PRELIMINARY DEFINITION OF THE SYSTEM PERFORMANCES AND INTERFACES

D5.7

29/06/2022

VERSION 1.1

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EXECUTIVE SUMMARY

This document is the deliverable "D5.7 - Preliminary definition of the system performances and interfaces" of the European project “Certifiable Localisation Unit with GNSS in the railway environment” (hereinafter also referred to as “CLUG”) as the main production delivery of the CLUG Work package WP5 "Application to the Train Localisation System".

This deliverable contains the core results of the CLUG project that will be made public:

- The mission definition and performance requirements for a train localisation unit
- The preliminary definition of failsafe multi-sensor localisation
- The feasibility (performances and assessed safety of life level) of the failsafe multi-sensor localisation unit.

This document is based on the terms and conditions established in the Grant Agreement (GA) and its Annexes, as well as in the Consortium Agreement (CA).

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APPLICABLE DOCUMENTS

The following documents define the contractual requirements that all project partners are required to comply with:

- Grant Agreement N°870276 (which includes DOW, Grant Preparation Forms, and annexes): This is the contract with the European Commission which defines what has to be done, how and the relevant efforts.
- Consortium Agreement CLUG_CA96_20001_V2.7_CO: This defines our obligations towards each other.

Each of the above documents was established at the start of the project, and copies were supplied to each partner. Each document could potentially be updated independently of the others during the course of the project following a prescribed process. In the event of any such update, the latest formal issued version shall apply.
In the event of a conflict between this document and any of the contractual documents referenced above, the contractual document(s) shall take precedence.

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ACRONYMS

A

ARAIM Advanced receiver autonomous integrity monitoring
ASIC Application-Specific Integrated Circuit
ATO Automatic Train Operation

C

CA Consortium Agreement
CAPEX CAPital EXpenditure
CI Confidence Interval
CAF Construcciones y Auxiliar de Ferrocarriles
CCS Control, Command and Signalling
CENELEC Comité Européen de Normalisation en Electronique et en Electrotechnique
CLUG Certifiable Localisation Unit with GNSS
COTS Component Of The Shelf
CPU Central Processing Unit

D

DAQ Data Acquisition
DB Deutsche Bahn
DBN Deutsche Bahn Netz
DCM : Device and Config Management
DFMC Dual Frequency Multi Constellation
DM-OB Digital Map On-Board

E

EGNOS European GNSS Navigation Overlay Service
ERTMS European Rail Traffic Management System
ETCS European Train Control System
EUG ERTMS User Group
EVC European Vital Computer

F

FDE Fault Detection and Exclusion
FRMCS Future Railway Mobile Communication System
FTP File Transfer Protocol

G

GA Grant Agreement
GPS Global Positionning System
GNSS Global Navigation Satellite System
GPU Graphics processing unit

I

ICAO International Civil Aviation Organisation
IMU Inertial Measurement Unit

L

LOC-OB Localisation On-Board
LRBG Last Relevant Balise Group

M

MCI Mission Confidence Interval
MOCI Maximum Operational Confidence Interval

O

OCORA Open CCS On-Board Reference Architecture
OPEX OPerational EXpenditure

R

RAM Reliability Availability Maintenability
RCA Reference CCS Architecture
RF Radio Frequency
RFI Radio Frequency Interference

S

SBAS Space Based Augmentation System
SBB Schweizerische Bundesbahnen
SDR Software Defined Radio
SiS Signal in Space
SMO Siemens MObility
SNCF Société Nationale des Chemins de fer Français

T

TCMS Train Control and Management System
TFFR Tolerable Functional Failure Rate
TLOBU Train Localisation Onboard Unit
TMS Traffic Management System
TRL Technology Readiness Level
TU Train Unit

V

VL Vehicle Locator
VLS Vehicle Locator Sensors
VS Vehicle Supervisor

W

WP Work Package
WSoI Wider System of Interest

1 INTRODUCTION

1.1 GNSS IN THE RAILWAYS

GNSS is already an important component of the railway system. Currently, it is used primarily for non-safety applications such as passenger information system and fleet management.
For instance, in France, GPS is already used onboard all French trains and Galileo is already used on board all TGV High speed trains, through the tablet Sirius, used as a relay to display passenger information and also for driver's assistance. Furthermore, SNCF will also install GNSS receivers using Galileo on many regional trains, freight trains to support customer information and fleet management services. This program was delayed because of Covid. The first 300 locomotives (out of 2600) will be equipped before the end of 2022.
DB is using GPS for location services already in a large number of vehicles for a variety of use cases. DB Cargo has fitted more than 64.000 vehicles with intelligent wagon sensors and GPS to provide real-time tracking and geo-fenced positioning of wagons to internal and external customers (see link to https://www.deutschebahn.com/de/konzern/bahnwelt/fahrzeuge_technik/intelligente_gueterwagen-6878120). Additionally, the IT System Colibri is the modular onboard system for vehicles and provides mobile data communication, Wi-Fi and onboard location service for the vehicles. The IT-System Colibri using GPS is integrated in more than 1000 vehicles, including more than 900 regional trains at DB Regio (source from Eisenbahntechnische Rundschau ETR, September 2019, Nr. 9).

According to the European Union Agency for Railways (ERA), GNSS is recognized in Europe as a game changer for safety-critical applications such as signalling by enabling trackside location equipment reduction and by improving the current localisation train performance (*Report on ERTMS Longer Term Perspective, ERA 2015)*.

The proposed CLUG solution is a multi-sensor localisation system that merges GNSS navigation data with other sensors (e.g. inertial sensor, speed sensor, and few trackside balises) to improve the performances of standalone GNSS, especially in the rail operational environment with reduced or even the absence of GNSS satellite visibility.

As of today, the odometer system and the balises are used to determine the position of a train for ERTMS/ETCS applications. The odometer is only capable to provide relative position information in one dimension. That's why a trackside balise is used in addition to the odometer to "reset" the position of the train and provide an absolute position.

With the CLUG project, an innovative approach for train localisation involving the use of GNSS (GPS and Galileo) augmented by the Safety of Life service (EGNOS SBAS) is offered to be implemented. The use of GNSS+SBAS is proposed to be combined with IMU as well as, in a second order of magnitude, with the tachometer and balise reader available on-board to provide safe localization information for the train safety applications (ERTMS). Topology data is used as an additional input for determining track selectivity and also for further improving the error models of the inertial sensors.

Train safety applications such as signalling require high level of safety and reliability in the received localization information. Due to local effects on GNSS e.g., multipath, Radio Frequency Interference (RFI) as well as the reception regular unavailability and non-integrity of GNSS signals, additional information is required to ensure the integrity of the GNSS signals. Therefore, the integrity of the GNSS information becomes critical and in civil aviation, is addressed by the use of EGNOS except the local effects in reception (not applicable for civil aviation). To augment GNSS data with integrity for railway applications, CLUG is assessing the potential of the upcoming EGNOS DFMC service designed for Safety of Life Aviation application to be used for Rail application. Preliminarily potential missing integrity data or limitations for rail application are also identified.

CLUG Objectives

Capitalising on the achievements of European Commission and European Union Agency for Space Applications (EUSPA) (formerly referred to as GSA) funded projects such as NGTC, ERSAT EAV, ERSAT GGC, and STARS, the CLUG project has performed a mission and requirements analysis, and a preliminary feasibility study of an on-board localisation unit with two proof of concept designs developed by two different companies aiming at:

- **To decrease** the cost of the **on-board and trackside** equipment for signalling
- To foster a **sustainable system for the entire European railway network**.

The CLUG Train Localisation On-Board Unit (TLOBU) architectural concept relies on a multi-sensor fusion engine empowered with integrity algorithms, taking benefit of a combination of sensors such as inertial unit, tachometer, trackside balise, digital map completed by **existing and future** GNSS including GALILEO (E1, E5), GPS (L1, L5) and EGNOS Safety-Of-Life DFMC Services (L1, L5). Its main characteristics:

- failsafe on-board multi-sensor navigation system, consisting of a navigation core (Inertial Measurement Unit, tachometer, radar, etc.) aided by GNSS, onboard digital map and a minimal number of reference points;
- continuous navigation system, providing speed and other dynamics of the train, to address the current weak points of signalling i.e. the limited odometry performance (accuracy, availability, CAPEX, OPEX, etc.) and the importance of trackside equipment;
- operational and interoperable across all the European rail network;
- compatible with the current ERTMS TSI or with its foreseeable future evolutions.

The following two preliminary designs studied are both consistent with the CLUG general architectural concept and preliminary architecture:

- “Solution A”: new design, driven by the requirements output of WP2, based on all partners assets, led by Airbus
- “Solution B”: adaptation of Naventik automotive Pathfinder product to the rail context, based on a GNSS front-end and a software GNSS receiver

1.2 SCOPE OF THE DOCUMENT

The purpose of this document is to define, according to the results of the different WPs, a comprehensive System definition based on principles, concepts, and properties logically related and consistent with each other.

The structure of this document “D5.7 Preliminary definition of the system performances and interfaces” is as follows:

- Section 2: Terms and Definition;
- Section 3: Mission definition and localisation system requirements;
- Section 4: System definition;
- Section 5: Performance evaluation;
- Section 6: Results and Perspective.

2 TERMS AND DEFINITION

2.1 SOME DEFINITIONS WITH RELATION TO PERFORMANCES AND SAFETY

As it is important for the reader to be aligned with the authors, these following definitions were agreed within the WP2 requirements work package in (CLUG: D2.5 Preliminary architecture definition 2020) and (CLUG, D2.3 - High Level System Requirements 2020), then lightly adjusted during the WP3 performance task and recalled from (CLUG, D3.3.1 - Peformance analysis report of the solution A 2022):

Term	Definition	Source
Accuracy	The accuracy of estimated or measured motion parameters of a craft (vehicle) at a given time is the degree of conformance of these motion parameters with the true motion parameters of the craft. Since accuracy is a statistical measure of performance, a statement of TLOBU accuracy is meaningless unless it includes a statement of the uncertainty in position that applies.	2008 Federal Radionavigation Plan ; Navipedia adaptation of the 2008 Federal Radionavigation Plan
Availability Or “CI<MCI Availability”[1]	Availability of the Positioning Service is the probability or the proportion of time that the Positioning service and the Integrity monitoring service are available and provide the required safe accuracy, integrity and continuity performances. Note 1: Therefore the system is available as long as it is providing localization parameters (position, speed) together with their Confidence Intervals smaller than the required Maximum Confidence Intervals and it complies with the required Tolerable Hazard Rate. Note 2: availability depends on external conditions of use (by model or by specification) Note 3 : this notion of availability with respect to compliance to performances is different from the definition of availability with respect to reliability exposed in CLUG D2.3 “High Level System Requirements”	Adapted from ICAO standards
Continuity	Continuity of the positioning service is defined as the probability that the availability and integrity requirements will be supported by the TLOBU throughout a phase of operation, given that they are supported at the beginning of the operation phase and that the TLOBU is initiated and its performances predicated to be supported all along the train’s operation phase. Note 1: planned Satellite outages, predicted at least 48 hours in advance of the outage, do not contribute to a loss of continuity. Note 2: CLUG investigations so far are showing that contrary to aviation, there is no safety critical continuity requirement in railway. Note 3: Continuity can also be specified per hour of operation.	Adapted from 2008 Federal Radionavigation Plan
Hazard	A condition that could lead to an accident.	CENELEC EN 50126-1

[1] “Availability” terms can be understood under two definitions:

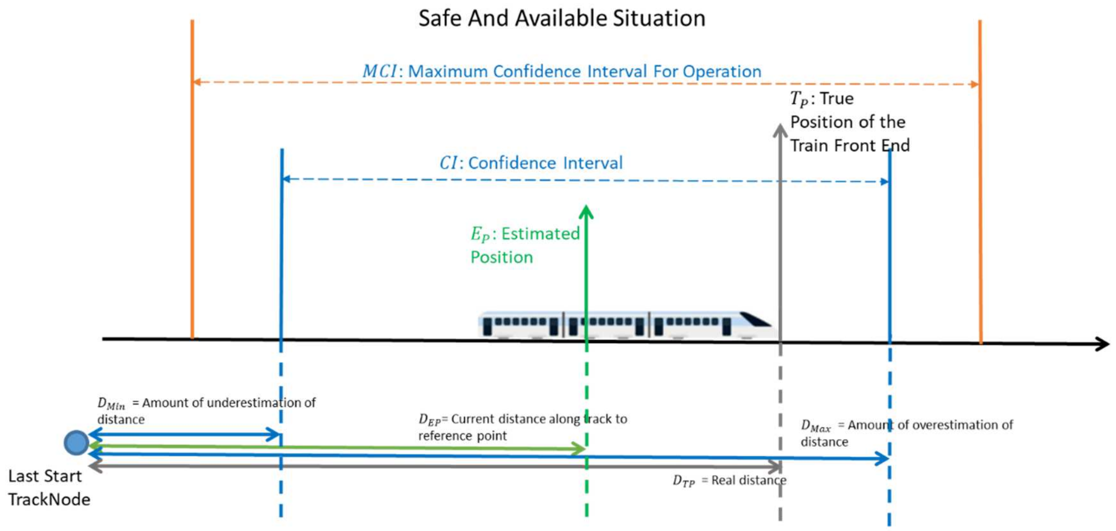
• (CLUG, D2.3 - High Level System Requirements, 2020): Availably requirement stands for the proportion of time for the TLOBU to provide outputs, compliant or not compliant to the technical safe requirements, corresponding to a reliability requirement against failures. Analysis of reliability performance is not in the scope of the present document because at this stage, the hardware / physical architecture (e.g. redundancy, HW robustness, …) is not yet defined.

• (CLUG: D2.5 Preliminary architecture definition, 2020) containing this definition where TLOBU outputs complies with position/speed MCI. This is that “CI<MCI availability” that is assessed into this document.

Integrity risk	The probability during the period of operation that an error, whatever is the source (but excluding malicious attacks), results in the real position being outside of the computed position Confidence Interval, or in the real speed being outside of the speed Confidence Interval, and the on-board localisation unit is not informed within the specific allocated time.	Adapted/clarified from (CLUG: D2.5 Preliminary architecture definition 2020)
Confidence Interval	Bound within which the target metrics is assumed to lay with a defined probability, used in railway for both safety critical and non-safety critical application. The degree of safety criticality of the said metrics is usually provided according to the SIL norm. Therefore, CI usually comes with a THR requirement.	Adapted from ERTMS subset 023
Mission Confidence Interval For Operations (MCI) Or Maximum Operational Confidence Interval (MOCI)	The interval bounded by Minimum Acceptable Front End For Operations and Maximum Acceptable Front End For Operations. Thus, the MCI is the maximum extent of the computed CI compatible with the operations. Note: also named “Mission Confidence Interval” in WP2.	(CLUG, D2.3 - High Level System Requirements 2020) And adapted from ERTMS subset 023

Figure 2-1 : Estimated position, computed Confidence Interval versus specified Maximum Confidence Interval below is an illustration of the computed position with its computed Confidence Interval (CI) versus the required Maximum Operational Confidence Interval (MCI or MOCI).

In both situations the train position remains safe, but in the second situation where CI > MCI, the TLOBU is considered not available (computed CI is higher than specified MCI). In the case of the speed CI > MCI, this situation is more an operational concern as quickly recoverable by slowing down the train for instance.



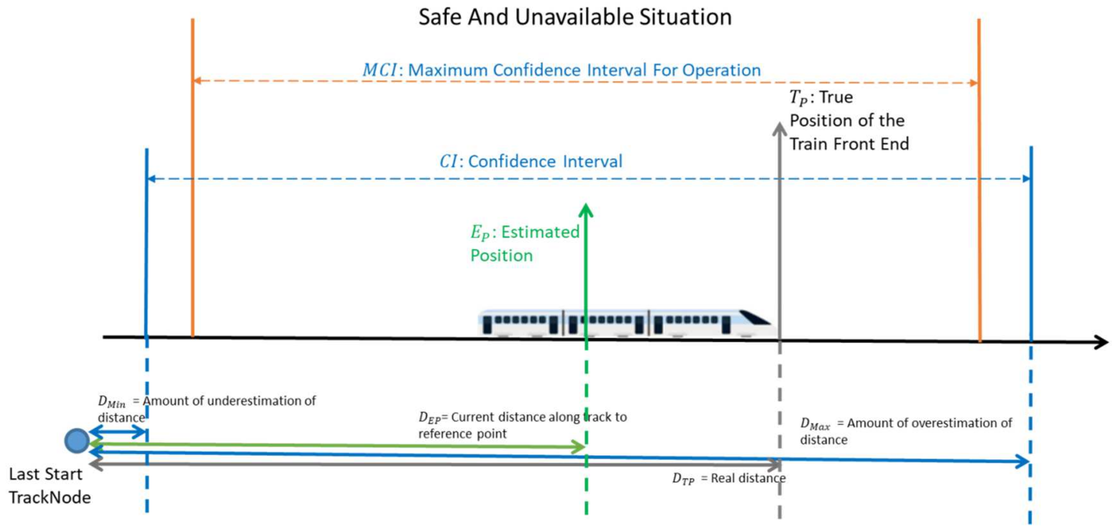


Figure 2-1 : Estimated position, computed Confidence Interval versus specified Maximum Confidence Interval

The Integrity risk, i.e. the probability that the real position/speed/… is outside of the computed position Confidence Interval, is a Safety issue; whereas the having a computed Confidence Interval exceeding the specified Maximum Confidence Interval is an operational concern.

2.2 TRACK TOPOLOGY

The track topology used as a reference system to determine and express TU positions in this document is a node edge model of the railway tracks and is defined in detail in D5.4 "Definition of the Required Maps for Localisation".

Note: In the document D5.4, the digital map on the airgap between trackside and train including the content and data model was specified. Mandatory further steps to realise a digital map for a fail-safe localisation unit are especially the establishment of a trackside data management process and a data distribution process. In addition, a risk analysis along the whole data process needs to be executed. This needs to be done on European level based on existing approaches from RCA.

2.3 TU FRONT END POSITION

2.3.1 Minimum and Maximum Acceptable Front End For Operation

The Minimum Acceptable Front End For Operations and Maximum Acceptable Front End For Operations are defined to bound the localisation accuracy requirements needed to fulfil the operational needs and mission requirements of consumers identified in D2.1 "High-level Mission Requirements Definition".

NOTE: Minimum and Maximum Acceptable Front End for Operations are not assumed to be distributed symmetrically.

2.3.2 Mission Confidence Interval for Operations (MCI)

The interval bounded by Minimum Acceptable Front End For Operations and Maximum Acceptable Front End For Operations is termed as the Mission Confidence Interval for Operations (MCI).

