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## **Deliverable D1.1-Baseline System Specification and Definition for Moving Block Systems**

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# Deliverable D1.1

## Baseline System Specification and Definition for Moving Block Systems

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## Executive Summary

The PERFORMINGRAIL project implements a holistic system approach to address the open challenges for the moving block concepts in terms of safe operational principles and specifications, reliable train integrity monitoring technologies, high-accuracy train positioning, and optimised moving block traffic management algorithms. In the frame of the PERFORMINGRAIL project, WP1 deals with the definition of specifications for minimum moving block performance to help with the development of formal methods and traffic management algorithms to be addressed later in the project.

The present document (Deliverable 1.1) is specifically dedicated to review and define future moving block systems including ETCS L3 and virtual coupling while specifying the operational performance requirements for moving block systems. The deliverable builds on the experience derived from academic and industrial projects on moving block systems such as X2Rail-1, X2Rail-2, X2Rail-3, MOVINGRAIL, ASTRAIL, and NGTC.

In this deliverable, the review of future moving block systems and definition of the system specifications have been carried out taking into consideration:

- Moving Block system architecture, variants, existing approaches, and main functionalities
- Moving Block system requirements including time constraints
- Moving Block operational and engineering Rules
- Moving Block hazard analysis including GNSS-specific hazards
- Moving Block use cases detailing external actors, related internal functions, expected system behaviour, system parameters, and safety hazards.
- Virtual Coupling functional layers, components, and main system functionalities.
- Virtual Coupling use cases as referenced from X2Rail-3 project.

The output of this document in terms of system definition and specifications represents a rigorous baseline for the subsequent modelling activities that are achieved in the framework of PERFORMINGRAIL WP2.

## Abbreviations and Acronyms

Abbreviation / Acronyms	Description
Abd	Absolute braking distance
ACC	Accepting area of control (during Handover process)
ATO	Automatic Train Operation
ATP	Automatic Train Protection
BG	Balise Group
BTM	Balise Transmission Module
CCS	Control/Command and Signalling
CRE	Confirmed Rear End
EoA	End of Authority
EoM	End of Mission
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
FMB	Full Moving Block
FVB	MB based on Fixed Virtual Block
GNSS	Global Navigation Satellite System
HO	Handing Over
LRBG	Last Relevant Balise Group
MA	Movement Authority
MB	Moving Block
MSFE	Max Safe Front End
MSRE	Max Safe Rear End
mSFE	min Safe Front End
mSRE	min Safe Rear End
OTI	On-board Train Integrity
PNT	Positioning, Navigation, and Timing services
RBC	Radio Block Centre
RV	Reversing mode of ETCS on-board
SB	Standby mode of ETCS on-board
SH	Shunting mode of ETCS on-board
SNR	Signal-to-Noise Ratio
SoM	Start of Mission
SvL	Supervised Location
T2I	Train to Infrastructure
T2T	Train to Train
TIMS	Train Integrity Monitoring System
TMS	Traffic Management System
TPR	Train Position Report
TTD	Trackside Train Detection
V2V	Vehicle to Vehicle



Abbreviation / Acronyms	Description
VCTS	Virtually Coupled Train Set
VBTS	Virtual Balise Transmission System
VSS	Virtual Sub-Section

ETCS Level 2 variables	Description
D_LRBG	Distance between the last relevant balise group and the estimated front end of the train
L_DOUBTOVER	over-reading amount (odometry error + error in detection of balises) + Q_LOCACC
L_DOUBTUNDER	under-reading amount (odometry error + error in detection of balises) + Q_LOCACC
L_TRAIN	Train length
L_TRAININT	Safe train length
NID_BG	Identity number of the balise group
Q_LOCACC	Accuracy (position error in meter) of the eurobalise location
Q_NVLOCACC	Default accuracy of the balise location (absolute value)
T_NVCONTACT	Timer related to the maximal time in second without new "safe" radio message (not supervised in radio holes)

## 1. Background

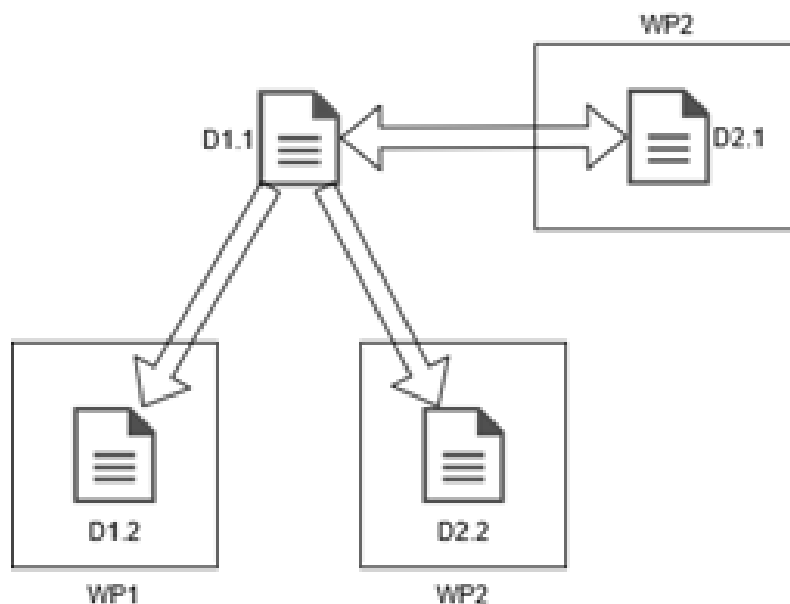
The present document constitutes the Deliverable D1.1 titled “Baseline System Specification and Definition for Moving Block Systems” in the framework of the PERFORMINGRAIL project. PERFORMINGRAIL consists of five main work packages including:

- **Identifying Specifications for minimum Moving Block performance standards:** this work package aims to review and define future moving block systems including ETCS L3 and virtual coupling while specifying the operational performance requirement for moving block systems.
- **Modelling and Analysis of Moving Block Specifications:** this work package aims to develop adequate parameterizable models to analyse the operation under moving block and investigate the system behaviour against possible hazards in diverse signalling systems and signalling market segments.
- **Designing of Fail-safe train Positioning:** the objective of this work package is to design and implement localization techniques of the rail platform based on GNSS and additional sensors including Inertial Measurement Units.
- **Definition of an Integrated Moving Block Architecture for safe and optimised traffic operations:** this work package aims to model an innovative integrated traffic management system for safe and optimised moving block operations.
- **Testing, Assessment, and Demonstration:** the main objective of this work package is to assess the ongoing results in terms of safety, feasibility, testability, and specifications.

This document is the first deliverable of WP1, and it incorporates the work undertaken in T1.1 and T1.2. The first task T1.1 focuses on reviewing ERTMS/ETCS Level 3 as the reference moving block system and the virtual coupling system in relevant academic and industrial projects such as X2Rail-1, X2Rail-2, X2Rail-3, MOVINGRAIL, ASTRAIL, and NGTC. The task also highlights the available technologies that enable moving block systems. On the other hand, the second task T1.2 incorporates the findings in T1.1 to define a baseline system specification including system requirements, engineering and operational rules, and hazard analysis. This deliverable will achieve the first milestone (MS1) of the PERFORMINGRAIL project titled “Baseline Moving Block System Specification”.

## 2. Objective/Aim

This document has been prepared to fulfil the first objective of the PERFORMINGRAIL on defining “Specification for safe moving block operation”. This objective will be addressed through the initial stage of WP1 (T1.1 and T1.2) by analysing, verifying, and enhancing principles and system specifications defined by X2Rail-1 and X2Rail-3 to enable safety and standard performance levels of moving-block railway operations. The output of this deliverable will set a rigorous baseline for the subsequent modelling and Verification and Validation (V&V) activities of the project. Figure 1 represents the relationship between D1.1 and other related deliverables.



**Figure 1:** Relationship with other deliverables

There are no deliverables that can be considered as an input for D1.1. The content of this deliverable will be used by:

- PERFORMINGRAIL D1.2 that will use the baseline to summarize the recommendations of all the WPs;
- PERFORMINGRAIL D2.2 that will develop semiformal and formal models on the ETCS L3 baseline here defined.

Furthermore, there is an intersection between the contents of this deliverable and of D2.1 since the related tasks have been conducted in parallel. The connection points between such deliverables are:

- Use case definition: the definition of the use cases that is present in this deliverable is used in D2.1 to build the Operational Scenarios that, according to the methodology described in D2.1, can be seen as specialisation of one or more use cases;

- Operational Scenario vs Use Case mapping: since one of the objectives of this deliverable is to detail the ETCS MB/VC behaviour within at least four use cases, the choice of which specific use case to model has been driven also by the necessity to maximise the coverage between OSs and UCs. This mapping has been added to this deliverable on the base of information present in D2.1;
- Modelling Guidelines: the requirements, the architectural and the behavioural diagrams detailing the structure and the dynamics of ETCS MB/VC are reported in this deliverable in conformity to the SysML specification language. Such a language has been chosen on the base of the modelling recommendations present in D2.1.

### 3. Introduction

To manage the traffic, railway lines are commonly divided into fixed track sections, known as fixed blocks. This characteristic allows Control, Command and Signalling (CCS) systems to achieve safe train movement the following principles:

- **Exclusive authorisation:** only one train gets authority to move in or be in a track section at any time;
- **Guarantee of authorisation:** the authorized section is available, usable and locked for one train until it has been assured that the section is no longer used by the train;
- **Safe usage of authorisation:** there is clear and timely information provided about the safe usage of the section by the train, i.e., no violation of boundaries in time, speed, and space limits;
- **Monitoring of authorisation violation:** a train warning or intervention occurs when safety is no longer guaranteed.

In order to implement the previously mentioned safety principles, the CCS system functionalities include:

1. Setting up a safe route for each train over the track that is to traverse,
2. Preventing conflicting routes of other trains,
3. Providing Movement Authority (MA) to the relevant train,
4. Holding the route during the train movement,
5. Supervising and/or enforcing train to stay within its movement authority,
6. Releasing the route after passage of train so that the route can be used by other trains.

The European Rail Traffic Management System (ERTMS) is the system of standards for management and interoperation for railway signalling introduced by the European Union (EU). ERTMS was introduced to ensure interoperability between national railway systems, while raising the network capacity and improving the safety level. The European Train Control System (ETCS) is the signalling element of ERTMS that include the control of movement authorities, automatic train protection, and the interface to interlocking.

Today, ETCS allows the implementation of functions 3, 4 and 5, mentioned above, through two possible configurations: ETCS Level 1 and ETCS Level 2, based on different trackside / on-board equipment arrangements. The rest of functions are still provided by the national interlocking systems that aim to establish and maintain routes in areas where conflicts can exist (e.g., junction, bifurcation, and crossing) by controlling block occupancy.

With ETCS Level 3, European railway stakeholders envisage implementing a promising train operating approach: the “Moving block”. For each train, ETCS L3 defines a surrounding virtual track area that is not accessible by other trains on the network. This area is established dynamically and only depends on the absolute braking distance between trains. Following this approach, trains can move more efficiently on the track with a minimised separation distance, which tackles the first railway challenge: an increased network capacity at high-density lines. Moreover, Moving Block (MB) systems aim to eliminate the dependency on trackside equipment

(e.g., track circuits, axle counters, and balises<sup>1</sup>) by providing most of the CCS functionalities from the train itself. In so doing, moving block signalling systems allow the installation and maintenance costs of trackside infrastructure to be significantly reduced and thus, tackling a second important railway challenge: life-cycle cost reduction; this is particularly crucial to ensure the competitiveness and viability of regional railway lines.

As mentioned above, the separation distance on a Moving Block system is highly dependent on the absolute braking distance between trains. As the braking rates are limited by adhesion between the wheels and the rail, the separation distance tends to increase considerably with speed. The virtual coupling concept (sometimes referred to as ETCS Level 4) aims to improve the network capacity further by running trains closer together. The virtual coupling assumes that the leading train will not stop immediately, as it will brake gradually until it stops. If the leading and the following trains are adopting a similar braking rate through vehicle-to-vehicle communications, the two trains can run at a distance that is smaller than the braking distance of the following train, which can enhance the network capacity significantly. In other words, the separation distance in a Moving Block system is based on the absolute braking distance between trains, while virtual coupling enables a relative braking distance by allowing the following train to incorporate the braking behaviour of the leading train.

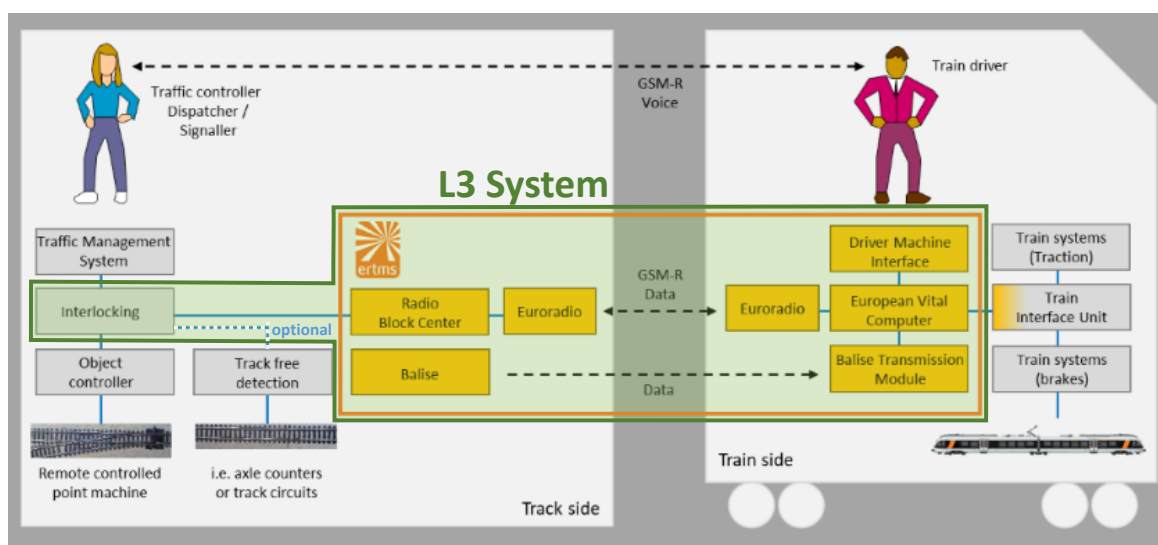
This document will focus on the Moving Block system definition in Section 4, highlighting the system architecture, main concepts and principles, and the main system functionalities. Section 5 will focus on defining the system specifications identifying the Moving Block requirements, engineering and operational rules, hazard analysis, and system uses cases. Virtual coupling system definition will be discussed in Section 6, while the virtual coupling specifications will be presented in Section 7.

## 4. Moving Block System Definition

The “ETCS Level 3 Moving Block signalling system” has been defined in X2Rail-1 and X2Rail-3 projects with the intent to extend the existing definition of ETCS L2, thus adopting an incremental innovation approach by minimising the changes needed in ETCS L2 specifications (D5.1 X2Rail-1, 2019) (D4.2 X2Rail-3, 2020). The current ETCS L2 specifications are defined with a set of documents, called Subsets, which are listed in the CCS EU regulation (TSI-CCS, 2016). The most recent specification corresponds to Baseline 3-Release 2 (B3R2). The MB system, known as L3 System, includes the on-board and the trackside subsystems called, respectively, L3 On-board and L3 Trackside. L3 Trackside includes enhanced functionalities of ETCS L2 and also, functionalities that are traditionally considered part of the interlocking system (D5.1 X2Rail-1, 2019) (D4.2 X2Rail-3, 2020) and not included in B3R2 such as : route request, route cancel, route availability checking, route setting, route locking, route holding, route release, flank protection, overlap management, point management.

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<sup>1</sup> Physical Balises are still currently needed as satellite solutions are not concrete in all zones. Also, physical balises are needed in proximity to non-L3 area. Annex C of this deliverable discusses the Virtual Balise concept that will enable the removal of trackside balises.



**Figure 2:** Simplified overview of the architecture of ETCS Level 3 Moving Block signalling system (Figure adapted from (Arcadis, 2018))

L3 System is also defined with the intent that a mixture of different systems could be used at the same time. In other words, the ETCS L3 system can act as an overlay over the existing conventional system. This approach allows a transition phase for lines on which a migration towards ETCS L3 is foreseen. During this phase, mixed traffic is possible with trains operating under the MB system while other trains are operating under the classical fixed block sections on the same line. Consequently, non-equipped trains can be gradually equipped or replaced with equipped ones.

Besides, existing L3 System specifications addressed different rail market segments including urban/suburban, high-speed, low-traffic, and freight lines. Some variations in terms of system attributes, but not explicitly detailed in X2Rail projects, allow the specifications to be applied according to the different railway types.

Two main principles differentiate the MB system and they are: **Movement Authority (MA) and Track occupancy determination**. In railway systems operating with moving blocks, a MA is passed to the on-board train computer using a radio-communication link and is issued until the rear of the train ahead (safety margins are however introduced, as will be seen later). As trains move, MA is regularly updated and transmitted to trains on the network. In such a way, trains can be continuously controlled and kept at a minimum distance from each other. Therefore, both MA issuing and control prevent train from entering a dangerous occupied area. This principle and the precise train location on the track allow the safe train separation principle to be applied.

In traditional railway systems, lines are divided into fixed blocks delimited by physical trackside equipment such as track circuits or axle counters. Based on the statuses of these track detectors (free/occupied), the trackside system approximately infers the train location based on the occupancy of the block sections. However, it cannot determine in which precise location the train lies in the block section. Knowing the block section each train occupies, the train driver is

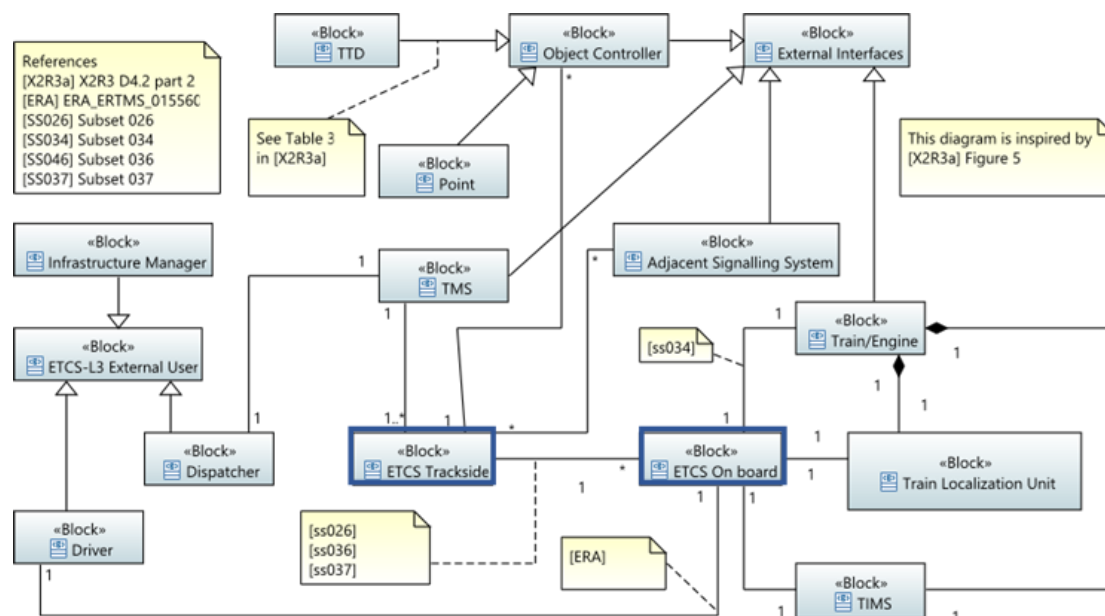
informed about the route allocation thanks to the state of lineside signals he/she has to respect.

In railway systems operating under moving blocks, MA data is transmitted through the “trackside-to-train” radio-link. In parallel, data transmitted on the “train-to-trackside” radio-link enables the track occupancy to be determined by the trackside system. For that, such data can include the train location: the train front-end position and, either the train length or the train rear-end position. For the sake of safety, the train rear-end position is preferred due to the potential loss of wagons if a mechanical link is broken. The train front-end position and the train integrity status (confirmed/loss) are information that can be determined by on-board devices. When such data are provided continuously through the radio link to the trackside system, the train location area, also called train footprint, can be known more precisely and the trackside system can then be decoupled of trackside detection equipment. Using a safe surrounding zone around the train footprint allows establishing the MA close to the rear of the leading train. As this zone moves with the train, this gives the name to the “moving block” concept.

The upcoming sections will describe the L3 System high-level architecture and functionalities, before highlighting the system main approaches and system types. Furthermore, the section will discuss in more details the system functionalities including train integrity, train localization and track status. The options for train localization and train-to-ground communications in MB systems will be discussed in Annex C (cf. section 12).

### 4.1. Moving Block System Architecture

Figure 3 presents the today high-level view of ETCS L3 surroundings modelled in SysML Block Definition Diagram (BDD).

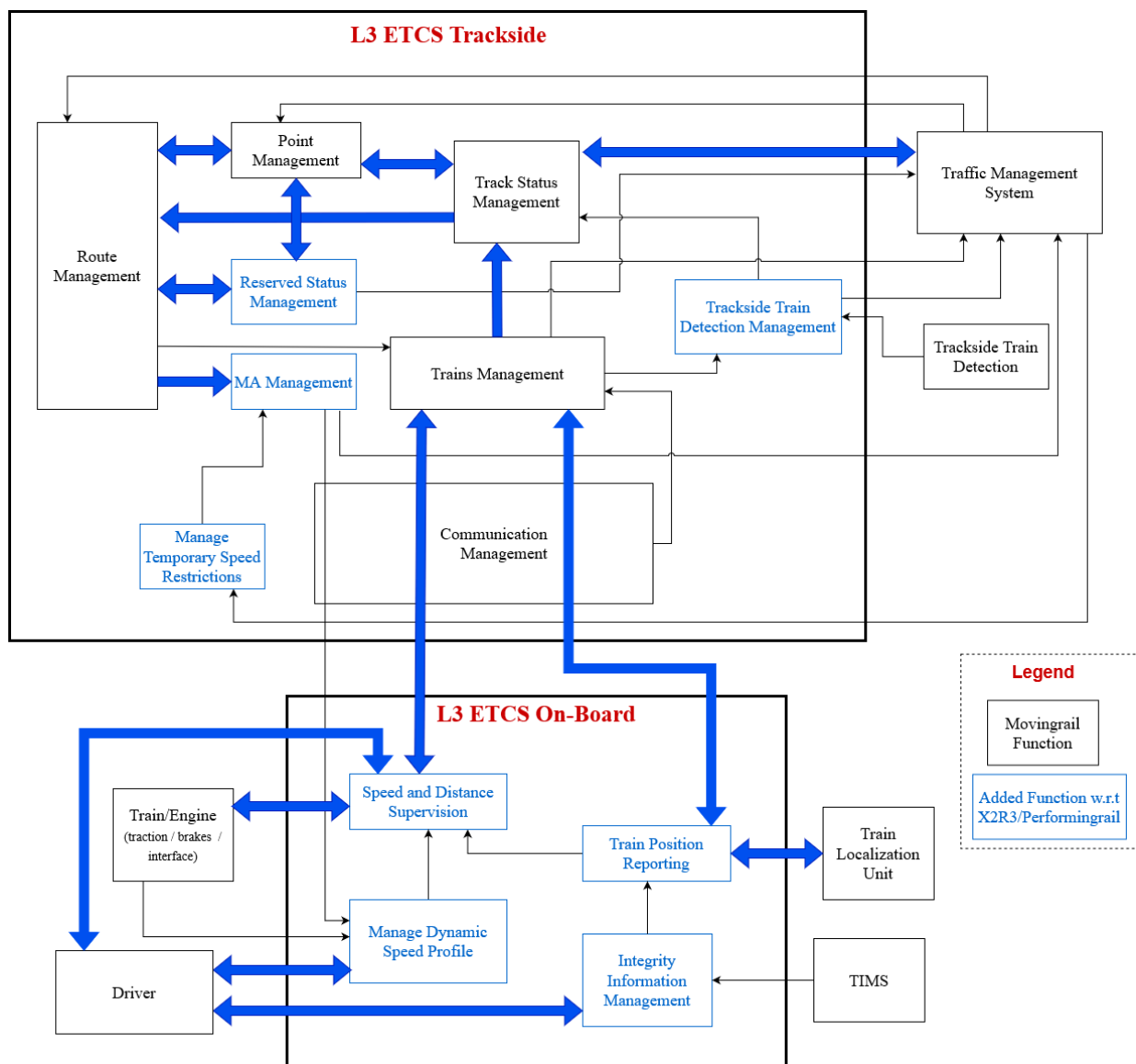


**Figure 3: ETCS L3 structural context**



The **External Users** to the L3 System are: TMS (Traffic Management System), Adjacent signalling System, Object Controllers, the Point Equipment, TTD (Trackside Train Detection), Train/Engine, Train Localization Unit, and TIMS (Train Integrity Management System). The **External Interfaces** to the L3 System are: Dispatcher, Infrastructure Manager, and Driver.

Besides, Figure 4 details the ETCS L3 high-level functional architecture derived from (D4.2 X2Rail-3, 2020) and (D1.1 MOVINGRAIL, 2020) comprising 9 trackside functions (the “Manage Low Adhesion Areas” function being not examined for the moment) and 4 on-board functions. This figure also shows an overview of the data flow between the external systems and the on-board and trackside systems. A more detailed view of this functional architecture is presented in Annex A (cf. section 10) after analysing the specification description in (D4.2 X2Rail-3, 2020) and (D1.1 MOVINGRAIL, 2020).



**Figure 4: ETCS L3 data flow overview**

Note that, in ETCS L1 & L2, the train position and speed is derived using components included in ETCS (balise/odometer). However, considering the use of possible new technologies using specific hybridization processes between components/sensors, the “Train Localization Unit” may be put outside ETCS L3 system. In PERFORMINGRAIL-WP3 activities, an IMU (Inertial Measurement Unit) is hybridized to a GNSS unit - Global Navigation Satellite System - to allow the train position to be obtained (D3.3 PERFORMINGRAIL, 2021).

Table 1 is a synthesis of the ETCS-L3 functionalities when compared with ETCS levels 1 and 2 to give an overview of some changes and enhancements amongst levels.

