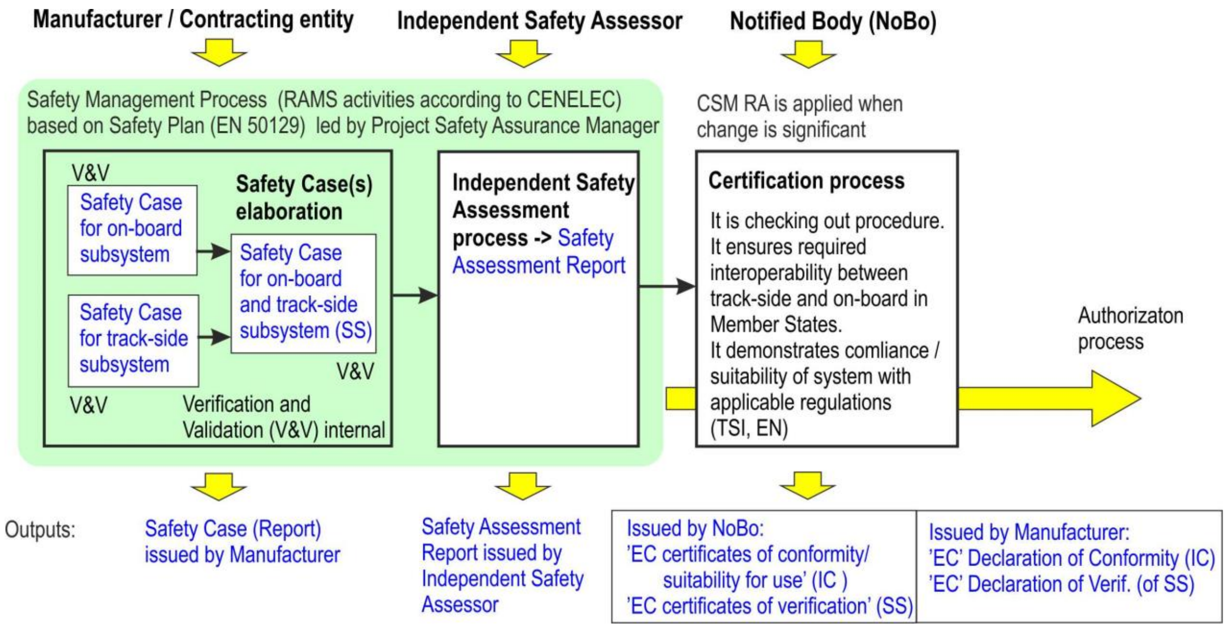

Figure 11: Activities within safety approval process.

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Provided all the conditions for safety acceptance have been satisfied, as demonstrated by the Safety Case, and subject to the results of the independent safety assessment, the system/ sub-system/equipment may be granted safety approval by the relevant safety authority.

5.5 Certification process within ERTMS: purpose and steps

Certification ensures that the required interoperability among on-board and track-side subsystems, while meeting the requirements of the CENELEC standards, is shared among many independent actors, mainly Infrastructure Managers (IM) and Railway Undertakings (RU). The corresponding certificate comprises either the assessment of the conformity of an interoperability constituent (IC), considered in isolation, to the technical specifications to be met, or the assessment of the suitability for use of an IC, considered within its railway environment, in relation to the technical specifications. The relation between the certification process and the safety management process according to CENELEC standards is illustrated in Figure **10** and Figure **11**. The safety management according to CENELEC will ensure the required safety and reliability/ availability of the safety-relevant system, while the certification process will verify the fulfilment of the ERTMS requirements according to the TSI.

Directive 2016/797 [8] extends authorization process of Control Command System (CCS) to entire railway system as defined in the Directive - it supports concept of “Cross-Acceptance” (mutual recognition) in different Member States as a stepping stone to the interoperability within the Trans European Network.

Certification process for railway safety-related systems includes 3 steps:

- Review reports on all evidence elaborated by system manufacturer for communication between the manufacturer /applicant and the Notify Body;
- Technical report detailing requirements to be met by the system, and how and why they are fulfilled; and
- Issue of the certificate as top level summary for potential customers. It is often a single page stating that the system requirements / standards have been met.

Infrastructure managers have a key responsibility for the safe design, maintenance and operation of their rail network. Infrastructure managers are subject to a safety authorisation by the railway National Safety Authority (NSA) concerning their safety management system and to other provisions so as to meet safety requirements. In order to be allowed to manage and operate a rail infrastructure, the infrastructure manager shall obtain a safety authorisation from the NSA in the Member State where the rail infrastructure is located.

An applicant (e.g. a natural or legal person requesting an authorisation, be it a railway undertaking, an infrastructure manager or any other person or legal entity, such as a manufacturer, ...) can place a vehicle on the market only after having received the vehicle authorisation for placing on the market issued by the Agency (European Union Railway Agency) or by the National Safety Authority. In its application for a vehicle authorisation, the applicant must specify the area of use of the vehicle and include evidence that the technical compatibility between the vehicle and the network of the area of use has been checked.