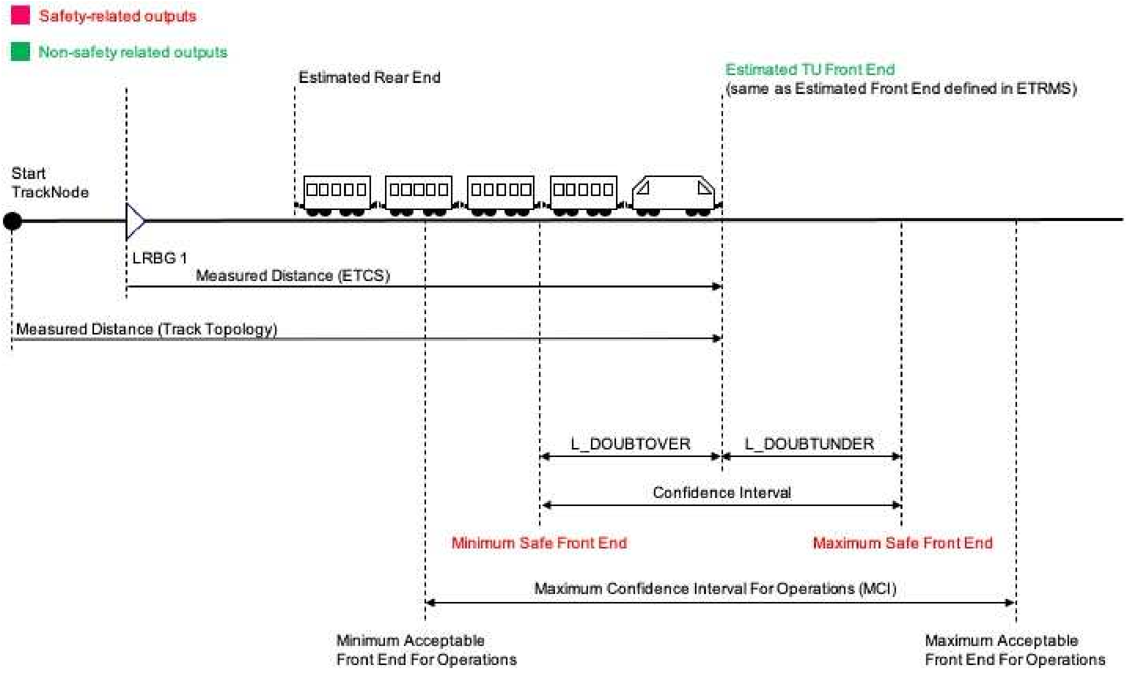


Figure 2-2 : Confidence Interval and Train Localisation according to track topology

2.3.3 Different terms for performance requirements

Figure 2-2 illustrates the different terms that have been used for specifying performance requirements for the functions of CLUG's TLOBU that relate to the train position.

During operation, Minimum and Maximum Safe Front End positions are used to ensure the protection of the train (e.g. granting train movement permission), to trigger safety reactions when required and if deemed necessary. The MCI formally bounds the expected accuracy for Minimum and Maximum Safe Front End needed to satisfy the external-user requirements defined in D2.1 "High-Level Mission Requirements Definition". Therefore, performance requirements for (safety-related) functions with safety integrity level of CLUG's TLOBU have been defined using the MCI. The MCI formally bounds the expected accuracy for Minimum and Maximum Safe Front End needed to satisfy the external-user requirements defined in D2.1 "High-Level Mission Requirements Definition".

INFO:

- When the confidence interval exceeds the MCI, the punctuality of operations may not be guaranteed anymore.
- The Estimated Front-End position together with the formal accuracy of the Estimated Front End was deemed as a sufficient output for use by non-safety-related applications and applications performing functions with basic integrity. Hence for all these outputs, the performance requirements have been defined using the Estimated Front-End position.

2.3.4 Different TU Position terms

The different TU position terms used in this document and their meaning are described below in Table 2-1.

Term	Brief Description
Estimated Front End	Measured distance of the TU Front End position from the Start TrackNode of the current TrackEdge.
Minimum Safe Front End	Differs from the Estimated Front End by the over-reading amount in the distance measured from the Start TrackNode of the current TrackEdge i.e., in relation to the orientation of the train this position is in rear of the Estimated Front End.
Maximum Safe Front End	Differs from the Estimated Front End by the under-reading amount in the distance measured from the Start TrackNode of the current TrackEdge i.e., in relation to the orientation of the train this position is in advance of the Estimated Front End.
3D Position	Estimated position of the TU Front End position in WGS84 coordinate system and map-matched to the current TrackEdge.

Table 2-1 : TU Position terms and description

2.3.5 Formal Accuracy

Formal accuracy is a measure of the uncertainty of the estimates, according to the statistical characterisation of the sensors uncertainties and the positioning error model.

2.4 TRACK SELECTIVITY

Today, for example, ETCS (European Train Control System) doesn't use track selectivity as provided by the on-board system while the train is travelling. The train is located using absolute reference points based on balises and distance run to the balises. By this principle while a train is passing point, the on-board system doesn't know exactly which path the train is using unless if balises are installed on each branches of point. The trackside train protection systems set the route for the train and provide the list of balises that the on-board balise reader has to encounter/read as the train travels from A to B.

It is targeted that the future standalone failsafe TLOBU provides track selectivity either without the use of any trackside equipment or by reducing the need for trackside equipment to a minimum. This will enable the on-board systems to continuously determine on which track the train is running. Thereby, enabling a complete and safe transition from trackside centric train localisation to train centric localisation.

2.5 TU REFERENCE FRAMES DEFINITION

The Train front reference frame {t} represents the nominal reference frame of the vehicle to be tracked. In order to respond to the high-level mission requirements, the origin of the reference frame will be placed at the TUFE (Train Unit Front End). For what concerns the orientation, following the standard [2] ISO 8855, the x-axis is directed along the vehicle longitudinal axis (positive forward), the z-axis is directed along the vertical direction (positive upward) and as a consequence the y-axis lies in the horizontal plane, pointing to the left.

The Bogie reference frame {o} is placed along the bogie axis and during straight paths is oriented as {t}. During curves a non-zero relative angle between {o} and {t} arises about the bogie pin axis. This rotation shall be compensated when processing the velocity measurements and null cross-track velocity constraints are enforced. In the scope of CLUG, only one bogie is associated with a reference frame.

Figure 2-3 depicts the above-mentioned reference frames {t} and {o}.

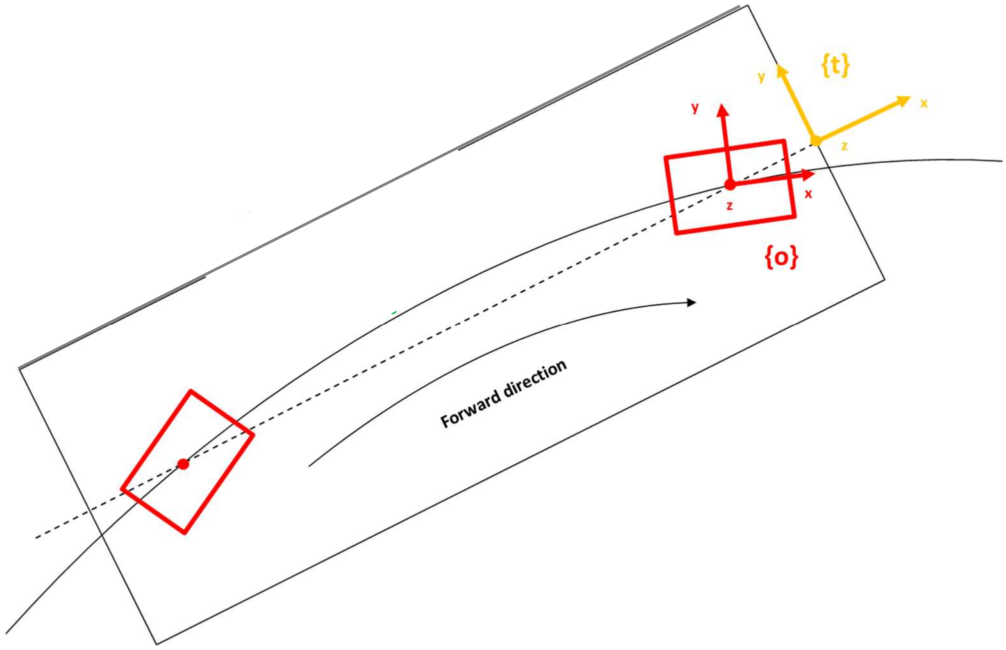


Figure 2-3 : On board reference frames: front train {t} and bogie {o} reference frames.

2.6 YAW, PITCH AND ROLL

A vehicle normally moves on a plane in space to travel a certain distance. At the same time, however, it can also rotate around its axes:

- When cornering, it will rotate around its vertical axis to lead the vehicle front end to the direction of travel. The vehicle also rotates around its vertical axis when driving as a result of the dynamic behaviour of the axles and bougies (sinusoidal run). The movement around the vertical axis is called yaw.
- At the same time the vehicle will rotate around the longitudinal axis due to the cornering force, the cant of the track, the suspension and possibly an active or passive tilting system, which is called roll.
- Due to the vehicle braking and accelerating and the caused breaking and driving forces, as well as the gradient of the track, the vehicle will rotate around the transverse axis. This movement is called pitch.

With reference to the train front reference frame {t}, the rotation about the x-axis is called roll, the rotation about the y-axis is called pitch and the rotation about the z-axis is called yaw. The angles are measured in mathematically positive direction (right hand rule) (see Figure 2-4).
The yaw, pitch and roll rotational rates are the first order derivatives of the yaw, pitch, and roll angles.

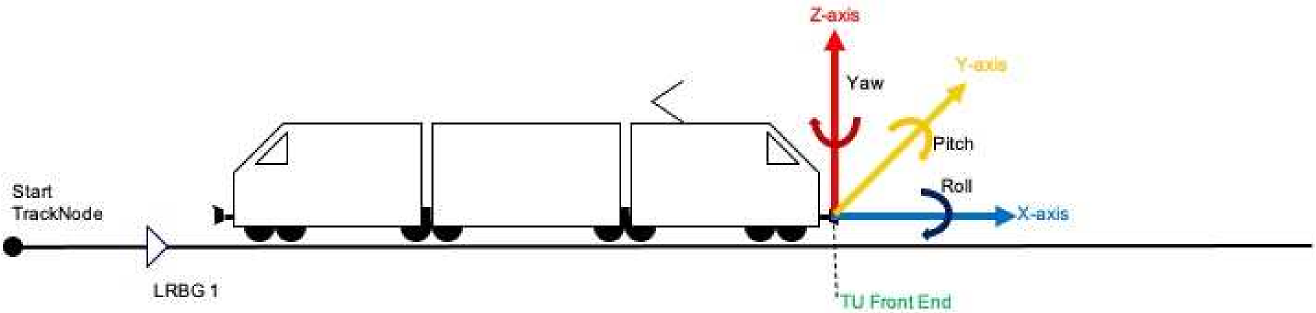


Figure 2-4 : Definition of the train fixed coordinate frame with x-, y-, z-coordinates and roll-, pitch- and yaw-angles.

2.7 TU SPEED, VELOCITY AND ACCELERATION

2.7.1 TU Speed

TU speed refers to the value of the velocity vector along the x axis of the bogie frame {o}. It is always reported with a positive sign. This function is used for the Train Protection.

2.7.2 TU Velocity

TU Velocity is the three-dimensional velocity vector at TU Front End, represented in the bogie reference frame {o} for Incident & Prevention Management On-Board (IPM-OB) application.

2.7.3 TU Along-track Acceleration

TU Along-track Acceleration is the value of acceleration vector along the x axis in the bogie frame {o}. This function is used for the Train Protection. It is reported with a positive sign if the TU speed increases or with a negative sign if TU speed decreases.

2.7.4 TU Acceleration

TU Acceleration is the three-dimensional acceleration vector expressed in the train bogie frame {o}, used for Perception and Incident Management.

2.7.5 Confidence Interval for TU Speed

The terminology for defining the required performance, safety-related outputs with safety integrity level and non-safety related outputs (incl. outputs with basic integrity) for TU Speed is illustrated in Figure 2-5.

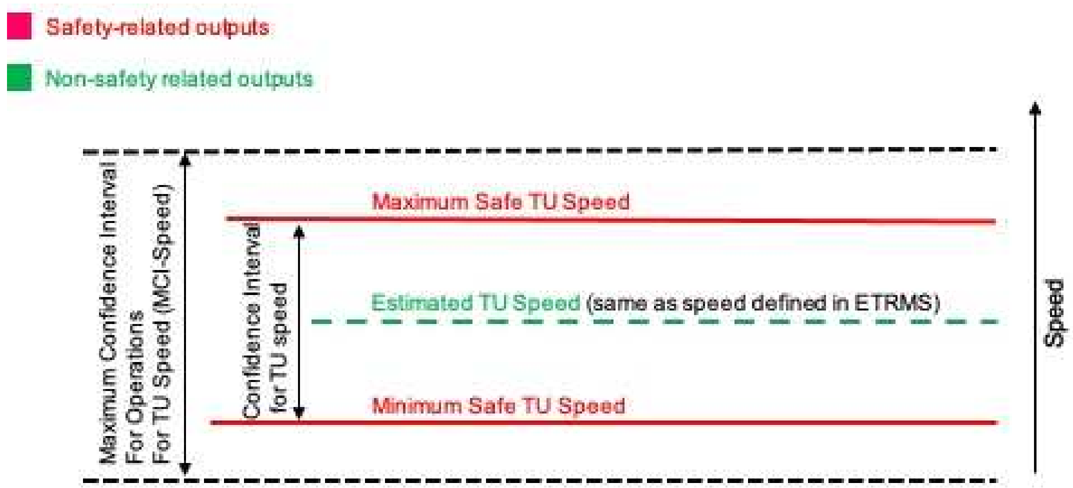


Figure 2-5 : Visualisation of the Confidence Interval for TU Speed.

2.7.6 Confidence Interval for TU Along-track Acceleration

The terminology for defining the required performance, safety-related outputs with safety integrity level and non-safety related outputs (incl. outputs with basic integrity) for TU Along-track acceleration is illustrated in Figure 2-6.

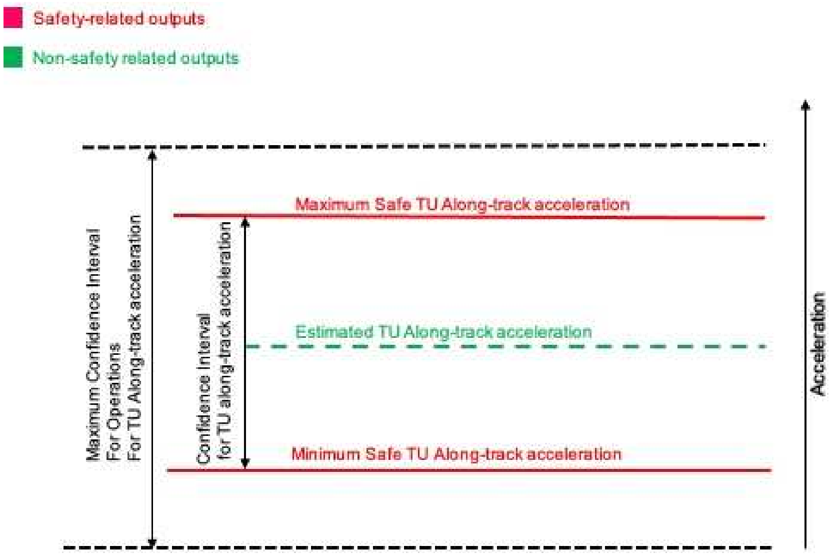


Figure 2-6 : Visualisation of the Confidence Interval for TU Along-track acceleration.

2.8 TU Movement Direction

The TU movement direction is defined following the principles of ETCS subset 026.

- Reference point Id: Unique identifier of the element from which an estimated distance is given. In ETCS the reference point is the LRBG (see ETCS subset 026). In the future the reference point could be any point of the track. The reference point is defining two directions: normal and reverse
- Train orientation: Orientation of the train according to the direction of the reference point (see ETCS subset 026, Q_DIRLRBG).
- Movement direction: Direction of train movement according to the direction of the reference point (see ETCS subset 026, Q_DIRTRAIN)
- Position qualifier: It tells on which side of the reference point the estimated train front end position is (see ETCS subset 026, Q_DLRBG).

The following picture depicts how the orientation of the LRBG influences the orientation of the train and the train movement. The picture is issued from ETCS subset 026.

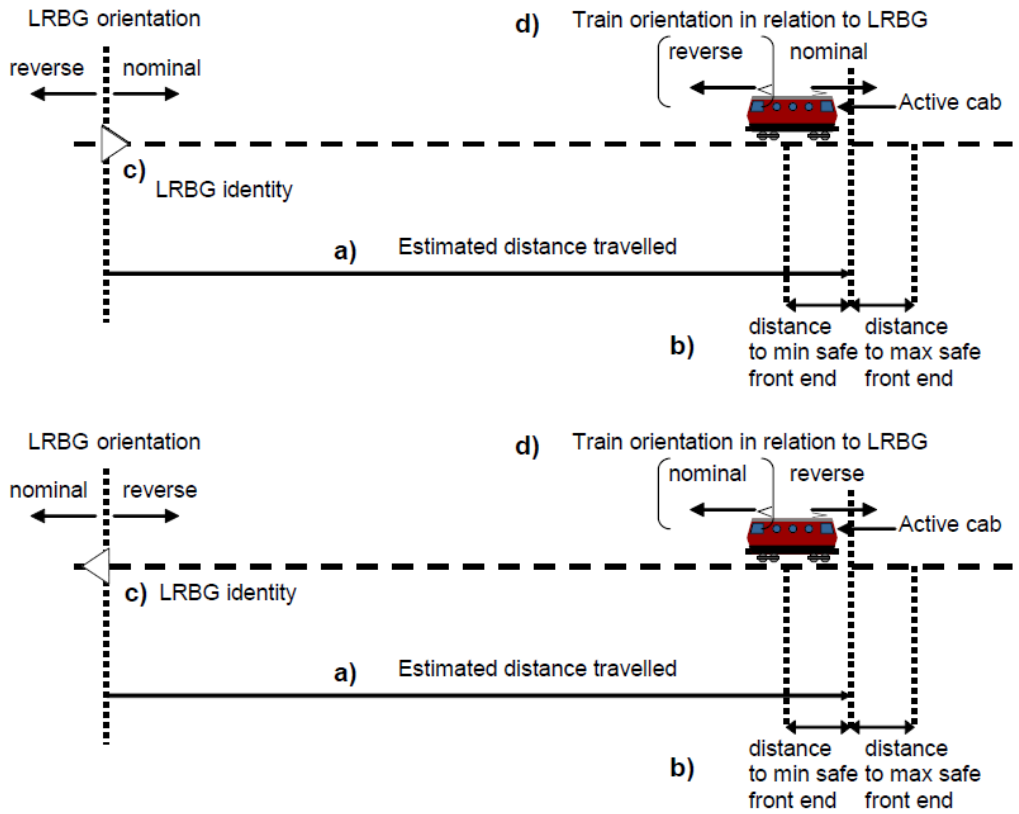


Figure 2-7 : Illustration of the terms reference point, train orientation, movement direction and position qualifier

2.9 Safety Terms

- A **safety-related function** carries responsibility for safety according to EN 50126-1 §3.74 i.e., involved in hazard risk reduction.
- A **non-safety-related function** does not carry a responsibility for safety i.e., not in involved in hazard risk reduction. Even if basic integrity requirements may be considered for the development of a such function according to EN 50126-1 §3.7 (it may be translated into SIL0 when applying EN 50128), no integrity indication to a **non-safety-related function** is given in this document for sake of clarity.
- **A function with basic integrity** is a **safety-related function** to which a basic integrity requirement is allocated according to EN 50126-2 §10.2.6/7
- **A function with safety integrity level** is a **safety-related function** to which a safety integrity level (within SIL1 - SIL4 bandwidth) is allocated according to EN50126-2 §10.2.6/7

3 MISSION DEFINITION AND SYSTEM REQUIREMENTS

This section gives an overview of the mission and operational scenario that the TLOBU shall comply. And then, the system requirements are specified for the safety and non-safety functions.