**Table 1:** ETCS functionalities in levels 1, 2 and 3

ETCS functionalities			
Description	Level 1	Level 2	Level 3
Trackside / on-board communication link	At discrete places (switchable Eurobalises), or Semi-continuous with radio infill	Continuous	Continuous
Train localization	On-board and trackside (odometry with error resetting using fixed Eurobalises info)	Evolution toward the localization essentially performed on-board (kinematic sensors, Satellite Navigation system, virtual balises with few fixed Eurobalises info)	
Trackside train detection (occupied/free track status)	Yes (track circuits, axle counters)	Yes (track circuits, axle counters)	<b>Optional</b>
Train Integrity Monitoring (for train with multiple units)	Trackside	Trackside	<b>On-board</b> (optional with TTD, not needed for single unit)
Block operation	Fixed	Fixed	<b>Moving blocks</b> (Full MB or virtual fixed blocks)
Fixed lateral signalling	Yes	Optional	<b>No</b>
Capacity gain	0	- Medium if mixed traffic - High if homogeneous traffic	<b>High</b>
Mixed with different national systems	Yes	Yes, without capacity gain	<b>Yes if hybrid level 3</b> (TTD and virtual block sections)
Targeted lines	Medium density lines	High density lines	- <b>Regional lines</b> with low or medium density when infrastructure costs have to be reduced - <b>very high density of one-directional lines</b> when performance is sought

Interlocking (route locking w.r.t. free track status, control of signals and points)	Not included (managed by national systems)	Not included (managed by national systems)	Included
Interface with the Traffic Management System (TMS)	Interface with the TMS that supervises the traffic circulation and performs the diagnostics of the system equipment (interlocking/RBC included). The TMS supports all traffic management life-cycle functions (plan, regulate, optimize) and integrates a human interface at control centres to display real-time status of the railway line in order to provide permanent control to actors (coordinators, dispatchers) across the network, to set train routes and to solve potential conflicts		Interface with <b>advanced TMS</b> for increasing the network throughput thanks to intelligent conflict detection and automated functionalities supporting the operators result-oriented decisions (e.g., re-routing, re-ordering, re-scheduling)

The operations in ETCS Level 1 involves the lineside signal states being reported to the on-board system through the switchable trackside balises. The reported states will then be displayed on the train Driver Machine Interface (DMI). In parallel, the train computer automatically controls that no closed signal is passed. However, in ETCS Level 2 and 3, the movement authority is provided through radio messages transmitted by the RBC to the on-board computer. ETCS L3 functionalities including train localization, integrity monitoring, options for train-to-ground communications, and trackside functions will be detailed later in this document.

## 4.2. Existing Moving Block Approaches

Two main Moving Block approaches differ based on how the track blocks are formed. These approaches are as follows:

- **Full Moving Blocks (FMB) approach:** this approach is based on the establishment of a dynamic area around trains.
- **Fixed Virtual Blocks (FVB) approach:** this approach is based on the establishment of fixed virtual blocks. However, in this approach, the MB principles can be still applied. As the virtual blocks are defined in trackside digital databases, they can finely discretize the railway track into fixed sections without the need for further trackside equipment.

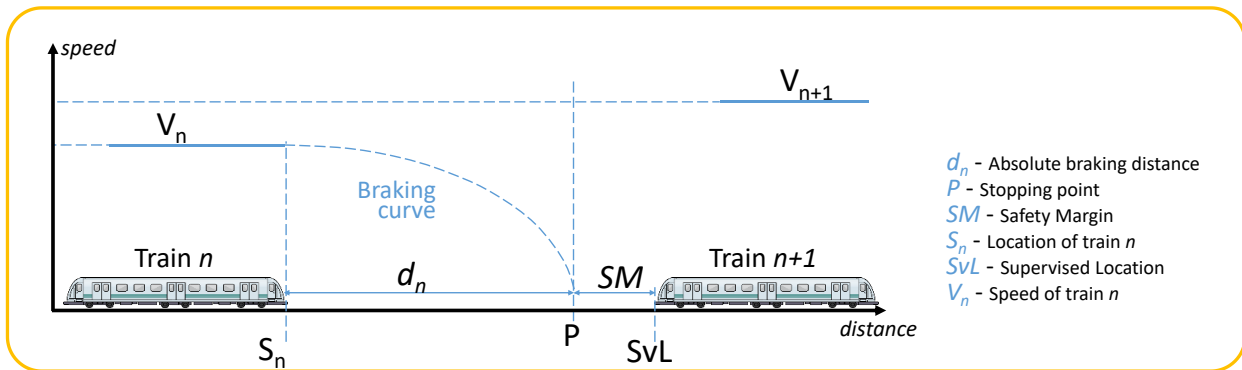
Both approaches are detailed next by explaining more precisely how the MA is managed.

### 4.2.1. Full Moving Blocks (FMB) Approach

In the FMB approach, the trackside system can issue a MA to a train, i.e. it reserves a track area for that train, based on the reported location of the rear of the preceding train (train ahead). End of Authority (EoA) can be in any place of the railway line (contrary to the approach with fixed virtual blocks detailed after).

In (Zhou & Mi, 2012), the three mechanisms for implementing FMB system are recalled below. The second (Pure Moving Block) gives the best performances and constitutes the basis of all currently implemented systems. In each case, the minimum instantaneous distance  $d_n$  between

the head of train  $n$  and the rear of train  $n+1$  corresponds to the braking distance when train  $n$  decelerates from the speed  $v_n$  to 0 at the rate of  $b_n$  (deceleration coefficient). The train separation is thus reduced to the distance needed to reach a standstill at EoA, it is then an **absolute braking distance**, as shown in Figure 5.  $v_{max}$  is the maximum velocity of train  $n$  and  $SM$  is the safety margin between train  $n$  and train  $n+1$ . Note that the time interval needed by the train for running  $d_n$  is called **headway**.



**Figure 5: The Full Moving Block mechanism**

► **Moving Space Block** allows adjusting the minimum instantaneous distance according to the maximal speed  $v_n = v_{max}$  which is the maximum line speed,  $v_n \leq v_{max}$  (cf. Eq.(1)). Thus  $d_n$  moves with the same distance as the displacement of train  $n$ .

$$d_n = \frac{v_{max}^2}{2b_n} + SM \quad \text{Eq.(1)}$$

► **Pure Moving Block** allows adjusting the minimum instantaneous distance according to the current speed  $v_n = v_f$  of train  $n$  (cf. Eq.(2)).

$$d_n = \frac{v_f^2}{2b_n} + SM \quad \text{Eq.(2)}$$

► In **Moving Time Block**, the 'headway time' between two trains passing any point along the line is constant (cf. Eq.(3): 'headway time' =  $\frac{d_{max}}{v_{max}}$ , which is constant).

$$d_n = v_f \cdot \frac{d_{max}}{v_{max}} + SM \quad \text{Eq.(3)}$$

$d_{max}$  is the braking distance when train  $n$  decelerates from  $v_{max}$  to 0 at the rate of  $b_n$ .

In each of the previous MB mechanism, the train integrity is supposed to be monitored and confirmed by on-board devices. Likewise, the speed and the braking curve are supposed to be correctly supervised by the on-board sub-system. Moreover, the only information required to ensure a safe headway is the precise positioning information of both trains. In reality, such information provided by an on-board localization system is associated with some nominal errors linked to the estimation process. That is why a safety margin is considered and is calculated according to the confidence interval provided with the estimation process.

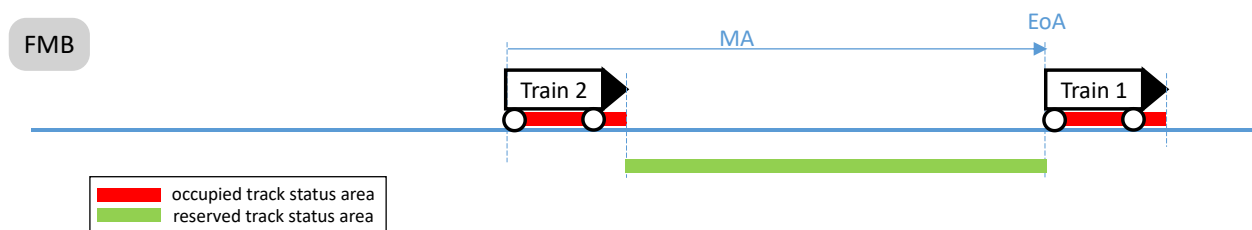
#### 4.2.2. Fixed Virtual Blocks (FVB) Approach

In the FVB approach, train traffic is managed using Fixed Virtual Blocks (FVB) in the same way as with classical fixed blocks. The difference is in their engineering design as the limits of classical blocks depend on where trackside train detectors are installed, while the FVB limits are known by the trackside system using information entered into **digital databases stored in the network infrastructure**. This will lead to a logical (rather than a physical) division of the line into sections of known lengths. Depending on traffic demands, the operational performance may be flexibly changed by reconfiguring the VB length (Pachl, 2018), i.e., their size can be reduced in order to separate trains with a smaller distance. Besides, the number of FVB can be increased without the need for additional equipment installations.

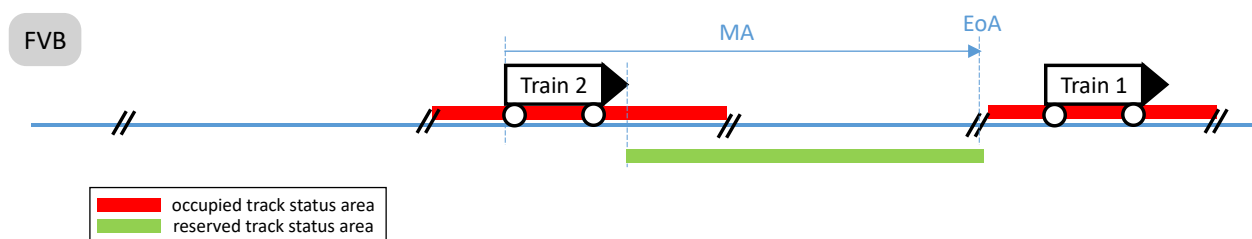
Similarly, to the classical fixed blocks, the train EoA can only be placed at discrete locations on the line predefined by the FVB limits. Figure 6 and Figure 7 show track occupancy respectively for FMB and FVB approaches to understand the differences between them (Furness, Van Houten, Arenas, & Bartholomeus, 2017):

- In Figure 6, occupied track sections are only determined by the position of the train rear and train head.
- In Figure 7, occupied track sections are occupied block sections.

A common feature for FMB and FVB is that track occupancy determination is based on train location information sent by train-to-ground communication link.



**Figure 6:** Track occupancy determination with FMB



**Figure 7:** Track occupancy determination with FVB

### 4.3. Moving Block System Variants

Based on the two approaches presented, 4 system types have been proposed for ETCS L3. The system types rely on the combined or separate use of 1) Trackside Train Detection (TTD) equipment used to detect trains on block sections and 2) either FMB or FVB approach is in place. Table 2 presents the 4 variants considered today in the specifications of the ETCS Level 3 Moving Block system.

The concept of Hybrid ETCS Level 3 is introduced. ETCS L3 is considered to be hybrid when both the TTD and the on-board train location determine the track occupancy. This hybrid concept allows not only the ETCS migration from L2 to L3, as TTD equipment is already used on ETCS L2 lines, but also enables the management of degraded situations as the track occupancy is determined using two separate systems. For example, TTD makes it possible that trains without confirmed integrity or non-communicating trains to be safely admitted by the L3 trackside system on Hybrid L3 lines.

**Table 2: Types of ETCS Level 3 adapted from (D2.1 MOVINGRAIL, 2018) (Furness, Van Houten, Arenas, & Bartholomeus, 2017)**

Type of level 3	Trackside infrastructure	Benefits and challenges
<b>1. Hybrid FVB</b>	<ul style="list-style-type: none"> <li>- No signals</li> <li>- Trackside train detection</li> <li>- Use of Fixed Virtual Blocks</li> </ul>	<ul style="list-style-type: none"> <li>- Increase in capacity for trains with Train Integrity Monitoring without adding trackside detection</li> <li>- Increase reliability because of redundancy in train localization</li> </ul>
<b>2. Hybrid FMB</b>	<ul style="list-style-type: none"> <li>- No signals</li> <li>- Limited trackside train detection</li> <li>- Use of Moving Blocks</li> </ul>	<ul style="list-style-type: none"> <li>- Increase of capacity by adapting the size of the blocks around trains</li> <li>- Impact on traffic management systems and operation impact (two trains in the same block) to be considered</li> </ul>
<b>3. FVB without TTD</b>	<ul style="list-style-type: none"> <li>- No signals</li> <li>- No need for trackside train detection</li> <li>- Use of Fixed Virtual Blocks</li> </ul>	<ul style="list-style-type: none"> <li>- Increase capacity by adapting the size of the virtual blocks in software database</li> <li>- Reduction of cost and increase in reliability due to the removal of trackside equipment. Solutions for trains without radio connection (e.g., intentional switch-off) and degraded situation (disconnected) have to be found.</li> </ul>
<b>4. FMB without TTD</b>	<ul style="list-style-type: none"> <li>- No signals</li> <li>- No need for trackside train detection</li> <li>- Use of Moving Blocks</li> </ul>	<ul style="list-style-type: none"> <li>- Maximised capacity on the available infrastructure</li> <li>- Reduction of costs due to the removal of trackside equipment. Solutions for trains without radio connection (e.g., intentional switch-off) and degraded situation (disconnected) have to be found.</li> </ul>

**Mixed traffic on lines equipped with Hybrid ETCS L3** (with ETCS L3 equipped / non-equipped trains) is also possible. However, this leads to some additional safety issues that have to be identified and managed like the potential presence of the non-communicating trains. These **ghost trains** are non-equipped trains or trains that are recognized by TTD, which experience communication failures. **Shadow trains** are also possible when an integer train is followed by a non-communicating train (EUG, 2020).

Hybrid FMB makes only sense on lines with a very high density of one-directional traffic with harmonized speed profiles. In many cases, Hybrid FVB will be a more efficient solution (Pachl,

2018).

The track occupancy determination (i.e., track status determination) differs according to the considered variant, as it will be explained in subsection 4.4.3 dedicated to track state. Before, the integrity **monitoring** and **train localization** functionalities will be detailed in subsections 4.4.1 and 4.4.2 as they provide input data for the track occupancy determination function. Note that systems implementing integrity and localization functionalities are under study in other Shift2rail projects: X2Rail-4 for train integrity and X2Rail-5 for train localization; both projects continue activities started in the X2Rail-2 project.

## 4.4. Moving Block Main Functionalities

### 4.4.1. Train Integrity Monitoring

To allow L3-Trackside to safely use the information about the train rear end position, a recent proposition of modification of ETCS Subset 026 (CR940, 2020) introduces the definition of the on-board **train integrity confirmation** as follows: “the train length is stored as a valid train data at the time the train was last known to be integer”. This definition was adopted in X2Rail projects (D5.1 X2Rail-1, 2019) (D4.2 X2Rail-3, 2020) even if it is not integrated in current railway regulation yet (TSI-CCS, 2016). This concept is also called Confirmed Rear End (CRE).

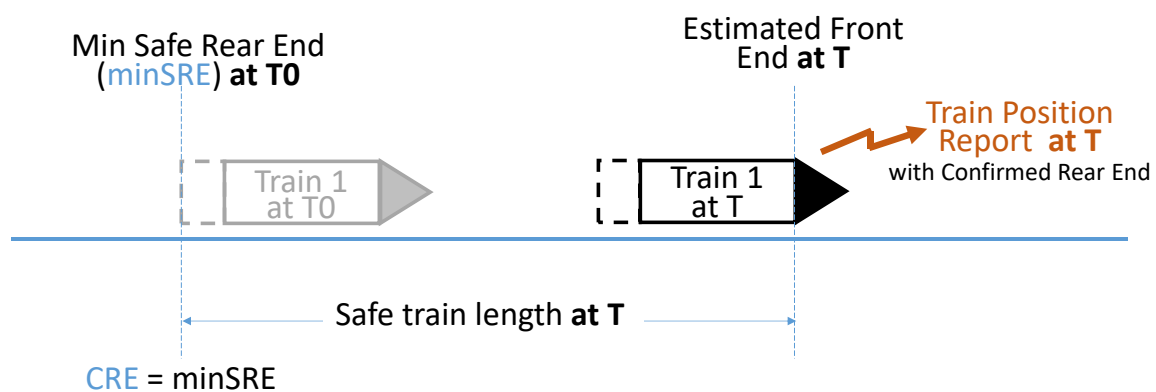
The Train Integrity (TI) information in the Train Position Report (TPR is detailed in the next subsection) consists of 1) **integrity status** (*unknown* TI information / TI *confirmed* by external device or by driver / TI *lost*), and 2) **safe train length** (only available when train integrity confirmation is reported). The transitions between values of TI status are detailed in (CR940, 2020) by using a table of conditions.

As detailed in (D4.1 X2Rail-2, 2020), the on-board determination of the integrity status in output of a Train Integrity Monitoring System (TIMS), which is an external device to ETCS on-board, is based on a regular communication between an On-board Train Integrity (OTI) master module located at the train head vehicle and a slave OTI module located at the train tail vehicle. Following the *Mastership* phase in which the master and slave roles are assigned, and the *Inauguration* phase which enables to pair the master and slave modules, the *Monitoring* phase can be initiated. During this phase, the master and slave modules exchange request/acknowledgement messages regularly and a number of timers are used to monitor the regularity of these communications. The determined integrity status (*Unknown*, *Confirmed* or *Lost*) is accordingly reported to the ETCS on-board regularly or in real time. The functional architecture elaborated (D4.1 X2Rail-2, 2020) distinguished between different possible configurations while considering:

- Whether the communication is in wired or wireless mode;
- Whether the ETCS module is located in train head or in a central position;
- The various train integrity criteria: difference between the train tail and front cabin positions AND/OR speeds AND/OR accelerations;
- Whether the train is fitted with diagnosis facilities.



The joining and splitting scenarios have also been detailed in (D4.1 X2Rail-2, 2020). The **safe train length** information is another information provided by the TIMS. It is the distance between the “min safe rear end” (at the time the train was last known to be integer) and “the estimated position of the train front end” at the time when the train integrity information is sent to the RBC, as shown in Figure 8. This information is useful when the train is running on a line that operates according to moving block principles. In that case, the **last Confirmed Rear End (CRE)** is the rear-end position deduced from the safe train length (contained in a position report confirming the train integrity) (CR940, 2020).



**Figure 8:** Safe Train Length when train integrity is reported to the RBC

As seen before, ETCS is based on radio areas for sending/receiving messages to/from trains. A Radio Block Centre (RBC) manages trains in the area it covers. Subsequently, a particular case in ETCS is to manage the radio session from one area to the next area in such a way that relevant information can transit from one RBC to the next one, especially the integrity information. This process is called the “handing-over”. (CR940, 2020) mentions that there is an implementation issue for integrity information when a train, operated in ETCS L3, is in a “handing-over” area: it has to be decided when it is appropriate to send the order to terminate the session to the on-board equipment (e.g. after the newly reached RBC has received for the first time a train integrity confirmation indicating that the min safe rear end of the train has passed the border).

#### 4.4.2. Train Localization

‘Train location’ is employed in this document for the track occupancy as seen by the trackside system. ‘Train localization’ is employed for train position determined on-board with a track-based coordinate system. It is here considered equivalent to the ‘train positioning’ notion.

In ETCS Levels 1 and 2, a position is determined on-board indirectly through a relative measured distance. This distance is provided by a device fitted on locomotive bogie axles or wheels, called the *odometer*, but generally speaking, the term ‘Odometry subsystem’ is preferred, the Odometry device depends on the wheel movement to measure some relative travelled distance. The imprecision (error) accumulated by the odometer is regularly reset by means of geo-referenced beacons, called *Eurobalises*. Thus, two ways are combined to localize a train: absolute positioning by balises and relative positioning by the odometry device.



Balises are often grouped in batches from two to eight. They are placed one behind the other on a few meters track zone and they are characterized with an internal sequence number. Such configuration has several purposes: to ensure a safe redundancy of transmitted information, to detect the direction of a train (nominal or reverse) and, when the size of a balise message to be transmitted is large, to send the message in several concatenated balise telegrams. If grouped, the position of the first balise in the Balise Group (BG) defines the location reference. The balise subsystem is finally composed of single balises or clusters of balises at the ETCS trackside level (called also information points, noted as IP) and of Balise Transmission Modules (BTM) at the ETCS on-board level. The train BTM reads the IP when the train passes over the cluster of balises.

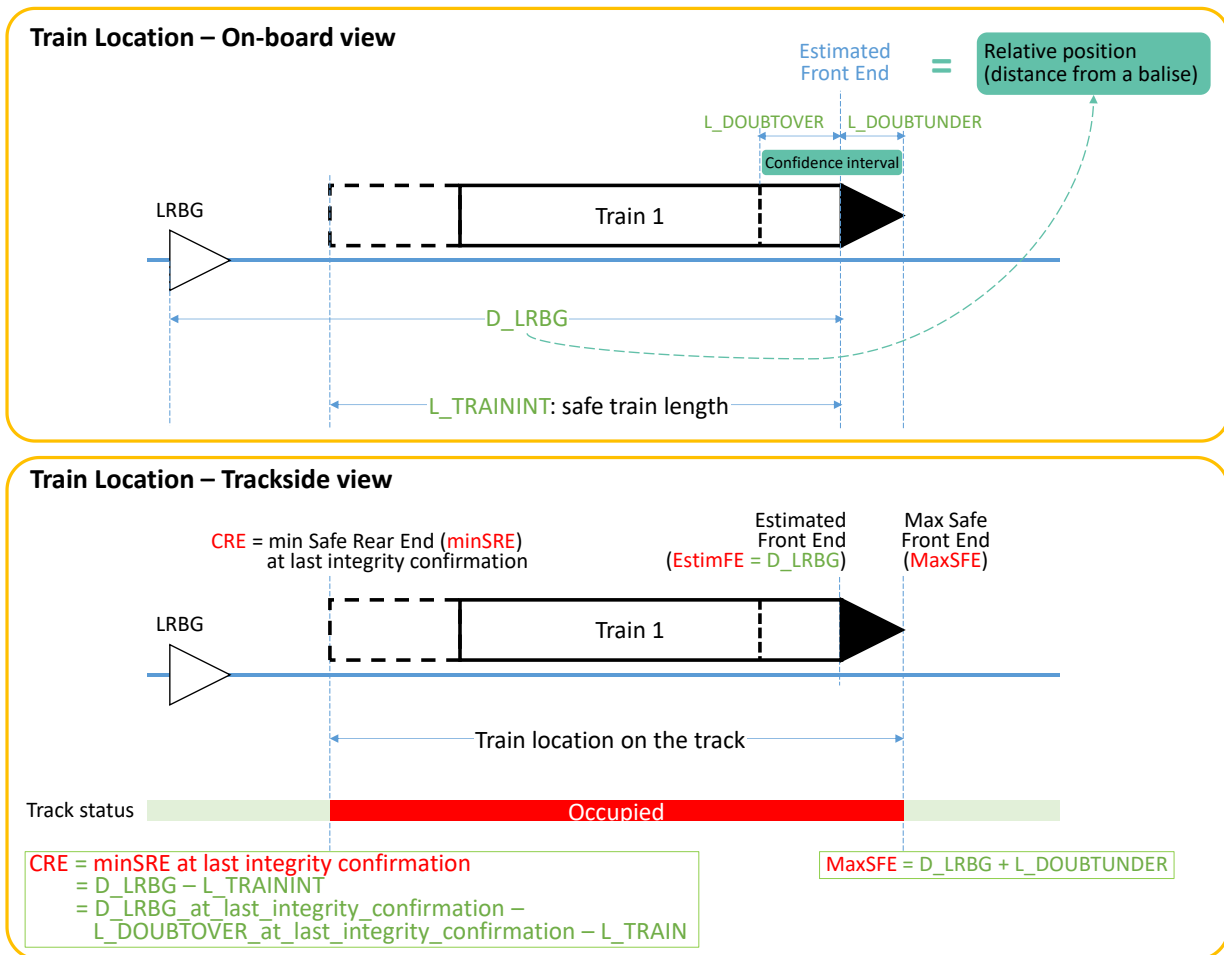
The odometry device measures train distance from the last IP (named also LRBG for Last Relevant Balise Group) thanks to a dead-reckoning method. It relies on velocity data that often come from angular speed sensors located on locomotive wheels. Inaccuracy of such device depends on the intrinsic characteristics of the device that can lead to small errors but that accumulate in time if they are not reset. It also depends on unpredictable environment conditions, in particular bad adhesion conditions between the wheel and the rail. These conditions can generate wheel slipping (particularly during acceleration phases) or wheel blocking (particularly during braking phases). Resulting inaccuracies are estimated by the on-board localization system, which provides a confidence interval associated to the measured distance.

Trains have to regularly report their position to the trackside system using a train-to-trackside radio message. The Train Position Report (TPR) is sent when the train reaches some particular positions on the track, and also periodically following a defined TPR frequency. The TPR message includes the following information, which allows the trackside system to determine the track occupancy, as shown in Figure 9:

- The distance between the LRBG and the estimated front end of the train:  $D\_LRBG$  variable in ETCS Level 2.
- The confidence interval on the estimated position (the train head):  $L\_DOUBTUNDER$  and  $L\_DOUBTOVER$  variables in ETCS Level 2.
- The train integrity information, i.e. the integrity status and the Confirmed Rear End (CRE) associated to the safe train length.

In existing (Subset-041 UNISIG, 2015), the today requirement on localization is  $\pm (5 + 5\%.d)$  meters, with  $d$  being the measured distance from the reference point (LRBG).

In ETCS L3, the train positioning will be determined by an on-board Train Localization Unit (TLU). Global Navigation Satellite Systems (GNSS) show to be “Game-changer” technologies for ERTMS stakeholders (EUAR, 2015). That is why they are envisaged inside the TLU giving the possibility to the L3 On-board to read virtual markers placed on the track at a higher frequency than trackside balises. In such a way, the GNSS-based equipment can play the role of a Virtual Balise (VB) that is functionally equivalent to a physical one (or to a balise group). In fact, VB are georeferenced points recorded in a database embedded in the train’s computer, which can be read by an on-board reader.