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The safety authorization and the vehicle authorization must thus also be obtained for ERTMS systems based on the GNSS Positioning. Therefore, the certification and authorisation for placing in service new Interoperability Constituent (IC), e.g. GNSS-based, is expected to include three main activities (see Figure **11**):

- EC declaration of Conformity issued by Applicant/Manufacturer with respect to specifications (e.g. new interoperable specification that will also include such a new technology) - i.e. certification of IC's conformity assessed by NoBo;
- EC declaration of verification of a subsystem (SS) issued by Applicant/ Manufacturer – i.e. certification of verification assessed by NoBo;
- Authorisation for the placing in a service of a new system/subsystem by Member State (MS)/ railway National Safety Authority (NSA).

5.6 Elements of certification and safety/ risk assessment process

5.6.1 Verification and Validation

During the development of safety-related systems, it is important to document that the system meets requirements and that it works correctly. It can be proven by means of the verification and validation (V&V) process, which must start early in the development life cycle – see Figure **11**. The verification is the process evaluating element or system during a given development phase and saying whether it meets the specified requirements for that phase. In other words, if the element or system was build correctly in accordance with the applicable specification for that phase. On the other hand, the validation checks for errors in the specification and demonstrates that the system works as it required. The V&V activities are to be carried out by verifiers and validators in accordance with the recommendations given by CENELEC EN 50716 [16] and EN 50129 [17] to guarantee the required independence (see Fig. 6 of [17]). The role of external specialists, e.g. Independent Safety Assessors (ISAs) or Notified Bodies (NoBos) is also included – see Figure **11**.

5.6.2 Safety Case and Independent Safety Assessment (ISA) Report

The application of V&V process along does not still provide sufficient evidence that the safety requirements for the system have been met. EN 50129 and EN 50126 require that this evidence is well described in documents named Safety Case for the Generic Product, Safety Case for the Generic Application and Safety Case for the Specific Application. Moreover, when the integration of subsystems is required (in particular, when these subsystems are provided by different suppliers), the Safety Case of the Integration is also required.

The safety case is based on: (1) safety requirements, (2) safety argument, and (3) safety evidence. A safety case shall include a structured argument supported by analytical and experimental evidence including simulations that provides a comprehensive and valid case that a generic product / system is safe for the intended application in the given operational environment.

The safety case has to be elaborated by the manufacturer of the generic product / subsystem / system and assessed by the independent safety assessor – ISA or AsBo. It is elaborated early in the development life cycle. In the safety case, the safety assessor verifies that safety requirements have been met, all potential safety hazards have been identified, risks associated with them have been carefully evaluated that appropriate safety mitigations with a sufficient quality have been designed as

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protection against the hazards. In addition, the safety case must also demonstrate that the quality and safety management controls adopted within the life cycle are suitable for the required safety integrity level, and appropriate development techniques have been adopted and they have been performed correctly.

Safety case is the structured document and its content is specified in details in EN 50126-1 [14] and the EN 50129 [17]. It includes:

- Part 1: Definition of System/Sub-system/Equipment,
- Part 2: Quality Management Report (evidence of Quality Management),
- Part 3: Safety Management Report (evidence of Safety Management),
- Part 4: Technical Safety Report (evidence of Functional/Technical Safety),
- Part 5: Related Safety Cases (if applicable),
- Part 6: Conclusion.

The independent safety assessor (ISA) elaborates the safety assessment report. The safety assessment report is a key deliverable that summarises the safety case at a particular instant of time. It is one of two major outputs (excepting V&V) forming the certification process. In contrast to the safety case, the structure and contents of the safety assessment report is not defined in standards. The content of safety case is defined in Section 7 of [17] and Section 8 of [14] so as to valid across different Member States of the Union.

5.6.3 Role of Safety Case in certification process

In some scenarios, even a safety case for an individual system/subsystem and its approval by an independent assessor cannot justify the required operational behaviour and safety at system level. For example, it is when the system requires both on-board unit and infrastructure parts for its proper functioning. Such examples can be found in aviation or on railway. Currently the management of the railway system is shared between independent actors, namely infrastructure managers and railway undertakings. Each of them is responsible for their part of the railway system. The situation can be further complicated if the system is also required to operate in several countries - i.e. to enable a so called cross-border operations. It is just the case of ERTMS/ ETCS or the possible future ERTMS/ ETCS based on GNSS positioning technology, which shall provide the required safe and dependable operations of trains throughout Europe or in other regions. ETCS on-board units from different manufactures must be able to properly function on track-side infrastructures also from different suppliers. In other words the required interoperability within such large scale system must always be assured [8]. The interoperability means in fact the correct interaction between different interoperable constituents as defined in point (7) of Article 2 of Directive (EU) 2016/797. In order to guarantee the interoperable, safe and dependable operations, it is necessary to provide certification of individual constituents, which is required by law [8]. The safety case at system level is important part of the certification process – see Figure **11**.

It is obvious that certification cannot prove correctness of the system. If a system receives certification, it simply means that it has met all the requirements needed to be met for certification. It doesn't mean that the product is error free. The safety assessment does neither replace own competence or knowledge, nor does it guarantee for 100% correctness of the project's work in all details. Therefore, the manufacturer is finally responsible for its legal or moral obligations.