3.1 MISSION DEFINITION AND OPERATIONAL SCENARIO

3.1.1 Mission Definition

3.1.1.1 *Localisation unit into overall RCA and OCORA architectures*

Reference CCS Architecture (RCA) defines the overall architecture of the CCS system (Figure 3-1) and delegates the definition of the CCS On-Board architecture to OCORA. The CCS On-Board is composed of Vehicle Locator (VL), Vehicle Supervisor (VS) and ATO vehicle.

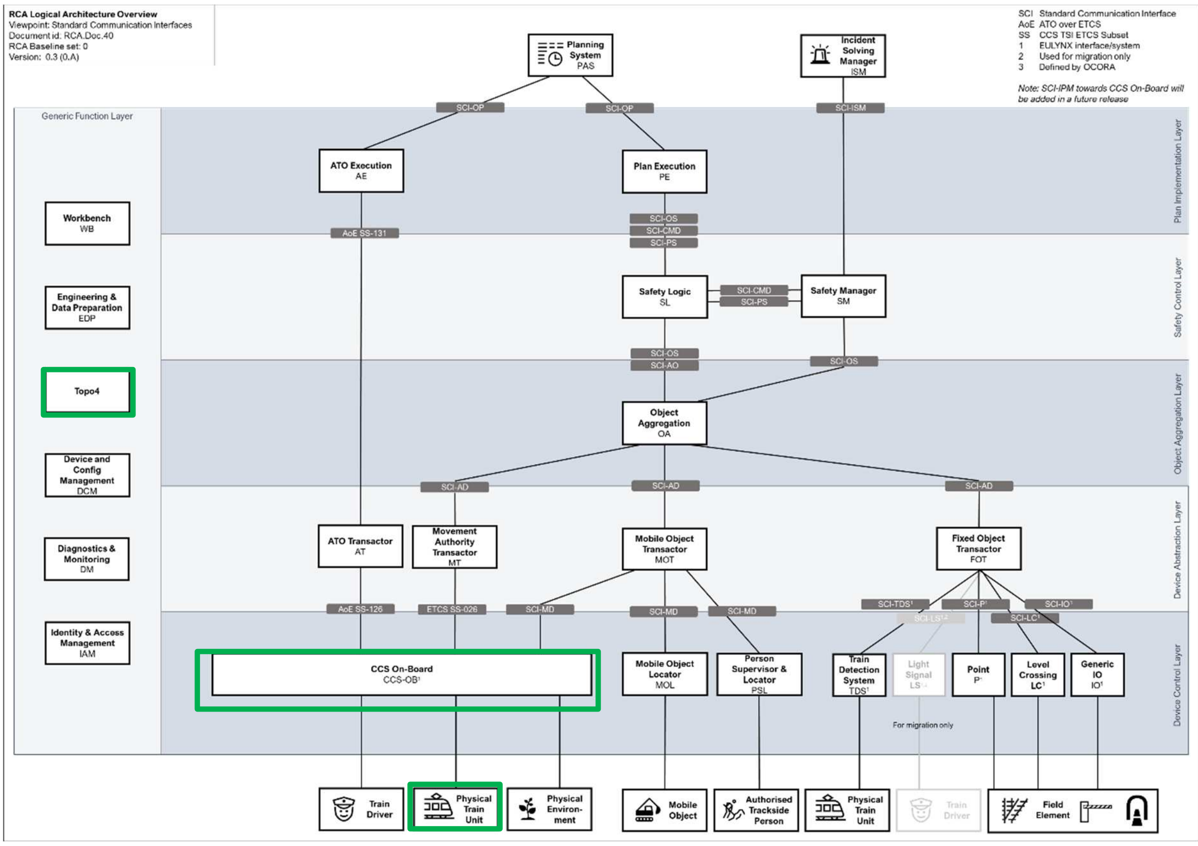


Figure 3-1: Reference CCS Architecture (RCA) Gamma architecture(RCA baseline set 0, version 0.3). The components considered in the project CLUG are marked with green boxes (Rail Vehicle, Vehicle Locator and TOPO4).

Further and more detailed information to the RCA can be found at the following link: https://public.3.basecamp.com/p/KeehzqFmXv5R2N7tGDjaEokq

OCORA defines the reference architecture for CCS on-board (Figure 3-2). The components considered in the CLUG project are:

- the Vehicle Locator (VL) and the Vehicle Locator Sensors (VLS) which constitute the train localisation on-board unit (denoted by LOC-OB in the OCORA project);
- the On-Board Digital Map (DM-OB).

The OCORA LOC-OB introduction document (see OCORA-TWS01-100_Localisation-On-Board-(LOC-OB)_Introduction) is providing an overview of the OCORA localisation on-board system. Some considerations on having a separated localisation system from ETCS core are produced. The following information issued from this document is presented here-below. In the context of OCORA, the CLUG TLOBU is named LOC-OB (localisation on-board system).

The LOC-OB is deployed on every OCORA based CCS On-Board system. In today's ETCS implementations, the LOC-OB is part of the monolithic ETCS OBU (On-Board Unit). Since the LOC-OB has a different technological life cycle than the Vehicle Supervisor (VS), it is essential that the LOC-OB is a separate component, containing just the functionality needed to locate safely and reliably the vehicle, its orientation on the track and determining associated kinematic parameters of the vehicle. Standardising the external interfaces of LOC-OB allows new localisation technologies to be introduced more quickly in the future without the need to modify the VS functionality.

Isolating the LOC-OB from the VS-functionality has the positive effect that the complexity of the LOC-OB is reduced. A very important aspect, since the LOC-OB is requiring a safe implementation and already many changes for the CCS on-board, impacting the LOC-OB, are foreseeable. New functionalities (game changers) with potential impact on the LOC-OB are:

- FRMCS
- ATO
- Train integrity detection for ETCS L3
- GNSS augmentation
- Digital map

It is the goal of the OCORA project to build a LOC-OB model that is mostly agnostic to these changes.

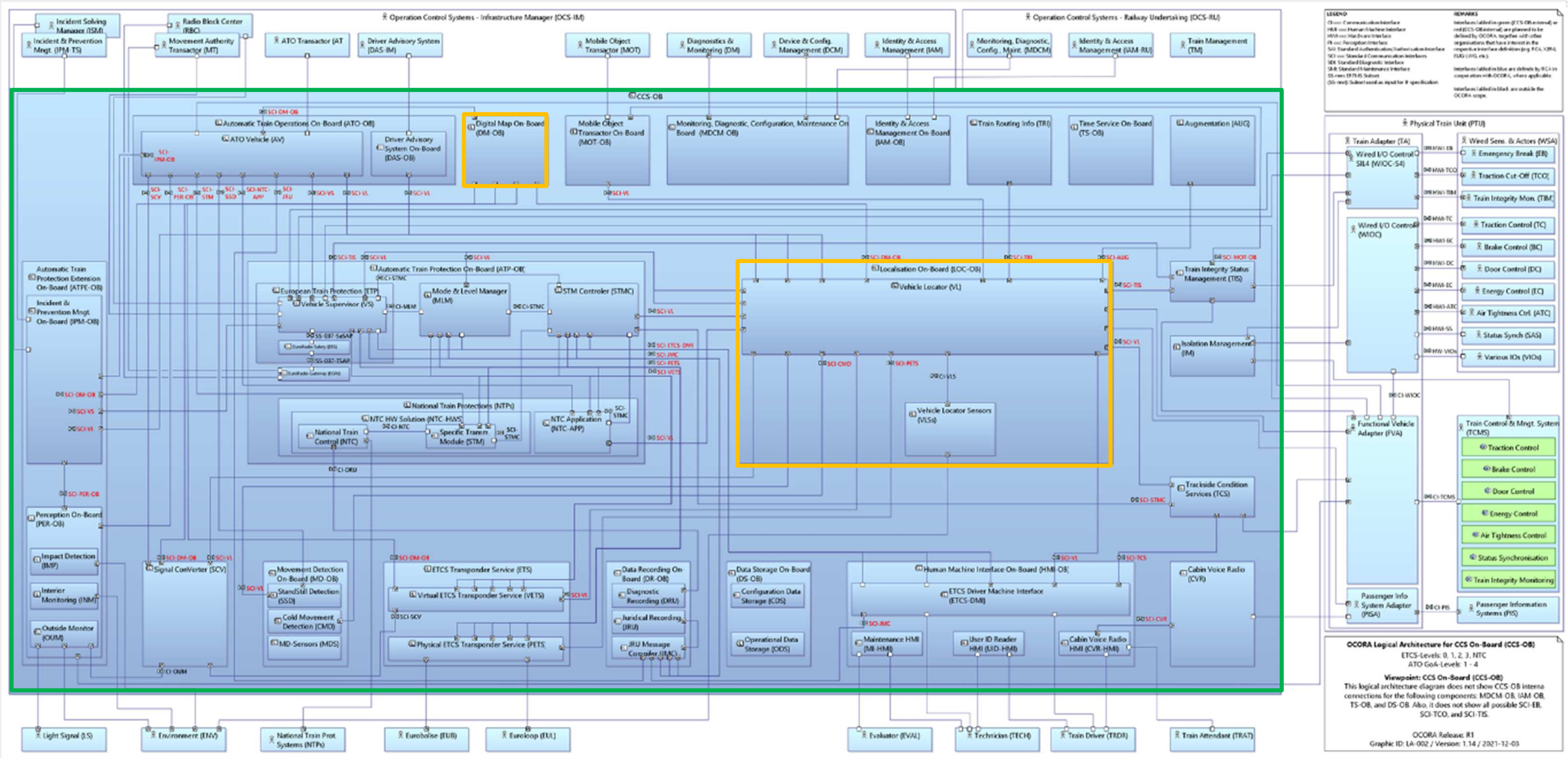


Figure 3-2 OCORA Logical Architecture for CCS On-Board (CCS-OB) – green border. The components considered in the project CLUG are marked with orange border (VL, VLS and DM-OB).

The CLUG's functional architecture of the TLOBU can be mapped to OCORA and RCA's logical architecture as in Table 3-1.

CLUG	RCA	OCORA
Sensors: GNSS Antenna/Receiver, IMU, tachometer or equivalent speed sensor, Eurobalises data	Vehicle Devices (Sensors) of the **Physical Train Unit**	**Vehicle Locator Sensors (VLS)**
On Board Digital Map	Thanks to the **Topo4** (trackside), the on-board digital map which is represented by topology/topography for safe applications (e.g., track data), is delivered through the Device and Config Management (DCM) subsystem to the train	**Digital Map On-board (DM-OB):** the external interface linked to the TLOBU is identified by SCI-DM-OB
Navigation Engine & Integrity Engine	**Vehicle Locator (VL)**	

Table 3-1 Mapping between CLUG's functional architecture and RCA & OCORA

3.1.1.2 *Railway System*

Train localisation system data are used by many consumers on-board and off the train through a unique distributor, the European Vital Computer (EVC). Consuming applications can operate on the trackside, i.e., out of the train, or on-board the train. Figure 3-3 below shows an exhaustive list of consumers when the train is running, i.e., ETCS mission.

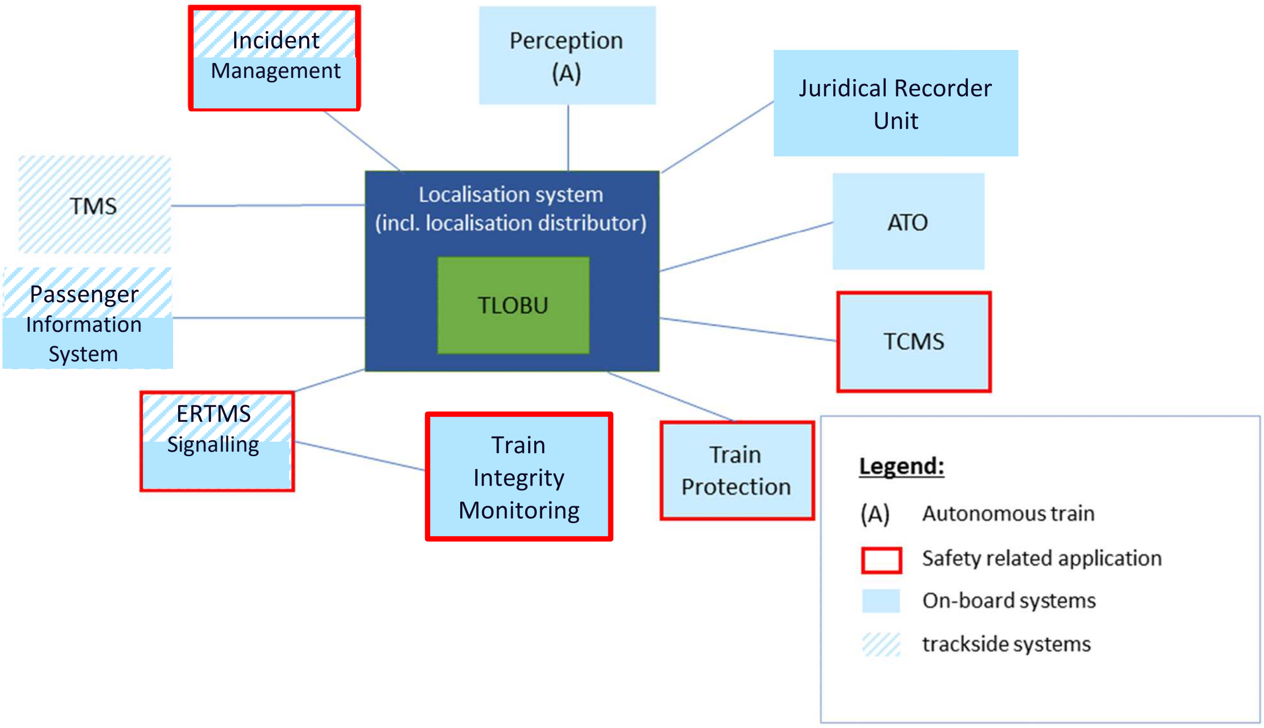


Figure 3-3: Wider System of Interest for the System Train Localisation On-Board Unit to be investigated under the CLUG project

Some of above-mentioned consumers are not safety relevant (e.g., Passenger Information System, Automatic Train Operation (ATO). In the case of Perception system that determines position object, detects obstacle on the track and recognizes status of signals, the precise safety integrity level is currently being investigated and a harmonized target has to be specified for ERTMS/ETCS applications.

3.1.1.3 *Mission requirements*

The entire set of mission requirements that an operational train localisation on-board system would have to fulfil are described in Table 4-2 of D2.1 "High Level Mission Requirements Definition".

The mission requirements fall into different categories:

- Capacity: An accuracy requirement that must be fulfilled in order to reach a railway capacity target
- Functional: Information what a user's function needs in order to fulfil its own purpose
- RAM requirements
- Safety requirements
- Other: Other performance requirements, mostly inherited by existing norms

3.1.2 Operational Scenarios

Requirements related to the mission definition of the testing scenarios depend on the categorization of scenarios by operation (for details see D2.2). The conducted typical operations in the railway environment are as follows:

- Cold Initialisation[2] / Warm Initialisation[3]
- Start rolling from standstill
- Acceleration
- Normal running (Drive with constant speed)
- Deceleration and target stop to standstill
- Standstill
- Coupling operation
- Uncoupling operation

From this operations list, taking into account missions, railway environments and constraints from train operation, chapter 6.1 of D2.2 derived the list of scenarios to be applied for testing the TLOBU (see table 10 of D2.2 document).

[2] Initialisation without any saved localisation

[3] Initialisation with saved localisation

3.2 High level system Requirements

The main preliminary functional requirements and non-functional requirements are listed here-below.
These requirements are derived from Table 4-2 of the public deliverable D2.1 "High Level Mission Requirements Definition" and from the confidential deliverable D2.3 "High-level system requirements".

NOTE: CLUG is a research project and as such the system requirements specified here are to the best knowledge and expertise available in the consortium at the time the document has been published. On-going European standardisation activities including in EUG, RCA, OCORA and SHIFT2RAIL are expected to provide further inputs and potential improvements to the system requirements.

3.2.1 Requirements for safety related functions

3.2.1.1 *Minimum and Maximum Safe Front End Position*

Rationale	This function is required to determine the safe train positioning used by the train protection.
Req#1	The TLOBU shall provide the Estimated Train Front End Position and the Minimum and Maximum Safe Front End.
Req#2	The half-width of the MCI is 10 m for speeds below 36 km/h then the distance run in 1 second at speeds higher than 36 km/h up to 600 km/h (illustrated in Figure 3-4 for reference).