**Figure 9:** Train location: on-board data and translation in FMB track occupancy status

This VB concept and their related risks (cf. section 5.2.2) have been and are still investigated in various European research projects related to ETCS operations and safety. More details on the architecture of the virtual balise system and the system limitations (accuracy, availability, continuity, and localization integrity) can be found in Annex C (section 12.1).

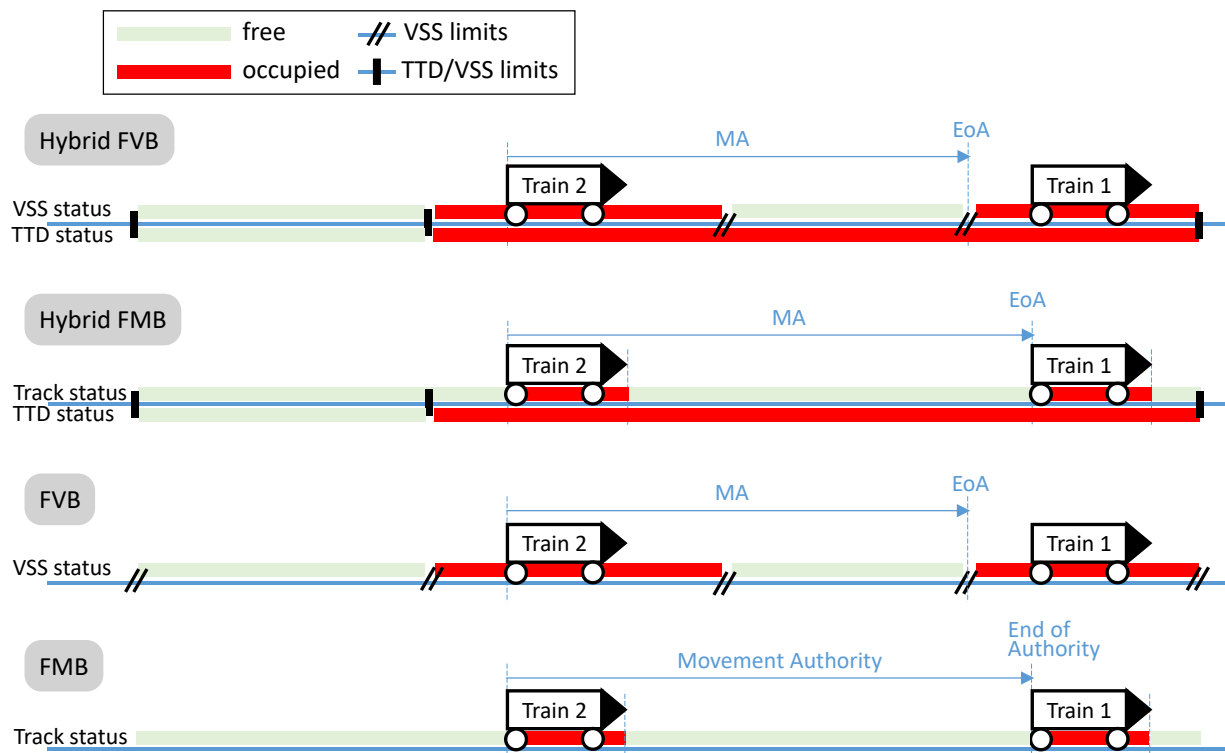
#### 4.4.3. Track Status

In Hybrid FVB, the L3 Trackside system has to manage 2 types of track occupancy status, as shown in Figure 10 representing them according to the MB system types:

- **Status of TTD:** free / occupied. This status is determined using track equipment outputs.
- **Status of FVB:** free / occupied / and others (see hereafter). In (EUG, 2020), the terms 'VSS status' (Virtual Sub-Sections) is used. This status is determined using information in the Train Position Report (refer to the previous subsection).

In FMB, a train clears the track behind its rear end in accordance with the progressing interval of train location. In Figure 10, the safety margin in rear of trains is not represented.

All Track Status Areas represent the track occupancy of a line. When the trackside system knows without any doubt the TTD status and train position information, track status areas are either Free (the term ‘Clear’ is also found) or Occupied. However, in case of any doubt, two other types of status are encountered: Unknown and Ambiguous. (D4.2 X2Rail-3, 2020) only defines the Unknown status for all MB system types.



**Figure 10:** Track status in the 4 types of ETCS-Level 3 MB system

In (EUG, 2020) dedicated to Hybrid FVB systems, the Unknown and Ambiguous status are defined. Therefore, in this last case, the Ambiguous status is only dedicated to lines with FVB, i.e., to the status of FVB (‘status of Virtual Sub-Section (VSS) is rather used in (EUG, 2020)).

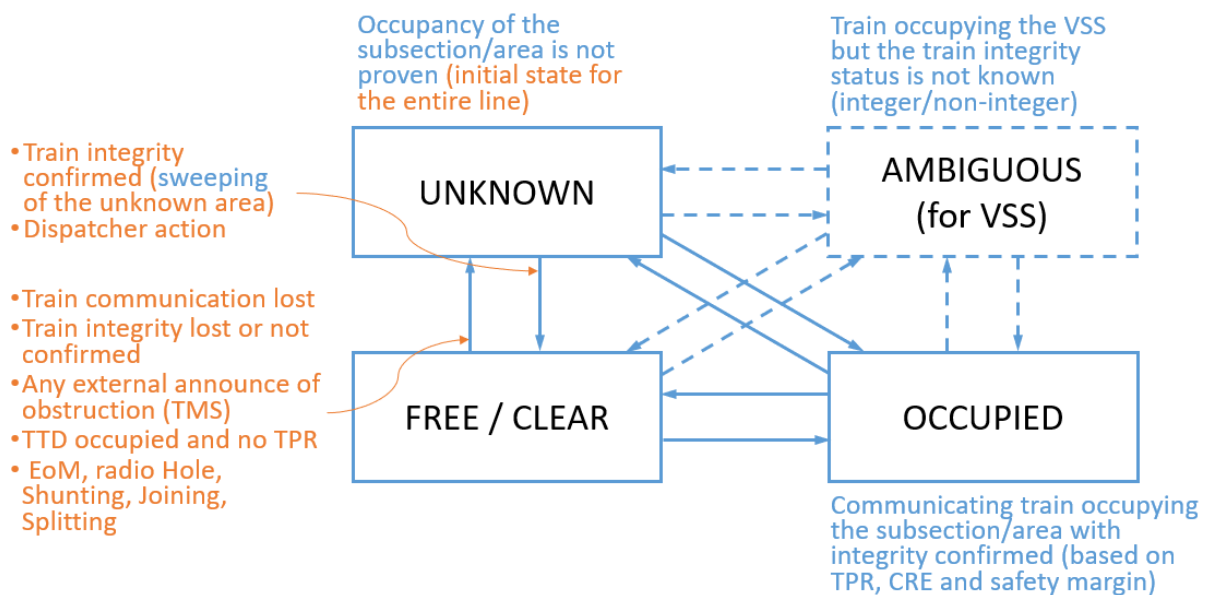
Unknown Track Status Areas can be Sweepable, i.e., partially or totally removed and replaced by a confirmed track status for normal train operations, i.e. Free / Occupied areas. An Unknown area can also be explicitly marked as unsweepable in given circumstances.

Figure 11 shows the different possible track status and the triggering conditions for switching from one state to another state. For example, the ‘Unknown’ -> ‘Free’ transition is triggered when a train, which has Train Integrity confirmed (refer to subsection 4.4.1 dedicated to integrity monitoring), enters an area that was initially having an Unknown Track Status. As a result, this Unknown area is ‘swept’ by the passing train.

Note that, as the **Ambiguous** status is only found in (EUG, 2020) and not in (D4.2 X2Rail-3, 2020),

the corresponding rectangle and transitions are in dotted lines. A Virtual Sub-Section (VSS) has an Ambiguous Track Status if the VSS is known to be occupied by a connected train (i.e., communicating with the trackside system) but it is unsure if another unconnected train is present.

The conditions for the transition from each state to each other are detailed in (EUG, 2020) for Hybrid FVB. Different Boolean variables are employed, some of them rely on the expiration of timers (refer to subsection 5.3). The conditions in orange colour are an overview of those found in (D4.2 X2Rail-3, 2020) - part 3.



**Figure 11:** Transitions between track status

## 5. Moving Block System Specification

### 5.1. Synthesis of Moving Block Requirements, Operational, and Engineering Rules

Annex B synthesizes result data of the X2Rail-3 project related to ETCS L3 MB system. This annex is a worksheet including the defined requirements, operational and engineering rules of the project (D4.2 X2Rail-3, 2020). Table 3 is taken from this annex to have an overview of the number of defined requirements and rules.

**Table 3:** Number of defined requirements, operational and engineering rules in **(D4.2 X2Rail-3, 2020)**

Topics		Requirements	Operational Rules	Engineering Rules
<b>GENERIC</b>	Train Location	14	1	2
	Track Status	19	6	1
	Reserved Status	6	0	1
	Fixed Virtual Blocks	1	0	4
	Trackside Train Detection	7	0	2
<b>OPERATIONAL SCENARIOS AND DEGRADED MODES</b>	Points Control	4	0	2
	Movement Authorities	12	0	0
	EoA Exclusion Area	2	0	0
	Start of Train	15	6	0
	On Sight movement	0	5	1
	Staff Responsible (SR) movement	5	0	1
	First MA	2	0	0
	Loss of Communication	6	4	1
	Recovery manag. after loss of com	3	1	0
	Radio hole	8	0	4
	Reverse movement	5	0	0
	End of Mission	4	1	2
	Loss of Train Integrity	10	2	6
	Level Transition	2	2	1
	Trackside Initialisation	5	5	3
	Handover	3	0	1
	Shunting movement	4	3	1
	Joining	3	0	0
	Splitting	1	0	0
Traffic Management System interface	1	0	0	
<b>Total</b>		142	36	33

Besides the synthesized data provided in Annex B, this document also demonstrates SysML diagrams for both the main requirements in Figure 12 and the timed requirements diagrams in Figure 13, as defined in (D4.2 X2Rail-3, 2020). The time constraints are defined later in Section 5.3.

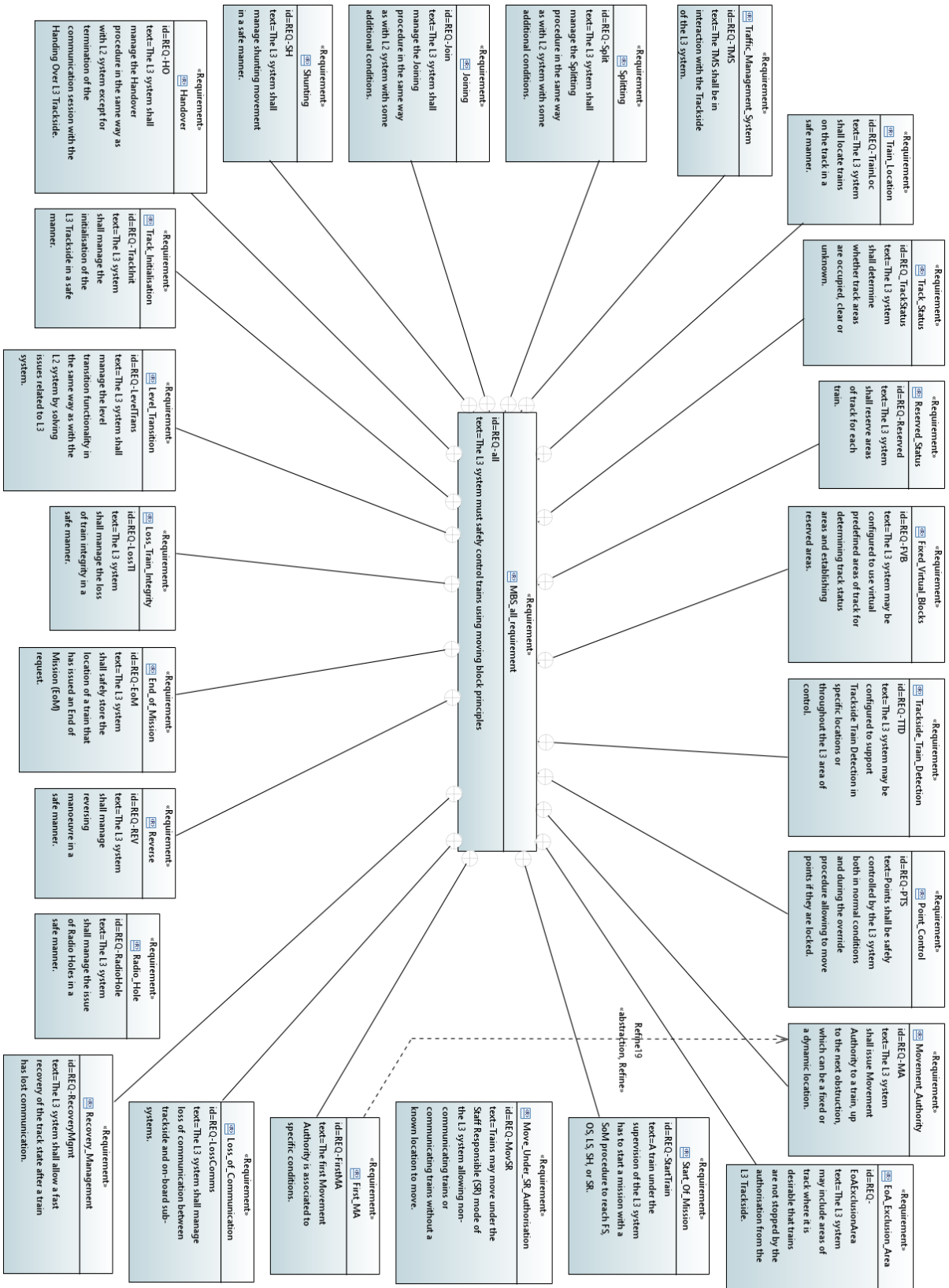


Figure 12: SysML Diagram for MB main requirements

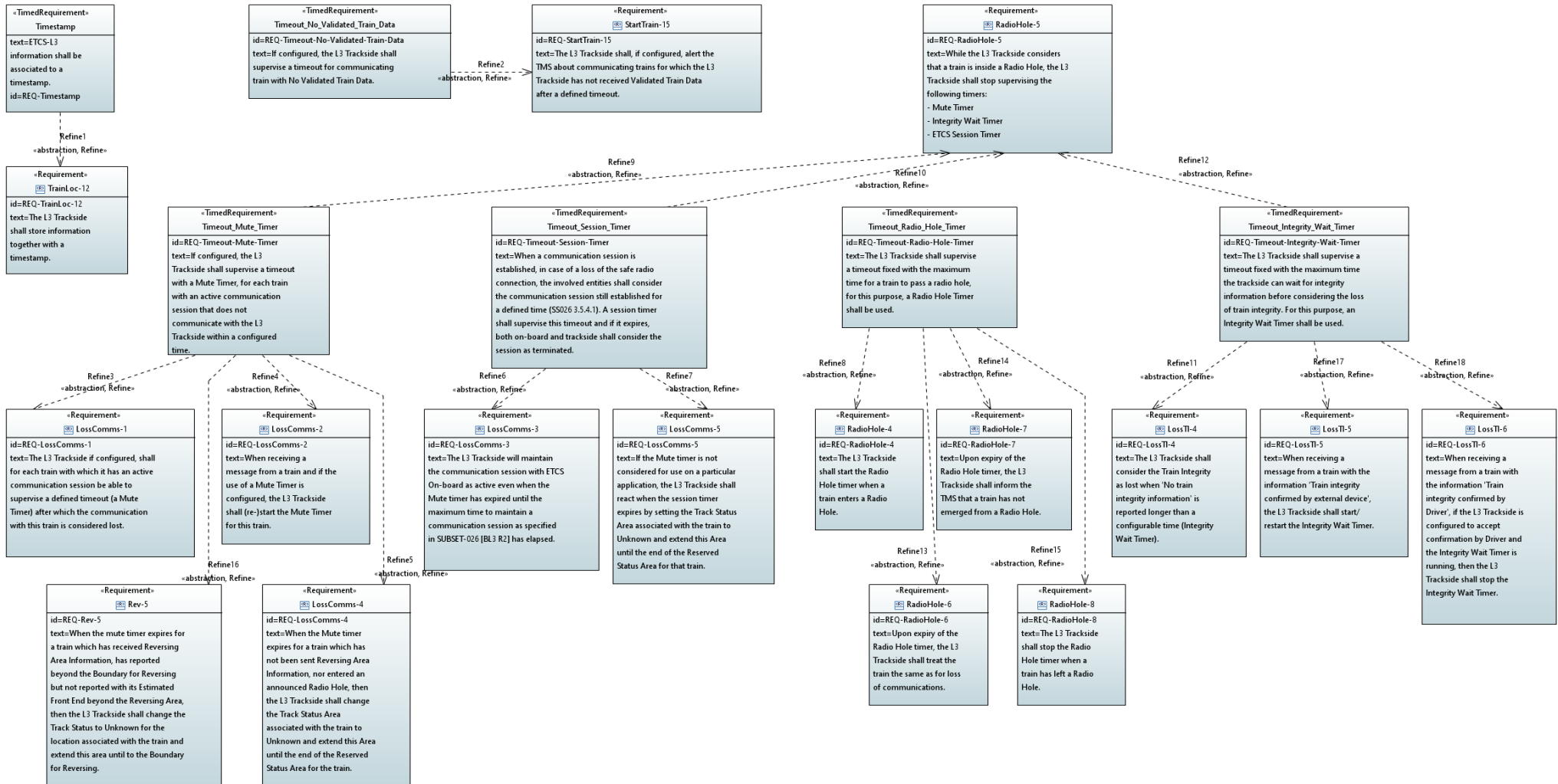


Figure 13: SysML Diagram for MB Timed Requirements



## 5.2. Hazards Analysis

### 5.2.1. Existing Hazard Analysis

(D4.2 X2Rail-3, 2020) – Part 6 titled “Safety Analysis” has identified all the hazards for a Moving Block Signalling system. Each hazard was described and referenced to specific Requirements (REQ), Operational & Engineering Rules (OPE/ENG) and Assumptions (ASM) related to potential mitigations. The hazards were classified into 6 categories including: Error in Train Location, Error in Train Length, Track Status Erroneously Cleared, CMD Erroneously Validates Position, Undetected Movements, TTD erroneously indicates track clear, and Points Moved under train. Afterwards, the deliverable developed a risk estimation for each hazard based on its severity and frequency to occur.

This deliverable extends the hazards to focus on GNSS-specific hazards used in terrestrial transportation. However, the GNSS-based VBTS (Virtual Balise Transmission System) appears to be the most mature GNSS-based solution envisaged in ERTMS/ETCS (D3.2 X2Rail-2, 2019). For this reason, this deliverable details the riskiest VBTS hazards. A hypothetical architecture of VBTS attempting to synthesize literature on such system is presented in Annex C of this deliverable. Also, this section provides some possible mitigations of hazards for each case.

### 5.2.2. GNSS Hazards

As it is known, Global Navigation Satellite Systems play a key role in the provision of position, velocity and time of a given receiver. Albeit rail applications account only for the 0.3% of the total GNSS revenues (in par with Manned aviation, 0.5%, (GSA, 2019)), their usage in this sector is gaining relevance, in view of the investment (in terms of public funding)<sup>2,3</sup>. In particular, the Shift2Rail programme has addressed GNSS in rail from various perspectives<sup>4</sup>: projects such as ASTRAIL and GATE4RAIL specifically focus on this topic. An extensive list of GNSS-related projects applied to rail is also curated by the European Space Agency, under the Space4Rail initiative<sup>5</sup>.

Obviously, as a sector in which safety is paramount in order to avoid risk on human life, accuracy and localization integrity must be guaranteed. However, GNSS is not exempt of factors that degrade its performances. That is why works are still in progress in various projects conducted in particular by EUSPA, ESA and Shift2Rail / Europe's Rail. The following sections include a list of potential GNSS hazards (and potential mitigations, see for instance (Zidan, et al., 2020)) that are relevant in the context of GNSS used in terrestrial transportation, especially where local environment can generate propagation phenomena impacting estimated positions:

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<sup>2</sup> For a list of funding prepared by the European Union Agency for the Space Programme (EUSPA, ex-GSA) please follow this link <https://www.gsa.europa.eu/sites/default/files/rail-roadmap2018.pdf>

<sup>3</sup> List of projects related to GNSS applied in the rail sector: <https://www.gsa.europa.eu/gnss-h2020-projects#rail>

<sup>4</sup> [https://projects.shift2rail.org/s2r\\_ip.aspx?ip=2](https://projects.shift2rail.org/s2r_ip.aspx?ip=2)

<sup>5</sup> Space4Rail page <https://space4rail.esa.int/projects>



<b>GNSShazard-001</b>
<b>Headline:</b> Partial lack of satellite visibility
<p><b>Description:</b>            At least 4 satellites are required to obtain a 3D position fix along with the receiver clock bias estimate (i.e., 4 unknowns). With the increased number of constellations available nowadays besides the American Global Positioning System (GPS), this requirement can be easily met. However, this is the bare minimum and will not allow for an accurate position fix. In fact, works such as (Misra &amp; Enge, 2001) point out of the effects of partial sky visibility into the final accuracy (through the analysis of the Dilution of Precision or DOP, which greatly depends on the satellite visibility).</p> <p>This scenario usually takes place when the train goes through an urban canyon (usually incoming or outgoing to/from a station) or in deep valleys with high mountains nearby.</p>
<p><b>Mitigation:</b>            Possible solutions may help mitigate this hazard:</p> <ul style="list-style-type: none"> <li>- Estimation of the train velocity and limiting the dynamics of the train (it can move only in the direction of the velocity unless there is a derailment) might help the navigation engine in the event of few satellites in view.</li> <li>- Assisting GNSS navigation engine with ancillary data such as inertial measurements in a loosely coupled configuration mitigates potential losses in visibility</li> </ul>
<b>Severity:</b> Moderate
<b>Frequency:</b> Probable
<b>Risk before mitigation:</b> Undesirable

<b>GNSShazard-002</b>
<b>Headline:</b> Total lack of visibility
<p><b>Description:</b>            Obviously, no GNSS-based position fix can be achieved if no GNSS satellites are in view. This is the situation when the train enters into a tunnel or goes underground.</p>
<p><b>Mitigation:</b>            In this case, a position fix may be obtained by using inertial measurement units and perform a loosely coupled integration model, in which the GNSS position fix is propagated in time using the time propagation of the accelerometer and gyroscope measurements (see for instance (Groves, 2007)).</p> <p>Other mitigation possibilities are using alternative systems as Positioning, Navigation, and Timing (PNT) providers, which can be challenging to apply in a railway environment (Wi-Fi, Ultra wideband or Bluetooth)</p>
<b>Severity:</b> Moderate
<b>Frequency:</b> Probable
<b>Risk before mitigation:</b> Undesirable

<b>GNSSHazard-003</b>
<b>Headline:</b> Jamming/interference
<b>Description:</b> Jamming and interference are caused by electronic devices that emit noise (or other signal) at the same frequency as GNSS (Dovis, 2015). Interference makes the receiver to not be able to lock into the GNSS signal (despite the presence of GNSS satellites), thus causing a denied GNSS scenario.
<b>Mitigation:</b> In practice, this hazard shall be tackled as a partial or total lack of GNSS visibility, thus using inertial sensors to propagate the last known position.
<b>Severity:</b> Critical
<b>Frequency:</b> Rare
<b>Risk before Mitigation:</b> Undesirable

<b>GNSSHazard-004</b>
<b>Headline:</b> Spoofing
<b>Description:</b> Spoofing is caused intentionally when a transmitter mimics the GNSS signal so that the target receiver computes a wrong position (see for instance (Psiaki & Humphreys, 2016)). This is a weakness that can potentially affect rail applications in a critical way due to its intentional nature and because it can totally disrupt its operations.
<b>Mitigation:</b> The safest way to deal with spoofing is through detection. The Galileo Open Service Navigation Message Authentication (OS-NMA) (Fernandez-Hernandez, Vecchione, & Díaz-Pulido, 2018) has been designed and deployed with the purpose of detecting spoofed scenarios and give a protection layer to the GNSS receiver. It is important to note, however, that the OS-NMA service only detects inconsistencies in the Galileo navigation message according to an authenticated key, therefore it is of no use in meaconing attack, where the GNSS signal is recorded and replayed (the signal is legit) by the attacker.  In addition, detection can be based by cross-comparison of the GNSS position fix with alternate PNT systems that are based on the train (inertial sensors, Wi-Fi. ...). Inconsistencies in position would trigger warnings.  Once the detection has been performed, in the event of a spoofing event, the mitigation strategy would be also based in the one described in GNSSHazard-002.
<b>Severity:</b> Critical
<b>Frequency:</b> Rare
<b>Risk before mitigation:</b> Undesirable

<b>GNSSHazard-005</b>
<b>Headline:</b> Multipath Propagation
<p><b>Description:</b> Is caused when GNSS signals that are not directly visible bounce from nearby buildings or structures (i.e., other nearby vehicles or trains) and are tracked by the receiver (see for instance (Townsend, Van Nee, Fenton, &amp; Van Dierenconck, 1995)). This usually results in jumps in the position estimates.</p>
<p><b>Mitigation:</b> Multipath propagation can be mitigated by:</p> <ul style="list-style-type: none"> <li>- Using detection techniques based on multi-frequency data (see for instance (Strode &amp; Groves, 2016)). Once the signal for a GNSS satellite is flagged as affected by multipath, this signal is ignored by the navigation filter.</li> <li>- Raising the elevation mask so that low-elevation signals, which are the ones mostly affected by multipath, do not enter the navigation filter. This approach is, however, risky as removing too many measurements could eventually increase the error in the horizontal dimension.</li> <li>- Weight the incoming measurements with the SNR (the higher the SNR, the higher the weight inside the navigation filter). Measurements with multipath are characterized by a higher noise (and thus lower SNR).</li> </ul>
<b>Severity:</b> Moderate
<b>Frequency:</b> Probable
<b>Risk before mitigation:</b> Undesirable

<b>GNSSHazard-006</b>
<b>Headline:</b> Increased number of cycle-slips (loss of lock)
<p><b>Description:</b> Loss-of-lock in carrier phase measurements are caused by signal panels above the train, signal interruption, foliage and vegetation. This loss of lock affects the GNSS carrier measurements in the form of cycle slips (i.e., phase breaks) which momentarily degrade the position estimate. If those breaks happen at various satellites at the same time, the navigation filter may be temporarily compromised and deliver a solution beyond the maximum allowed positioning error.</p>
<p><b>Mitigation:</b> This hazard may be treated similarly as partial or loss of GNSS visibility, thus using assistance information such as inertial measurements to mitigate any upsetting of the navigation filter.</p>
<b>Severity:</b> Moderate
<b>Frequency:</b> Probable
<b>Risk before mitigation:</b> Undesirable

The preliminary hazard analysis in (D3.2 X2Rail-2, 2019) examined the failure modes of the following VBTS functionalities:

- a. **Virtual Balise Detection:** the “Virtual Balise Reader” (VBR) is the on-board ETCS constituent that realizes this function. It is responsible for the “Estimate Safe Train Position” function based on GNSS Data as well as Odometry Info (and Kinematic Sensors, if included) and providing Virtual Balises (when Virtual Balise Detection occurs) to the ETCS Kernel.
- b. **Static Track Data Management:** the “static Track Data” includes the Virtual Balise representation that is necessary to VBR in order to perform the Virtual Balise Detection.
- c. **Track Discrimination:** this function allows the “Estimate Safe Train Position” function to provide a position without any track-route ambiguity. It uses the “dynamic Route Info” (status of switch points relevant for the train route, initial train position, initial train orientation) in addition to “Static Track Data”.