5.7 Risk Management Process according to CSM-RA

A single implementation of Safety Management process according to CENELEC safety standards is not sufficient for application of GNSS in railway signalling and train control. Since the introduction of GNSS into ERTMS/ETCS represents a significant change within the European railway network, then a so-called Common Safety Method for Risk evaluation and Assessment (CSM-RA) according EU legislation must be applied [9], [13].

Railway actors must safely manage changes of the European railway system – including GNSS/SBAS integration with ERTMS. Except V&V and Safety Case, system compliance with Control Command and Signalling (CCS) Technical Specifications for Interoperability (TSI) should be checked – see Figure **11**. V&V reports and Safety Case including assessment reports are important inputs for the certification process. Excepting this, the European railway sector utilises CSM-RA for harmonisation of risk assessment. CSM-RA harmonises in fact the whole Risk Management Process. CSM-RA covers the following activities:

1) Risk assessment process and demonstration of compliance with the safety requirements, 2) Hazard Management 3) Independent Assessment by CSM Assessment Body (AsBo) - see sketch on the left in Figure **12**. This sketch represents a simplification of the scheme illustrating CSM-RA in Appendix of Regulation (EU) 402/2013 [13].

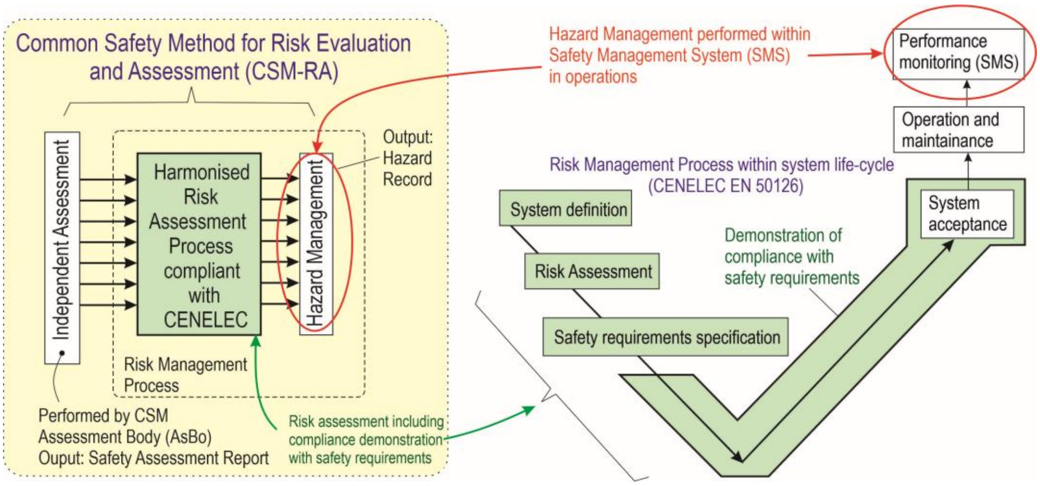

Figure 12: Compliance of CSM-RA with CENELEC safety life cycle.

5.7.1 Compliance of CSM-RA with CENELEC standards

In the Figure **12**, the compliance of CSM-RA with CENELEC standards is outlined as well. The safety monitoring during real system operations is not covered by the harmonised risk assessment within CSM-RA. In order to be CSM-RA compliant with the CENELEC life cycle, CSM-RA requires a separate Safety Management System (SMS) to be implemented and provided within activities of the proposer of the significant change. The proposer can be e.g. a railway undertaking, an infrastructure manager, an entity in charge of maintenance, etc.

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CSM-RA enables mutual recognition (cross-acceptance) of results including harmonization of risk acceptance and safety requirements in EU Member States. Harmonization and mutual recognition of safety requirements is performed via Risk Acceptance principles (RAP) and Risk Acceptance Criteria (RAC) – see Figure **13**. This figure represents simplification of the scheme illustrating CSM-RA in Appendix of Regulation (EU) 402/2013. CSM-RA is in fact the iterative process. The iterative risk assessment process is considered to be completed when it is demonstrated that all safety requirements are fulfilled, and no additional reasonably foreseeable hazards have to be considered.

The proposer shall systematically identify, using wide-ranging expertise from a competent team, all reasonably foreseeable hazards for the whole system under assessment, its functions where appropriate and its interfaces. All identified hazards shall be registered in the hazard record.