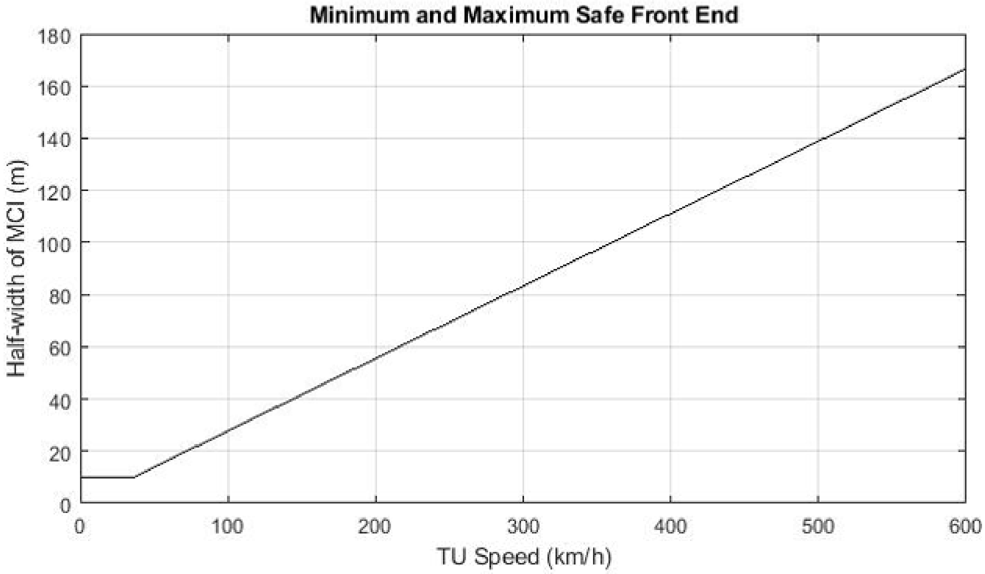


Figure 3-4 Half-width of MCI for Min and Max Safe Front End

This preliminary finding of the half-width of MCI based on a linear model to optimise line capacity independent of balise placement is under discussion in European standardisation initiatives.

Req#3	The TLOBU shall be integrated in the OCORA architecture. A first approach has been defined.
INFO	OCORA is an ongoing project. Future results from OCORA shall be taken into consideration to consolidate the interface needs in terms of frequency, latency, among other non-functional requirements.
Req#4	The outputs of this function shall meet the safety targets defined in the Preliminary Hazard Analysis based on a high-level approach of the overall CCS system architecture.

The apportionment of hazards leads to a TFFR ≤ 5E-10/h and consequently to a SIL4 function.

INFO Future safety analysis from RCA, OCORA projects shall be taken into consideration to expand the preliminary analysis and consolidate this data.

Req#5 In case compliance to Req#2 cannot be accomplished within the required safety requirement defined in Req#4, the Minimum and Maximum Safe Front End output shall as a conservative estimate comply to the safety requirement defined in Req#4.

INFO Req#5 means that the true position shall always be bound by the confidence interval (i.e., Min and Max Safe Front End). And in challenging conditions where the accuracy requirements might not be fulfilled, the Min and Max Safe Front End interval shall continue to ensure compliance to the safety requirement Req#4.

INFO The Minimum and Maximum Safe Front End shall be estimated as an interval around the reported position (Estimated Front End), within which the front end of the train is located.

3.2.1.2 *Safe TU Speed*

Rationale This function is required to determine the safe TU speed used by the train protection.

Req#6 The TLOBU shall provide the Estimated TU Speed and the Minimum and Maximum TU Speed.

Req#7 The half-width of the MCI is ± 2 km/h for speed lower than 30 km/h, then increasing linearly up to ± 14 km/h at 600 km/h (illustrated in Figure 3-5 reference).

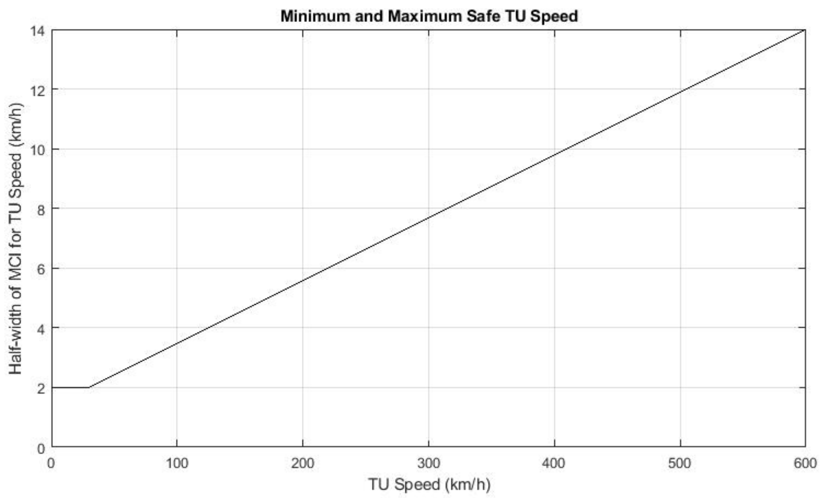


Figure 3-5 Half-width of MCI for Min and Max Safe TU Speed

Req#8 The TLOBU shall be integrated in the OCORA architecture. A first approach has been defined.

INFO OCORA is an ongoing project. Future results from OCORA shall be taken into consideration to consolidate the interface needs in terms of frequency, latency, among other non-functional requirements.

Req#9 The outputs of this function shall meet the safety targets defined in the Preliminary Hazard Analysis based on a high-level approach of the overall CCS system architecture. The apportionment of hazards leads to a TFFR ≤ 5E-10/h and consequently to a SIL4 function.

INFO Future safety analysis from RCA, OCORA projects shall be taken into consideration to expand the preliminary analysis and consolidate this data.

Req#10 In case compliance to Req#7 cannot be accomplished within the required safety requirement defined in Req#9, the Minimum and Maximum TU Speed output shall as a conservative estimate comply to the safety requirement defined in Req#9.

INFO Req#10 means that the true speed shall always be bound by the confidence interval for TU Speed. And in challenging conditions where the accuracy requirements might not be fulfilled, the Min and Max Safe TU Speed interval shall continue to ensure compliance to the safety requirement Req#9.

INFO TU speed is always a positive value; when the TU is moving in reverse, the TU Actual Movement Direction will be 'reverse' and TU speed will therefore indicate the speed in the reverse direction.

INFO The Minimum and Maximum Safe TU speed shall be estimated as an interval around the reported speed (Estimated TU Speed), within which the speed of the train is bound.

3.2.1.3 *Minimum and Maximum Safe Accurate Front End Position*

Rationale This function is required to determine safe accurate front end position. It is used mainly under ATO operation to determine by safety application that the train is stopped correctly to allow train door opening (e.g., constraints between the size of the platform and the length of the train, platform equipped with platform doors).

Req#11 The TLOBU shall provide the Estimated Front End Position and the Minimum and Maximum Safe Accurate Front End.

Req#12 The half-width of the MCI is 0.5 m for speeds below 40 km/h.

INFO This preliminary finding of the half-width of MCI is under discussion This requirement as described in the rationale is dependent on the constrains between size of platform and length of the train and therefore might need to be optimized in some mission profiles.

Req#13 The TLOBU shall be integrated in the OCORA architecture. A first approach has been defined.

INFO OCORA is an ongoing project. Future results from OCORA shall be taken into consideration to consolidate the interface needs in terms of frequency, latency, among other non-functional requirements.

Req#14 The outputs of this function shall meet the safety targets defined in the Preliminary Hazard Analysis based on a high-level approach of the overall CCS system architecture. The apportionment of hazards leads to a TFFR ≤ 5E-8/h.

INFO	Future safety analysis from RCA, OCORA projects shall be taken into consideration to expand the preliminary analysis and consolidate this data.
Req#15	In case compliance to Req#12 cannot be accomplished within the required safety requirement defined in Req#14, the Minimum and Maximum Safe Front End output shall as a conservative estimate comply to the safety requirement defined in Req#14.
INFO	Req#15 means that the true position shall always be bound by the confidence interval (i.e., Min and Max Safe Front End). And in challenging conditions where the accuracy requirements might not be fulfilled, the Min and Max Safe Front End interval shall continue to ensure compliance to the safety requirement Req#14.
INFO	The Minimum and Maximum Safe Front End shall be estimated as a confidence interval around the reported position (Estimated Front End), within which the front end of the train is located.

3.2.1.4 *Safe TU Along-track Acceleration*

Rationale	This function is required to determine the safe TU along-track acceleration used by the train protection.
Req#16	The TLOBU shall provide the Estimated TU Along-track acceleration and the Minimum and Maximum TU Along-track acceleration.
Req#17	The TLOBU shall be integrated in the OCORA architecture. A first approach has been defined.
INFO	OCORA is an ongoing project. Future results from OCORA shall be taken into consideration to consolidate the interface needs in terms of frequency, latency, among other non-functional requirements.
Req#18	The outputs of this function shall meet the safety targets defined in the Preliminary Hazard Analysis based on a high-level approach of the overall CCS system architecture. The apportionment of hazards leads to a TFFR ≤ 5E-10/h and consequently to a SIL4 function.
INFO	Future safety analysis from RCA, OCORA projects shall be taken into consideration to expand the preliminary analysis and consolidate this data.
NOTE	No performance requirements have been specified for this function.
INFO	The Minimum and Maximum Safe TU along-track acceleration shall be estimated as an interval around the reported along-track acceleration (Estimated TU along-track acceleration), within which the along-track acceleration of the train is bound.

3.2.1.5 *Track Selective Positioning*

Rationale The TrackEdge ID is used to locate the train. The move from trackside centric train localisation to an on-board centric train localisation requires the current TrackEdge ID of the train to be provided by the on-board system to the trackside systems and the on-board train protection.

Req#19 The TLOBU shall provide the TrackEdge ID and the Status of track selectivity determination.

Req#20 Valid outputs for the Status of track selectivity determination are as follows:

Valid output	Description of the output
Unknown	No TrackEdge ID can be provided by the TLOBU e.g., during start-up phase of the TLOBU.
Safe to use	TrackEdge ID output by this function complies with safety target defined in Req#22.
Not safe to use	TrackEdge ID output by this function is unable to comply with safety target defined in Req#22.

Req#21 The TLOBU shall be integrated in the OCORA architecture. A first approach has been defined.

INFO OCORA is an ongoing project. Future results from OCORA shall be taken into consideration to consolidate the interface needs in terms of frequency, latency, among other non-functional requirements.

Req#22 The outputs of this function shall meet the safety targets defined in the Preliminary Hazard Analysis based on a high-level approach of the overall CCS system architecture. The apportionment of hazards leads to a TFFR ≤ 5E-10/h and consequently to a SIL4 function.

INFO Future safety analysis from RCA, OCORA projects shall be taken into consideration to expand the preliminary analysis and consolidate this data.

INFO The function is expected to determine TrackEdge ID and Status only using digital maps and onboard sensor data input to this function.

INFO The output “Status of the track selectivity determination” is only defined for evaluating the performance of the function in the CLUG project.
The safety reactions necessary when a future standalone failsafe TLOBU outputs ‘Not safe to use’ flag is outside the scope of CLUG project.

3.2.1.6 *Actual Movement Direction*

Rational The determination of the TU actual movement direction is required by the train protection, the ATO.

Req#23 The TLOBU shall provide the TU Actual Movement Direction.

Req#24 Valid outputs for the actual movement direction of the train are “nominal”, “reverse” and “unknown”.

Req#25 The TLOBU shall be integrated in the OCORA architecture. A first approach has been defined.

INFO OCORA is an ongoing project. Future results from OCORA shall be taken into consideration to consolidate the interface needs in terms of frequency, latency, among other non-functional requirements.

Req#26 The outputs of this function shall meet the safety targets defined in the Preliminary Hazard Analysis based on a high-level approach of the overall CCS system architecture. The apportionment of hazards leads to a TFFR ≤ 5E-10/h and consequently to a SIL4 function.

INFO Future safety analysis from RCA, OCORA projects shall be taken into consideration to expand the preliminary analysis and consolidate this data.

3.2.1.7 *Health flag*

Rational The system diagnosis is providing a health flag used by consumers of the TLOBU.

Req#27 The TLOBU shall provide a health flag with every system output.

Req#28 Valid outputs for the health flag of each function are “OK” and “NOT OK”.

The health flag shall be set to “OK” when the system function of the TLOBU is working as expected.

The health flag shall be set to “NOT OK” when the system function of the TLOBU is not working as expected and the output shall be considered erroneous.

Req#29 When the TLOBU outputs are correctly declared as invalid, the effect shall be a detrimental impact on availability, not safety.

Req#30 The outputs of this function shall meet the safety targets defined in the Preliminary Hazard Analysis based on a high-level approach of the overall CCS system architecture. The outputs of this function shall meet the safety targets to the function accompanying all other TLOBU outputs.

INFO Future safety analysis from RCA, OCORA projects shall be taken into consideration to expand the preliminary analysis and consolidate this data.

3.2.2 Requirements for other functions non-safety related functions

This chapter presents requirements of functions which the safety properties are not yet determined. Some of them address needs of new functions (e.g. perception, incident management, obstacle detection…). Results from the overall system architecture analysis shall be taken into consideration to derive the safety constraints on the TLOBU.

Rationale Data required are used by the ATO, the perception system, the TMS, the perception and incident management, the passenger information.

Req#30 The TLOBU shall provide the Estimated Front End Position and the Formal accuracy of the Estimated Front End Position.

Req#31 The TLOBU shall provide the Estimated TU Speed and Formal accuracy of the Estimated TU Speed.

Req#32 The TLOBU shall provide the Estimated TU Along-track acceleration and Formal accuracy of the Estimated TU Along-track acceleration.

Req#33 The TLOBU shall provide the Estimated TU 3D Position and the Formal accuracy of the Estimated TU 3D Position.

Req#34 The TLOBU shall provide the Estimated TU 3D Velocity and the Formal accuracy of the Estimated TU 3D Velocity.

Req#35 The TLOBU shall provide the Estimated TU 3D Acceleration and the Formal accuracy of the Estimated TU 3D Acceleration.

Req#36 The TLOBU shall provide and Estimated Yaw, Pitch and Roll Angles and the Formal accuracy of the Estimated Yaw, Pitch and Roll Angles.

Req#37 The TLOBU shall provide the Estimated Yaw, Pitch and Roll rates and the Formal accuracy of the Estimated Yaw, Pitch and Roll rates.

4 SYSTEM DESCRIPTION

Two solutions have been designed during the project:

- "Solution A" led by Airbus, driven by the safety requirements as well as targeting full compliance to rail requirements. The TLOBU architecture is based on Solution A, hence Figure 4-1 illustrates the TLOBU functional architecture and in particular the Solution A architecture.

- "Solution B" led by Naventik, which is an adaptation of Naventik automotive Pathfinder product to the rail context. This solution focuses mostly on the fusion filter, re-using the other functions from Solution A.

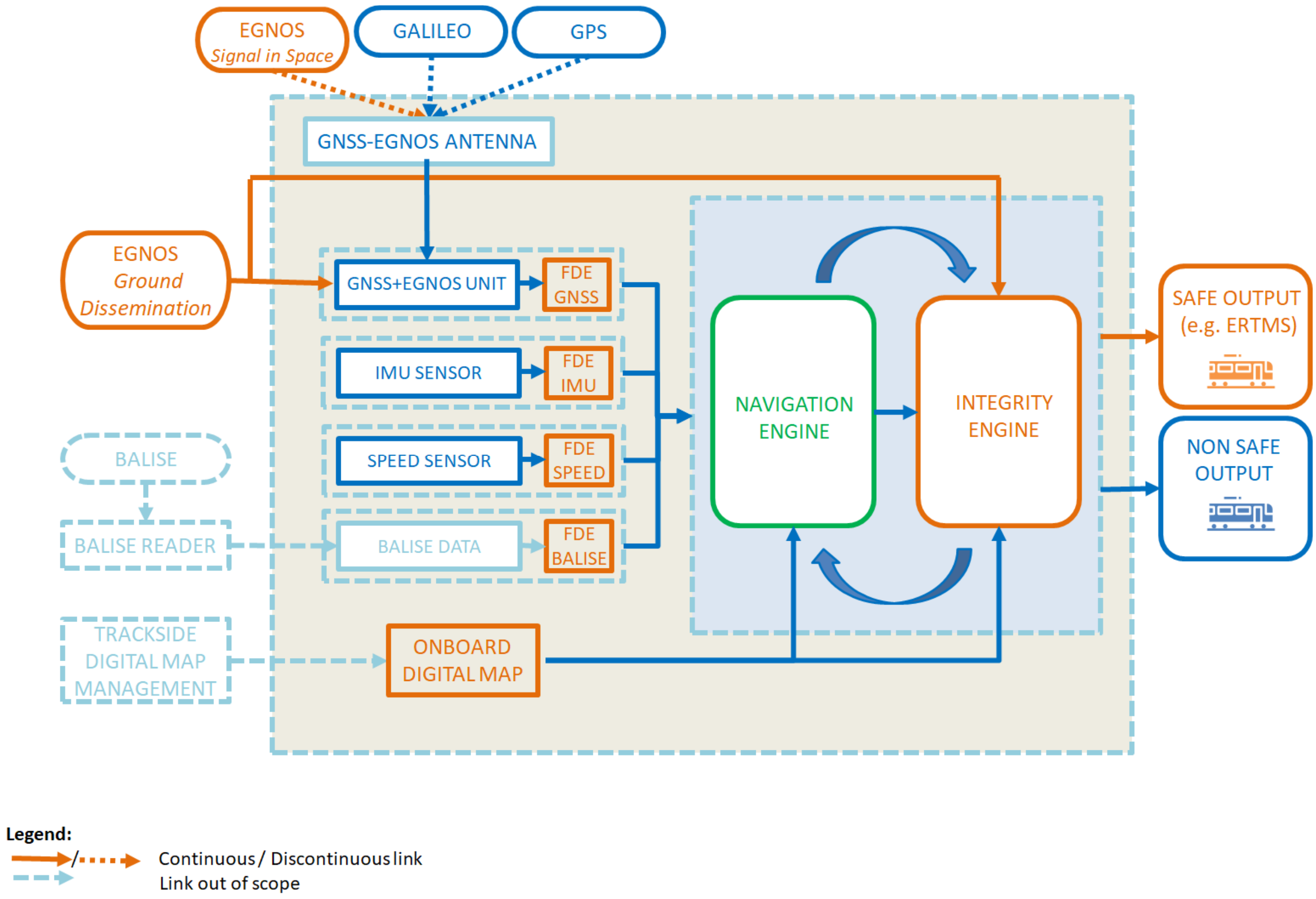


Figure 4-1: CLUG Train Localisation Unit functional diagram

The two solutions have similarities described in the subsections below:

- They use the same set of sensors
- They have the same TLOBU **safe** requested outputs with their integrity (Safe Confidence Intervals)
- They use similar strategy targeting fusion / tight coupling via Kalman filters
- Additional unsafe data are implicitly available: 3D position/velocity/acceleration, attitude angles & rates (Yaw, Pitch & Roll)

4.1 ON-BOARD LOCALISATION SYSTEM ARCHITECTURE

4.1.1 Solution A

The Solution A functional architecture has been used to define the TLOBU functional architecture and is therefore described on Figure 4-1.