The identified hazards are provided in Table 4 below with some possible mitigations (not exhaustive) listed in (D3.2 X2Rail-2, 2019). Mitigations AC\_VBTS\_003 and AC\_VBTS\_006 have been investigated in S2R GATE4Rail project.

**Table 4:** Functional failure modes of the VBTS and possible mitigations

Functional failure modes of the VBTS	Possible mitigations
<b>Virtual Balise Detection</b>	
A virtual balise present on the track is detected before its position	<ul style="list-style-type: none"> <li>– <b>SR_VBTS_002:</b> The VBTS, during the start up, shall check that the current Static Track Data stored on-board are consistent with the VBTS wayside segment Static Track Data</li> <li>– <b>SR_VBTS_003:</b> The VBR shall provide to the ETCS Kernel both the virtual balise and the "accuracy values" at the same time</li> <li>– <b>SR_VBTS_004:</b> The VBR shall provide the "accuracy values" related to the detected virtual balise location that will assure the presence of the virtual balise in a window properly dimensioned taking into account this "accuracy values"</li> <li>– <b>SR_VBTS_006:</b> The confidence interval related to the virtual balise location shall be calculated with a proper safety level</li> <li>– <b>SR_ATP_002:</b> The ETCS Kernel shall include, in the evaluation of the Balise Group Location Accuracy, the "accuracy values" provided by VBR in the Balise Information</li> <li>– <b>AC_VBTS_003:</b> The Virtual Balises shall be located within the areas assessed as valid by performing a GNSS signal quality Survey</li> <li>– <b>AC_VBTS_004:</b> Specific maintenance around the railway line shall be done in order to avoid the arising of new multipath and EMI causes (e.g.: threes, buildings, RF antennas)</li> <li>– <b>AC_VBTS_006:</b> The Virtual Balises shall be installed in geographic position where the environment does not have reflections phenomena and reverberations (cause of multipath and EMI)</li> </ul>

A virtual balise present on the track is detected after its position	Same as previous failure hazards
The same virtual balise is detected several times without any change of the train movement direction	<ul style="list-style-type: none"> <li>– <b>SR_VBTS_002:</b> The VBTS, during the start up, shall check that the current Static Track Data stored on-board are consistent with the VBTS wayside segment Static Track Data</li> <li>– <b>SR_VBTS_005:</b> The VBR shall generate the correct sequence of balises according to the train running direction</li> <li>– <b>AC_VBTS_003:</b> The Virtual Balises shall be located within the areas assessed as valid by performing a GNSS signal quality Survey</li> <li>– <b>AC_VBTS_004:</b> Specific maintenance around the railway line shall be done in order to avoid the arising of new multipath and EMI causes (e.g.: trees, buildings, RF antennas)</li> <li>– <b>AC_VBTS_006:</b> The Virtual Balises shall be installed in geographic position where the environment does not have reflections phenomena and reverberations (cause of multipath and EMI)</li> </ul>
A virtual balise belonging to the adjacent track is detected	<p>Hazard related to Track Discrimination Failure Mode on parallel tracks is <b>not considered in X2R3</b> because, on the examined scenario, there were no parallel tracks. So, it is not applicable due to :</p> <ul style="list-style-type: none"> <li>– <b>AC_VBTS_008:</b> The signalling system shall use proper technologies and/or procedures in order to discriminate, during the VBR initialization, the actual train position in case of parallel tracks (e.g. real balises properly placed)</li> <li>– <b>AC_VBTS_009:</b> The signalling system shall consider as "parallel tracks" all the tracks located within a distance properly evaluated taking into account the confidence interval related to the position detected by the VBR system</li> <li>– <b>AC_VBTS_010:</b> The signalling system shall evaluate the impact of using VBTS on the railway lines with parallel tracks in line</li> </ul>
<b>Static Track Data Management</b>	
Static Track Data updated when not required	<ul style="list-style-type: none"> <li>– <b>SR_VBTS_002:</b> The VBTS, during the start up, shall check that the current Static Track Data stored on-board are consistent with the VBTS wayside segment Static Track Data</li> <li>– <b>SR_VBTS_093:</b> The VBTS shall check that the current Static Track Data stored on-board are consistent with the VBTS wayside segment Static Track Data whenever the Static Track Data are updated on-board</li> </ul>
Static Track Data not updated	—
Static Track Data updated more than needed	<ul style="list-style-type: none"> <li>– <b>SR_VBTS_002:</b> The VBTS, during the start up, shall check that the current Static Track Data stored on-board are consistent with the VBTS wayside segment Static Track Data</li> </ul>
Static Track Data partially updated	Same as previous failure hazards
Static Track Data corrupted during the update	Same as previous failure hazards

Track Discrimination	
Selected Track behind the actual train position	<ul style="list-style-type: none"> <li>– <b>SR_VBTS_037:</b> The VBR shall be initialized by proper procedures and/or technologies able to autonomously provide the actual train position</li> <li>– <b>SR_RBC_012:</b> The RBC shall include the List of Balises in Staff Responsible Authority packet (i.e. Packet 63) in every Staff Responsible Authorization message (i.e. Message 2) sent to the ETCS Kernel in case of parallel track</li> <li>– <b>SR_RBC_013:</b> The RBC shall not send any authority to move the train if it has not received from VBR any information that the Static Track Data stored on-board are updated</li> <li>– <b>AC_VBTS_001:</b> An External Entity shall select the position where the train is localized when requested for VBR initialization</li> <li>– <b>AC_VBTS_002:</b> The position communicated by the External Entity and received by the VBR shall be independently reviewed to ensure that the information is correct</li> <li>– <b>AC_VBTS_005:</b> An external entity shall provide the vehicle orientation when requested for VBR initialization</li> <li>– <b>AC_VBTS_008:</b> The signalling system shall use proper technologies and/or procedures in order to discriminate, during the VBR initialization, the actual train position in case of parallel tracks (e.g. real balises properly placed)</li> <li>– <b>AC_VBTS_011:</b> The signalling system shall allow to the driver the track ID discrimination (e.g. with marker boards)</li> </ul>
Selected Track beyond the actual train position	Idem than previous hazard
Selected Track adjacent to the actual train position (i.e., parallel track)	In addition to previous hazard: <ul style="list-style-type: none"> <li>– <b>AC_VBTS_009:</b> The signalling system shall consider as "parallel tracks" all the tracks located within a distance properly evaluated taking into account the confidence interval related to the position detected by the VBR system</li> </ul>

### 5.3. Time Constraints

This section highlights the timer constraints including timers' definition for ETCS L3 Moving Block System specifications. The use cases introduced in the next subsection will cross-reference the time constraints defined here.

#### 5.3.1. Frequency and Latency Delays

Main encountered frequencies and latency delays are the following:

- Frequency of the Train Position Report,
- Frequency of TIMS reporting,
- Normal communication latency delay.

In (D2.1 ASTRAIL, 2019), different values are given for communication delays, for different processing duration (including localization unit) and their associated probability of success.

### 5.3.2. Supervision of Elapsed Timeouts

Different timers are considered in ETCS Level 3 MB system specifications (D4.2 X2Rail-3, 2020). They are mitigation measures against train collisions. Some of them are defined to tackle abnormal communication latency delays of trackside-to-train or train-to-trackside radio messages indicating a loss of information (or un-freshness of the received data based on time stamp of messages):

- The **Mute timer** is an optional timer for ETCS-L3 MB systems. When the timeout is elapsed, the L3 Trackside considers the communication with the train as lost. This timer has the same purpose as the T\_NVCONTACT timer (defined below) but it can be longer based on the needs of the system,
- The **T\_NVCONTACT timer** is an existing timer in ETCS-L2 for the maximal time (in second) without new “safe” message (it is not supervised in radio holes),
- The **Session Expired timer**: is the maximal time after which a previously supervised train that does not communicate with the trackside is disconnected (a session is the process for initiating and terminating an applicative dialogue between trackside and on-board via radio),
- The **Radio Hole** timer is the maximal time for the train to pass a radio hole,
- The **Integrity Wait timer** is the maximal time the trackside can wait for integrity information before considering the loss of train integrity.

Different **train reactions** can be triggered when the previous timer elapses: service braking, emergency braking, no reaction. Different **trackside reactions** can also be triggered: create an additional margin behind the train or shortened/updated the Movement Authority of that train, create a new unknown area.

A **propagation timer** is defined for areas with track status ‘Unknown’. The concept of ‘Propagation’ is based on the idea that an area with Unknown Track Status may need to increase, possibly after a period of time, to allow any railway vehicles in the area with an Unknown status to move without knowledge of the L3 Trackside system.

#### **Timer for desynchronization of Track status with TTD and TPR:**

For a MB system using Trackside Train Detection, L3 Trackside has to manage the lack of synchronisation between TTD occupancy and Train Position Reports for a train during normal operation. For a train during normal movement, it will occur that the train physically occupies a TTD before it has reported its position within the TTD boundary (or vice versa). The L3 Trackside must correlate these two events, such that it does not react in an overly restrictive manner to what is normal behaviour (D4.2 X2Rail-3, 2020). The use of a delay timer is to account for lack of synchronisation between TPR and TTD occupancy. If a train is still not detected when the timer expires, the L3 Trackside would react suitably.

The starting conditions for each configurable timer and the ending conditions are detailed in Table 5. Possible reactions when a timer is elapsed are also detailed.



**Table 5: Starting/ending conditions of timers in (D4.2 X2Rail-3, 2020) (EUG, 2020)**

Timer name	Configured entity	(Re)-starting condition	Ending condition before elapsing	Reaction if elapsed
<b>MUTE timer</b>	<ul style="list-style-type: none"> <li>- Configured at L3 Trackside level</li> <li>- One timer/train</li> </ul>	<ul style="list-style-type: none"> <li>- Information is received by Trackside from the train</li> <li>- The train exits a Radio Hole area.</li> </ul>	<ul style="list-style-type: none"> <li>- The train enters in a Radio Hole area</li> <li>- There is no communication session with the train.</li> </ul>	The Trackside sets the Track Status Area associated with the train to Unknown and extend this Area until the end of the Reserved Status Area for that train.
<b>T_NVCONTACT Timer</b>	<ul style="list-style-type: none"> <li>- Configured at on-board level</li> <li>- One timer/train</li> </ul>	(Similar to MUTE timer)		<ul style="list-style-type: none"> <li>- Train trip</li> <li>- Apply service brake</li> <li>- No reaction</li> </ul>
<b>SESSION_EXPIRED timer</b>	<p>(Cf. (Subset 026 UNISIG, 2016))</p> <ul style="list-style-type: none"> <li>- Configured at L3 on-board level</li> <li>- One timer/train</li> <li>- Maximum time to maintain a communication session in case of failed re-connection attempts: 5min (cf. (Subset 026 UNISIG, 2016) - part 3-Appendix A.3.1)</li> </ul>	<ul style="list-style-type: none"> <li>- The on-board system version corresponding with the one sent by Trackside (initialisation)</li> <li>- A communication session shall be terminated with a RBC to open a session with a new Accepting RBC</li> <li>- The train exits a Radio Hole area</li> </ul>	<ul style="list-style-type: none"> <li>- The train enters in a Radio Hole area.</li> <li>- The on-board system version does not correspond with the one sent by trackside.</li> <li>- A session is already established.</li> <li>- Cf. (Subset 026 UNISIG, 2016) - part 3-3.5.3.8</li> </ul>	The Trackside sets the Track Status Area associated with the train to Unknown and extend this Area until the end of the Reserved Status Area for that train.
<b>RADIO_HOLE timer</b>	<ul style="list-style-type: none"> <li>- Configured at L3 Trackside level</li> <li>- One timer/train</li> </ul>	The train enters in a Radio Hole area.	The train exits a Radio Hole area.	<ul style="list-style-type: none"> <li>- The Trackside sets the Track Status Area associated with the train to Unknown and extend this Area until the end of the Reserved Status Area for that train.</li> <li>-The Trackside alert the TMS that the train has not reported clear of the area.</li> </ul>
<b>INTEGRITY_WAIT timer</b>	<ul style="list-style-type: none"> <li>- Configured at L3 Trackside level</li> <li>- One timer/train</li> </ul>	<ul style="list-style-type: none"> <li>- The Trackside receives a message from a train with the information 'train integrity confirmed by external device' (or 'train integrity confirmed by</li> </ul>	<ul style="list-style-type: none"> <li>- The train reports 'integrity lost'.</li> <li>- The train reports a change of train data and train length.</li> <li>- The mute timer expires.</li> </ul>	<p>Non-exhaustive possibilities:</p> <ul style="list-style-type: none"> <li>-Cause the train to Trip</li> <li>- Create an additional margin behind the train</li> <li>- The Movement Authority may be shortened/updated</li> <li>- no reaction</li> </ul>



		driver' if configured) - The train exits a Radio Hole area.	- The train enters in a Radio Hole area.	
<b>PROPAGATION timer</b>	(Not defined)			
<b>DESYN-CHRONIZATION timer</b>	- Configured at L3 Trackside level (only for hybrid FMB and hybrid FVB) - One timer/TTD	- TTD occupied and no corresponding TPR for the same track section - TPR informing of an occupied track section and corresponding TTD free	TTD/TPR aligned	(only said that the L3 Trackside should react suitably)

**Shadow\_Train timer, Ghost\_Train propagation timer, Integrity\_Loss\_Propagation timer and Disconnect\_Propagation timer** are additionally defined in (EUG, 2020). As they only concern Hybrid FVB systems, they are not developed more here.

## 5.4. Use Cases for Moving Block System

In this section, a detailed description of the ETCS L3 MB use cases is reported. In this document, an ETCS L3 MB use case is defined as a specific context, involving L3 on-board, trackside and external actors and interfaces. It is characterized by specific features, system hazards or applicable operational/engineering rules. A use case could be related to **functionalities** of the ETCS L3 MB system (e.g., handover, train splitting), to **operation on trackside entities** (e.g., track status initialization), to **coexistence of ETCS and non-ETCS traffic** (e.g., ghost trains) and to a **degraded mode** (e.g., march in SR). Table 6 enumerates the use cases and reports how they are distributed on the considered source documents; then, each use case is described in a dedicated subsection. For each use case, a structured description will be provided, considering:

- A description of the **scope**;
- A list of involved external **actors** (with respect to ETCS L3);
- A list of related ETCS L3 **internal functions** (both on-board and trackside);
- A description of the most important functional features classified in the **behaviour** category;
- A list of system **parameters**, referring to operational and/or engineering rules;
- A list of the most relevant **safety hazards** (cf. part 6 of (D4.2 X2Rail-3, 2020)).

**Table 6:** Use cases considered in X2R projects and in EUG (D5.1 X2Rail-1, 2019) (D4.2 X2Rail-3, 2020) (EUG, 2020)

No	Use Case	X2R1 MB	X2R3 MB	EUG hybrid L3	Comments
1	Trackside Initialisation	X	X		
2	Start of Mission	X	X	X <sup>(1/2)</sup>	In (EUG, 2020), SoM and EoM are together
3	Normal Train Movement	X		X	
4	Level transitions	X	X		
5	Handover	X	X		
6	On Sight (OS) Movement	X			
7	End of Mission	X	X	X <sup>(1/2)</sup>	In (EUG, 2020), SoM and EoM are together
8	Reversing	X	X		
9	Splitting	X	X	X	
10	Joining	X	X		
11	Shunting	X	X		
12	Mixed Traffic	X			
13	Loss/Restore of Communications	X	X	X <sup>(2)</sup>	In (EUG, 2020), the reconnection is also in this scenario and can be followed or not by a VSS release
14	Loss of Train Integrity	X	X	X	
15	Recovery of a Failed Train	X			
16	Staff Responsible (SR) movement	X	X		
17	Radio Hole		X		
18	Points Control		X		
19	Sweeping		X	X	
20	Shadow train			X	
21	Ghost train			X	
22	Change of direction			X	
<b>Total</b>		<b>16</b>	<b>15</b>	<b>10</b>	

### 5.4.1. Trackside Initialisation

**Scope:** The Trackside Initialisation use case is related to the safe initialisation of an Area of Control when starting or restarting the L3 Trackside system in an ETCS Level 3 Moving Block system. The process will depend on whether or not TTD is provided. The main objective of the related functionality is to correctly identify the status of the parts of the area (i.e., which parts can be considered Clear and which are not) and avoid that MAs are sent during the Initialisation procedure. At this aim the L3 Trackside uses Stored Information to obtain the current state of the railway (In the absence of TTD). A responsible person oversees initialising the L3 Trackside and confirm the end of procedure if the Stored Information cannot be considered valid. Criteria for considering Stored information as valid are project dependent.

External Actors: Dispatcher, Infrastructure Manager, Traffic Management System (TMS), Trackside Train Detection (TTD)

Related Internal Functions:

- Trackside: Track Status Management, Reserved Status Management

Behaviour:

- The entire L3 Area of Control must be in Track Status Unknown at the start of the procedure.
- The L3 Trackside creates Occupied areas for Trains in communication, Unknown areas based on stored data, and accept any additional Unknown areas created at the request of the TMS. Once the procedure is confirmed to be completed, the remaining track can be considered Clear.
- The validity of the stored information about the state of the railway before the L3 Trackside restarting is carefully considered.
  - in case of valid information: the L3 Trackside utilises it to enable faster initialisation without the need of a confirmation at the end of the procedure;
  - otherwise: the responsible person, in charge of initialising the L3 Trackside, has to confirm that all the obstacles on the railway are known to the L3 Trackside and when the procedure is completed, after receiving confirmation of completion of the Initialisation procedure from the responsible person, the L3 Trackside sets the remaining Unknown areas not associated with any obstruction as Clear.

System Parameters:

- Status variables: Track Status (Occupied, Clear/Free, Unknown)
- Status of stored data about the state of the railway (valid, not valid)

Safety Hazards:

- **H-Clearing-001:** Track Status Area erroneously cleared during L3 Trackside initialisation by dispatcher leading to collision (due to the responsible person)
- **H-Clearing-002:** Track Status Area erroneously cleared during L3 Trackside initialisation by system leading to collision (due to invalid/outdated information)

## 5.4.2. Start of Mission

Scope: The Start of Mission (a.k.a. Start of Train - SoM) use case for an L3 Area is related to the initialisation/configuration of all the data structures/sub systems associated with a specific train that has issued a Start of Mission request. By means of the SoM, an on-board and the related trackside start communicating in a safe manner, the train communicates its parameters that are validated from the trackside and the trip of the train can start. The situation to analyse here is similar to the same use case for an L2 Area, as the main differences just reside in the way the position of the train is detected (particularly when the optional TTD system is missing). Another important difference is constituted by the checking of the train/trackside of the train integrity, which is of paramount importance in L3.

External Actors: Traffic Management System, Train Integrity Management System

Related Internal Functions:

- Trackside: Train Management, Track Status Management, TTD Management
- On-board: Train Position Reporting, Integrity Information Management

Behaviour:

- When a train issues a Start of Mission request, the L3 Trackside accepts and maintains a connection, regardless of the fact that the train has an invalid/unknown position. By means of a valid Position Report, the L3 Trackside can determine whether train is within its Area of Control.
- Every time a L3 Trackside establishes a safe communication session with a train, the Trackside compares the received information against the information stored at the same location for a previous train. This is to determine whether the train is performing a Start of Mission or is recovering from a previous loss of communication (see Loss/Recover of Communication).
- Here some cases of PRs, when not yet sent Validated Train data,
  - The train reports a position with both the Min Safe Front End and the Max Safe Front End in an area of track considered Clear. In this case, the L3 Trackside shall create an Unknown Track Status Area for the front end of this train from the reported Min Safe Front End to Max Safe Front End.
  - The train reports a position with a Confidence Interval which is partly in an Unknown Track Status Area and the Estimated Front End outside this Unknown Track Status Area. Hence, the L3 Trackside shall extend this Unknown Track Status Area to the boundary of the reported Confidence Interval for the Estimated Front End of this train.
- When receiving Validated Train Data from a train which is not associated with an Unknown Track Status Area except for the Estimated Front End of this train, then the L3 Trackside shall extend this Unknown Track Status Area with the reported Train Length to the Min Safe Rear End.
- For a train reporting an invalid/unknown position, the L3 Trackside accepts from the TMS a position assigned by the Dispatcher.
- Cases when to alert TMS/Dispatcher:
  - a train which terminated its communication session without sending Validated Train Data to the L3 Trackside (TMS),
  - no L\_TRAIN has been received to establish the location for this train (TMS, Dispatcher),
  - not received Validated Train Data after a defined timeout,
  - for a train reporting an invalid/unknown position, if this position lies within an existing Unknown Track Status Area under its control (TMS),
  - for a train reporting an invalid/unknown position, if this position is not within an existing Unknown Track Status Area (TMS, Dispatcher),

- Validated Train Data from a train with a position within an Unknown Track Status Area for which the stored train length is different than what was previously reported by this train (TMS),
- A train reporting an invalid/unknown position or a valid position with an unknown (to the L3 trackside) NID\_BG (identifier of balise group) (TMS). In this case, the L3 Trackside puts to the Unknown the Track Status Area but from the MaxSRE to the minSFE of that train.
- On request from the TMS, the L3 Trackside shall order the train to terminate the communication session (see End of Mission use case).

System Parameters:

- L\_TRAIN: The absolute real length of the train.

### 5.4.3. Level Transitions

Scope: Management of the entering/exiting of L3 area is almost the same of what happens in L2, with the main challenge due to understanding the correct position of the train.

External Actors: none

Related Internal Functions:

- Trackside: Track Status Management, TTD Management, Communication Management

Behaviour:

- At the border of the L3 area, small TTD area should be placed to detect ghost trains trying to enter in the L3 area.
- For a train that has been authorised to leave the L3 Area, the L3 Trackside shall maintain the communication session with a train reporting a position with an LRBG which is not known to the L3 Trackside. This is due mainly to availability purposes to avoid that, at the first unknown balise group, the trackside terminates the communication interrupting the update of the CRE of the train. In this way, some track area should be placed in the unknown state. Communication should be kept until:
  - The CRE of this train is still located in the L3 Area or
  - The L3 Trackside decides that it is suitable to terminate the session with this train or
  - The TMS requests to terminate the session with this train.

System Parameters: none

Safety Hazards: none

#### 5.4.4. Handover

Scope: The handover procedure manages the passage of a train from the area of control of an L3 Trackside equipment (Handing Over – HO) to the area of another one (Accepting - ACC). As this procedure already exists in L2, this description is devoted to the difference in from L2 and L3 procedure, mainly focused is track management.

External Actors: none

Related Internal Functions:

- Trackside: Track Status Management, Reserved Status Management, Communication Management
- On-board: Train Position Reporting

Behaviour:

- The Route Related Information the HO sends to the ACC must be considered from the ACC as reserved since the HO could have considered them as part of an MA. In this case a mechanism to free unoccupied track areas of ACC should be considered to improve availability.
- The communication with the HO can be terminated (by means of a Communication Termination Message from HO) when the On-Board communicates to HO a Position Report with the CSRE beyond the border.
- In case an ACC that is communicating with a handing-over train considers terminated its communication with the train, the ACC must set to Unknown the tracks that have been reserved to that train. This case can be seen the same as the entering in L3 Area.

System Parameters: none

Safety Hazards: none

#### 5.4.5. End of Mission

Scope: The End of Mission (EoM) use case for an L3 Area is related to the storing, by the L3 Trackside, of the location of a train that has issued an EoM request. This is done mainly for the following two reasons.

- To permit a correspondence check between the data stored by the L3 Trackside and the information transmitted by the train, whenever it will issue a future SoM request. This check allows the change of the Track Status of the part of the track assigned to the train from Unknown to Occupied.
- To safely free part of the railway line to the use of other trains. Lack of Train Integrity information in this case has, indeed, a significant impact on the performance of the line. Therefore, it is important that the L3 Trackside receives a recent Train Position Report with the Integrity Confirmed just prior to EoM. If this does not happen, then there is the potential for a large area of the railway remaining unavailable, e.g., when the CRE remains over points and crossings.

- With respect to a L2 Area, no L3-specific operational rules are required, as it is assumed that L2 rules regarding leaving trains with brakes applied and secured at the end of a mission are sufficient.