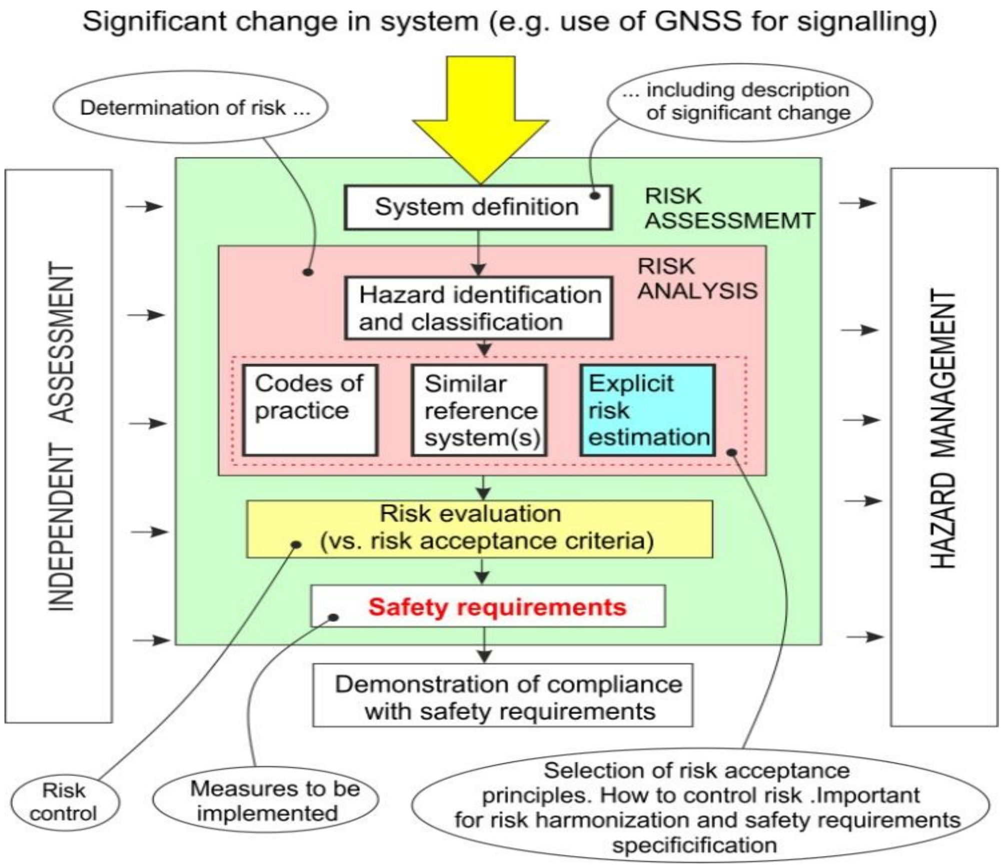

Figure 13: Harmonization of risk acceptance and safety requirements using CSM-RA.

Widely acceptable Codes of Practice (e.g. CCS TSI, CENELEC standards, etc.) as Risk Acceptance principle enables to harmonise risk and thus also safety requirements across Europe. Both Code of Practice and similar Reference Systems as Risk Acceptance Principles can be considered at the same time also as Risk Acceptance Criteria.

When a widely recognised code of practice is applied, it should therefore be possible to reduce the impact of applying the CSM, in accordance with the principle of proportionality. In the same way, where there are provisions at the level of the Union which require specific intervention by the national safety authority, that authority should be allowed to act as the independent assessment body in order to reduce double checking, undue costs to the industry and time to market.

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5.7.2 Safety Management System

Railway Undertaking (RU) and Infrastructure Manager (IM) have a duty to establish a Safety Management System (SMS) - Directives 2004/49/EC [38] and 2016/798 [9]. It shall demonstrate that all mandatory functions required for interoperability have been implemented. The SMS shall ensure the control of all risks associated with activities of IM and RU, including maintenance.

The risk management process covered by the CSM can be represented within the EN 50 126-1 [14] V-Cycle (life cycle) that starts with the preliminary system definition and finishes with the system acceptance. However, CSM doesn't cover Performance Monitoring, and Operation and Maintenance. These two phases are covered by the Railway Undertaking and Infrastructure Manager Safety Management System (SMS) – see Figure 12.

5.8 Risk assessment (CENELEC, EN 50126-1, §6.3)

'Risk assessment' means the overall process comprising a risk analysis and a risk evaluation, where 1) 'Risk analysis' means systematic use of all available information to identify hazards and to estimate the risk, and 2) 'Risk evaluation' means a procedure based on the risk analysis to determine whether an acceptable level of risk has been achieved. The Risk assessment process is outlined in Figure **14** [14]. It is evident from Figure **12** and Figure **13** that the CENELEC risk assessment process is compliant with the risk assessment employed within CSM-RA.