The TLOBU is split into 2 parts:

- Sensors’ part: representing all data that are injecting into the TLOBU algorithms for localisation and safety purpose;
- Algorithms’ part: representing all data evaluations by data FDE (Fault Detection and Exclusion of sensors data), transformations and computations including integrity of the outputs to provide TLOBU outputs in real time.

NOTE: Real-time implementation of the solution was not in the scope of the CLUG project, therefore the sensor data are recorded using different test trains and are injected into the TLOBU interface for offline processing.

It is composed of:

- "Sensors" - are grouped as "sensors" the following physical components pre-imposing the functional architecture:
  - GNSS+EGNOS unit: that receive Galileo and GPS signals via a roof antenna when non masking and augment EGNOS data (via SiS and/or via ground network);
  - IMU (inertial unit): that measure and provide acceleration and angular rate (attitudes);
  - Speed data (e.g., tachometer or equivalent): this is not to be confused with “SIL4 odometer system” that embed several speed sensors.
  - Balise data reader: Even CLUG aims to reduce the use of trackside balises for reference points, this sensor is kept as potential sensor to be used by the localisation and integrity engine pending reached performances in real tests and environments.
  - Digital map data: that is used to map match 3D position data to a linear movement along the current TrackEdge, to enable the track selectivity algorithm and to bound errors of the inertial sensors.

- Data Fault Detection and Exclusion (FDE): at sensors level and at fusion level, these functions aim to detect and filter the faulty data before their uses into the fusion algorithms. They are ventilated into sensor function and just before system algorithms.

- "Fusion localisation and integrity engine" containing algorithms:
  - Sensors’ fusion algorithms that compute localisation parameters and track selectivity,
  - Integrity algorithms that compute the confidence intervals and integrity data associated to the estimated localisation parameters (protection levels).

4.1.2 Solution B

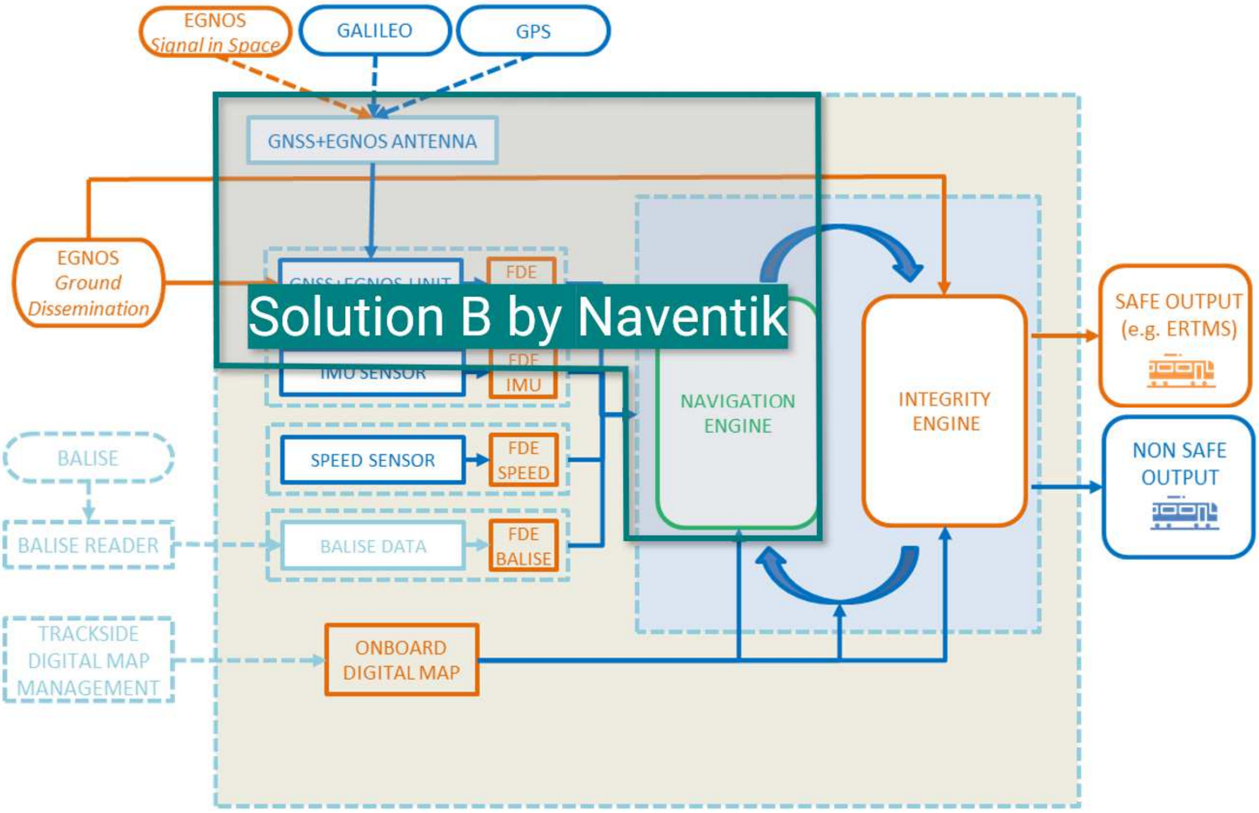


Figure 4-2: « Solution B » Train Localisation Unit functional scope

The Solution B for the TLOBU is composed of a sensor layer, GNSS receiver (radio frequency frontend and baseband processor), a positioning engine and train specific components, such as the Digital map and the track matching algorithm. The sensor layer summarizes all external and internal sensors and interfaces like GNSS radio frequency front end with antenna, inertial and odometry sensors, correction data and infrastructure data (track ID and maps). As for Solution A, balise reader data can also be used to reach the required performance. A subset of the sensors is used to aid the GNSS receiver baseband processing and another subset of the sensors is used to be integrated with the train specific components. From functional perspective, the receiver is decomposed into the frontend and the baseband processing block (GNSS SDR) and positioning engine (tightly coupled GNSS filter). Thus, further requirements can be implemented to signal processing at receiver level. Also, error detection is integrated on signal level. This includes multipath detection measures and consistency checks. All train specific adaptions and sensor integration are done within the "Track specific calculations" block. This includes map matching in terms of shortest distance to the track, speed sensor integration, track ID integration and error detection/consistency checks.

The following block diagram presents more details in terms of functions, I/O flux, and the breakdown of the localisation and integrity engine:

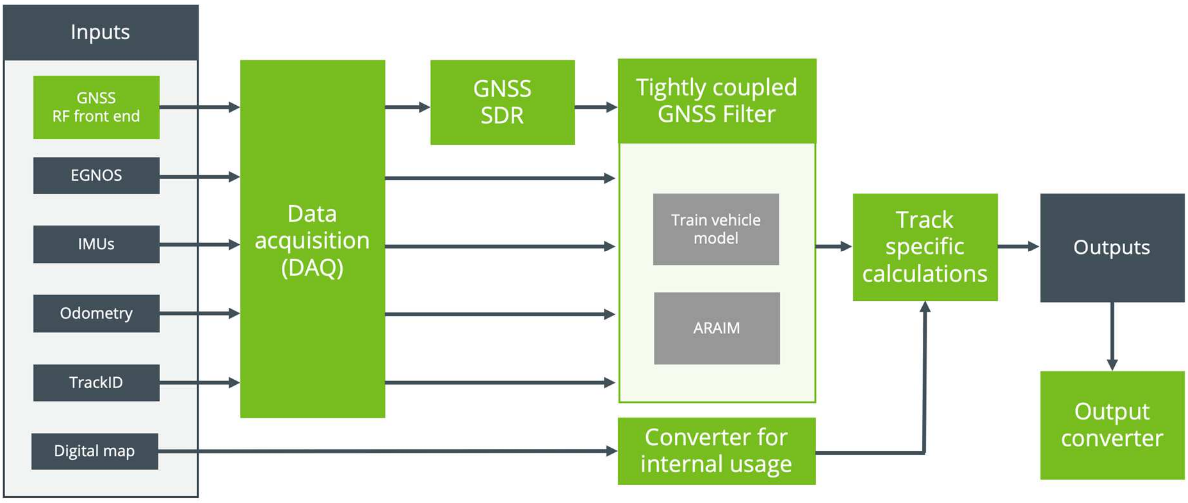


Figure 4-3: Architecture of TLOBU Solution B.

Based on the architecture shown in Figure 4-2 the functionality of the solution spreads over several components. First, there is the **Data Acquisition** (DAQ) for the TLOBU Solution B. The DAQ is also designed to collect CLUG-specific input data and forward it to the localisation engine. The DAQ component acts as a common entry for all inputs except for the information from the digital map. These are translated into an internal format for further processing by means of an additional special converter. The next component is the **Software Defined Radio (SDR)** component. Figure 4-3 provides more detailed insight into the SDR component architecture of TLOBU Solution B.

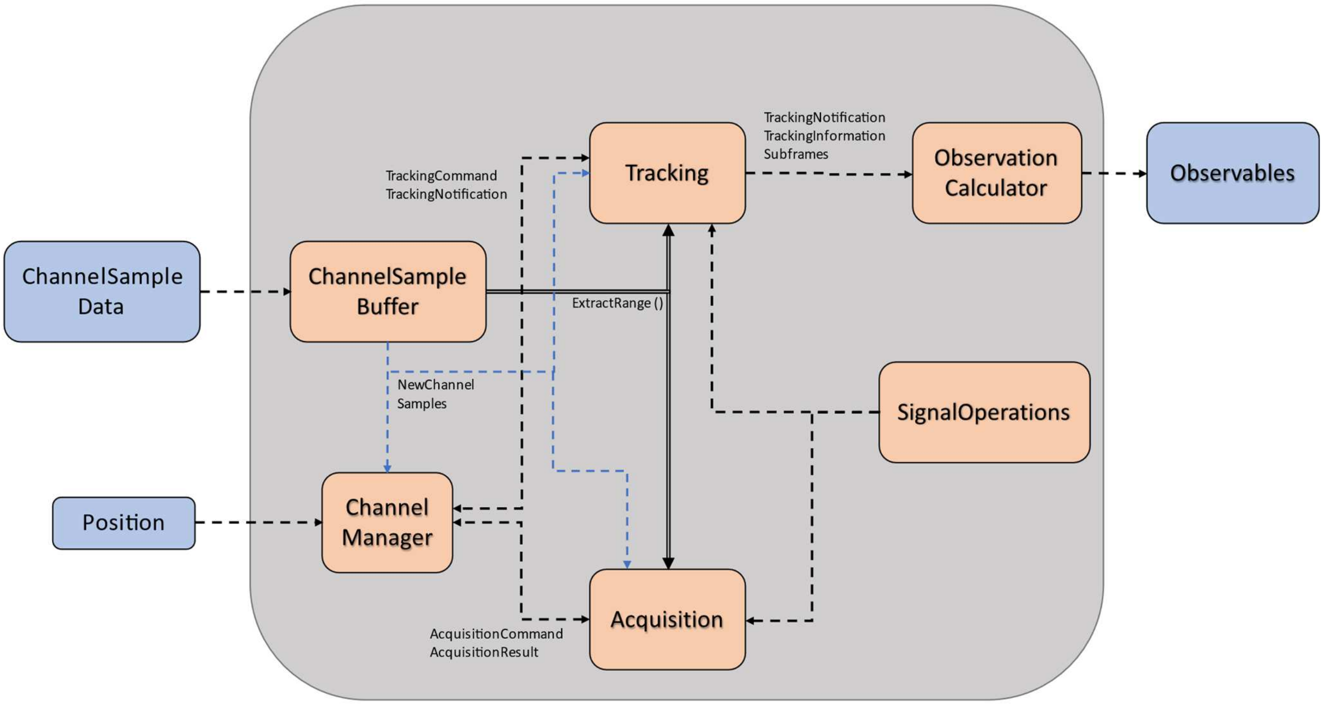


Figure 4-4 Detailed View SDR

The digitized RF data of the GNSS frequency band reaches the SDR component from the DAQ module as a data stream and is first temporarily stored in the ChannelSampleData block. The channel manager controls and starts the satellite acquisition on the L1/E1 band. Once a satellite acquisition was successful a handover to the signal tracking will be done. To perform the very computationally intensive signal processing operations of tracking and acquisition the GPU hardware acceleration provided by the CUDA framework is utilized. The signal tracking

generates continuously observations. After that, the baseband processing - which is described in detail in D3.1.3 section 2.4.3 (GNSS baseband processing) - the observables will be forwarded to the localization engine (tightly coupled GNSS filter), that computes the positioning solution including further information such as correction data or movement/rotation data of the vehicle. The calculated position, time and velocity information is fed back into the *Channel Manager* to make the acquisition of satellites more effective. Only visible satellites are searched for using the own position and the almanac, and the Doppler search window is reduced depending on the current speed.
The remaining components of TLOBU solution B are explained in Table 4-1.

Component	Functional description
Data acquisitions (DAQ)	Acquires input data and converts it into common internal format
GNSS SDR	GNSS base band processing to generate GNSS raw data
Tightly coupled GNSS Filter	The Kalman filter calculates the position using ARAIM techniques and a towing vehicle model. This component is also responsible for integrity and consistency. It combines both the localization and integrity engines and fuses vehicle motion data with GNSS measurements.
Track specific calculations	Calculates the other required outputs as described section 3.2.
Map converter for internal usage	Converts the map into a more efficient internal data format (C++ array)
Output converter	Converts the outputs into the common output format defined in Deliverable (D2.5 Preliminary Architecture Definition)

Table 4-1: Component usage

The central component for generating a position solution is the Tightly Coupled GNSS Filter. The raw GNSS data from the SDR component is combined here with motion and rotation information from the vehicle. In addition, the localisation engine includes a correction processor that monitors the integrity and availability of the correction data from EGNOS. The localization engine also includes an integrity engine based on ARAIM algorithms. If validation is successful, a protection level is calculated and combined with the position data.

4.2 SYSTEMS INTERFACES

The TLOBU is the logical block whose main responsibility is to determine and provide localisation information of the train to other on-board systems. On-board systems in turn consume the localisation information and may pass it to further systems (e.g., trackside systems as part of position reports [SS026]). This section describes the internal and external interfaces in terms of received and provided information of the functional box of TLOBU which represents the algorithms' part composed of positioning and integrity engines. It is also called Vehicle Locator (VL) to be in line with other projects (e.g., RCA and OCORA). Figure 4-6 gives an overview of the full defined interfaces of the VL in the EUG/LWG concept architecture that combines major on-board localisation architectures from current and previous initiatives and innovation projects (e.g., CLUG, OCORA, RCA), in order to create a single reference architecture. As depicted in Figure 4-6, the VL is surrounded by different elements grouped by their influence into:

- **Sensor Data**: Data for the localisation of the train. These data can come from elements deployed on tracks such as balises, other on-board equipment that can acquire data from the environment or the kinematic characteristics of the vehicle itself.
- **Supporting Information**: Information not directly translatable into localisation information but needed to provide the desired output. This information will be used by internal VL processes to enable, improve, or validate localisation information (e.g. EGNOS…).
- **VL Output Consumers**: Grouping of on-board and trackside consumers of localisation information I.e. systems that require train localisation information to perform their own functions.
- **Generic Functions**: Generic functions common to every functional box (diagnostic, maintenance, and access control).

Based on RCA/OCORA interfaces, the VL internal interfaces are linked to the train-based sensor data such as odometry and IMU measurements. The VL external interfaces are related to track-based sensor, CCS supporting information, and other on-board user applications (VL Output Consumers and Generic Functions). In CLUG project, the external interfaces are simplified and not fully considered as in OCORA project at this study level as system integration into ERTMS/ETCS is not in the scope of the CLUG project.

Figure 4-5 presents the different CLUG TLOBU interfaces that can be put in relation of the OCORA interfaces on Figure 4-6.

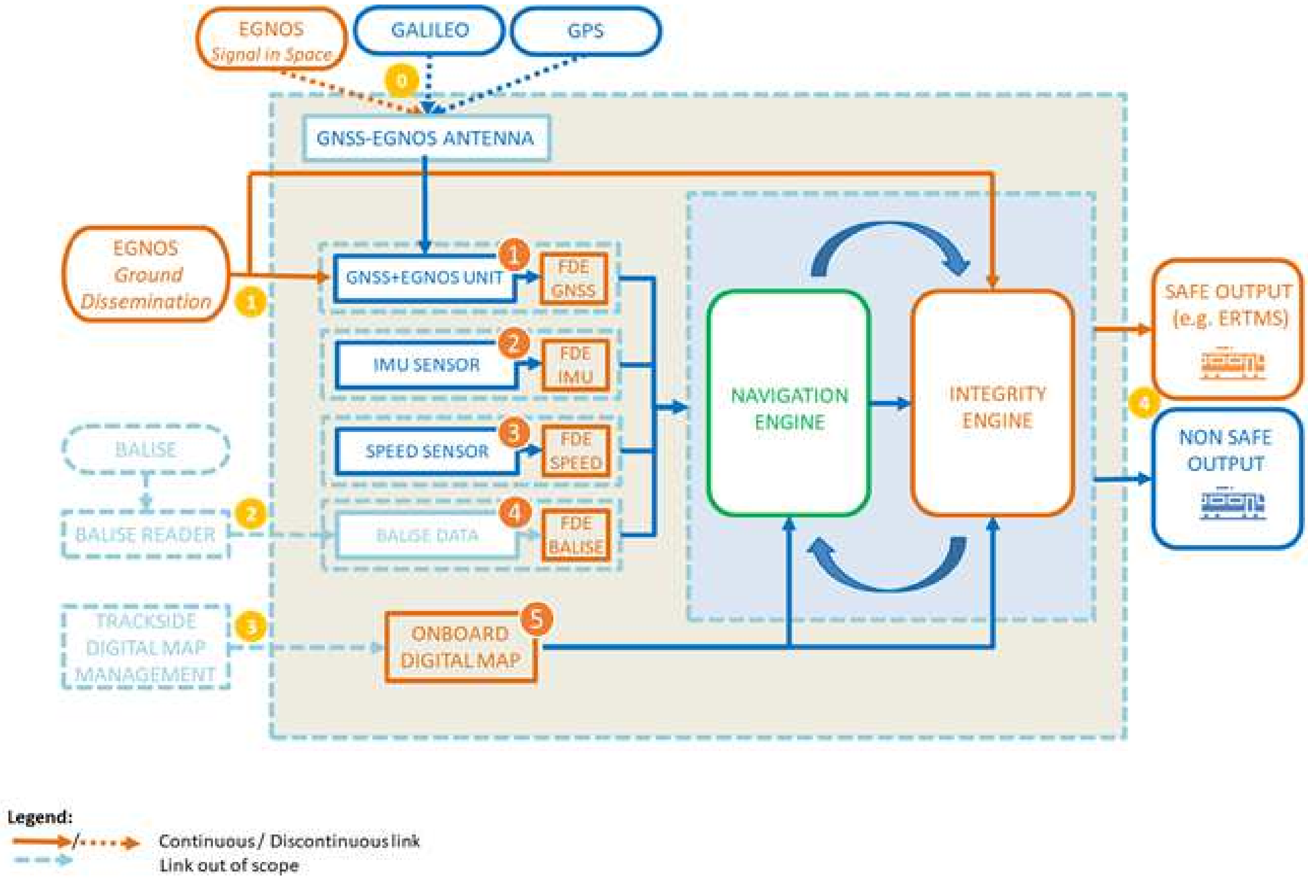


Figure 4-5: CLUG Train Localisation Unit functional diagram with interface numbering

Figure 4-6 presents the considered internal and external VL interfaces in CLUG with reference to RCA/OCORA interfaces.