External Actors: Traffic Management System, Train Integrity Management System

Related Internal Functions:

- Trackside: Train Management, Track Status Management
- On-board: Train Position Reporting, Integrity Information Management

Behaviour:

- When a train completes a journey and the Driver closes the desk, the on-board ETCS issues an EoM request and the train disconnects. At this point, the L3 Trackside updates the information associated with that specific train.
  - Since a train after an EoM is no longer authorised to move, there is no reason to reserve a track for the train to move. As consequence any Reserved Status Area associated with the train has to be removed.
  - The L3 Trackside needs to determine the area that could be occupied by the train in order to protect it. To this aim, the L3 Trackside is expected to use the location information received from the train.
  - The L3 Trackside needs to cope with differences in the confidence interval provided in the report transmitted at the EoM, due to an ambiguity in the ETCS specifications around how to calculate the train location accuracy when linking information is deleted due to the change to SB mode. In particular, the L3 Trackside does not apply a safe reaction if a train reports a different confidence interval without the train moving (i.e., different L\_DOUBTOVER and L\_DOUBTUNDER with the same D\_LRBG and LRBG). In general, the train must cope with the safety mechanism of linking information by which information about the next balise group to match is contained in the previous balise group. This mechanism is very important in EoM procedure due to the criticality the train routing plays in this use case.
- If the train issuing an EoM request is completely located inside an Active Shunting Area, the L3 Trackside removes the Track Status Area associated with this train, since protection after End of Mission is provided by the Unknown area associated with the Active Shunting Area.

System Parameters:

- *L\_TRAIN*: The absolute real length of the train.
- *L\_DOUBTOVER*: The over-reading amount plus the *Q\_LOCACC* of the LRBG.
- *L\_DOUBTUNDER*: The under-reading amount plus the *Q\_LOCACC* of the LRBG.
- *D\_LRBG*: Distance between the last relevant balise group and the estimated front end of the train (the side of the active cab).
- *Q\_LOCACC*: Accuracy of the balise location.
- *Q\_NVLOCACC*: Default accuracy of the balise location (absolute value).

Safety Hazards:

- **H-TrainLoc-001:** Error in Train Location from reduced confidence interval at EoM leads to collision.

### 5.4.6. Reversing

Scope: The Reversing use case addresses authorised reverse movements of a train: the main scope is to regulate not only the permission of a train backwards movement, but also the management of the reservation of the track behind the reversing train. Given the behaviour of the reversing procedure of ETCS L2 between the on-board, the train driver and the trackside, here the focus is on Track Status and Reserved Status since the biggest problem is to guarantee to the reversing train a proper space of (reversed) movement.

External Actors: none

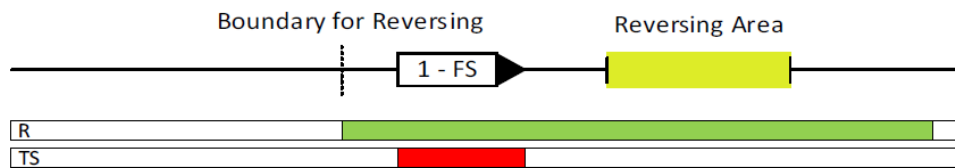
Related Internal Functions:

- Trackside: Track Status Management, Reversed Status Management, Train Management
- On-board: Train Position Reporting

Behaviour:

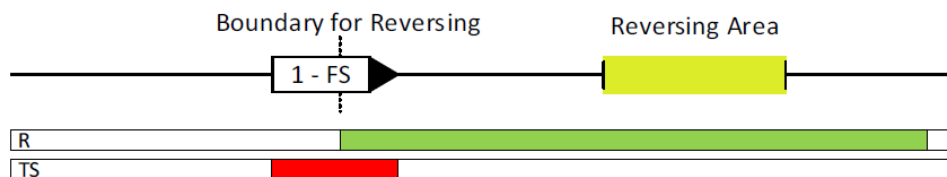
- As soon as the Reversing Area information are available to the train, the Reserved Status Area in rear of the track, starting from a Boundary for Reversing and ending with the end of the Reversing Area, is kept reserved until the train has passed the end of the Reversing Area. The L3 Trackside shall release the Reserved Status Area behind the train only once it has proceeded beyond the Reversing Area.
- The Boundary for Reversing is computed by summing up the Reversing Distance to a Reversing Margin.
- When receiving a position report from a train in Reversing mode, the L3 Trackside shall change the Track Status to Unknown for the area from the Max Safe Front End to the Boundary for Reversing. As the train continues to send position reports, the Unknown area extent can be updated with the reported Max Safe Front End.
- **If communications are lost** with a train in Reversing mode, the Trackside has to extend the Unknown Track Status Area from the Boundary for Reversing to the end of the Reserved Status Area.
- **Special cases:**
  - A train performing SoM, with a Reversing Area in advance of its location and its CRE past the Boundary for Reversing: the L3 Trackside may have to establish the Reserved Area to start at the Boundary for Reversing (see Figure 14).





**Figure 14: SoM near reversing area (D4.2 X2Rail-3, 2020).**

- A train with its MaxSFE past the Boundary for Reversing: track status is Occupied from train's rear to train's MaxSFE, the track is Reserved starting from the Boundary for Reversing (see Figure 15).



**Figure 15: Track occupation/reserving in reversing (D4.2 X2Rail-3, 2020)**

- The L3 Trackside could decide to shorten the Reserved Status Area for the train by shortening the area in front of the train to the Max Safe Front End of this train (project specific feature).

System Parameters:

- Status variables: Track Status, Reserved status, Mute timer;
- Size of Reversing area, Reversing distance, Reversing Margin;
- L\_TRAIN (from ETCS L2): length of the train as it is declared by the train during the session establishment phase. It may be used to evaluate the Reversing Margin

Safety Hazards:

**H-Level2-002** Train moves backwards after loss of train integrity leading to collision.

### 5.4.7. Splitting

Scope: This use case is related to the splitting procedures (also known as controlled loss of integrity) of a composite train. When such an event occurs, the L3 Trackside subsystem shall be able to properly reduce the size of the Unknown Track Status Area after one of the trains after splitting confirms integrity within the Unknown Track Status Area.

External Actors: none

Related Internal Functions:

- Trackside: Track Status Management, Train Management

#### Behaviour:

- After the splitting, the first split train that moves and leaves the area can leave in any direction. In this case, the extent of the Unknown Track Status Area is reduced accordingly to the direction in which the train departed.
- In particular, the length of the moving split train (L\_TRAIN) that confirmed its integrity and position is used to (1) reduce the length of the Unknown Track Status Area, and (2) compute the length of the remaining part of the original train (by subtracting L\_TRAIN from the original length of the composite train that was split).
- The above two steps are repeated when other split trains leave the Unknown Track Status Area (possibly moving in a different direction) and confirm integrity.
- If the lengths of the moving split trains confirming integrity is equal to the length of the original composite train, the Unknown Track Status Area created after the splitting is entirely removed. There is an allowed tolerance, which is the same as that defined for the configurable minimum length of Unknown Track Status Areas.

#### System Parameters:

- Minimum length of Unknown Track Status Areas: configurable parameter to account for small variations in the train length calculation. After the split train move and report integrity, if the length of the Unknown Track Status Area is smaller than this given threshold, the Unknown Track Status Area is cleared.
- L\_TRAIN (from ETCS L2): length of the train as it is declared by the train during the session establishment phase.

#### Safety Hazards:

- **H-TrainLength-002:** Train Length value longer than the actual length leading to collision or exceeding speed limits. This could happen when the Driver does not update the train length after splitting.
- If the split train reports a new train length (L\_TRAIN) greater or equal to the train length of the train that was splitting, the Unknown Track Status Area resulting from the splitting is removed, and the remaining part of the train that was split is managed as a Ghost Train.

### 5.4.8. Joining

Scope: The joining use case concerns the joining of two trains that, after the operation, continue their journey as one. For a joining to occur, one of the trains – the train to be joined – needs to be stationary, whereas the other one – the joining train – moves towards the latter.

We consider the scenario in which the joining train performs End of Mission, while the train to be joined does not. When a joining occurs, the L3 Trackside subsystem shall be able to properly reduce the size of the Unknown Track Status Area after the joined train confirms its position, length, and integrity.

External Actors: none

### Related Internal Functions:

- Trackside: Track Status Management, Train Management

### Behaviour:

- After the joining, both the area occupied by the joining train and that occupied by the train to be joined have an Unknown track status. When the joined train leaves the area and confirms its position, length, and integrity, two cases arise, depending on whether the length  $L\_TRAIN$  of the joined train is equal to the sum of the lengths of the joining train and of the train to be joined.
  - If the joined train has a length  $L\_TRAIN$  which is equal to the sum of the lengths of the joining train and of the train to be joined, the Unknown Track Status area corresponding to the two trains can be removed. As in the splitting use case, there is an allowed tolerance, which is the same as that defined for the configurable minimum length of Unknown Track Status Areas.
  - If, on the other hand, the length of the joined train is smaller than the sum of the lengths of the trains that were joined, the Unknown Track Status area corresponding to the latter is not completely accounted for and cannot be removed. In this case, L3 trackside properly reduces the extent of the Unknown Track Status Area and the stored length of the train that occupied it by subtracting from both the reported length of the joined train.

### System Parameters:

- Minimum length of Unknown Track Status Areas: configurable parameter to account for small variations in the train length calculation. After the joined train moves and reports integrity and length, if the remaining extent of the Unknown Track Status Area is smaller than this given threshold, the Unknown Track Status Area is cleared.
- $L\_TRAIN$  (from ETCS L2): length of the train as it is declared by the train during the session establishment phase.

### Safety Hazards:

- **H-TrainLength-001:** Train Length value shorter than the actual length leading to collision, derailment, or exceeding speed limits. This could happen when the Driver does not update the train length after joining.

## 5.4.9. Shunting

Scope: The Shunting use case concerns the management of train maneuvers in absence of TTD. Shunting may lead to hazardous situations because the trains disconnect while in SH mode. For this reason, the best way to cope with shunting is to restrict maneuvers to predefined shunting areas. Two types of shunting areas are foreseen: Permanent or Temporary. Permanent SH areas are predefined sections of the track dedicated to shunting. Temporary SH areas can be activated or deactivated under the control of the Traffic Management System. Hence, the Trackside has to

be configurable with predefined Permanent and Temporary Shunting Areas and provide an interface to allow the TMS to enable and disable Temporary Shunting Areas. Temporary SH areas could be defined by the Infrastructure Manager by pre-configuring a set of areas where movements in SH mode could take place and allowing the *Dispatcher to activate and deactivate them* where needed.

External Actors: Traffic Management System, Dispatcher, Infrastructure Manager

Related Internal Functions:

- Trackside: Track Status Management

Behaviour:

- The Track Status of an active shunting area is considered Unknown and Non-Sweepable.
- A train transitioning to SH mode is considered as an End of Mission by the L3 Trackside, this implies that the related requirements apply.
- Stored information could be useful to provide a quick recovery after SH movements.

System Parameters:

- Status variables: Track Status

Safety Hazards:

- **H-Movements-007:** Undetected movement out of an activated shunting area leading to collision. The cause of this hazard is in the possibility that Shunting movements unintentionally move beyond the border of an active shunting area without the L3 Trackside being aware of this.

#### 5.4.10. Mixed Traffic

Scope: In a mixed traffic area there are, in normal operation, trains moving which are not able to report Train Integrity confirmation - even if equipped with ETCS On-Board. This could be the case during migration to Level 3, pending ETCS on-board and/or TIMS installations, or for applications giving priority to ETCS equipped trains able to report train integrity confirmation during peak hour traffic.

External Actors: none

Related Internal Functions:

- Trackside: Track Status Management, Train Management

Behaviour:

- Mixed Traffic is permitted in system with TTD to cope with trains that are not equipped with TIMS nor ETCS communication equipment.
- There could be optical signals in areas with mixed traffic, i.e., the ETCS Level 3 Moving Block system is an overlay on a conventional signalling system. Therefore, the possibility to benefit from train integrity confirmation and authorise another

communicating ETCS train into a route occupied by a train with confirmed train integrity depends on if the train drivers will be allowed to pass a signal at stop or if some signal additional aspect can be used for such authorisations.

- L3 Trackside should be able to manage ETCS delivery of MAs to connected trains as well as traditional line signals.

System Parameters: none

Safety Hazards:

**H-Level2-001:** Non-ETCS train erroneously enters a route for an ETCS L3 train leading to collision.

#### 5.4.11. Loss/Restore of Communication

Scope: The Loss/Restore of Communication use case is related to the degraded mode occurring when the L3 Trackside loses the supervisions of one or more train under its control. From the perspective of the on-board unit, there is no meaningful difference between the L3 MB and the classical L2 system. On the other hand, there is a substantial difference in how the L3 Trackside manages a train losing its connection. Such a difference involves not only the train status management but also the track and the reserved status. The use case also considers the actions to take to restore the communication between on-board and trackside subsystems. In fact, fast recovery of the railway state after a train has lost communication is of paramount importance to match the ETCS Level 3 Moving Block availability system requirements. As stated before, the main difficulty in ETCS L3 MB is related to the restoration of Track Status from 'Unknown' to 'Clear'.

External Actors: Traffic Management System, Trackside Train Detection, Infrastructure Manager

Related Internal Functions:

- Trackside: Communication Management, Track Status Management, Reserved Status Management

Behaviour:

- For each supervised and connected train, the L3 Trackside can be configured to have and supervise a defined timeout (the Mute Timer). Every time a valid message is received from the train, the L3 Trackside resets such a timeout.
- When the timeout triggers, the communication with this train is considered lost; in this case, the area of the track in front of the train is considered to have Track Status Unknown, as the train may be anywhere between the last Confirmed Rear End of the train and the most recent End of Authority.
- If the communication session is restored, then the Track Status will be recovered, after L3 Trackside has checked that TRAIN\_ID and TRAIN\_LENGTH have not changed. In this case, Track Status is cleared according to the presence or not of TTD and MA assignment can proceed according to the other functional requirements.
- If the communication session is not restored, or communication is restored but the train is not recognised as the same train, then the Track Status will remain Unknown,

and it will need to be cleared by some other method (e.g., Traffic Management System, running the train in On Sight to sweep the Unknown tracks).

- The Mute Timer does not affect the SESSION\_EXPIRED\_TIMEOUT since, between the expiry of the Mute timer and the expiry of the session timer, the L3 Trackside will treat the train as having lost communications. This is necessary to maintain the session during this period in case the train regains communications.
- The Mute Timer is not mandatory: if not used, the SESSION\_EXPIRED\_TIMEOUT can play its role. When this last timeout triggers, the effects of the track status and reserved status are the same of what described for Mute Timer.
- When the reconnection occurs after session expiry, it is, in principle the same as a train performing Start of Mission, but it is important to consider this case as special since Unknown Track Status Area could be large, as it extends from the previous CRE to the End of Authority

#### System Parameters:

- T\_NVCONTACT: timeout related to the maximum period of time on-board can safely continue its march in absence of a safe connection with the Trackside.
- SESSION\_EXPIRED\_TIMEOUT: timeout of the trackside, after which a previously supervised train that does not communicate with the trackside is disconnected.
- Mute Timer: The Infrastructure Manager shall establish the value of a mute timer within the L3 Trackside to detect a loss of regular train position reports (see ENG-LossComms-1). In general, the Mute Timer is longer than the T\_NVCONTACT but shorter than the SESSION\_EXPIRED\_TIMEOUT to allow faster reaction for performance and safety reasons.

#### Safety Hazards:

- **H-Clearing-001:** Track Status Area erroneously cleared during L3 Trackside initialisation by dispatcher leading to collision. The hazard applicable to this use case is mainly related to the incorrect clearing of tracks after the recovery of a communication (after the Mute Timer timeout).

### 5.4.12. Loss of Train Integrity

Scope: The loss of train integrity use case is a hazardous scenario that may occur, for different reasons, in the event that a train is unintentionally divided, and the Dispatcher needs to take relevant steps to protect the potentially hazardous situation. Following Loss of Train Integrity by a train, from the train protection point of view, it can continue its mission. The Track Status Area for the train will change to be an Unknown Track Status Area. If Train Integrity is restored, then if the train length is unchanged, the Track Status Area for the train will change to be an Occupied Track Status Area, based on the new Train Position Report. If Train Integrity is not restored, then the Track Status Area for the train will be maintained as an Unknown Track Status Area, and it will need to be cleared by some other method.

External Actors: Dispatcher, Driver, Traffic Management System, Trackside Train Detection, Train Localization Unit, TIMS

### Related Internal Functions:

- Trackside: Track Status Management, TTD Management, Trains Management
- On-board: Train Position Reporting, Integrity Information Management

### Behaviour:

- The Trackside considers the train as having lost Integrity after one of the following conditions:
  - If the train sends a position report with the information 'Train integrity lost',
  - If the Trackside does not receive a position report with 'Train integrity confirmed by external device' before the expiring of the Integrity Wait Timer,
  - If the Trackside receives new Validated Train Data with a train length different from previously reported within the same communication session.
- The Trackside changes the Track Status Area associated with the train to Unknown to prevent collisions.
- The Trackside shall react as configured. Examples are:
  - Cause the train to Trip
  - Create an additional margin behind the train
  - The Movement Authority may be shortened/updated
  - Alternatively, the Trackside could be configured to take no action.
- When receiving a message from a train with the information 'Train integrity confirmed by external device', the Trackside shall start/restart the Integrity Wait Timer.
- When receiving a message from a train with the information 'Train integrity confirmed by Driver', if the Trackside is configured to accept confirmation by Driver and the Integrity Wait Timer is running, then the Trackside shall stop the Integrity Wait Timer. In this condition, it is not necessary to supervise the Integrity Wait Timer.
- When advised of loss of train integrity, the Dispatcher shall, in accordance with non-harmonised rules, protect the area in which a train division may have occurred. The required actions may be to contact the Driver, to issue an emergency stop order to other trains in the area, to make an emergency voice call or to establish a track status Unknown Area to prevent other trains approaching the divided train. The rules should take account of the potential that a division of the train is caused by the derailment of part of the train which may be obstructing adjacent lines.
- When advised of loss of train integrity through an in-cab indication, the Driver shall follow non-harmonised rules. The required actions may be to stop the train, to contact the Dispatcher, to visually inspect the system, and/or reset the TIMS.

### System Parameters:

- INTEGRITY WAIT TIMER: timeout related to the maximum period of time Trackside can wait before considering that the integrity is lost, without receiving 'Train integrity confirmed by external device' message.
- Train Integrity confirmation by the driver: the L3 Trackside shall be able to be configured whether to accept Train Integrity confirmation by the driver.



- Movement Authority for a train that has lost Integrity: the L3 Trackside shall be configurable as to whether it authorises a Movement Authority for a train that has lost Integrity.

#### Safety Hazards:

- **H-Clearing-003:** Track Status Area erroneously cleared after deactivation of a shunting area leading to collision. This could happen when deactivating a shunting area, responsible staff may have the possibility to clear any remaining Unknown Track Status Area. Doing this, an Occupied Track Status Area can be set to Clear leading to collision.
- **H-Movements-003:** Undetected movement entering the L3 area leading to collision. This could happen when, in degraded conditions, a train incorrectly enters the L3 area when it is not authorised and it is not detected by the Trackside.
- **H-Movements-005:** Undetected movement of a part of the train after loss of integrity leading to collision. The hazard is related to this use case since part of the train can roll backwards due to the gradient profile and may result in a collision with other vehicles. In case of derailment, collisions can also occur on adjacent tracks.
- **H-TTDfailure-001:** TTD erroneously indicates a Clear Track Status Area leading to collision or derailment. When TTD is used to clear track irrespective of Train Locations, this hazard could happen since either an Unknown Track Status Area could be cleared without being swept, or Infrastructure could be released or moved under a train, or erroneously updating the CRE of the train in front, and consequently providing an MA to a following train that could result in a collision.

### 5.4.13. Movement in SR Mode

Scope: Non-communicating trains or communicating trains without a known location can be moved by Staff Responsible (SR). This represents the primary mean to manage these situations and it is described in this use case. There are three possible situations. If the train has no connection with the Trackside, the Driver must use the Override function to enter SR Mode; the Dispatcher may be able to establish a location for the train from the Driver and create an Unknown Track Status Area to protect the train and its subsequent movement. On the contrary, if the train has a connection to the Trackside but it cannot be located to invalid/unknown position, the Dispatcher must enter an estimate for the train location to the Trackside and protect the path the train will take with an Unknown Track Status Area; the Trackside can then authorise the train for movement in SR Mode with a distance to the end of the Unknown Track Status Area, such that the train can establish a known location. If the train has a connection to the Trackside and can be located but it is not possible to issue an MA, the Trackside can calculate the distance and a list of balises that can be passed before authorising the train for movement in SR Mode. In this last scenario, if the Trackside is still not able to authorise SR movement (e.g., for an obstruction), the driver must still use the override functionality following operational procedures.

External Actors: Dispatcher, Driver



Related Internal Functions:

- Trackside: Track Status Management, TTD Management, MA Management
- On-board: Speed and Distance Supervision

Behaviour:

- The train sends an MA Request.
- If the train is located in rear of an adjacent Unknown Track Status Area created by the TMS and not used for another train, the Trackside provides an SR Authorisation to this train with the distance to run limited to the Unknown Track Status Area.
- If the train has a position given by the Dispatcher in rear of an adjacent Reserved Status Area, the Trackside provides an SR Authorisation to this train with the distance to run within the Reserved Status Area. The Trackside shall extend the Unknown Track Status Area associated with this train to the end of the Reserved Status Area. If possible, the Trackside shall include a list of balise groups the train is allowed to pass in the given authorisation.
- If the train knows the location, the Trackside maintains the previous Confirmed Rear End (position of the rear of a train deduced from the safe train length information confirmed in a position report confirming train integrity) of a train in SR mode from when the train reports in SR until the train transitions out of SR to FS/OS mode and reports with Train Integrity confirmed.

System Parameters:

- Train status: train located in rear of an adjacent Unknown Track Status Area created by the TMS and not used for another train, train with a position given by the Dispatcher in rear of an adjacent Reserved Status Area, or if the train knows the location.

Safety Hazards: none

#### 5.4.14. Radio Hole

Scope: Radio Holes, due to the need of L3 Trackside to know the position of the train in a continuous and reliable manner, are requested to satisfy further requirements in L3. As radio holes can be permanent or temporary, according to the scope they are created in TMS, the L3 Trackside system should be aware of each train is entering in a Radio Hole and should manage properly the communication with the train, also in case of communication timeouts.

External Actors: Traffic Management System

Related Internal Functions:

- Trackside: Communication Management, Train Management

Behaviour:

- The management of the End of Authority Exclusion Area is crucial for Radio Hole. There is in fact a problem of availability, occurring in case of a EoA set in a Radio Hole and a train that, after reaching this point, can proceed in SR. To overcome this effect,

L3 Trackside cannot send MA ending in a Radio Hole. In case of Temporary Radio Hole, this EoA Exclusion Area should be removed.

- On request from the TMS, the L3 Trackside shall activate or deactivate predefined Temporary Radio Holes.
- The L3 Trackside shall start the Radio Hole timer when a train enters a Radio Hole. The criteria for determining when a train has entered a Radio Hole are project specific and could include: (1) reception of a PR with the MSFE in the Radio Hole; Mute timer expiry following sending radio hole track condition information to the train.
- With a train in the Radio Hole area, the L3 Trackside does not monitor the following timers: While the L3 Trackside considers that a train is inside a Radio Hole, the L3 Trackside shall stop supervising the following timers: Mute timer, Integrity Wait Timer, ETCS session timer
- When a Radio Hole Timer ends, the L3 Trackside must deal with the train in the same way of a train with loss of communication. In this case, the TMS should be informed.

System Parameters:

- Radio Hole Timer: time needed by the train to pass into a radio hole, defined by the Dispatcher/TMS.

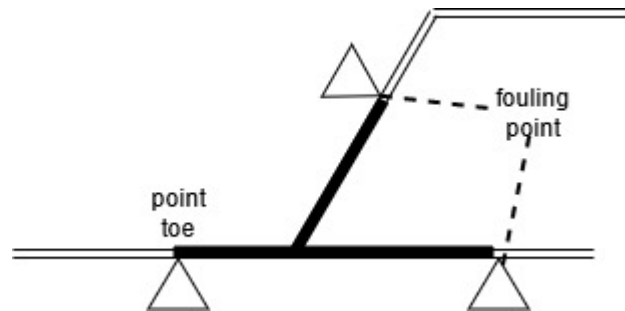
Safety Hazards: none

#### 5.4.15. Points Control

Scope: The use case Points Control is related to the movement of points or other moveable infrastructure. When the routes are set, points are controlled by the Trackside. This use case defines the behaviour for the locking of points and the override procedure to move points when they are locked. Points are locked by:

- Track Status if any part of the area defined by the Fouling Points and the Point Toe has status Unknown or Occupied. This area is defined by rail topology and is individual for each set of points.
- Reserved Status if any part of the area defined by the associated Release Points has status Reserved. This area is defined by design, and can cover several sets of points, and can also cover diamond crossings.

The rationale is to avoid a point movement while there is a train over it or about to pass over it. Hence, the Trackside shall prevent movement of points within an Unknown or Occupied Track Status Area, or within a Reserved Status Area, unless using an operational procedure.



**Figure 16:** Area where Unknown or Occupied track Status lead to a locking point

External Actors: Traffic Management System

Related Internal Functions:

- Trackside: Points Management, Track Status Management, Reserved Status Management, Route Management

Behaviour:

- Points are within an Unknown or Occupied Track Status Area, or within Reserved Status Area, if any part of the track between the Fouling Points and the Point Toe is within an Unknown or Occupied Track Status Area, or within a Reserved Status Area. All points in an Unknown or Occupied Track Status Area, or within a Reserved Status Area, must remain locked unless they are moved under an operational procedure.
- The Trackside shall be configured with Release Points to enable Points to be moved when the area of track containing the Points has Consolidated Track Status Clear and does not contain any part of a Reserved Status Area.
- The TMS may request to move points that are in an Unknown or Occupied Track Status Area to allow to move a train to a different location in a degraded situation or in a Shunting area. However, the MA can be issued when the points are locked and detected. If this is not possible, an SR movement would be required instead.
- When a train is sweeping a set of points, the Trackside shall remove or reduce a Sweepable Unknown Track Status Area from the alternate leg of the points as far as the Fouling Point, in addition to the path that the train takes. This is to consider the area up to the Fouling Point swept if the sweeping train successfully traverses it.

System Parameters:

- None

Safety Hazards:

- **H-Points-001:** A point is moved in an Unknown/Occupied/Reserved Track Status Area with a train over it, or when it is about to pass over it, leading to derailment. This hazard is related to a Dispatcher would need to move points so that the train can be moved to a siding, so moving a train inside an Unknown, Occupied or Reserved Track Status Area to a new location.