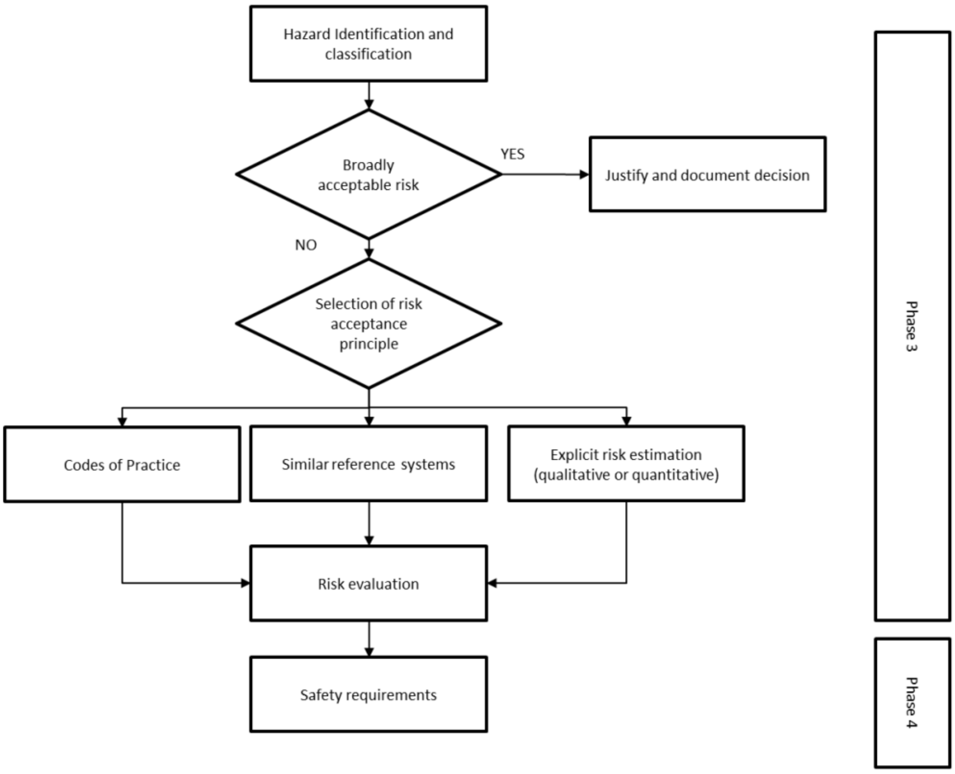

Figure 14: Risk assessment process according to CENELEC [8].

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For each identified hazard, it shall be decided if the related risk can be considered as “Broadly Acceptable” on the basis of the related consequences. The choice of “Broadly Acceptable Risk” can include cases where no injury to human apply or cases with no consequences on safety but only on availability. In these cases, requirements for RAM can still apply.

If the risk analysis identified cases with risk "Broadly Acceptable", there is no need to specify safety requirements for those cases. The choice shall be justified and recorded. If the risk analysis identified that the risk is not "Broadly Acceptable”, a risk evaluation activity shall be continued.

Risk evaluation consists in comparing the determined risk against an associated Risk Acceptance Criteria. These include [13]:

- use of Code of Practice (CoP);
- comparison with a similar system as a reference;
- explicit risk estimation (qualitative or quantitative).

Widely acceptable CoP based on CCS TSI, CENELEC standards, etc., used as RAP enable to harmonise risk and thus railway safety requirements across Europe. These CoP have been elaborated on the basis of a long-term experience with designing of railway safety-related systems. Reference systems can be used as Risk Acceptance Principles in a very similar way as Codes of Practice because a reference system is a system that has been proven in practice to have an acceptable safety level. Both Code of Practice and similar Reference Systems used as Risk Acceptance Principles can be also considered at the same time as Risk Acceptance Criteria. If a sufficient experience with the specific safety system design and assessment is missing, then explicit risk estimation as RAP must be applied.

Risk assessment process is described in detail in EN 50126-1 [14], EN 50126-2 [15] and also e.g. in Regulation EU No. 402/2013 [13] on CSM-RA. The expectation is that CSM-RA would be applied to assess changes introduced by GNSS-based localization solution in ERTMS. It would not be necessary to repeat the whole risk assessment process for ERTMS.

5.9 System safety requirements

Safety requirements shall consider the following [15]:

- safety-related functions.
- safety-related assumptions such as occurrence or mitigation barriers (e.g. protection systems, redundancies) with their required effectiveness (probability of failure on demand, per hour, etc.).
- tolerable hazard rates (THR), if defined during the explicit risk estimation, considering definition of safe states; definition of the maximum permitted time to enter a safe state; failure detection measures or facilities or devices.
- requirements resulting from the hazard analysis performed at the higher level.
- organisational rules.
- operational rules.
- maintenance rules.

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- environmental conditions.
- legal requirements should be taken into account as well.

Classification of system requirements according to [15] is depicted in Figure **15**.

Safety requirements may be categorized as follows:

- functional safety requirements.
- technical safety requirements.
- contextual safety requirements.

Functional safety requirements shall comprise:

- the expected functional behaviour of safety-related functions.
- the failure behaviour of the safety-related functions, divided into:
  - hazardous failure behaviour, including the required safety integrity requirements (quantitative target or qualitative tolerability).
  - non-hazardous failure behaviour.

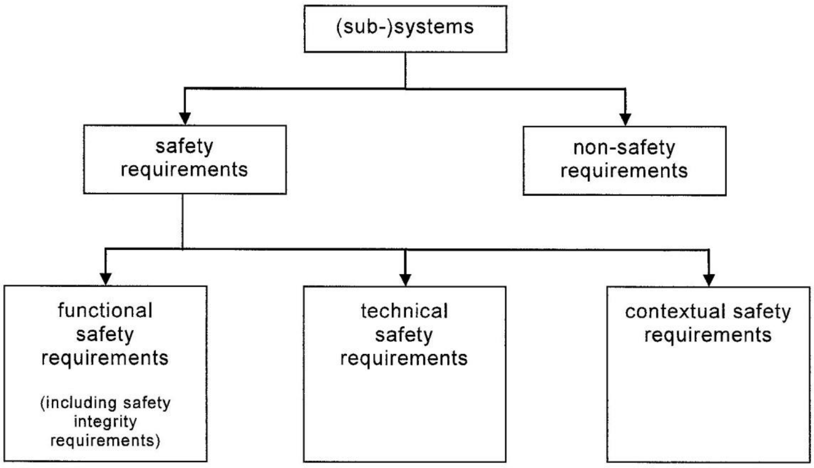

Figure 15: System requirements classification [15]

Functional safety means that all required safety functions realised by electronic/ electrical systems will be performed correctly in the expected environmental conditions. Failure/fault free conditions are assumed and related safety integrity requirements for safety functions shall be derived.