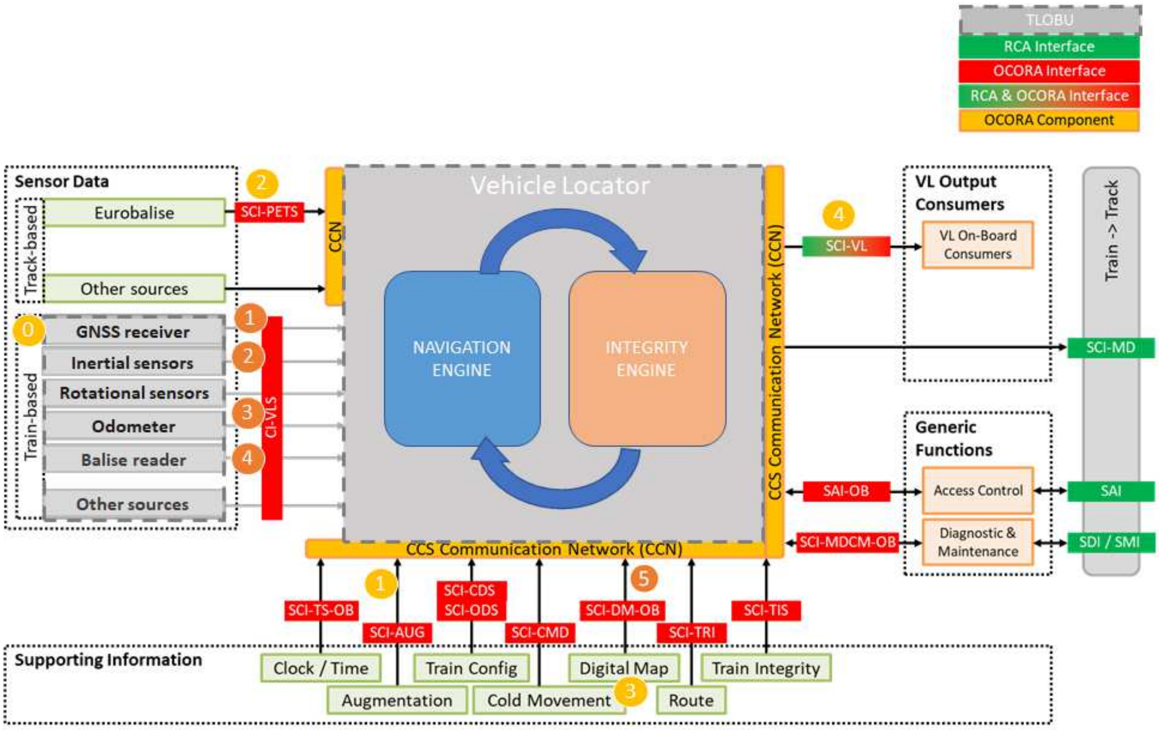


Figure 4-6 The considered RCA/OCORA interfaces in the CLUG project. Orange dots mark the internal interfaces. Yellow dots are external interfaces.

The complete CLUG interfaces list is discussed hereafter.

4.2.1 Internal Interfaces

ID	Device	Input	Outputs	Additional Requirements
1	GNSS receiver	GPS signal in space, Galileo signal in space, EGNOS signal	Time (e.g., UTC) Raw GNSS data (e.g., pseudo range, Doppler) Telemetry data / navigation data FDE report, including quality indicators (e.g., lock indicators)	This device shall provide information about the availability of the hardware by different checks (power consumption, ASIC monitoring, …)
2	IMU	IMU configuration	Timestamps Angular rates Specific forces FDE report	This device shall provide information about the availability of the hardware by different checks (power consumption, CPU rate, ASIC monitoring, …) The IMU shall calibrate and filter the different impacts of temperature and vibration (on a specified range of frequency) according to the producer laboratory calibration test.
3	Speed sensor	speed sensor configuration	Timestamps Pulses per seconds	This device shall provide information about the availability of

			Speed FDE report	the hardware by different checks (power consumption, CPU rate, ASIC monitoring, …)
4	Balise reader	Balise configuration Time	Info from the balise telegram Time	This device shall provide information about the availability of the hardware by different checks (power consumption, CPU rate, ASIC monitoring, …)
5	Digital Map	Map	Map	The logical component on-board the train or the device storing the digital map should be able to perform health check and output diagnostic data to its consumers.

Table 4-2 Internal interfaces of the TLOBU.

All these sensors' inputs are provided to the VL through the SCI-VLS.

4.2.2 External interfaces

Ext-IF	External Interface Name	I/O Type	Brief Description
0	Ext-IF 0: Satellite Signal in Space	Input	GPS signal in space, Galileo signal in space, EGNOS signal
1	Ext-IF 1: EGNOS via TELECOM receiver (EDAS)	Input	Internet service offering ground-based access to EGNOS in near real-time. In addition to the GPS and Galileo signals, TLOBU can use EGNOS augmentation messages from geo-stationary satellites. These messages can be received either via the GNSS receiver or via a telecom receiver (internet service). Within the CLUG project, EGNOS augmentation messages will only be downloaded from an FTP server containing historical data. Note: At time of writing this document, EGNOS SiS (dissemination by Signal in Space) is Safety of Life for Aviation only (so not for rail) and EDAS (dissemination by Internet) is used for test or monitoring so not Safety of Life for any sector. CLUG assumes TLOBU full access to SBAS message being in future Safety of Life for rail, disseminated by a potential mix of Space dissemination and/or ground radio LTE ground dissemination. Studies regarding SBAS dissemination for rail and service are undergoing.
2	Ext-IF 2: Eurobalises data	Input	Data Telegram from Eurobalises and times of balise passages.

			Within the CLUG Project, the use of balise data is optional. The system highly relies on absolute positioning measurements obtained by GNSS/EGNOS.
3	Ext-IF 3: Trackside Digital Map Management	Input	Track topology and topography data used for sensor fusion provided by the trackside Digital Map Management system. Not represented in Figure 4-6.
4	Ext-IF 4: User Applications	Output	Location information such as train position, velocity (speed and direction of travel), acceleration, confidence intervals and a safety profile (SIL1 – SIL4) for safety-related applications. According to the different needs of the end user, there will be more than one Localisation Report.

Table 4-3 External interfaces of the TLOBU.

The TLOBU outputs safe localisation data in real time provided to the ETCS On-Board so referred to as EVC (European Vital Computer) with associated safety critical confidence intervals. In addition, non-safe localisation data, identical or derived from safe localisation data, are output for non-safety critical application such as travel information for passengers. Focus is made on the most critical safety parameters. The TLOBU safe and non-safe outputs are summarized here-below:

Generic data	Specific data	Output set 1 Freq: 5 Hz SIL4	Output set 2 Freq: 5 Hz SIL2	Output set 3 Freq: 10 Hz SIL: not determined	Output set 4 Freq: 20 Hz SIL: not determined
TrackEdge_ID	TrackEdge_ID	X	X	X	
TrackEdge Status	TrackEdge Status	X			
Reference Point	Reference Point	X	X	X	
Direction	Direction	X	X	X	
Timestamp	Timestamp	X	X	X	
1D Position	Distance to Reference Point	X	X	X	
	Confidence Interval	X	X		
	3σ standard deviation			X	
1D Speed	Speed	X		X	
	Confidence Interval	X			
	3σ standard deviation			X	
1D Acceleration	Acceleration	X		X	
	Confidence Interval	X			
	3σ standard deviation			X	

3D data	Position and standard deviation				X
	Speed and standard deviation				X
	Acceleration and standard deviation				X
Attitude angles & rates	Attitude angles & rates with standard deviation				X

Table 4-4 : Allocation of the localisation data to the output

The additional interfaces not presented in RCA/OCORA are the GNSS services represented by the GPS L1 & L5 and the Galileo E1 & E5a signals to be measured and data collected by the TLOBU and the EGNOS services broadcasted from space by two geostationary satellites (SiS). To augment the continuity of this collection, another EGNOS dissemination by ground network (e.g., LTE/3G/5G/GSM-R/Euroradio/FRMCS or other rail network) should prime from the space dissemination.

5 PERFORMANCES EVALUATION

5.1 SAFETY ANALYSIS

The Preliminary Hazard Analysis identifies a set of safety requirements for each function.
Then, RAMS analyses have been conducted for both solutions A and B (see chapter 4).
However, these analyses have been limited due to:

- Some functions have not been assessed during CLUG (e.g., the track selectivity function and the actual movement direction function).
- The TLOBU physical architecture (hardware and software solution) was out of the scope of the CLUG project targeting a Proof-of-Concept maturity; in addition, no values for the sensors regarding failure rate leading to erroneous data were set available. Worst case has been used for the analysis.
- Consequently, redundancies and independencies in terms of hardware and software architecture have not been studied and should be the object of further analyses to prevent single failure events.
- Evaluation of some complex algorithms as data fusion using Kalman filters is difficult to provide using traditional fault tree analysis.
- Reached Safety Level:
    - Solution A: some assumptions on probability failure of the sensors and of some modules, as sensor data FDE (Fault Detection and Exclusion), have been made to provide a quantitative evaluation of the TFFR (Tolerable Functional Failure Rate) which allow to reach SIL3 target for the core safety functions;
    - Solution B: probability failures have not been evaluated, so the results are based only on a qualitative analysis which allow to reach SIL2 target for the core safety functions.

However, these targets need to be consolidated by expanding the preliminary approach into the context of the RCA/OCORA architecture.
Therefore, the synthesis of the results for each solution presented in Table 5-1 shows that for some functions the expected safety requirements were not achieved at the CLUG project targeting a proof-of-concept maturity level. Future additional developments need to be carried out to enhance the safety and hence to meet the expected TFFR figures. This would include:

- more detailed analyses on the sensor models, on the data FDE modules, on the track selectivity function, and on the integrity engine;
- a completion once the physical architecture or a product solution is defined, so a more complete description of the hardware and software;
- and a completion depending on the EGNOS service (DFMC, EGNOS for rail…).

Requirement	Solution A - Safety demonstration results	Solution B - Safety demonstration results
Provide Minimum and Maximum Safe Front End Position		
Shall have a TFFR of 5E-10/h	in clear sky condition: TFFR of 2.24E-8/h In masked area: TFFR of 9E-9/h	Not quantified
Shall be designed to SIL 4.	SIL3, Single failure leads directly to Feared Events (Estimated Max Safe Front End Position out of the confidence interval)	SIL2, Single failure leads directly to Feared Events (Estimated Max Safe Front End Position out of the confidence interval)
Provide Minimum and Maximum Safe Accurate Front End		
Shall have a TFFR of 5E-8/h	See function **Minimum and Maximum Safe Front End Position**	See function **Minimum and Maximum Safe Front End Position**
Shall be designed to SIL 2	See function **Minimum and Maximum Safe Front End Position**	See function **Minimum and Maximum Safe Front End Position**
Provide Estimated Front End Position		
Shall be designed to Basic Integrity level	*No safety requirement*	
Provide TU Front End 3D Position		
For this function, no safety requirements will be defined in the scope of CLUG.	*No safety requirement*	
Provide Safe TU Speed		
Shall have a TFFR of 5E-10/h	in clear sky condition: TFFR of 1.94E-8/h in masked area: TFFR of 5E-9/h	Not quantified
Shall be designed to SIL 4.	SIL3, Single failure leads directly to Feared Event	SIL2, Single failure leads directly to Feared Event
Provide Estimated TU Speed		
Shall be designed to Basic Integrity level	*Not quantified*	
Provide TU Velocity		
For this function, no safety requirements will be defined in the scope of CLUG.	*No safety requirement*	
Provide Safe TU Along-track Acceleration		
Shall have a TFFR of 5E-10/h.	TFFR of 5E-9/h	Not quantified

Shall be designed to SIL4.	SIL3, Single failure leads directly to Feared Event	SIL2, Single failure leads directly to Feared Event
Provide Estimated TU Along-track acceleration		
Shall be designed to Basic Integrity	*Not quantified*	
Provide TU Acceleration		
For this function, no safety requirements will be defined in the scope of CLUG	*No safety requirement*	
Provide Yaw, Pitch and Roll Rates		
For this function, no safety requirements will be defined in the scope of CLUG	*No safety requirement*	
Provide System Diagnostics		
The validity flag when joined to the output of a function, shall have the same safety requirement as the function. Note the independency requirement shall apply when it is relevant.	*See other functions*	
Provide Yaw, Pitch and Roll Angles		
For this function, no safety requirements will be defined in the scope of CLUG	*No safety requirement*	

Table 5-1 Safety analyses results

5.2 ACHIEVABLE INTEGRITY PERFORMANCE WITH GNSS/SBAS ONLY SOLUTION

This section summarizes an appendix of the (CLUG, D3.3.1 - Peformance analysis report of the solution A 2022). It provides an estimation of the availability performances in position that an architecture **only based** on GNSS+SBAS would reach, computation based on the same models than those defined by ENAC and ADS for the solution A.

The context and made assumptions are:

- The SBAS data **are assumed 100% available at TLOBU inputs,** i.e., the safe dissemination of EGNOS data up to TLOBU is ensured without any failure whatever the terrestrial and/or spatial network chosen solution;
- The Galileo constellation is supposed complete, operational and 100% available (as defined in SPS performance ICD[4]);
- The GPS constellation is supposed complete, operational and 100% available (as defined in GALILEO OS SDD[5]);

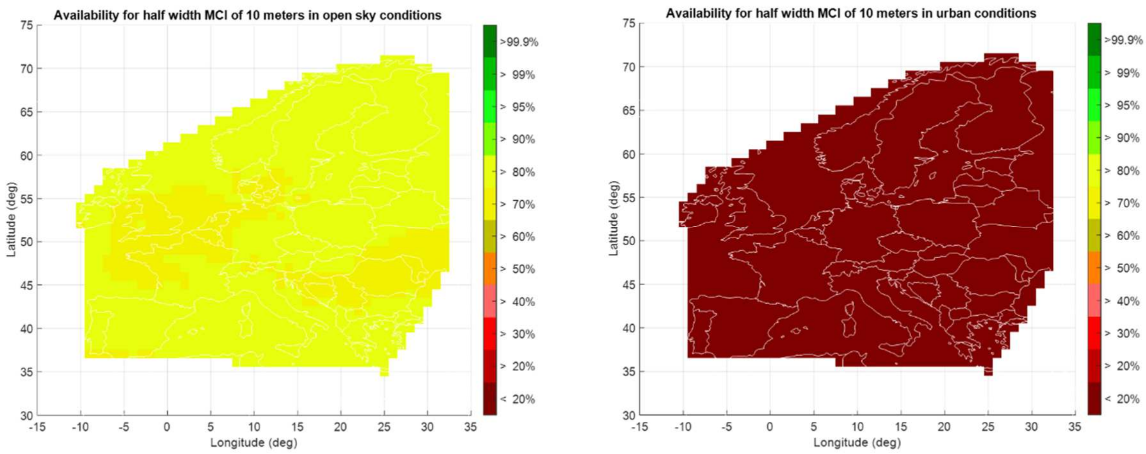
[4] https://www.gps.gov/technical/ps/

[5] https://www.euspa.europa.eu/newsroom/news/galileo-open-service-definition-document-version-12-now-available-download

- The **EGNOS associated integrity risk is 1E^{-7}/150 seconds (2.4E^{-6}/hours) when CLUG TLOBU is requested at 5E^{-10}/hour** in (CLUG, D2.4 - Preliminary Hazard Analysis and Safety Requirements 2020); so, integrity augmentation by other means is requested.
- This section is concentrated on the values of the position half MCI at 10m (resp. speed half MCI at 2km/h) requirements in (CLUG, D2.3 - High Level System Requirements 2020) at speed <36km/h (resp. <30km/h).

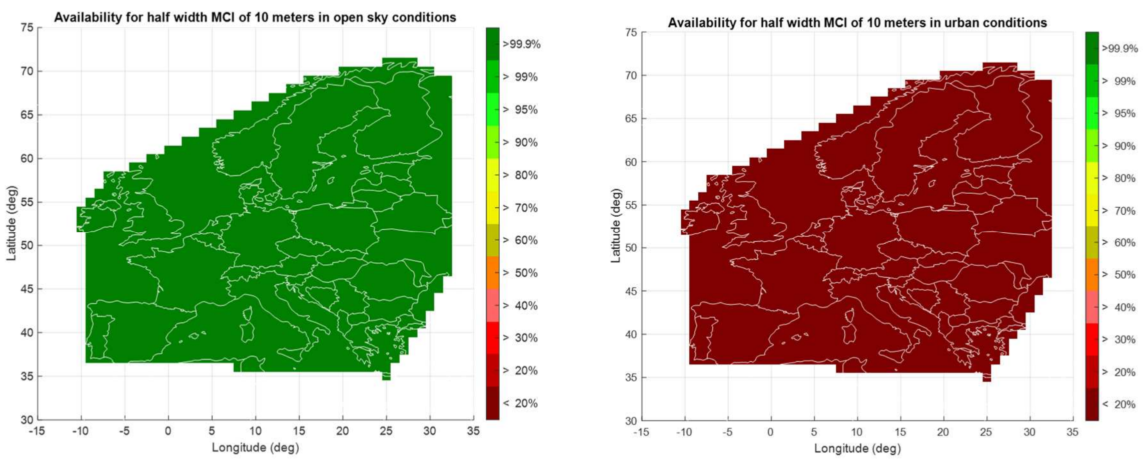
Results:

EGNOS V3.1 Single Frequency (only GPS augmentation), or EGNOS V2 offering lower performances: a positioning solution **only** using GNSS/EGNOS Single Frequency is not able to provide an acceptable availability (up to 70% max) due to the few numbers of GPS satellites against the impact of the train local environment whatever from in open sky to urban conditions:



Figures 5-1 Availability of EGNOS V3 SF for a half width MCI of 10m in open sky and in urban visibility with train local signal distortion and masking area

EGNOS V3.2 Dual Frequency Multi Constellation (GPS and Galileo augmented): a positioning solution **only** using GNSS/EGNOS DFMC is able to provide an acceptable availability only in clear sky (like for aviation) even better nevertheless:



Figures 5-2 Availability of EGNOS DFMC for a half width MCI of 10m in open sky, in sub-urban, and in urban visibility with train local signal distortion and masking area

Conclusion: no solution only based on GNSS+EGNOS, even DFMC, does allow to comply with the required half confidence interval “CI<MCI” in a sufficient availability performance.