#### 5.4.16. Sweeping

**Scope:** Sweeping is that state of the system where a train, that is authorized by the L3 Trackside in OS or SR mode, moves into a Track Area that is in the Unknown state. The objective of this functionality is having a train that “cleans” the area in a safe manner.

**External Actors:** Trackside Train Detection, Traffic Management System, Driver, Dispatcher

**Related Internal Functions:**

- Trackside: Route Management, TTD Management, Track Status Management, Trains Management
- On-board: Train Position Reporting

**Behaviour:**

- This behaviour can occur when the Trackside is not able to determine the actual track status of a track area. The causes of this situation can be different:
  - In case of no TTD, the cause of using a sweeping train is the loss of communication with a train and the triggering of the Mute Timer.
  - In case of presence of TTD, the cause of a sweeping train is the malfunctioning of a TTD element (e.g., a track circuit).
- It is worthy to underline that sweeping train can be used as an operational solution for keeping the system running also in presence of hazardous situation. This mechanism could be considered a mitigation of many hazards in alternative to simply reaching the safe state (i.e., blocking the circulation).
- When a train is sweeping an area, the sweep occurs starting from the mSFE: behind, the area is swept and occupied (i.e., in a Consolidated Occupied status), beyond this point, the area is to sweep.
- When the Driver is asked to sweep an area, he/she must follow non-harmonised rules that could be nationality-dependent and application-dependent (high speed lines, metro systems, etc.).
- When advised by the Driver that a section has observed as free of issues, the Dispatcher can remove Unknown Track Status Areas.

**System Parameters:**

- Maximum length of an Unknown Track Status Area that can be safely cleared by the L3 Trackside without sweeping or visual inspection

**Safety Hazards:** none

Not all the use cases of Table 7 are described since some overlaps with other use cases. The following table summarises the non-described use cases and the motivations of their exclusion.

**Table 7:** Motivation for non-described use cases

No	Use Case	Comments
3	Normal Train Movement	The content of the use case is already reported in the previous subsections.
6	On Sight Movement	The use case has been joined with the Sweeping use case since the On-sight L3 features are related to the sweeping functionality.
15	Recovery of a Failed Train	Described just in [D5.1–X2Rail-1 2019] and covered by Loss of Communication, Movement in SR Mode, On Sight Movement
20	Shadow train	Described just in [EUG 2020], covered by Mixed Traffic, Level Transition and Sweeping
21	Ghost train	Described just in [EUG 2020], covered by Mixed Traffic, Loss of Communication and Sweeping
22	Change of direction	Covered by Reversing.

### 5.5. Selected Use cases

As one of the objectives of this document is to specify the behavioural aspects of four UCs by means of some behavioural models, the detection process of these UCs is reported in the following. We use for this purpose both the list of the Operational Scenarios (OSs) (D2.1 PERFORMINGRAIL, 2021), and a list of the UCs where positioning functionalities of ERTMS on-board as well as GNSS technologies play a crucial role. Table 8 reports the coverage between the OSs and the UCs. **On the rows we have all the UCs** (both Moving Block and Virtual Coupling related) while **on the column we have all the OSs**. An “x” inside a cell means that the related OS is built upon the UC, according to its definition reported in (D2.1 PERFORMINGRAIL, 2021).

**Table 8:** Intersection between UCs and OSs to select relevant UCs

	Use Case		Radio Hole	Loss of Communication	Track initialisation	Shunting	VC supervising distance	Splitting of a VCTS Initiated by Slave	End of Mission	Loss of Integrity	Start of Mission in line	Points Control
MB	Trackside Initialisation				x							
	Start of Mission										x	
	Normal Train Movement		x	x		x		x		x		x
	Level transitions											
	Handover											
	On Sight (OS) Movement									x		
	End of Mission					x			x			
	Reversing											
Splitting												

	Joining										
	Shunting				X						
	Mixed Traffic										
	Loss/Restore of Communications	X	X		X				X		
	Loss of Train Integrity		X						X	X	
	Recovery of a Failed Train										
	Staff Responsible (SR) movement	X		X					X	X	
	Radio Hole	X									
	Points Control										X
	Sweeping		X								X
	Shadow train										
	Ghost train										
	Change of direction										
VC	Initiation of Virtual Coupling										
	Coupling of Platoon with more than 1 Slave										
	Supervising Distance in normal driving					X	X				
	Master Train Braking										
	All Platoon Stopping at Station										
	Change of Cabin (Master/slave)/Direction										
	Platoon Coasting at Station										
	Splitting of a VCTS – Initiated by Slave						X				
	Splitting of a VCTS – Initiated by Master										
	Loss of Radio Link										
	Platoon in Proximity of Switching Points										
	Route Lock Function and Virtual Coupling										
	Level Crossings Management with Platoons										

The list of the GNSS-critical UCs is here reported as: Normal Train Movement, Loss/Restore of Communications, Loss of Train Integrity.

The criteria used to make this choice are the following:

- At least one modelled UC should be related to Virtual Coupling;
- Maximize the number of UCs related to train positioning;
- Maximize the number of impacted OSs according to the OS-UC mapping table.

According to all these inputs, the following UCs will be described: **Normal Train Movement**, **Supervising Distance in normal driving** in subsection 7.2, **Loss/Restore of Communications** in subsection 5.4.11, and **Loss of Train Integrity** in subsection 5.4.12. This section will highlight the behavioural description of **three use cases that relate to the MB system**, while the VC use case of Supervising Distance in normal driving will be listed in Section 7.2.

The level of the description of these UCs' behaviours depends on the objective of this deliverable. This document aims to define a baseline for the ETCS MB/VC but without defining a formal model. The formal modelling will take place in Task 2.3 and Task 2.4 following the guidelines identified in (D2.1 PERFORMINGRAIL, 2021). Hence, the use case will be modelled in this document following a semi-formal approach. Using the SysML language, the behaviour will be specified using high level Sequence Diagrams to highlight the interactions between components. Detailed Sequence diagrams and State Machine Diagrams used for specifying components' inner behaviours will be provided in (D2.2 PERFORMINGRAIL, 2022).

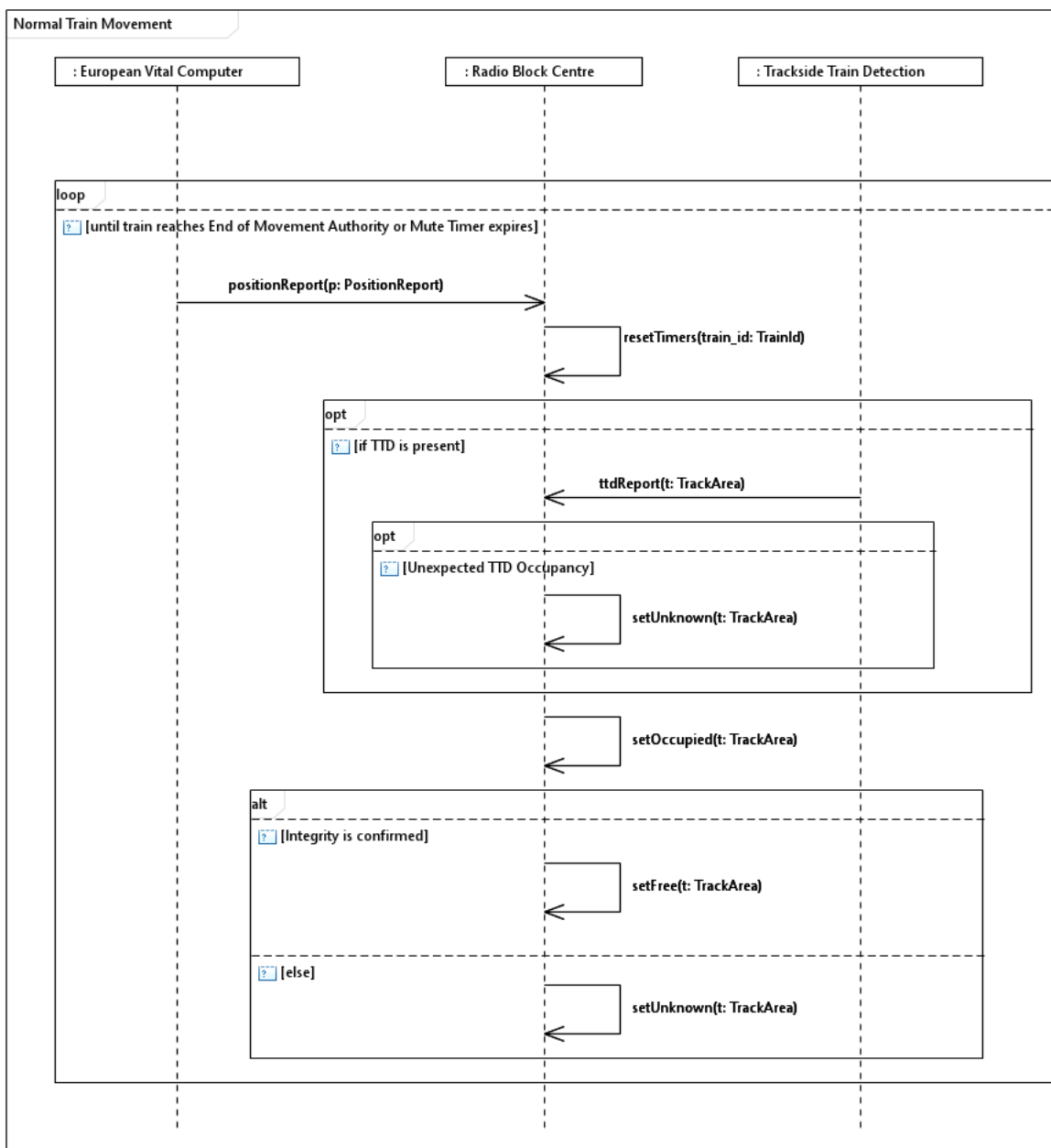


Figure 17: SysML Diagram for Normal train Movement



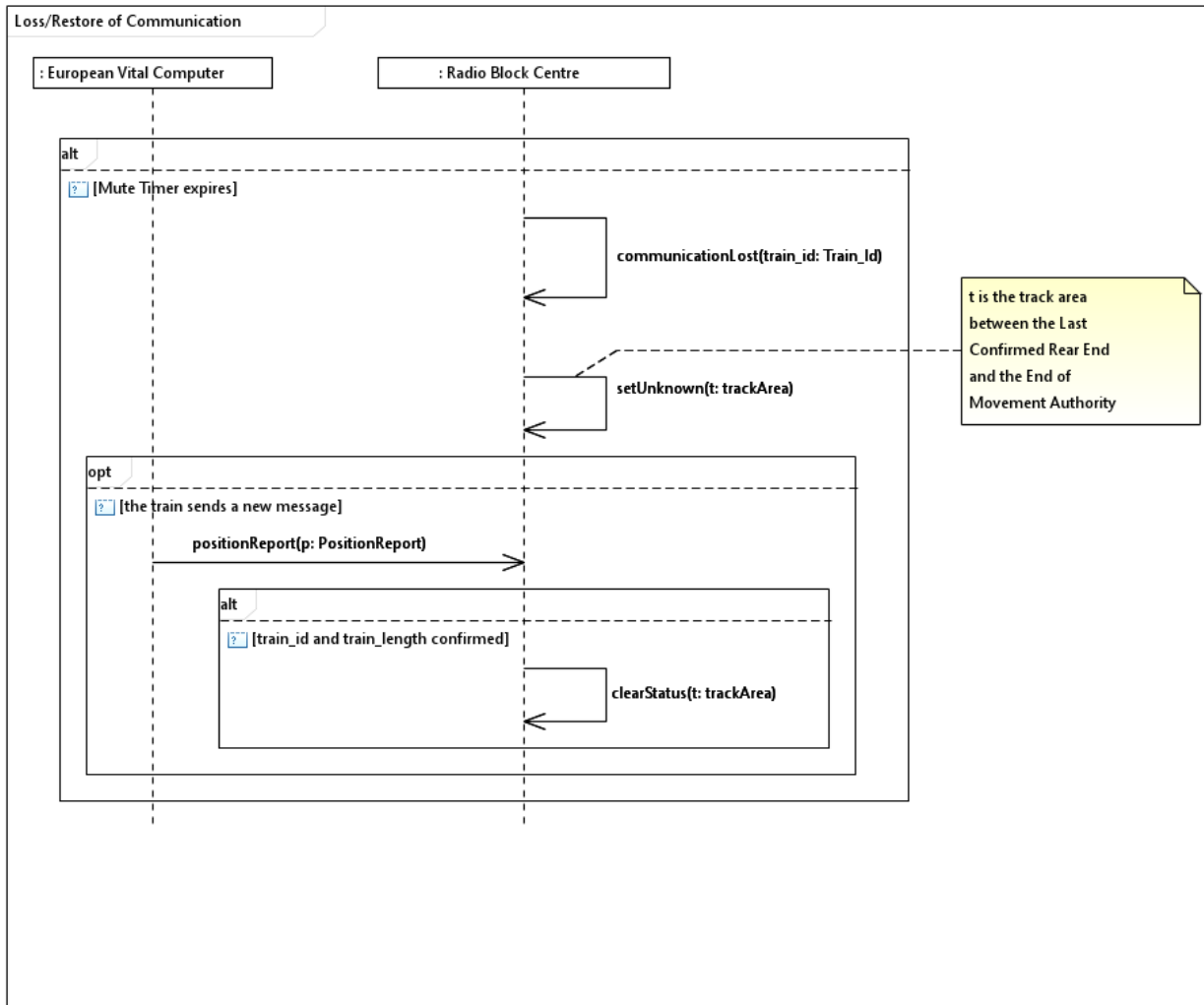
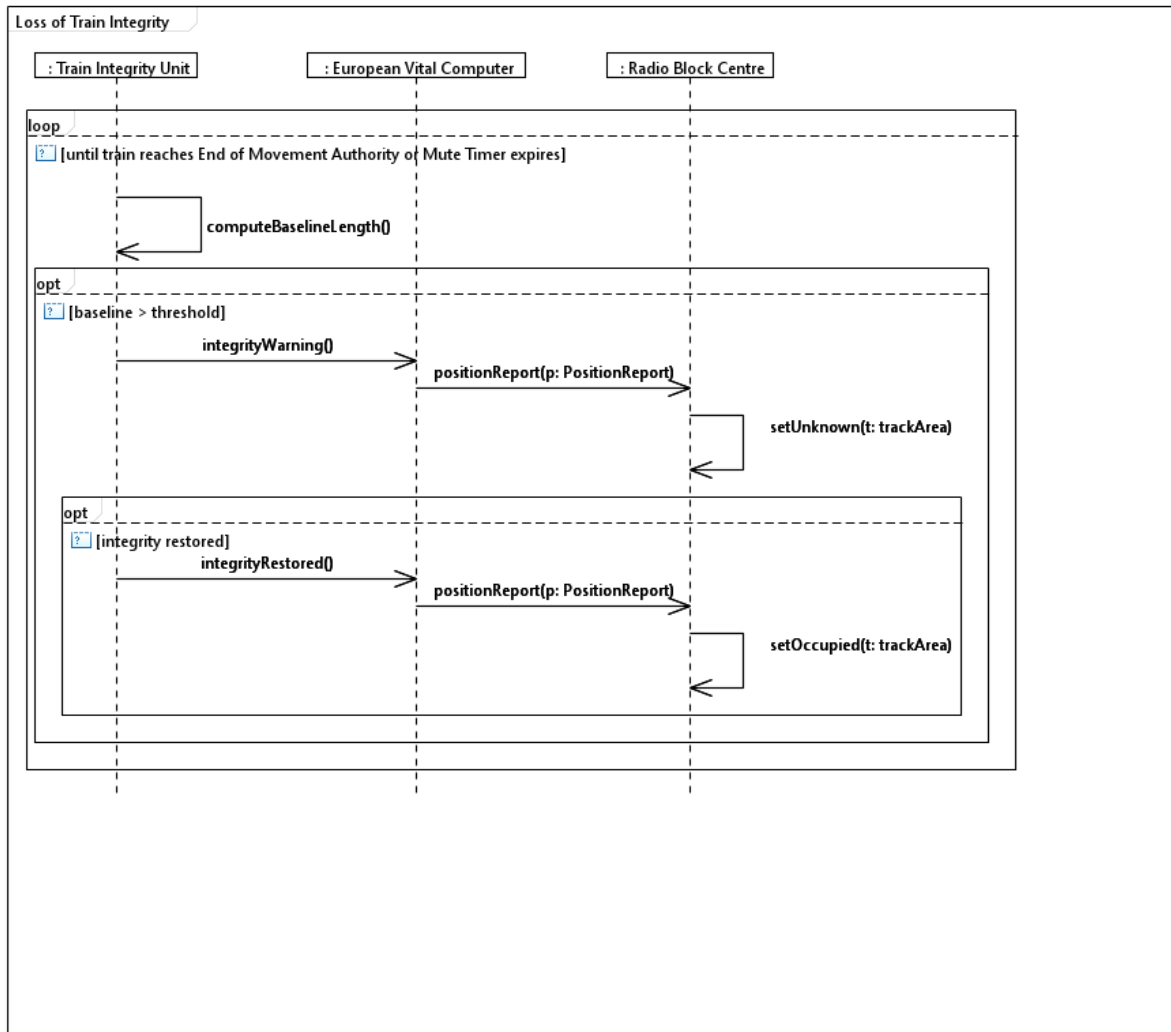


Figure 18: Loss/Restore of Communications



**Figure 19:** Loss of Train Integrity

## 6. Virtual Coupling System Definition

Virtually Coupled Train Sets is the topic of Shift2Rail Technology Demonstrator TD 2.8. According to Shift2Rail, Virtual Coupling (TD 2.8) aims to enable ‘virtually coupled trains’ to operate much closer to one another (within their absolute braking distance) and dynamically modify their own composition on the move (virtual coupling/uncoupling of train convoys), while ensuring at least the same level of safety as is currently provided.

Virtual Coupling has been the topic of two complementary Shift2Rail projects:

- X2RAIL-3: Advanced Signalling, Automation and Communication System – Prototyping the future by means of capacity increase, autonomy and flexible communication (01/12/2018 – 30/11/2021),
- MOVINGRAIL: MOving block and Virtual coupling New Generations of RAIL signalling (01/12/2018 – 31/12/2020).

In X2RAIL-3 work packages 6 and 7 were devoted to Virtual Coupled Trains, with WP6 targeting the overall functional requirements and safety analysis of the solution, and WP7 considering the technological solution and associated business case. In MOVINGRAIL work packages 3 and 4 were devoted to Virtual Coupling, with WP3 on Communication Technology for Virtual Coupling that identified and proposed appropriate Virtual Coupling technical communication solutions, and WP4 on Business Analysis of Virtual Coupling that identified the potential markets and scenarios of the Virtual Coupling concept, provided a cost-effectiveness analysis (CEA) for Virtual Coupling, and developed a roadmap and business risk analysis for the introduction of Virtual Coupling.

At the time of writing this deliverable, X2RAIL-3 delivered one *public* deliverable on VCTS Concept and Application Conditions (D6.1 X2Rail-3, 2020). The other five deliverables on VCTS from X2Rail-3 were confidential and not released. They consider VCTS Performance and Safety Analysis in D6.2, VCTS Feasibility Analysis in D7.1, VCTS System Requirements Specification in D7.2, VCTS Impact Analysis in D7.3, and VCTS Business Model Analysis in D7.4. In particular, D7.2 is relevant for this chapter.

MOVINGRAIL has delivered six public deliverables on Virtual Coupling. Two deliverables are about communication technology and consider Virtual Coupling Communication Solutions Analysis (D3.1 MOVINGRAIL, 2020) and Proposals for Virtual Coupling Communication Structures (D3.3 MOVINGRAIL, 2020). The other four cover the business analysis of Virtual Coupling and consider market potential and operational scenarios (D4.1 MOVINGRAIL, 2019), cost-effectiveness analysis (D4.2 MOVINGRAIL, 2020), application roadmap for the introduction of Virtual Coupling (D4.3 MOVINGRAIL, 2020), and business risk analysis (D4.4 MOVINGRAIL, 2020).

In contrast to ETCS L3, Virtual coupling is still in the conceptual phase. Requirements, operational rules or engineering rules are not yet defined or only confidential. X2RAIL-3 D6.1 contains a system concept and application conditions. X2RAIL-3 D7.2 will contain the System Requirements Specification but this is confidential and so are all other deliverables from X2RAIL-3. MOVINGRAIL D3.3 proposes a potential future V2V communication solution that is most promising to be used with Virtual Coupling. (D4.1 MOVINGRAIL, 2019) and (D4.2 MOVINGRAIL, 2020) include

operational scenarios. (D4.3 MOVINGRAIL, 2020) contains conceptual descriptions of Virtual Coupling components and the required changes to existing safety, communication and control technology that will be affected by Virtual Coupling.

In addition, Virtual Coupling builds on technology that has been developed for moving block signalling, such as train integrity monitoring and train localization.

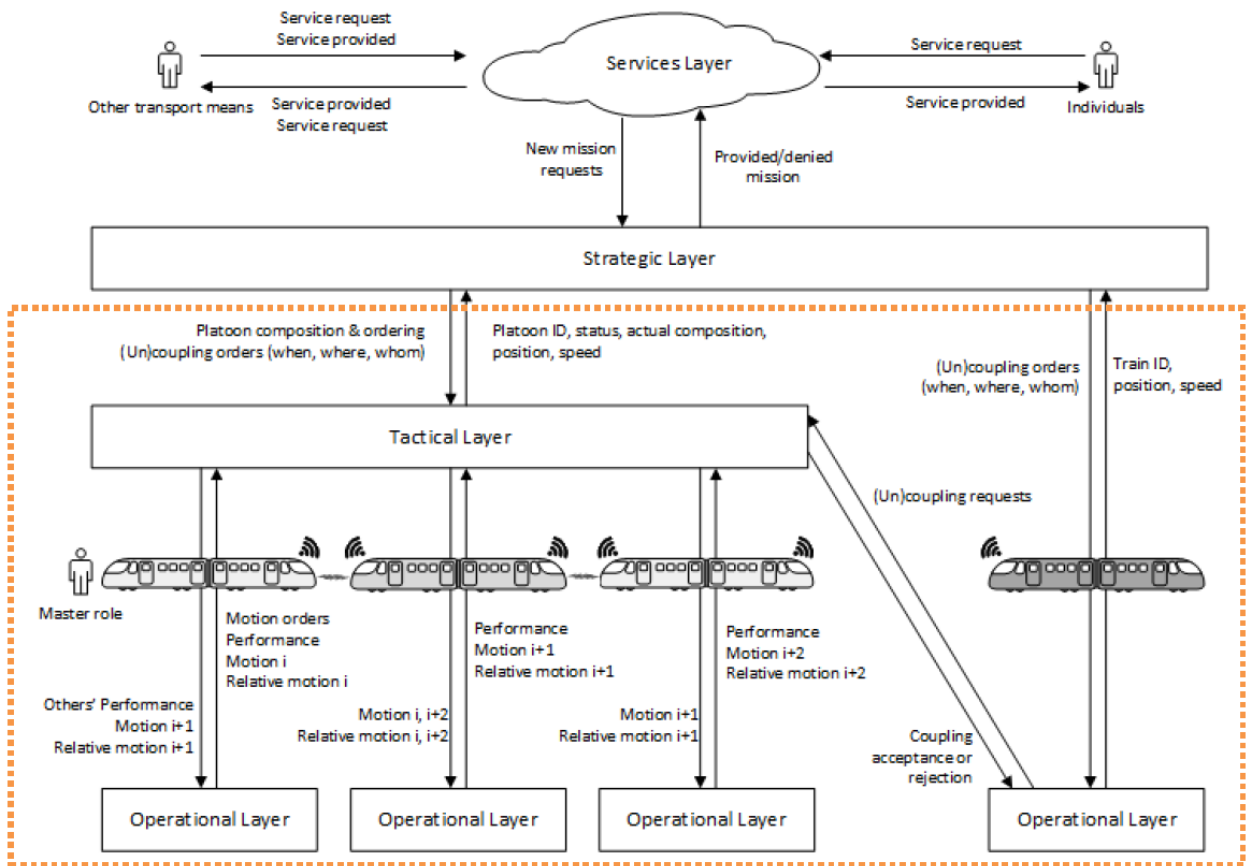
## 6.1. Virtual Coupling System Functionalities and Architecture

### 6.1.1. Functional Layers

(D6.1 X2Rail-3, 2020) envisages four functional layers to implement Virtual Coupling, see Figure 20,

- **Service layer:** this layer represents the service provider and is out of the scope of the actual Virtual Coupling system.
- **Strategic layer:** the traffic management layer with the objective to maximise the capacity of the infrastructure, identify potential conflicts, deal with delays and disruptions and supervise the traffic flow and its safety. It is in charge of defining the convoys, their composition and ordering, based on compatibility, destinations and schedules. It also defines when and where the trains are joining and leaving the platoon.
- **Tactical layer:** the on-board convoy management layer that coordinates the actual platoon movements and manoeuvres like the joining and leaving operations. It manages unexpected events and sudden degraded modes of any of the platoon units. This layer is connected to the signalling system and is responsible for defining the speed and acceleration targets and the headway between trains. The master and slave trains have different interactions with this layer according to their role.
- **Operational layer:** the local control layer that manages the local movement of each train (acceleration and braking) following the commands provided by the tactical layer in a safe way. The main function of this layer is to regulate the safe distance while keeping the stability of the platoon, as well as the safe movements for joining or leaving the platoon.

Detailed descriptions of the service and strategic layers were out of the scope of X2RAIL-3.