Technical safety requirements are related to technical safety and they are linked to technical design and implementation of the system. Technical safety is that part of safety that is dependent upon the characteristics of a product, which derive from the system functional requirements and/or of the system design. Technical safety means safe system construction – also in case of a failure. System must remain safe also in case of a failure. It means that basic railway safety principle called fail-safe belongs among technical safety requirements.

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Technical safety requirements do not derive from the system functions but from their technical implementation. They impact the system build. Technical requirements for each subsystem/product may be derived from different aspects such as maintainability, environmental conditions, potential hazard causes due to the technology/ system/ subsystem regardless of their intended functions.

Technical safety requirements comprise technical constraints for design/ installation/ use. They may include safety requirements such as:

- conformity to external standards – e.g. regarding how to build SIL 4 systems,
- relevant regulations – e.g. regulation on technical interoperability, use of CSM-RA, etc.
- Codes of Practice – e.g. CCS TSI, national rules etc.

Contextual safety requirements cover operational, maintenance and environmental safety requirements. Operators shall ensure the implementation of operational safety requirements, including:

- specific actions expected for any category of personnel concerned.
- the expected operational procedures for normal and abnormal operation modes.
- assumptions about safety-related operational restrictions.

Maintenance safety requirements consist of a list of safety-related maintenance actions such as:

- maintenance (intervals; rules; procedures for specific applications).
- limitations (of spare parts storage condition; on type of tools used; on physical characteristics of tools to be used).

5.10 Activities and stakeholders in safety assessment and certification process

Figure **16** illustrates the different activities and outputs of the certification and approval process at national level. The framework of the process is represented by the Common Safety Method (CSM-RA), which is used to evaluate and assess the risks associated with a significant change from a safety perspective. The following paragraphs shortly describe the activities of the various stakeholders.

The manufacturer [8] will design and manufacture the equipment. From the beginning of the safety lifecycle, verification is performed, followed by validation in the form of field tests, which is authorised by the National Safety Authority (NSA) based on a request from the proposer of the change (e.g. infrastructure manager). The manufacturer/integrator develops the relevant safety evidence for the on-board subsystem, track-side subsystem and for the integration of the overall solution. The output of these activities are verification and validation reports, initial/ intermediate safety cases (for onboard subsystem, trackside subsystem, integration of on-board and trackside subsystems) including the final /operational safety case.

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The Independent Safety Assessor (ISA) [14] [15] is involved in all activities of the manufacturer within the safety life cycle. Normally it is the safety assessor according to CENELEC, but in case of additional use of CSM-RA, ERA recommends that the safety assessment is carried out by an assessment body (AsBo) according to Regulation (EU) 402/2013 with ISA (CENELEC) authorisation to avoid unwanted duplication of assessment activities. The output of the independent safety assessment according to EN 50129 is a safety assessment report to be produced by the AsBo.

The Notified Body (NoBo) [18, 19, 9, 8] assesses, at the request of the proposer/manufacturer, the conformity of a GNSS-based ERTMS solution with the European Technical Specification for Interoperability for Control-Command and Signalling Systems (CCS TSI). The manufacturer issues an EC declaration of conformity for the interoperability constituent (IC) and an EC declaration of verification for the subsystem (SS). After assessment of the documentation, NoBo issues an EC certificate of conformity/suitability for the interoperability constituent IC or an EC certificate of verification for the SS.