The use of multiple sensors is mandatory to offer sufficient availability with integrity within required position accuracy.
Other simulations for performance in **speed** conducted to this similar outcome.

5.3 SOLUTION A PERFORMANCE

Based on the availability, integrity, confidence intervals… definitions recalled in §2.1, the following performance are assessing in 2 different ways per solution leaders:

5.3.1 Safety performance

This section reports a preliminary performance analysis of the **TLOBU solution A** designed by **Airbus** assessing the **achievable safe performances with respect to the required Mission Confidence Interval for operations values (MCI)**, specified by the railway operators in the WP2 (CLUG, D2.3 - High Level System Requirements 2020), and based on ENAC and Airbus defined method.
This study assumes SBAS augmentation is performed using the upcoming EGNOS DFMC service, the non-use of balises even they may be required in some locations where access to GNSS and EGNOS is insufficient. Focus is made on the position and speed confidence intervals, under the following availability and integrity objectives, following this preliminary approach:

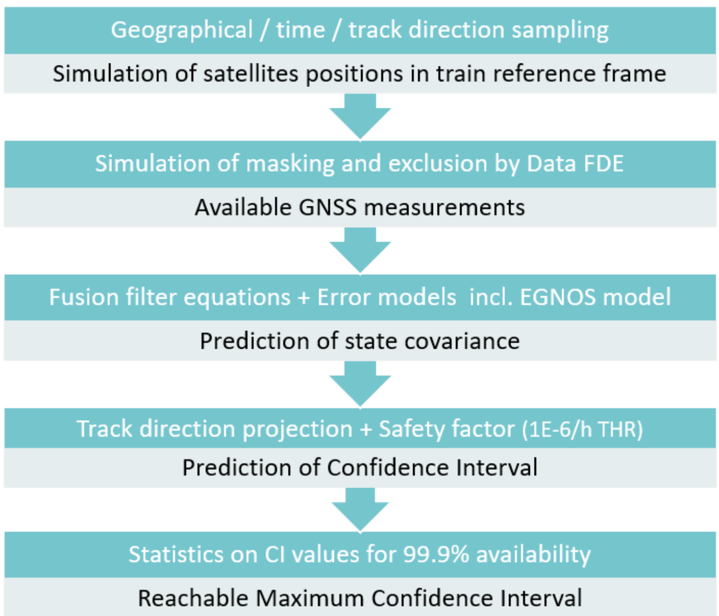


Figure 5-3 : Solution A model approach

Behavior of CI estimate
GNSS measurements combined with map matching enable the estimation of along-track absolute position. IMU and speed sensor data provide relative position information and enable the estimation of the train speed, being more a speed relative value as the integration of the IMU acceleration measurements. GNSS can also contribute to the train absolute speed estimate by pseudo range and Doppler measurements.

When the train moves along its route, the computed Confidence Intervals on position and speed will evolve depending on the number and geometry of available GNSS satellites and on the train direction. Confidence Interval values also depend on the IMU bias performances, but these ones are assumed not to vary significantly in time unlike GNSS availability. The tight-fusion algorithm is a continuous process that we can assume to remain in a nearly-converged state after the initialisation phase, because the context does not change quickly with time even for high-speed trains. The factor that changes most quickly is the satellite availability due to local environment effects impacting the receptiveness of GNSS signals and data.

When a large number of GNSS satellites is available, we can expect a small Confidence Interval, fluctuating with the geometry of GNSS pseudo-ranges. The CI may increase (possibly significantly and beyond the MCI requirement) due to the loss of several satellites from loss of visibility, masking by environment, from system unavailability causes or from exclusion by a barrier protecting against feared events like multi-path.
When GNSS is not available or almost all satellites are discarded, no absolute localization data is available, the TLOBU will continue to provide safe position and speed, with behaviour equivalent to dead-reckoning based only on inertial and speed sensors (IMU and tachometer). In this configuration, Confidence Intervals will increase with time (at a pace mainly driven by the IMU performances). When GNSS data is recovered, the tight-fusion algorithm will converge back to smaller Confidence Intervals.

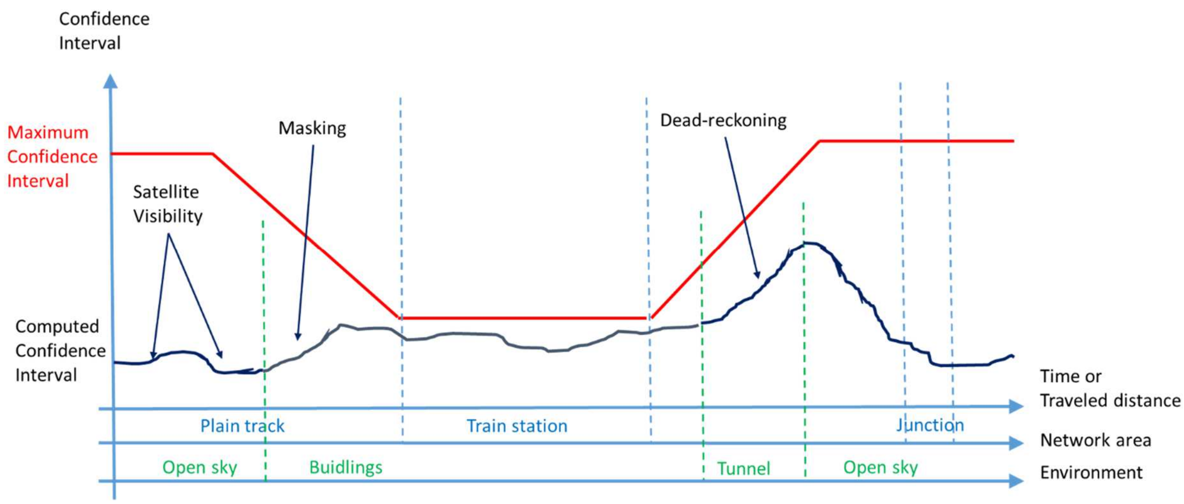


Figure 5-4 : Confidence Interval along a train journey (illustrative)

Figure 5-4 illustrates the Confidence Interval behaviour along a sample train journey. The illustrated required half-Maximum Confidence Interval (red curve) depends on the train speed (hypothesis in the current CLUG study). The actual Confidence Interval (black curve) is low when the train runs in open sky, fluctuating depending on the varying number of visible satellites, and increases to a higher stable value when in buildings surrounding, then increasing faster when in a tunnel following the IMU deviation model. The TLOBU is formally available with respect to the MCI requirements when the black curve is below the red curve.

TLOBU "CI<MCI Availability" requirement
Once the confidence interval computed and compared to MCI, a targeted "CI<MCI Availability", as defined in section §2.1, has been defined following a requirement from (ERTMS/ETCS. « RAMS Requirements Specification Chapter 2-RAM » 1998):

The probability of having delay caused by ERTMS/ETCS failures shall be lower than 0.0027.

Understanding of that requirement is that the probability that information from ERTMS/ETCS induces a delay of the train trip should be lower than 0.0027 due to:

- ERTMS/ETCS failure;
- Failure of the communication link between on-board and track-side;
- The confidence interval provided by TLOBU is non-compliant [CI > MCI] or not available;

Preliminary budget allocation of 0.0027 has been equally distributed between these three causes so the probability for TLOBU part (third bullet) is 9.10^{-4} giving this **"CI<MCI Availability" requirement of 99.9%** of time.

Note: This availability figure doesn't take into account the impact on the operation (induced delay due to the TLOBU), it is therefore not the operational availability.

Estimation of half-MCI corresponding to desired availability

For each combination of environmental conditions (open sky, suburban, urban), Confidence Intervals achievable values have been estimated for:

- 848 users' locations spread over Europe landmass
- 577 different dates
- 6 different track directions (every 30° from 0° to 180°)

This represents nearly 3 million simulated cases for each of the 30 {environment+GNSS_data_exclusion+σ combinations}.

The half-MCI for which the availability is 99.9% is the half-CI value for which 99.9% of the simulated cases half-CIs are lower than this value.

Figure 5-5 shows an example of a half-CI statistical distribution for **position** in one particular combination. Similar distributions have been observed for other combinations and also for **speed**.

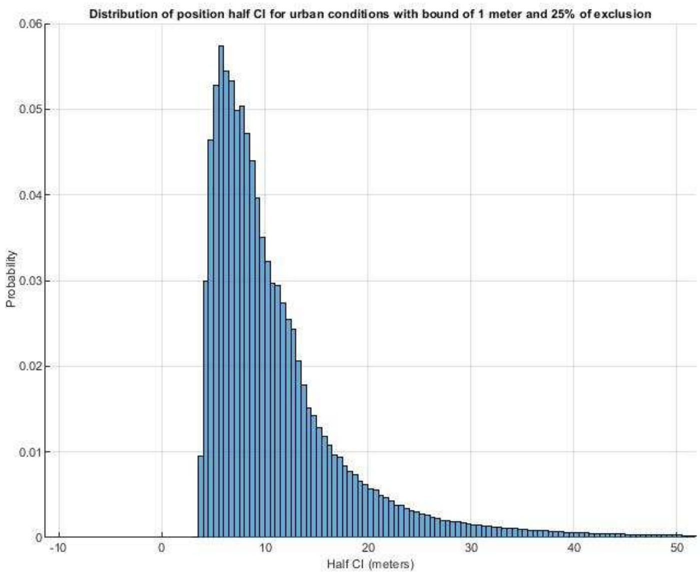


*Figure 5-5 : Statistical distribution in **position** of half-CI values for Urban, 25% exclusion and σ=1m*

Here below other examples of a half-CI statistical distribution for **position** at a given specific user location (near Toulouse) over dates and track directions, in order to check that this distribution shape is very similar to the global one over all user locations above:

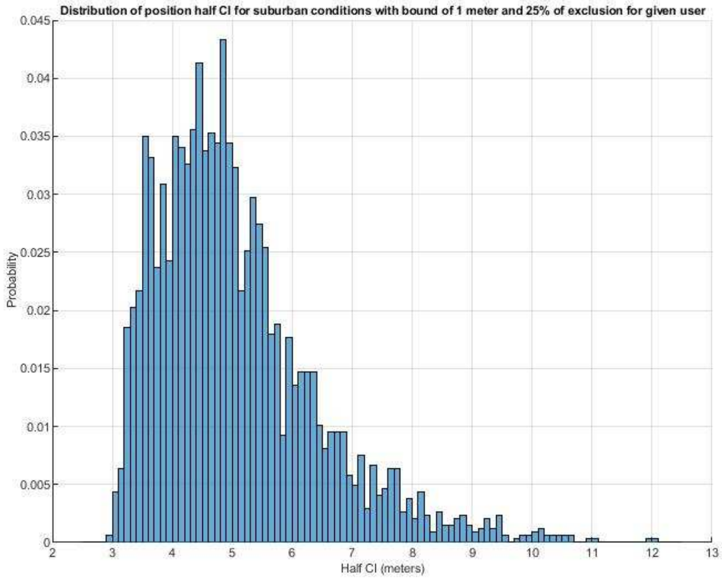


*Figure 5-6 : **Position** statistical distribution of half-CI values for Suburban, 25% exclusion and σ=1m for a specific user location (near Toulouse)*

Another one for **speed** at the same specific user location (near Toulouse):

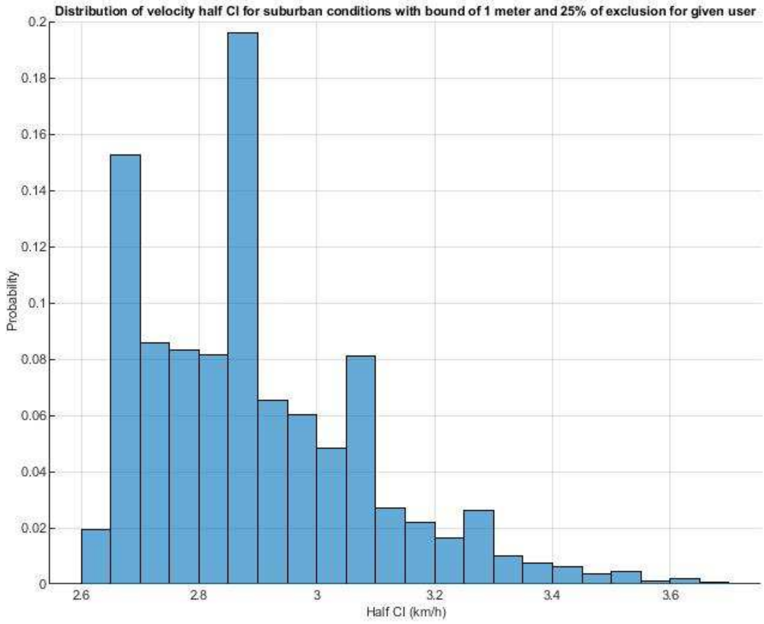


*Figure 5-7 : **Speed** statistical distribution of half-CI values for Suburban, 25% exclusion and σ=1m for a specific user location (near Toulouse)*

Then over Europe, the next figure shows the geographical variations of **position** half-MCI values for 99.9% availability, i.e., at each user location. Values are globally quite homogeneous over Europe. Some spots with atypical values can be observed, that could be analysed in further studies.

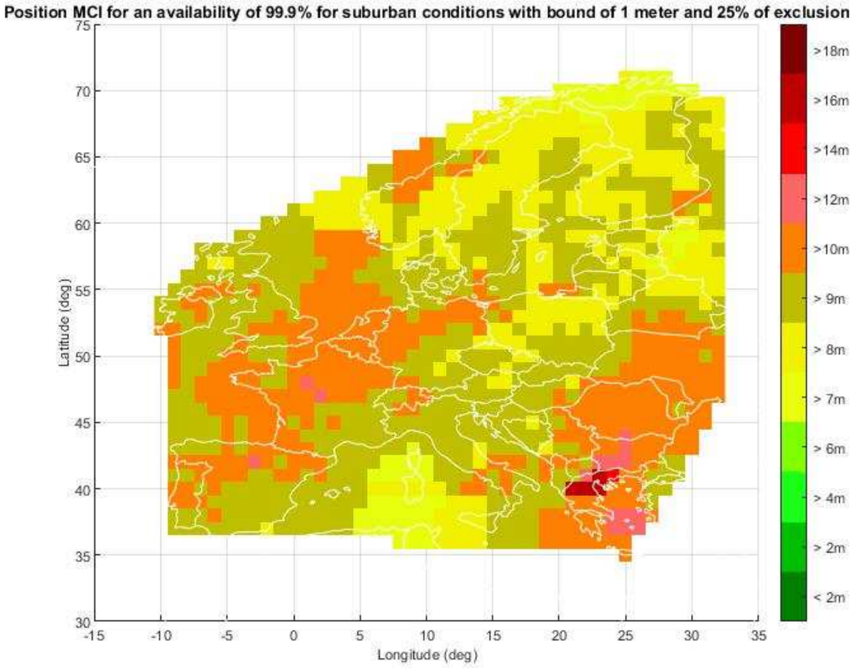


*Figure 5-8 : Geographical distribution over Europe of **Position** half-MCI values for Suburban, 25% exclusion and σ=1m*

And the same for **speed**:

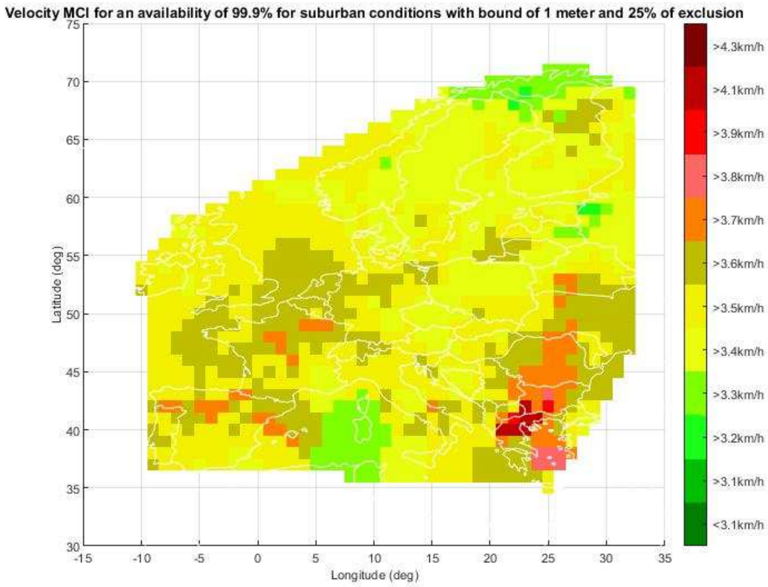


*Figure 5-9 : Geographical distribution over Europe of **Speed** half-MCI values for Suburban, 25% exclusion and σ=1m*

Figures below illustrate synthetically the results, for **position** half-MCI and **speed** half-MCI at 99.9% availability (i.e. CI<MCI). For each environment conditions, Open sky, Suburban and Urban, for different values of FDE exclusion rate, the vertical extension of values of the half-MCI correspond to the different values of residual range error σ from 0.5m to 5 m.