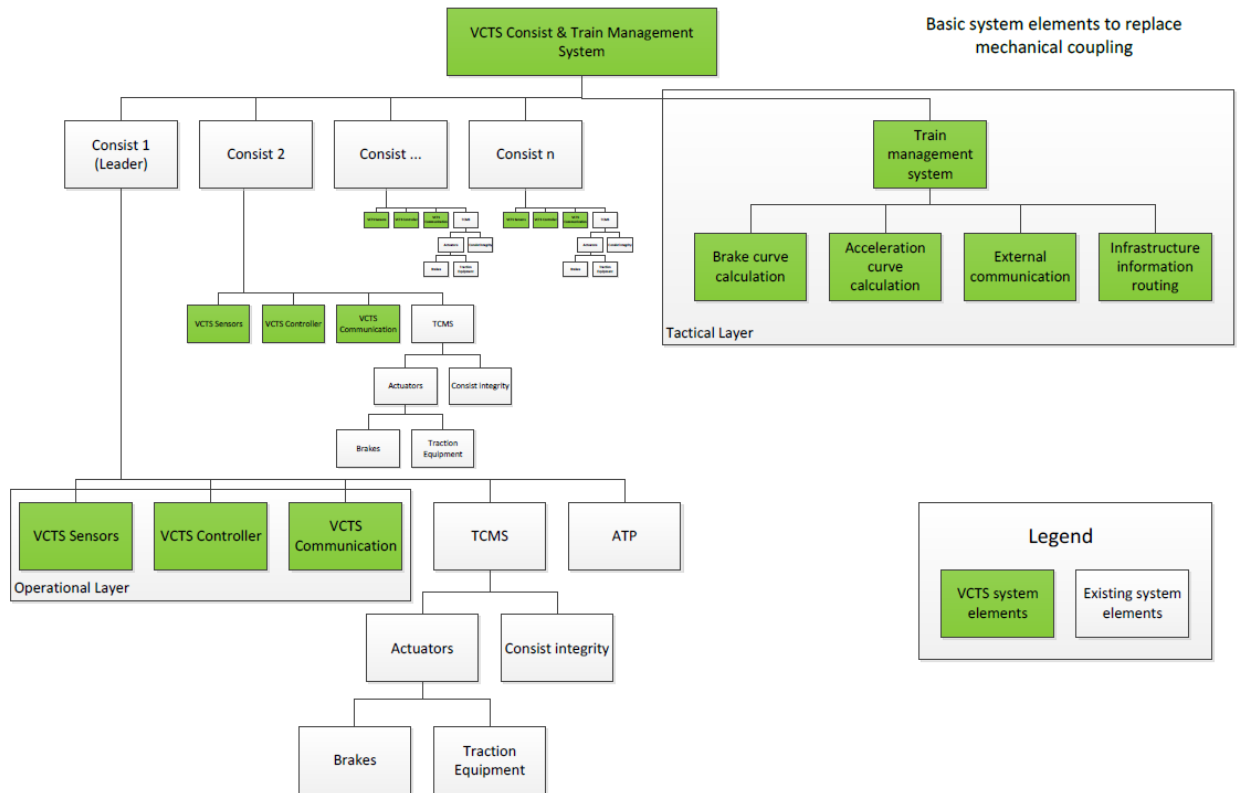
**Figure 20:** Functional layers of Virtual Coupling [D6.1 X2RAIL-3]

### 6.1.2. On-board Functionalities

(D6.1 X2Rail-3, 2020) distinguishes five main functions for VC on-board systems:

- Protect trains inside a convoy from collisions,
- Virtual Coupling set up,
- Coupled running,
- Termination of virtual coupling,
- Interaction with external systems (TMS, interlocking).

In the concept of X2RAIL-3 D6.1 these functions are distributed over a tactical VCTS Train Management System and operational VCTS Controllers, supported by operational VCTS Sensors and VCTS Communication, see Figure 21.



**Figure 21: VCTS System description of X2RAIL-3**

A brief description of the VCTS components is as follows.

- VCTS Train Management System (VCTS-TMS):** the tactical on-board system that is installed on all VCTS trains (or consists). A master train uses this system to coordinate the convoy behaviour, while the other virtually-coupled trains use it for cross-checking to guarantee integrity of the tactical decisions. It coordinates the movements of virtual-coupled trains within the convoy, as well the coupling of new trains and the decoupling of trains. It receives coupling and decoupling orders (when, where, who) from a strategic (trackside) convoy management layer corresponding to the planned convoy compositions and ordering, and sends back the convoy ID and state. It collects relevant information from all trains in the convoy (integrity, braking and acceleration capabilities), derives the coordinated train characteristics (braking and acceleration curves), and provides high-level target states and relevant information to all trains in the convoy. The VCTS-TMS of the master train also provides the interface to the signalling system (e.g., train ID).
- VCTS Controller (VCTS-CTRL):** the operational on-board system that supervises the safe movement of each train following the tactical commands from the master train, including the commands for coupling and decoupling. It uses relative distance, speed and acceleration with adjacent trains and the master, as well as the absolute state, to guarantee a safety margin between the virtually coupled trains.

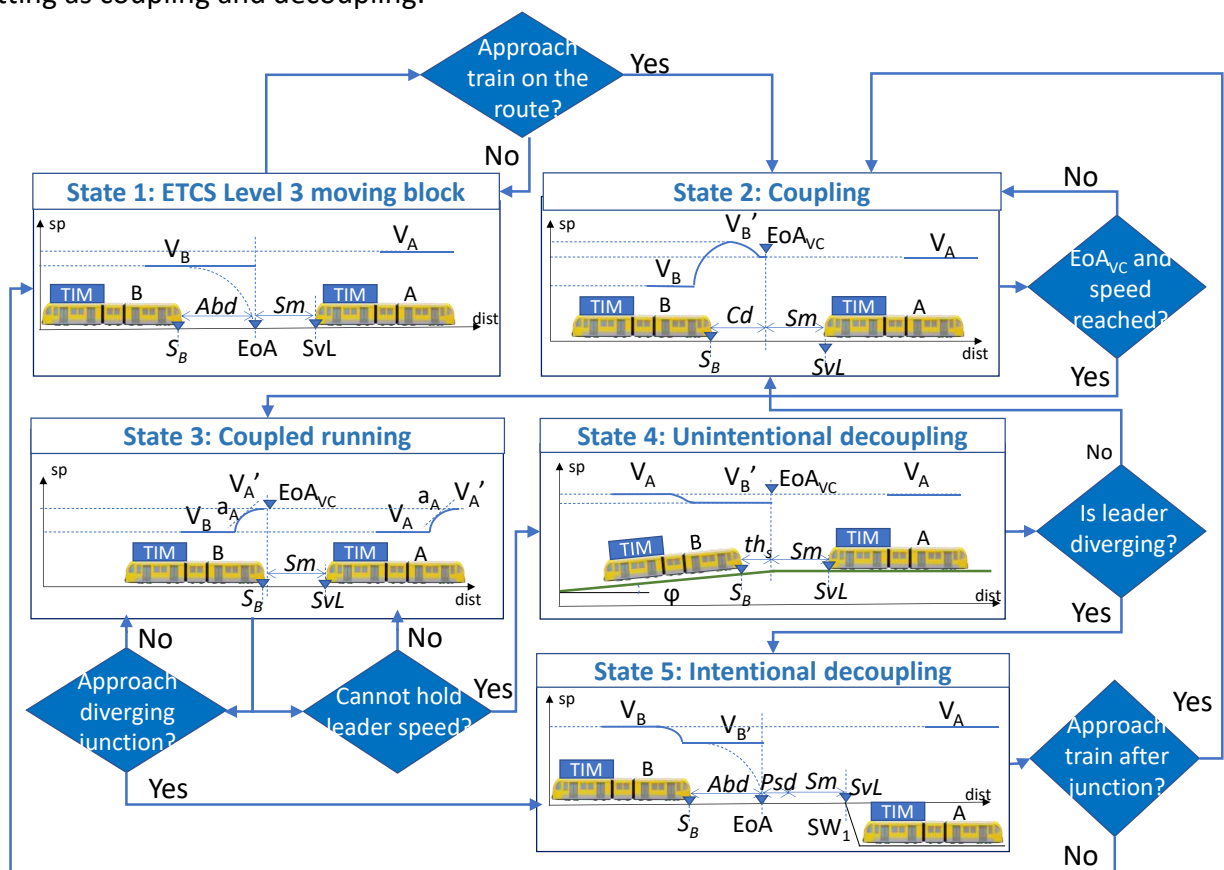
These VCTS safety-critical functions are facilitated by two operational subsystems that are connected to the existing Train Control and Management System (TCMS):

- **VCTS Sensors (VCTS-SENS):** the additional sensors installed on each train. They are additional to the existing TCMS sensors and should guarantee high quality measurements under all conditions, including the absolute dynamic state (distance, speed, acceleration) and the relative dynamic state to adjacent and master trains. In particular, the relative dynamic states between trains at close distance (below 300 m) requires new sensors to increase the measurements accuracy.
- **VCTS Communication (VCTS-COM):** the V2V communication that is active on all trains in the convoy. It takes care of the communication of the current state of the trains to the VCTS-TMS of the master and other trains, performs handshakes during the coupling process, closes communication after decoupling, communicates relevant TCMS information updates like braking and acceleration curves of the train to the VCTS-TMS, and communicates VCTS-TMS parameters to the TCMS to update the local braking and acceleration curves of the consist to the coordinated requirements from the VCTS.

Virtual Coupling assumes that trains and convoys operate under an existing ATP based on absolute braking distances (in particular ETCS Level 3 moving block), which is switched off on all trains except the leading train during virtually-coupled operations. The existing ATP on board of the trains may interface (or not) with the VCTS system to exchange relevant supervision data (D6.1 X2Rail-3, 2020). Hence, the VCTS system replaces ATP for the safe train separation of virtual coupled trains up to relative braking distances using coordinated braking curves. The leading train uses ATP with absolute braking distance for the safe train separation of the convoy to other trains or convoys. In particular, when a train wants to couple to a train or an existing convoy, it tries to establish a remote radio contact (V2V) with the targeted convoy. A dialogue starts in order to verify the coupling ability and to get the coupling acceptance. This procedure occurs under ETCS Level 3 moving block or other signalling system keeping at least an absolute braking distance. Once this 'handshake' is completed successfully the train can start approaching the preceding train in the convoy within the absolute braking distance towards the desired relative distance while the relative braking distance to the safety margin behind the preceding train is supervised by the VCTS Controller.

(D4.3 MOVINGRAIL, 2020) notes that the tactical and operational layers have both vital safety functions and non-vital control functions. In particular, for coupled running cooperative control algorithms must be used to join a platoon, maintain platoon stability, and split from a platoon. In principle, these could also be manual driving processes but that would be at the cost of large relative distances due to the longer reaction times of the human driver. Moreover, maintaining a stable close distance to the predecessor is not easy due to the varying gradients that will affect all trains in the platoon one after another. The approach of a platoon must be done in a controlled cooperative manner as a function of the relative state (distance, speed and acceleration) to the predecessor and/or master train, which requires automatic cooperative control rather than manual driving. Likewise, stable platoon movements require cooperative train following control to manage gradient variations and disturbances. Moreover, splitting from a platoon and

successive decoupling from the convoy at more than the absolute braking distance requires advanced control algorithms for the typical situation that decoupling must occur before a diverging route (D4.3 MOVINGRAIL, 2020). In (D4.1 MOVINGRAIL, 2019) a state transition diagram has been developed describing the transitions between five states: 1) Moving Block running, 2) Coupling, 3) Coupled running, 4) Unintentional decoupling, and 5) Intentional decoupling, see Figure 22. In this picture the target relative distance from the preceding train is indicated as Virtual Coupling End-of-Authority  $EoA_{VC}$ , which is in fact a Limit of Authority with as target speed the speed from the predecessor (or leading train). This diagram does not include the set up and termination of the virtual coupling but instead refers to the platoon joining and splitting as coupling and decoupling.



**Figure 22:** State transition diagram of Virtual Coupling operation

(D4.3 MOVINGRAIL, 2020) recommends a functional separation between VCTS train protection functions and cooperative train operation functions, similar to ATP and ATO but then for virtually-coupled trains in a convoy. In particular, VCTS-TMS and VCTS-CTR are vital on-board safety subsystems that allows virtually-coupled trains to follow each other up to relative braking distances within a convoy, while a Cooperative Train Operation system controls the optimal coupled platoon operation, including platoon joining and splitting. The Cooperative Train Operation system then guarantees stable operation in a platoon, while the VCTS train protection system coordinates and supervises safe relative braking distances. A smooth interaction between both systems is essential for optimal performance of virtually-coupled trains running in platoons



within convoys. Hence, the Virtual Coupling architecture should add the Cooperative Train Operation functions to the tactical and operational layers, including the interfaces with the conceptual VCTS Train Management System and VCTS Controller.

### 6.1.3. Track-side Functionalities and Track State

Virtual coupling also has an impact on the trackside safety systems, and in particular the interlocking systems, level crossing protection, and the trackside train detection in case of hybrid virtual or moving block signalling (D4.3 MOVINGRAIL, 2020). The route release procedure changes drastically with virtual coupling in the sense that routes must be set and locked for the entire train convoy given that the virtually-coupled trains are following closer than the absolute braking distance. This holds in particular for routes over moving elements such as point zones and moveable bridges, and routes including crossings and level crossings.

From the interlocking perspective a train convoy must be treated as a single train. When the train (convoy) positioning is purely based on moving block the master train shall use the rear end of the last virtually-coupled train in the Train Position Report. This should be based on the train positioning from this last train communicated to the master train since the train convoy length is variable as opposed to physical coupled train compositions. So, this will imply a change in the ETCS messages regarding the Train Position Report.

In hybrid virtual block or hybrid moving block systems track-side train detection is still retained. Also, trackside train detection may still be used in interlocking areas to release points or detect standing trains, and the same for level crossings. Where track-side train detection is used, track occupation can no longer be based on the physical occupation of a track section. Instead, the track status should remain occupied until the entire convoy has passed. This is an extension to the route holding procedure, which must be based on the train convoy length rather than the passage of a single train.

Besides the route holding functionality, also flank protection and overlaps must be maintained for train convoys. This holds for both hybrid and moving block systems. Hence, in the interaction between the train convoy and the interlocking the latter must be aware that a route is being set and locked in for a convoy of virtually-coupled trains to properly execute the interlocking functionalities with additional constraints between points and routes over the movement of the entire convoy. This also affects the track status for tracks used for flank protection (D4.3 MOVINGRAIL, 2020).

Virtual Coupling allows close following of virtually-coupled trains sharing the same (partial) route. Trains can virtually couple on a platform in a station if the platform length allows and then depart as a convoy. However, trains destined for a certain convoy may also come from different railway lines or from different platform tracks in a station, which requires sequential route setting of successive trains over a junction or point zone before they can virtually couple and form a platoon on a plain track. This is because a route must be set and locked before a train gets a Movement Authority into that route. Consider for instance a scenario in which two trains start from different platform tracks in a station while they will form a convoy further down the line. In this case, the

first train will get an outbound route and depart. The outbound route from the other platform track can be set only after this first train released the critical point shared between the two merging routes. This point can then be moved in the proper direction after which the route can be locked for the second train. Then the second train gets a Movement Authority and will depart in the direction of the first train. Only after the second train catches up with the first it could set up a Virtual Coupling connection. Clearly, this process should be optimized so that the second train can depart as fast as possible after the first. A different scenario occurs at a junction where a train from another line merges to the main line and then will couple to the train or convoy who just passed the junction. In this case the merging train must still be at the absolute braking distance before the point into the main line is released by the train or convoy, moved in the other direction and then locked, after which the route can be locked in, and a Movement Authority given to the merging train. Up to this moment the merging train cannot approach the point within the absolute braking distance to avoid the risk of a point locking failure. This process thus requires a careful coordination at the strategic traffic management level between both the trains involved and the route setting. Likewise, diverging train movements after decoupling from a convoy needs perfect alignment with the route setting into the diverging route. In this case, the train should be decoupled from the convoy and reach a distance larger than the absolute braking distance from the point, to allow sufficient time for the point to be released by the preceding train, the diverging route to be set and locked, and the Movement Authority into the diverging route to be received from the RBC (D4.3 MOVINGRAIL, 2020).

The conceptual functional layers and VCTS system description from X2RAIL-3 focused on the on-board functionalities, see Figure 20 and Figure 21. The interaction of a train convoy with the interlocking must go via a strategic Traffic Management layer, which requires coordination between Traffic Management, interlocking and train convoy operation, to synchronize route setting of merging and diverging routes with the coupling and decoupling to/from a convoy. This must still be formalized in the Virtual Coupling systems architecture.

## 6.2. Virtual Coupling Cooperation Variants

As explained in Section 6.1, three variants of Virtual Coupling can be distinguished depending on the amount of cooperation/coordination of the braking and acceleration of the trains in the convoy. (D4.3 MOVINGRAIL, 2020) distinguished between three modes of Virtual Coupling:

1. **Uncooperative braking:** each train in the convoy computes its relative braking distance with respect to its own specific braking curve and the braking behaviour of its predecessor.
2. **Cooperative braking:** the master train computes a cooperative braking curve for all virtually coupled trains based on the characteristics of each train in the convoy.
3. **Platooning** (cooperative braking and acceleration): the master train synchronizes the movement of all virtually coupled trains in the convoy including cooperative braking curves.

In the UK RSSB Closer Running project, a distinction was made between Motorway-style driving and Virtual Coupling (Fenner, 2016). The Motorway-style driving is similar to the Uncooperative

braking mode above with a following train getting speed and position information from the predecessor train using V2V communication. Virtual Coupling was used for the two cooperative braking modes above. In addition, the Closer Running study used the term Platooning for coordinated following under moving block signalling with additional information from V2V communication to minimize the distances between the successive train, but thus respecting the absolute braking distance. Indeed, platooning can be used generally as a multi-vehicle cooperative control concept that enables vehicles to move synchronously and stable together. Within the railways, the safe train separation is then supervised by the ATP system, which can be ETCS Level 3 moving block as in the Closer Running study or Virtual Coupling when considering relative braking distances. With Platooning under Virtual Coupling the latter is meant. Note however that we also defined platooning as a control concept while the term train convoy or virtually-coupled Train Set (VCTS) is used for the safety-critical concept of virtually-coupled trains.

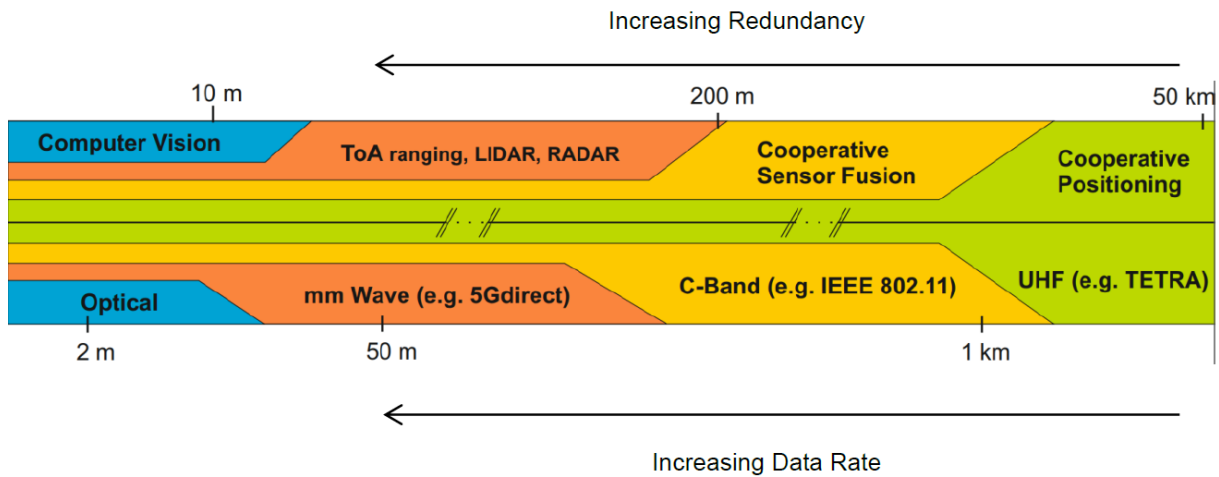
### 6.3. Train localization and Train Integrity Monitoring

Train integrity monitoring is used by all trains within a convoy to guarantee a safe rear-end for each of the virtually-coupled trains similar to Moving Block. However, if only the master train will be connected to the RBC, it must also guarantee the integrity of all virtually coupled trains within the convoy via the V2V communication with all the trains in the convoy. For physically coupled trains the last train has a rear-end marker (nowadays mostly a red tail light) indicating the end of the train which gives a visual clue of the train integrity. For virtually-coupled trains this would mean that only the last virtually-coupled train in the convoy would have a rear-end marker, while all other virtually-coupled trains would not have a tail light. When the distances between the virtually-coupled trains can still be large this might cause confusion, such as with trains that are still running at absolute braking distance which can be several kilometres for high-speed rail. A possible technical solution could be a secondary tail light without signalling meaning.

On-board train positioning is used by all virtually-coupled trains to provide safe front-end and rear-end positions for all trains within the convoy. For Virtually Coupling a separate rear-end positioning independent of the front-end positioning is essential to provide the highest accuracy required for keeping a safe relative braking distance. In particular, the distance between the trains, or the relative distance, is highly critical. To control a safe and stable distance between successive virtually-coupled trains in a platoon highly dynamic information is needed including the relative distance, the relative speed, and the relative acceleration/deceleration. Also note that the train convoy length is not fixed as with a physically coupled train composition. The convoy length increases instantaneously when a new train sets up a virtual coupling to the convoy, is likewise reduced when a train decouples from the convoy, and is further dynamically dependent on the relative distances between the successive virtually-coupled trains which may vary even in a platoon in response to e.g. varying gradients.

For Virtual Coupling sensors are needed for the absolute position, the relative position between trains, the absolute and relative speeds, and the absolute and relative accelerations. For the relative states, communication is needed between the trains. For long-distance a 5G cellular network connection can be used, while for short-range communication a 5G peer-to-peer direct communication can be used to guarantee low latency (D3.3 MOVINGRAIL, 2020). For very close

distances other technology can be added such as RADAR and LiDAR. Figure 23 shows the various technology means to implement cooperative train movements with increasing redundancy and data rate the closer the distance between trains (D6.1 X2Rail-3, 2020).



**Figure 23:** Technological means to implement coordinated movements [D6.1 X2RAIL-3]

## 7. Virtual Coupling System Specifications

### 7.1. Time Constraints

On top of the moving block time constraints, Virtual Coupling depends on the latency of the V2V communication. Moreover, the braking models are essential with in particular the brake built-up time. For merging and splitting before or after coupling/decoupling the point movement and locking time is important as well as the overall route setting time from calling to locking the route.

### 7.2. Use Cases for Virtual Coupling System

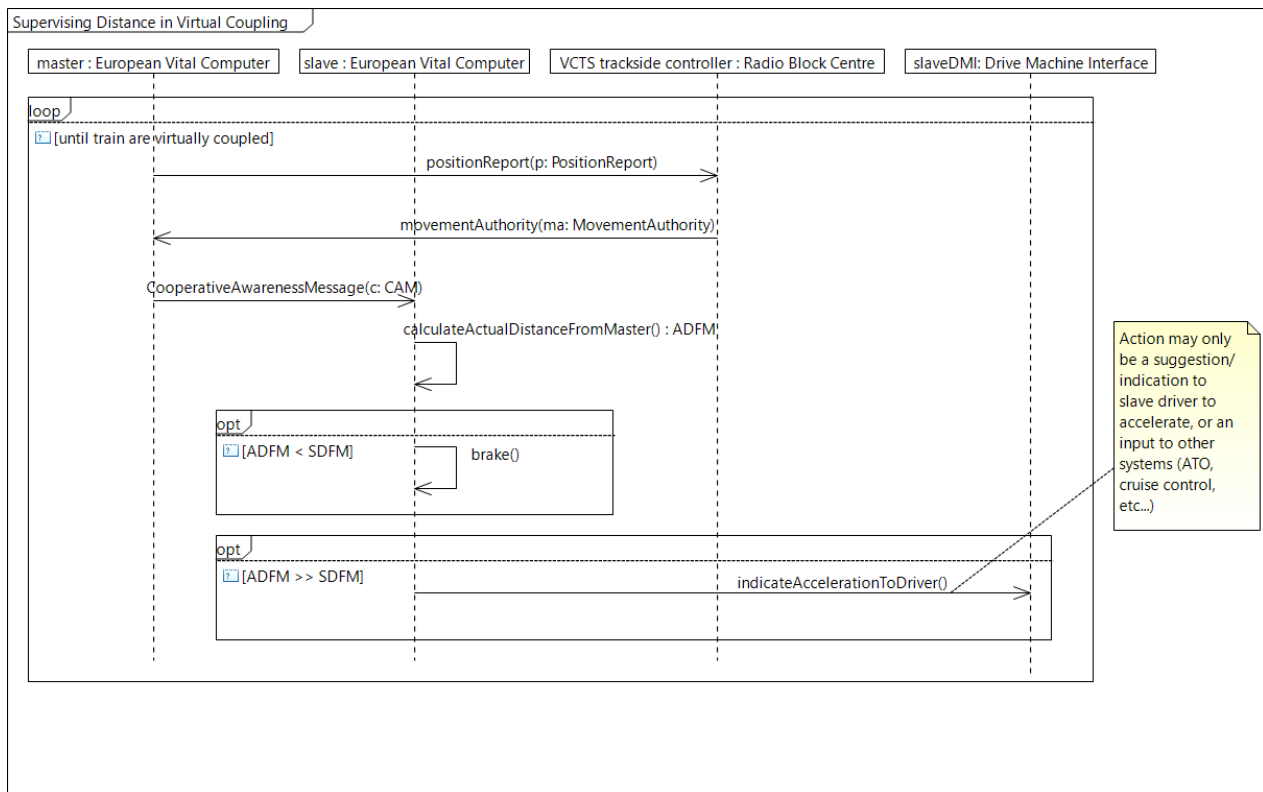
X2RAIL-3 defined the operational scenarios for Virtual Coupling as summarized in Table 9. For each scenario (D6.1 X2Rail-3, 2020) described the initial conditions and expected functional behaviour, along with illustrative drawings.

One of the main objectives of this document is to specify behavioural aspects of four key UCs by means of behavioural models (e.g., sequence diagrams). Section 5.5 discussed the selection criteria considered in this document and listed the three UCs that relate to the MB system.

Figure 24 represents the 4th UC that relate to the VC system on Supervising Train Separation Distance during Normal Driving (No. 3 in Table 9). According to the description reported in (D6.1 X2Rail-3, 2020), control techniques ensuring the platoon stability, which may require monitoring the relative distance and speed between each of the slave trains and the master, are not part of this deliverable.