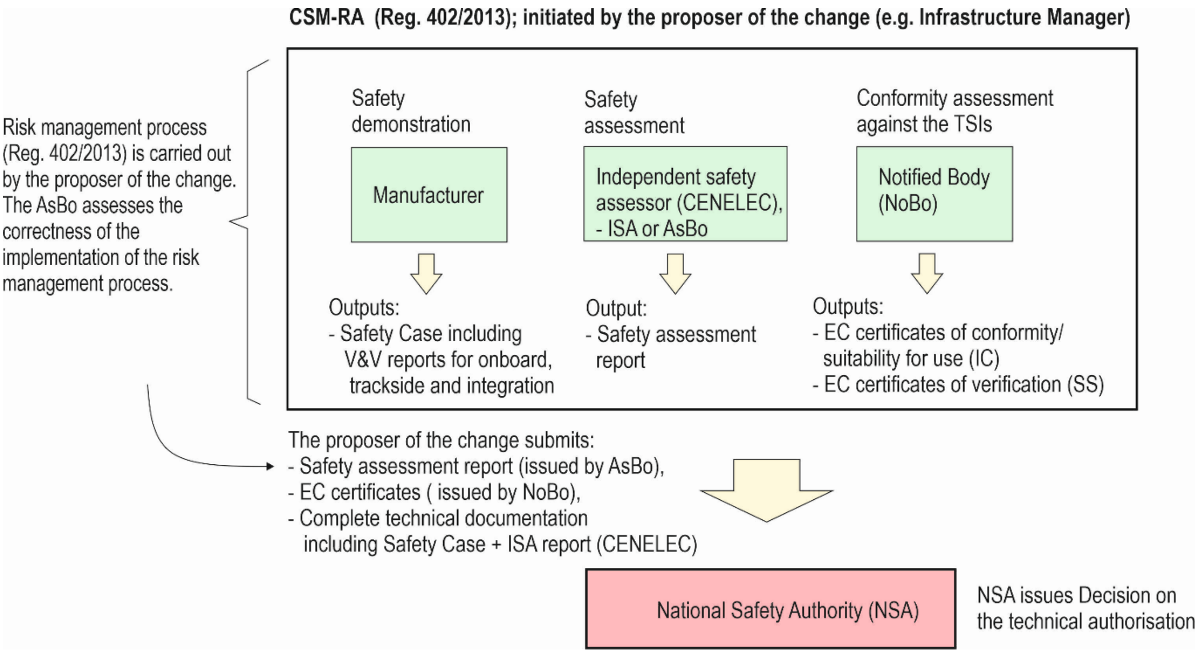

Figure 16: Activities and roles of stakeholders during safety/ risk assessment and certification of ERTMS.

The Designated Body (DeBo) [9, 8] carries out the conformity assessment of the proposed solution with respect to the national regulations and issues a certificate of verification.

The proposer of change, in accordance with Regulation (EU) 402/2013 [13], is initiating the risk assessment process according to the CSM-RA common safety method, which is the intended ERTMS/GNSS interoperable solution. The proposer can be e.g. the Infrastructure Manager. The independent safety assessor AsBo (Assessment Body) according to Regulation (EU) 402/2013, which is mandated by the proposer and approved by the National Safety Authority (NSA), prepares a so-called Safety Assessment Report (SAR) based on the above steps and conclusions of the evaluation of the test operation. The SAR is a document by which the recognised/accredited assessment body confirms, after verification, that the promoter has applied the risk management process described in

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Annex I of the Regulation to the declared technical, operational or organisational change, that it has identified all hazards, that it has applied the process correctly, i.e. has chosen an appropriate method for assessing the acceptability of the risks and that it has achieved compliance with the safety requirements for the change in question by reducing the risks to an acceptable level. In the case of integration of GNSS with ERTMS, where an interoperability (conformity) assessment is required, the proposer shall submit the following documents to the NSA: Safety Assessment Report (SAR), EC Certificates (prepared by NoBo), EC Declaration of Subsystem Verification (prepared by the manufacturer/proposer) and a complete technical file. In case conformity assessment is needed in relation to national rules, the proposer shall also submit a certificate of verification drawn up by the DeBo.

The National Safety Authority (NSA) [9] decides on the basis of the submission of the required documentation to approve the change, which in this case is the introduction of GNSS into ERTMS. The NSA considers the Safety Assessment Report (SAR) as the top document assessing the safety of the whole subsystem. Therefore, the NSA does not require the NoBo or DeBo to take into account the results presented in the SAR, but instead requires the assessment bodies (NoBo or DeBo) to include the conclusions presented in their certificates.

5.11 Guideline for technical documentation/arguments for Certification

Based on previous experience achieved in similar projects (STARS, ERSAT EAV, ERSAT GGC, GATE4RAIL, HELMET, X2RAIL-2, X2RAIL-5, CLUG, VOLIERA, SBS, RAILGAP, R2DATO, etc.), and considering input requirements coming from the applicable Regulatory framework (CENELEC EN5012x, Reg. 402/2013, TSI CCS (Regulation (EU) 2023/1695), etc.), in Appendix 1 of the present document it is reported a table providing an high-level general guideline for all the technical documents/arguments (including VICE4RAIL contractual deliverables) to be considered within the project's scope; this table would represent a *trait-d'union* between contractual tasks and regulatory duties in order to move towards a suitable synthesis of what can be reasonably delivered (also considering the final scope of the VICE4RAIL project), in terms of documents, for the following phases of the VICE4RAIl project.

It is to be noted that the mentioned document/argument list should be considered as a guideline proposed at this initial phase of the VICE4RAIl project; that list will be monitored and, if necessary, reviewed/updated in the following phases of the project (for instance some documents/arguments could be removed/added/merged depending on the future developments of the project itself).

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6 Conclusions

The main objective of this deliverable was to establish a comprehensive understanding of rail user and system requirements as a foundation for developing a hybrid virtualized testing and certification framework tailored specifically for EGNSS-based railway localization solutions within the European Rail Traffic Management System (ERTMS).

The analysis of European railway regulations and standards has provided a solid foundation for understanding the complex certification landscape that GNSS-based solutions must navigate.