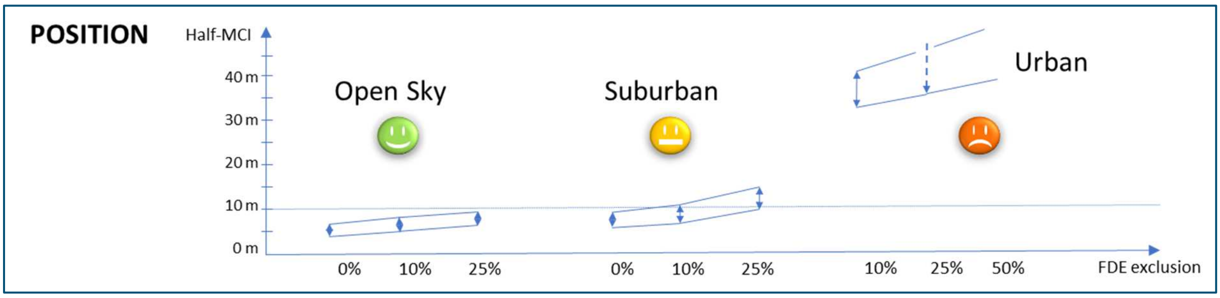


Figure 5-10 : Position Half MCI expected performance at 99.9% availability

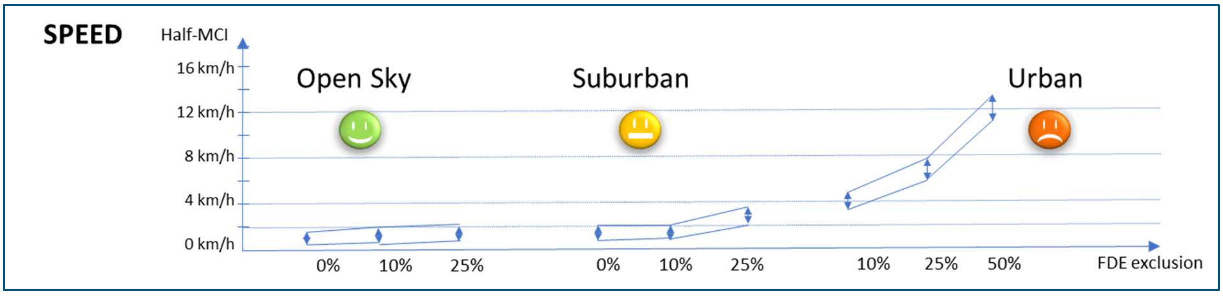


Figure 5-11 : Speed Half MCI expected performance at 99.9% availability

As a summary, the **TLOBU using EGNOS DFMC** would be compliant to MCI requirements (for 99.9% of time) in Open sky for all speeds, partially in suburban conditions, and unlikely in urban environments. Several assumptions have been made that should be confirmed or adjusted by further studies to allow more precise conclusions. Most of these assumptions or approximations lead to optimistic results.

Within the frame of the CLUG TLOBU design and still using EGNOS DFMC service, in specific area where reaching the desired level of MCI performance is not achievable due to insufficient GNSS measurements availability (i.e. in suburban or urban environments), performance can be improved by the two following means:

- Placing balises in these specific areas, that will allow to reduce the computed CI;
- Using a higher grade IMU, that will allow to reduce the distance between balise(s) and GNSS access in these areas.

These two physical architecture improvements are local to the area deterministic topology.

The overall objective of rail operators is to reduce as much as possible the number of balises. To reach that objective, an **enhanced EGNOS for Rail service**, such as proposed in (CLUG. (2020). D3.4 - GNSS Augmentation Needs for Rail.), would certainly be a major contributor in achieving the Train Localization performance targets on a wider scale with minimal trackside infrastructure.

5.3.2 Accuracy performances on real data

The following plots show the speed and horizontal position errors produced by the algorithm of solution A compared to the respective data from the Ground Truth over the lines covered by the Domino train in Switzerland.

5.3.2.1 *Ground truth generation*

The Domino train ground truth is generated using the SBB track map data, the Eurobalise reader to detect precisely the localisation of the balises accurately known, and several odometers (wheel tachos and higher end speed sensors) to accurately determine the speed of the train in between balises. A process has been set up to calibrate the sensors and compute in post-processing the accurate position of the train over the tracks.

This process however depends on the quality of the track maps. Experience has shown that maps are not always updated on a daily basis, track changes might only be included in maps a significant time

after the have been performed trackside, leading to errors in the map and notably wrong balise position over the tracks. This required supplementary debugging to identify the map errors and remove or flag them.
Unfortunately, some errors are still remaining so far, leading to position error artefacts in the performance results.
This process of definition of the ground truth also has some limitations as it cannot produce attitude reference. It will have to be complemented in the future to produce also attitude.

5.3.2.2 *Solution A position and velocity accuracy performance*

The analysis has been performed on the following sensor set:

- GNSS measurement (E1 and L1 Pseudodistance and Dopplers) from a ublox F9P receiver
- IMU measurements from an ADIS 16545 IMU sensor
- Tachometer measurements from a Hasler wigan sensor.

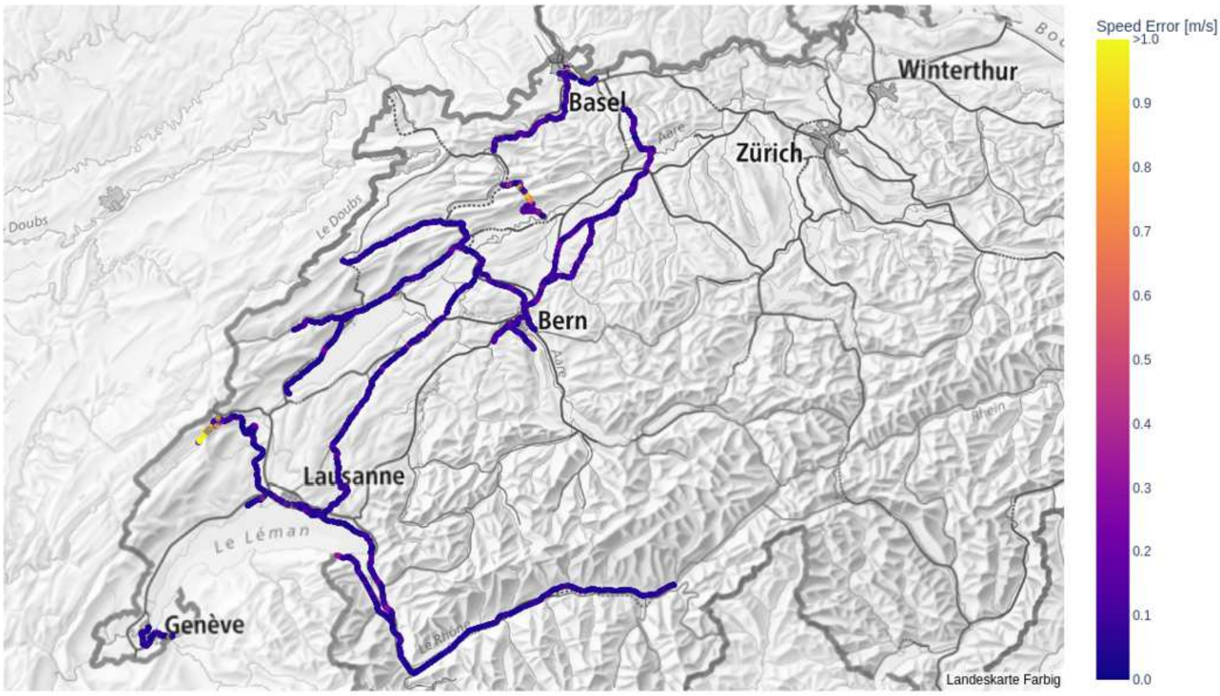


Figure 5-12: Map of Speed Error

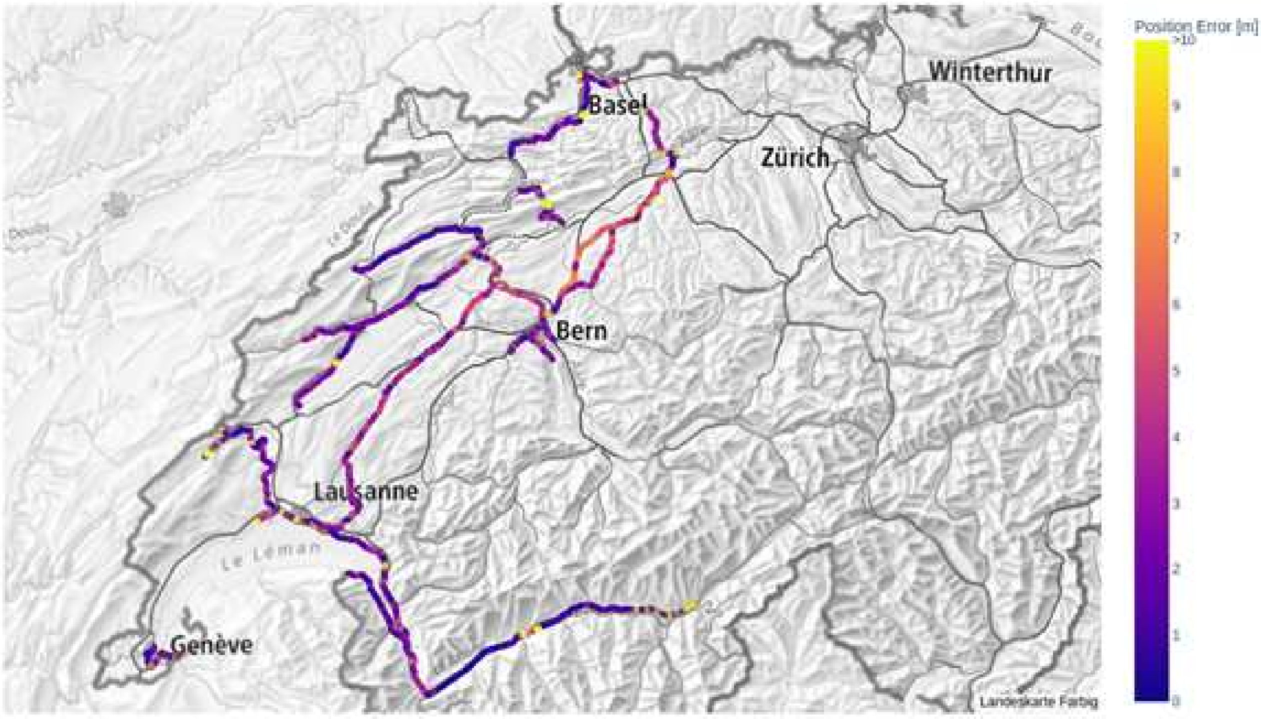


Figure 5-13: Map of Horizontal Position Error

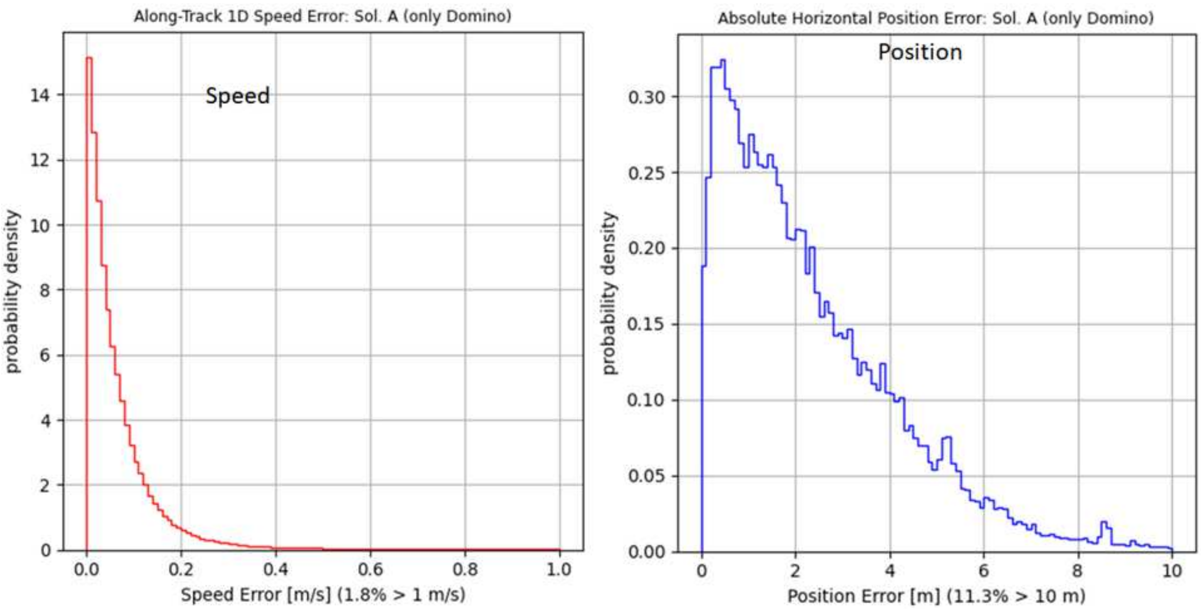


Figure 5-14: Histogram of Speed and Horizontal Position Error

Figure 5-14 shows the same information as in Figure 5-12 and Figure 5-13, but in form of a histogram. Care however has to be taken when interpreting such histograms, as the data is shown in relation to samples over time and the train has been at standstill for some time during most trips.

Also, the analysis reported some high value errors that could not yet be assigned to the algorithm or to the computed Ground Truth. It has therefore been decided to suppress those errors from the plots above, with the threshold mentioned in each speed/position legend above:

- Speed: 1.8% of samples with an error > 1m/s have been removed
- Position: 11.3% of samples with an error > 10m have been removed

A deeper analyse will have to be made to identify remaining issues related to the ground truth and then to remove the corrupted samples (due to ground truth errors) from the position error set used

for this statistical analysis. After this task, consolidated statistics of the Solution A performance will be generated and used as basis to further improve the algorithm in the future, notably in the areas where the solution A provides position with an accuracy worse than 10m.
One of the already identified improvement to be made, is the implementation of robust FDE algorithms to remove faulty measurements of each sensor (GNSS, IMU and tachometer). The fusion algorithm also only uses EGNOS V2 corrections so far. The use of corrections from EGNOS v3 will also improve the accuracy of Solution A.

6 CONCLUSIONS AND PERSPECTIVE

6.1 REQUIREMENTS

The mission requirements defined in D2.1 and the system requirements defined in D2.3 have been specified to the best knowledge and expertise available during the course of the project. There are several European initiatives currently on-going including RCA, OCORA, Shift2Rail among others where the topic of satellite-based localisation and the improvement of the odometry functionality of the ETCS core are being discussed and requirements are being specified. The CLUG consortium, especially the railway infrastructure managers i.e., SNCF, SBB and DBN supported by the railway companies i.e., SMO and CAF have already begun efforts to gather inputs and feedback from other railway infrastructure managers, undertaking and companies with regard to the mission and system requirements specified in CLUG.

We expect that these discussions will lead to further refinement of both the mission and the system requirements. The methodology used in the CLUG project to derive these requirements i.e., starting with the Wider System of Interest (WSoI) which contains the systems and functions that require localisation information and the purpose of the functions and then deriving the system requirements so as to fulfil the mission needs is certainly an advantage for future European standardisation discussions. The methodology in CLUG where clear rationale and non-functional needs were specified at the highest-level i.e., mission requirements make it easier for stakeholders to validate the system requirements and suggest improvements, if needed.

In addition to reviewing the existing mission and system requirements, based on the experience gained during the CLUG project and on-going European initiatives, there are a few areas where work needs to be done in order to specify additional requirements.

Area #1: Start of Mission

Start of Mission i.e., the initialisation of the train and preparation for a mission especially when the ETCS OBU does not know its last saved position before start-up costs the infrastructure managers extensive effort and coordination in order to allow the train to begin its mission. This results in loss of capacity.

The ERTMS/ETCS operational procedures have to been reviewed and current challenges need to be documented. Based on these additional mission and system requirements need to be specified in order to ensure that the future localisation system is able to initialize and provide a safe position during start-up in an optimal way for operations.
These additional mission and system requirements goals shall allow to achieve the following requirements during start-up of the localisation system: Req#1, Req#6, Req#11, Req#16, Req#19, Req#23, Req#30, Req#31, Req#32, Req#33, Req#34, Req#35, Req#36, Req#37 (see chapter 3.2).

Area #2: Track selectivity

The current ERTMS/ETCS is designed with Eurobalises playing an important role as a reference point for both distance measurement and for ensuring that the train is travelling along its pre-defined route. A perquisite for a stand-alone fail-safe localisation system is that is not only able to provide along-track position but also its current TrackEdge Id. Track selective localisation is not just a technical challenge for the localisation system but also requires railway system-wide safety and operational analysis. Additional work is overseen here in order to specify mission requirements, functional and non-functional system requirements including safety targets. The high level system requirements involve in this additional works are: Req#19, Req#22 (see chapter 3.2).

Area #3: On-board / Hardware requirements

In CLUG, no specific requirements have been specified that might be needed when the localisation system is to be integrated into the on-board platform of a train. This was not in the scope of the project. A future project that deals with the topic needs to address these requirements. The following requirements might be updated: Req#3, Req#8, Req#13, Req#17, Req#21, Req#25 (see chapter 3.2).

Area #4: Modularisation of the ETCS On-Board

The external interfaces defined in CLUG need to be aligned with the possible interfaces that might be defined in the future in order to decouple the ETCS odometry from the European Vital Computer (EVC). It will also lead to additional system requirements that need to be fulfilled by the localisation system. The following requirements might be updated: Req#1, Req#6, Req#11, Req#16, Req#19, Req#23, Req#27, Req#30 (see chapter 3.2).

Area #5: Preliminary hazard analysis

In CLUG the preliminary hazard analysis was carried out based on a high-level approach of the overall CCS system architecture. This approach needs to be aligned with future analysis made in the context of ERTMS/OCORA/RCA. This future work should consolidate the apportionment of hazards used for the TLOBU and the derived TFFR on functions. The following requirements might be updated: Req#4, Req#9, Req#14, Req#18, Req#22, Req#26, Req#30 (see chapter 3.2).

6.2 TLOBU DESIGN & DEVELOPMENT

From the mission requirements defined in D2.1 and the system requirements defined in D2.3 two solutions have been derived.
Each solution reached at least the expected proof of concept level 2 to 4 referring to the European Union TRL (Technology Readiness Levels), and higher TRL for some functions being then prototyped with real data and in real train environment:

- Common solution A/B functions:
  - All COTS sensors: TRL 6 Technology demonstrated in relevant environment;
  - Digital map: TRL 4 – 5 Technology validated in lab - in relevant environment;

- Solution A by Airbus Defence and Space:
  - Fusion Along track & Map matching: TRL 5 Technology validated in relevant environment;
  - Data FDEs, GNSS+EGNOS data unit, Start of Mission & Init, Track Selectivity, Integrity Confidence Intervals & status: TRL 2 – 4 Technology concept - proof of concept - Technology validated in lab;

- Solution B by Naventik:
  - Sensor GNSS SDR: TRL5 Technology validated in relevant environment;
  - GNSS FDE (ARAIM): TRL 2 – 4 Technology concept formulated - proof of concept - Technology validated in lab;
  - Fusion Along track & Map matching: TRL 5 Technology validated in relevant environment;

The performance evaluation shows that localisation system for train onboard system based on new technologies is achievable. Nevertheless, room for improvements is foreseen and should be considered in future projects. Priority for a next study would be to increase the TRL level in particular on the track selectivity algorithm, on the data FDE functions and on the integrity algorithm for future prototyping in relevant environment.