The user needs and system requirements derived in this document reflect a strategic alignment with the Advanced Safe Train Positioning (ASTP) approach being developed within Europe's Rail Joint Undertaking. This alignment positions VICE4RAIL as a direct contributor to the broader European standardization trajectory, with potential to influence the inclusion of GNSS-based positioning solutions in future Technical Specifications for Interoperability by 2032. However, the evolving nature of the ASTP specification within Europe's Rail required careful consideration to ensure alignment without prematurely committing to unstable requirements.

The preliminary requirements for the HyVICE platform, with its dual approach incorporating both laboratory testing and on-field validation, provide a clear architectural vision for a certification environment capable of thoroughly evaluating the performance, safety, and interoperability of GNSS-based localization solutions under varied and realistic conditions. This hybrid approach balances the need for controlled, reproducible testing with the validation capabilities offered by real-world operational environments.

The description of safety assessment and certification processes offers a methodological framework that will guide the development of certification procedures specific to GNSS-based train positioning. By integrating concepts from CENELEC standards, CSM-RA, and certification practices, we have established a foundation for the rigorous evaluation needed to ensure that GNSS technologies meet the stringent safety requirements of the railway sector.

Moving forward, the work will continue with the detailed design and implementation of the HyVICE platform based on the requirements established in this document. These will be complemented by the development of comprehensive risk assessment methodologies which will be outlined in the forthcoming D2.2 deliverable. Furthermore, a detailed certification plan will be elaborated in D2.3, incorporating the requirements and processes identified in this document to create a robust framework for GNSS certification in railway applications.

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8 Appendix 1: Guideline for technical documentation/arguments for Certification

As anticipated in the § 5.11 of this document, here below it is reported a high-level general guideline for all the technical documents/arguments (including VICE4RAIL contractual deliverables) to be considered within this project; the list here below will be monitored and, if necessary, reviewed/updated in the following phases of the project (for instance some documents/arguments could be removed/added/merged depending on the future developments of the project itself).

In the table here below 3 levels of System Architecture are defined:

1) Component Level: ASTP as individual component

2) Sub-system Level: ASTP as integrated with EVC (ETCS-OB)

3) System Level: ASTP as integrated with complete CCS On-board, CCS Track-side and GNSS

Document/Argument	***System Level***	***Sub-system Level***	***Component Level***
Documentation Plan (this table)		x	
Quality Plan		x	
Safety, Verification and Validation Plan		x	
Certification Plan [NoBo/DeBo/AsBo]		D2.3 Certification Plan D2.4 Synergies in Certification Process for Use in Multimodal Transport	
Specification of User Requirements		D2.1 Rail User & System Requirements	
Preliminary Hazard Analysis	x	x	x
Differences Analysis / Impact Analysis	x	x	x
Analysis of Relevance / Risk Analysis against Reg. 402/2013	x	x	x
Independent evaluation of Analysis of Relevance / Risk Analysis against		D2.2 Risk Analysis Evaluation Report	

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Document/Argument	*System Level*	*Sub-system Level*	*Component Level*
Reg.402/2013 [AsBo]			
System Requirements Specification (Functional, RAM, Safety Requirements)	D3.3 System Requirement Document		
Preliminary System Specification / System Architecture	D3.1 Overall Architecture Design Document		
Interface Specification	x	x	--
HW Components Requirements Specification	--	--	x
SW Components Requirements Specification	--	--	x
SW Coding Regulations	--	--	x
Detailed System Architecture Specification (including HW and SW)	D3.2 Detailed Design Document	x	x
HW Configuration and SW Release Notes	--	--	x
Hazard/Safety Analysis & Hazard-Log (including Fault Tree Analysis / FMECA)	x	x	x
RAM Report	--	--	x
Test Plan	D3.4 Test Plan		
HW Components Tests Specification/Procedure (including Type Tests / Fault Tests)	--	--	x
SW Modules Tests Specification/Procedure	--	--	x
HW-SW Integration/Validation Test Specification/Procedure	--	--	x
Interface Test Specification/Procedure	x	x	--
System Requirement Tests Specification/Procedure	x	--	--
Design Verification Table (traceability between Req Specs and Test Specs)	D5.1 Validation Strategies	x	x
Development/Manufacturing Documents	D4.1 Procurement List Document		

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Document/Argument	*System Level*	*Sub-system Level*	*Component Level*
		D4.2 Development Report	
HW Components Test Report (including Type Tests / Fault Tests)	--	--	x
SW Modules Test Report	--	--	x
Static Analysis Report / Source Code Verification Report	--	--	x
HW-SW Integration/Validation Test Report	--	--	x
Interface Test Report	x	x	--
System Requirement Test Report	D4.3 Test Report	--	--
System / HW / SW Verification Reports	x	x	x
System Validation Report	x	x	x
User & Maintenance Manuals	--	--	x
Safety Case (including Application Conditions)	x	x	x
Independent Safety Assessment [AsBo]	x	x	x
Safety Acceptance Dossier against Reg. 402/2013	x	x	x
Certification Documents [NoBo/DeBo/AsBo]		D5.2 Certification On-Board Subsystem D5.3 Certification on Track Subsystem and related System Integration	

In the table above the character 'x' indicates a document/argument not directly associated to a VICE4RAIL contractual deliverable; in this case it will be considered, within VICE4RAIL project, if a dedicated document has to be produced.

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