**Table 9: Operational scenarios defined in (D6.1 X2Rail-3, 2020)**

No.	Use case	Phase
1	Initiation of Virtual Coupling	VC set up
2	Coupling of Platoon with more than one Slave	VC set up
3	Supervising Train Separation Distance during normal driving	Coupled driving
4	Master Train Braking	Coupled driving
5	All Platoon Stopping at Station	Coupled driving
6	Change of Cabin (Master/slave), Change of Running Direction	Coupled driving
7	Platoon Coasting at Station	Coupled driving
8	Splitting of a VCTS – Initiated by Slave	Termination of VC session
9	Splitting of a VCTS – Initiated by Master	Termination of VC session
10	Loss of Radio Link	Termination of VC session
11	Platoon in Proximity of Switching Points	Additional scenarios
12	Route Lock Function and Virtual Coupling	Additional scenarios
13	Level Crossings (LX) Management with Platoons	Additional scenarios



**Figure 24: Supervising Distance in normal driving**

## 8. Conclusions

This document has reviewed the moving block systems including ETCS L3 and virtual coupling, and it has defined a baseline specification for both systems including system requirements, engineering and operational rules, and hazard analysis. The document is divided into four main sections with Chapters 4 and 5 focus on the Moving Block system, while Chapters 6 and 7 discuss the virtual coupling signalling system.

Chapter 4 has reviewed relevant academic and industrial projects to define the moving block system in terms of system architecture, existing approaches and variants, and the main system functionalities. First, the chapter has presented a high-level architecture of ETCS L3 including the trackside and on-board systems. The architecture diagram has also highlighted how the ETCS L3 would interface with external systems and actors using an explanatory use case for normal train movement. Then, the two main moving block approaches (Full Moving Blocks and Fixed Virtual Blocks) have been reviewed alongside the four induced system variants. Finally, the chapter detailed the main moving block system functionalities including train integrity modelling, train localization, and determination of track status.

Chapter 5 introduced a baseline system specification for moving block signalling system. The chapter has synthesized the X2Rail-3 data on system requirements, operational and engineering rules, and hazards analysis. The chapter has demonstrated SysML requirements diagrams for both the main and timed requirements of the moving block system considering the system time constraints. Besides, the document has extended the hazards analysis introduced in X2Rail-3 to focus on GNSS-specific hazards used on terrestrial transportation as well as the GNSS-based VBTS hazards as the most mature GNSS-based solution. Finally, chapter 7 has introduced a detailed description of 16 use cases detailing their external actors, related internal functions, expected system behaviour, system parameters, and safety hazards. A criterion has been set to select the most common use cases to represent their behaviour using SysML sequence diagrams. The contribution of this chapter will help in the subsequent modelling in PERFORMINGRAIL WP2.

Chapter 6 reviewed X2Rail-3 and MOVINGRAIL projects alongside other academic research to provide a comprehensive definition of the virtual coupling signalling system. First, the chapter demonstrated the four functional layers needed to implement the virtual coupling system including the service layer, the strategic layer, the tactical layer, and the operational layer. Then, the chapter discussed the virtual coupling on-board and trackside components highlighting each component functionality. Finally, the chapter demonstrated how the train integrity and the train localization are considered with the virtual coupling approach. Afterwards, Chapter 7 has slightly touched on the publicly available specifications for virtual coupling system. The chapter extended the moving block time constraints to include the V2V communication latency, braking built-up time, the point movement time, and the route setting time. Also, the chapter summarized the use cases for virtual coupling as defined in the X2Rail-3 project.

The system definition and specifications provided in this document represents a baseline for the subsequent modelling activities that are part of PERFORMINGRAIL WP2.



## 9. References

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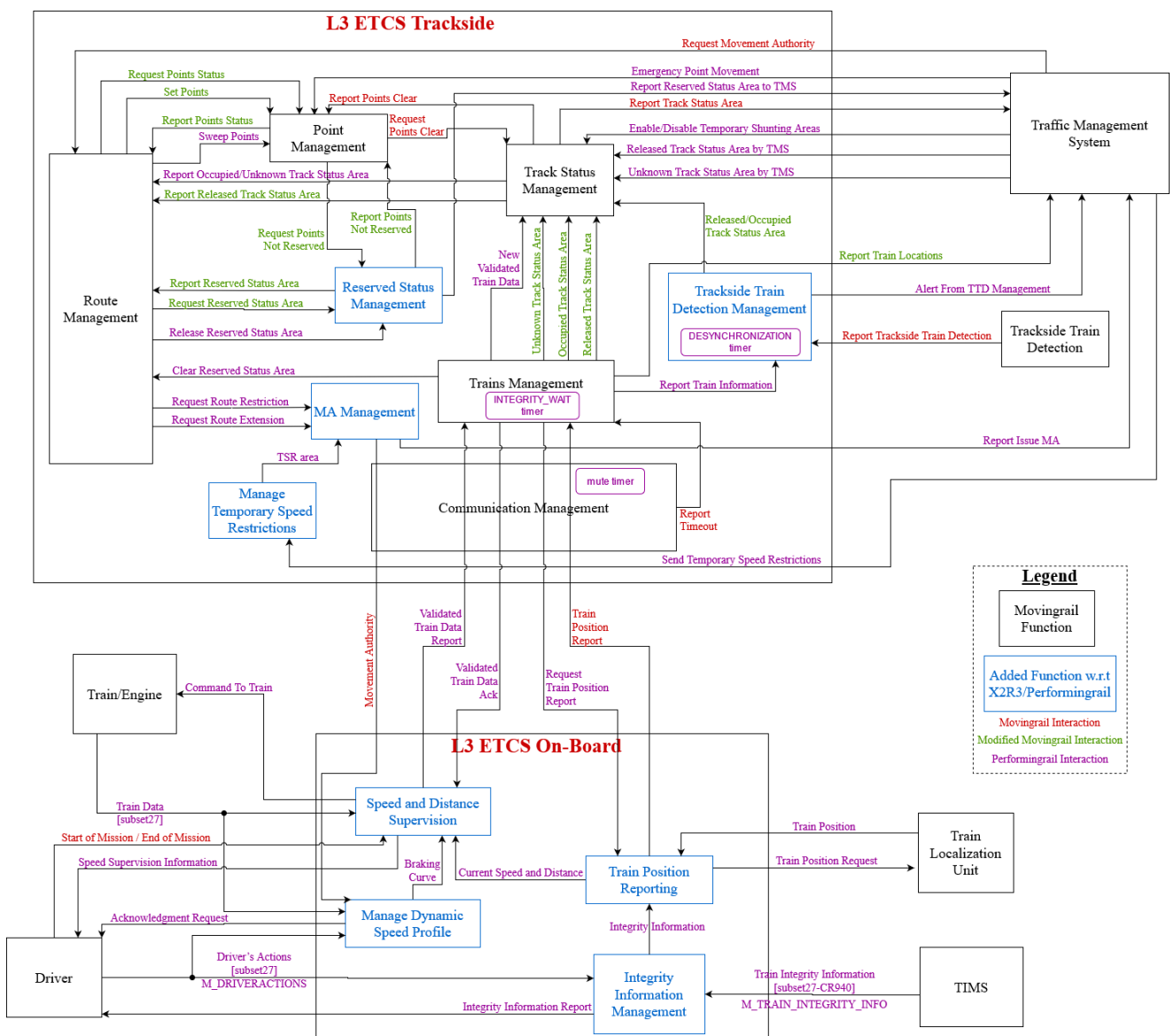
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## 10. Annex A: Functional architecture of the L3 System

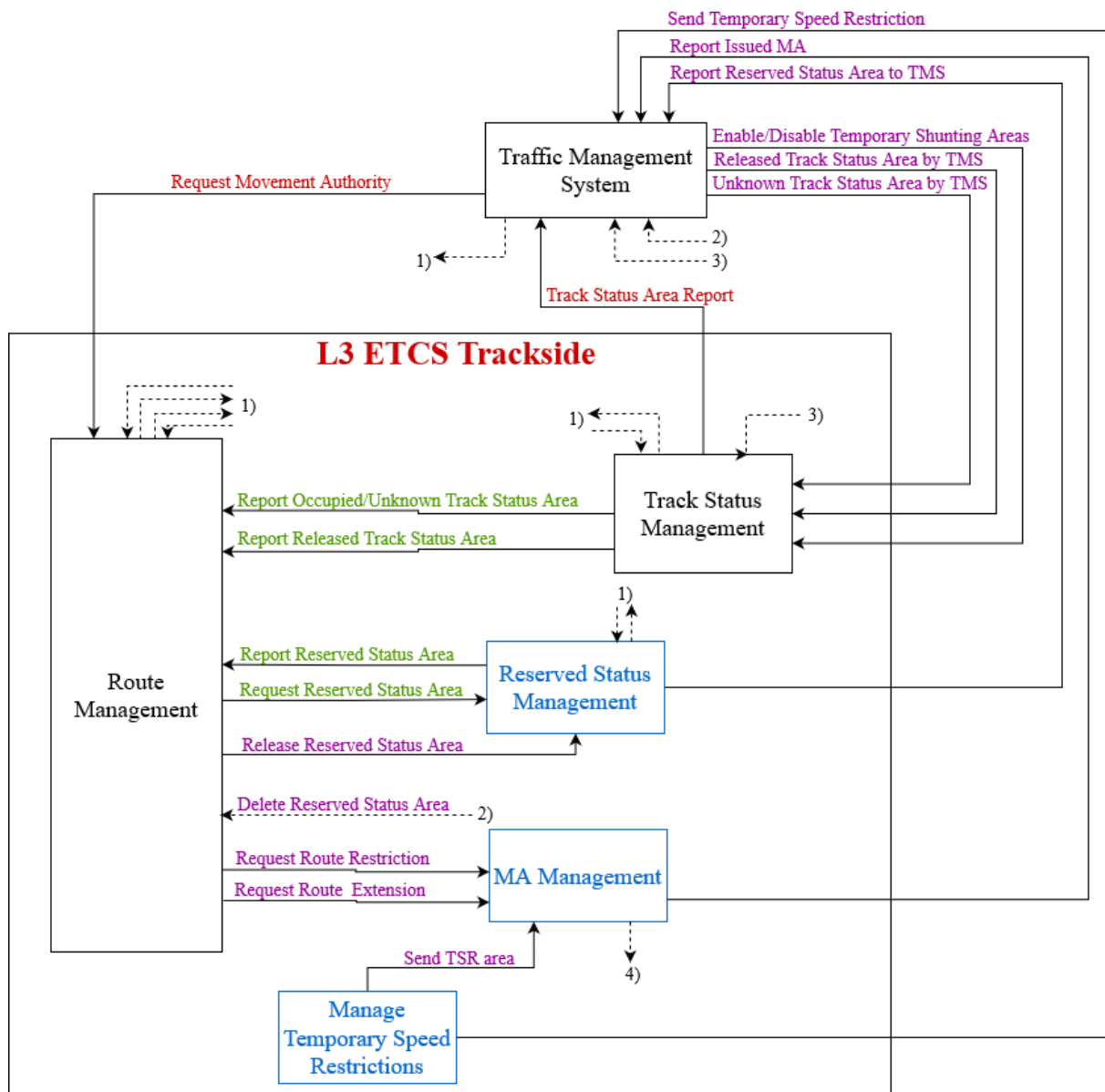
After analysing the specification description in (D4.2 X2Rail-3, 2020) and (D1.1 MOVINGRAIL, 2020), an updated and more detailed view of the functional architecture of the L3 System is presented in Figure 25<sup>6</sup>. In order to focus on some specific aspects and get a better visibility on the different interaction names, Figure 25 has been split into Figure 26 focusing on the “Route Management” and “Traffic Management System” interactions, Figure 27 focusing on the “Points Management” interactions, and Figure 28 focusing on the “L3 ETCS On-Board” and “Trains Management” interactions. These 56 interactions are described in Table 10.



**Figure 25: Functional Architecture of the L3 System**

<sup>6</sup> The 5 diagrams are available online on (Sept-2022):

<https://drive.google.com/file/d/1SfUZwgWipq1LbIF5wmGFOyBmJ-5wvvtG/view?usp=sharing>



**Legend**

Movingrail Function

Added Function w.r.t X2R3/Performingrail

Movingrail Interaction

Modified Movingrail Interaction

Performingrail Interaction

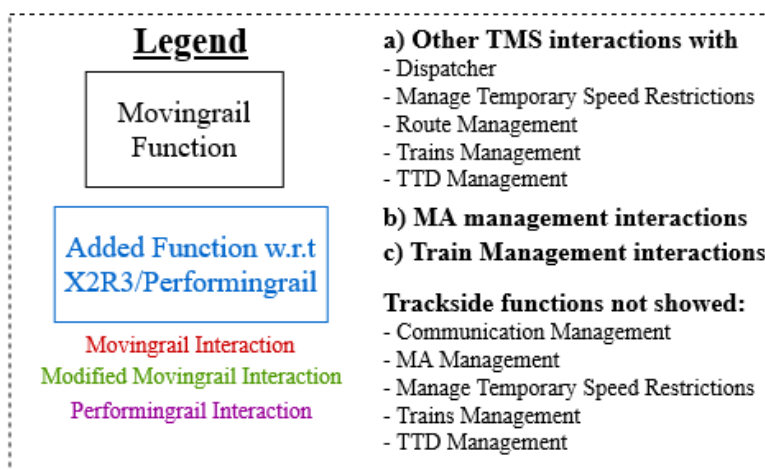
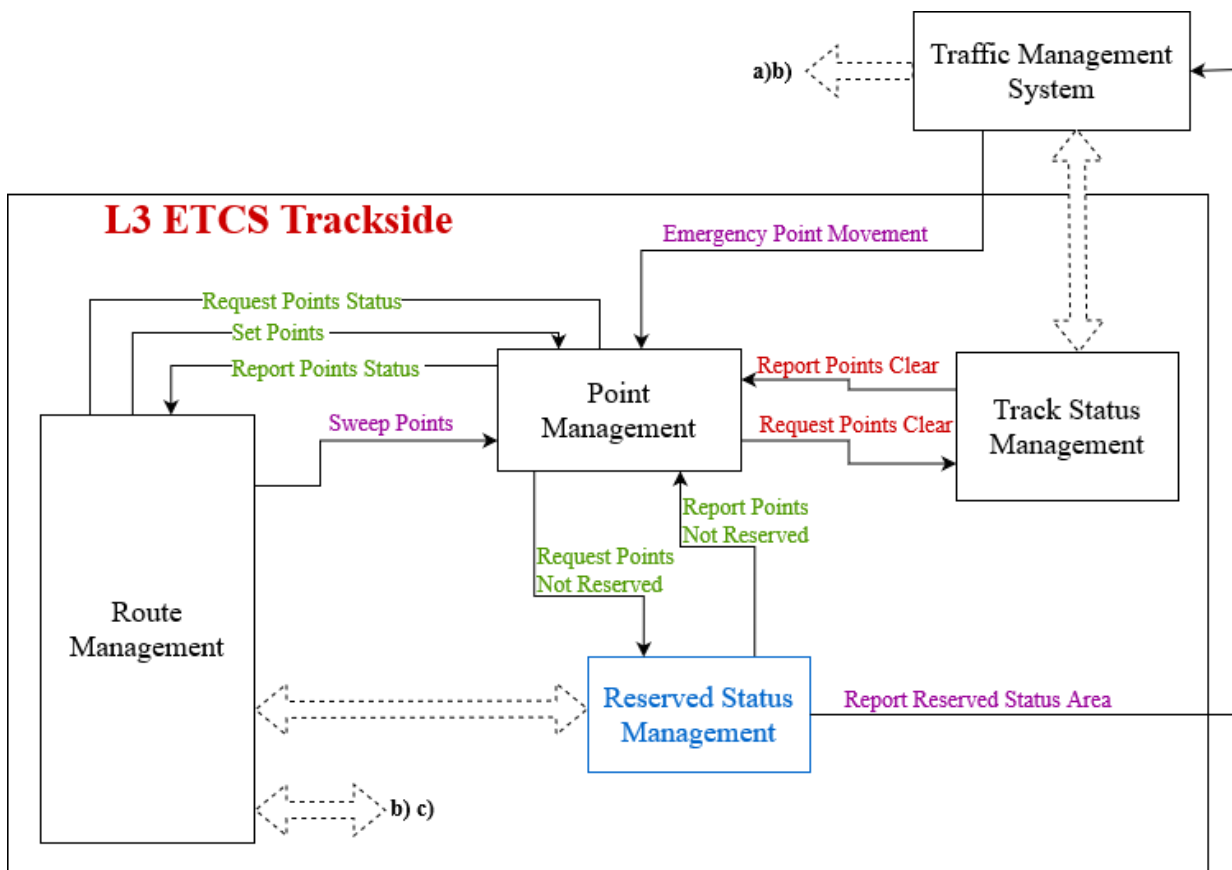
**Other interactions**

- 1) 'Point management' interactions
- 2) 'Trains Management' interactions
- 3) 'TTD Management' interactions
- 4) 'Manage Dynamic Speed Profile' interactions

**Trackside functions not showed:**

- Communication Management
- Point Management
- Trains Management
- TTD Management

Figure 26: “Route Management” and “Traffic Management System” interaction details



**Figure 27: "Point Management" interaction details**

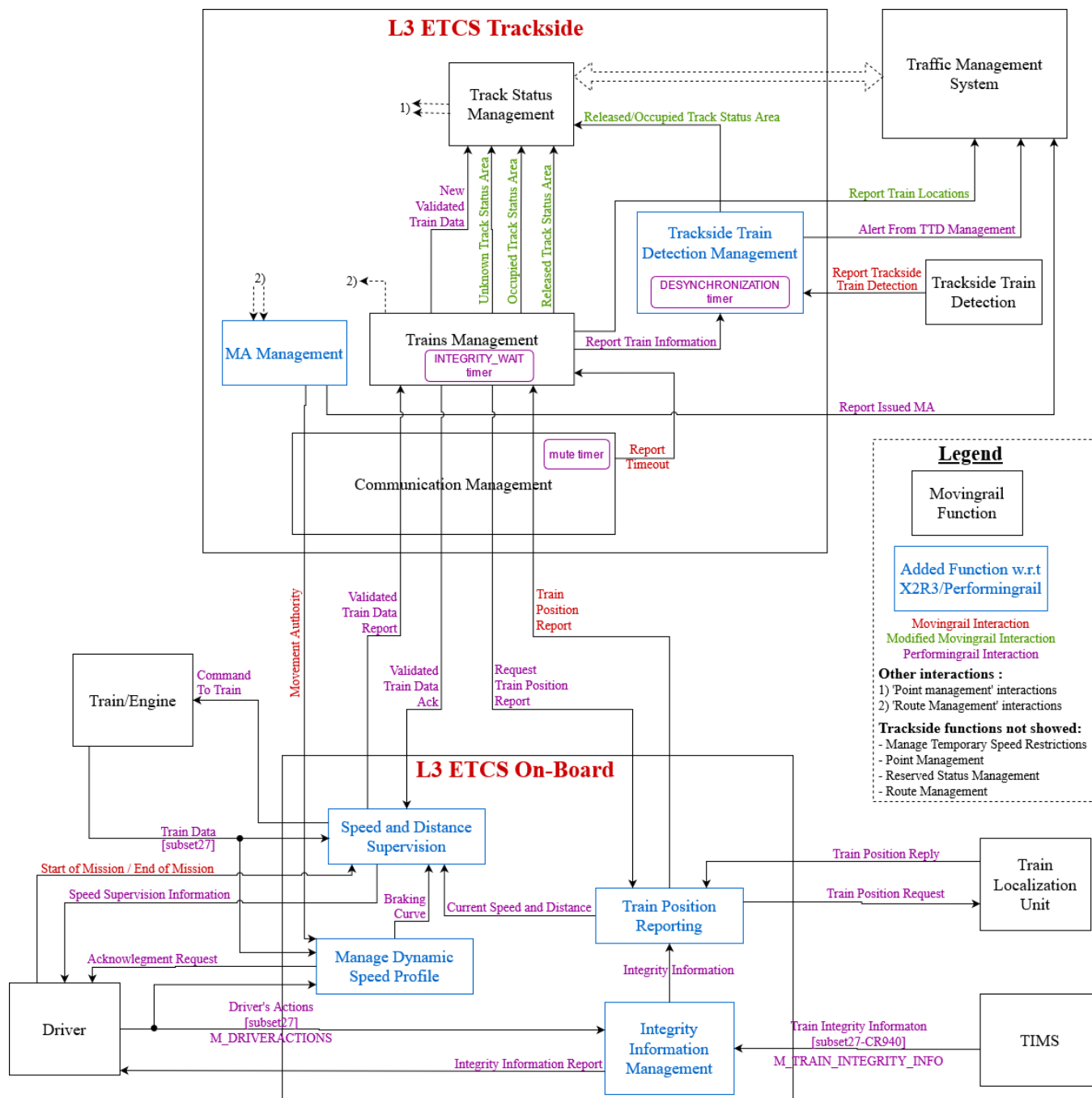


Figure 28: “L3 ETCS On-Board” and “Train Management” interaction details

**Table 10:** Description of the interactions in the ETCS L3 functional architecture

Interactions	Source	Description
<b>ROUTE MANAGEMENT (Trackside)</b>		
Delete Reserved Status Area	Trains Management	When a train disconnects, its related reserved area is removed.
Report Occupied/Unknown Track Status Area	Track Status Management	Used to inform of a track area that is occupied/unknown.
Report Points Status	Point Management	The "Point Management" indicates points status: their position, if they are locked / unlocked.
Report Released Track Status Area	Track Status Management	Triggered when an area of the track is released according to the passage of a train.
Report Reserved Status Area	Reserved Status Management	Used to inform of the status of the reserved area: reserved or not reserved.
Request Movement Authority	Traffic Management System	Triggered when the TMS asks for a MA for a given train on a specific route.
<b>TRACK STATUS MANAGEMENT (Trackside)</b>		
Enable/Disable Temporary Shunting Area	Traffic Management System	Used to enable/disable a shunting area.
New Validated Train Data	Trains Management	Used to react to a change in Train Data.
Occupied Track Status Area	Trains Management	When "Train Management" informs of an area of track to be changed to Occupied.
Released Track Status Area	Trains Management	When "Train Management" informs of an area of track to be changed to Released.
Released Track Status Area by TMS	Traffic Management System	When "TMS" informs of an area of track to be changed to Released.
Released/Occupied Track Status Area	Trackside Train Detection Management	To get occupancy information of TTDs.
Request Points Clear	Point Management	Used to know whether some points are in an Occupied/Unknown area.
Unknown Track Status Area	Trains Management	When "Train Management" informs of an area of track to be changed to Unknown.
Unknown Track Status Area by TMS	Traffic Management System	When "TMS" informs of an area of track to be changed to Unknown "manually".
<b>MANAGE TEMPORARY SPEED RESTRICTIONS (Trackside)</b>		
Send Temporary Speed Restriction	Traffic Management System	Used when the TMS commands a TSR.

<b>POINT MANAGEMENT (Trackside)</b>		
Emergency Point Movement	Traffic Management System	Used to move points for which all or parts of it is in an Unknown/Occupied area.
Report Points Clear	Track Status Management	Used to know if points do not belong to an Occupied/Unknown area.
Report Points Not Reserved	Reserved Status Management	Used to know if points do not belong to a Reserved area.
Request Points Status	Route Management	Used to request the status of a point.
Set Points	Route Management	Used to move and lock points on a train route or for the flank protection of a route.
Sweep Point	Route Management	Used to sweep points by a sweeping train.
<b>RESERVED STATUS MANAGEMENT (Trackside)</b>		
Release Reserved Status Area	Route Management	Triggered by "Route Management" when a Reserved Status Area is requested to be released.
Request Points Not Reserved	Point Management	Used by "Points Management" to request whether points belong or not to a Reserved Status Area.
Request Reserved Status Area	Route Management	Triggered by "Route Management" when an area is requested to be reserved for a train route or for the flank protection of a route.
<b>TRACKSIDE TRAIN DETECTION MANAGEMENT (Trackside)</b>		
Report Trackside Train Detection	Trackside Train Detection	TTDs give block section occupancy knowing the state of the track circuits / axle counters.
Report Train Information	Trains Management	"Trains Management" indicates the location of trains to synchronise with "TTD Management".
<b>TRAIN MANAGEMENT (Trackside)</b>		
Report Timeout	Communication Management	Used to know if one or more of the communication timers have elapsed.
Train Position Report	Train Position Reporting	The received TPR is used by "Train Management" to compute the train location from MaxSFE to CRE knowing the train integrity info.
Validated Train Data Report	Speed and Distance Supervision	Used to know the parameters of the train.

<b>MA MANAGEMENT (Trackside)</b>		
Request Route Extension	Route Management	Used to extend a MA.
Request Route Restriction	Route Management	Used to restrict a MA.
TSR Area	Manage Temporary Speed Restrictions	Create/Revoke/Modify Temporary Speed Restrictions.
<b>SPEED AND DISTANCE SUPERVISION (On-Board)</b>		
Braking Curve	Manage Dynamic Speed Profile	Update the Braking Curve of a train.
Current Speed and Distance	Train Position Reporting	Update the position/speed of the train for the supervision.
Start of Mission / End of Mission	Driver	SoM/EoM procedure initiated by the driver.
Train Data 1	Train/Engine	Data of the train used to follow the dynamic speed profile.
Validated Train Data Ack	Trains Management	Acknowledgement of the Validated Train Data message.
<b>MANAGE DYNAMIC SPEED PROFILE (On-Board)</b>		
Driver's Actions 1	Driver	Ack. of entering On Sight/Shunting/ Train Trip/SR/etc. mode.
Movement Authority	MA Management	The MA is updated.
Train Data 2	Train/Engine	Data of the train used to compute the dynamic speed profile on the reserved status area.
<b>TRAIN POSITION REPORTING (On-Board)</b>		
Integrity Information	Integrity Information Management	Received integrity information to be included in TPR.
Request Train Position Report	Trains Management	Request of a position punctually by the "Trains Management".
Train Position Reply	Train Localization Unit	Received position/speed by the Train Localization Unit.
<b>INTEGRITY INFORMATION MANAGEMENT (On-Board)</b>		
Driver's Actions 2	Driver	Integrity confirmation by the train.
Train Integrity Information	TIMS	Integrity confirmation by the driver.
<b>TRAIN LOCALIZATION UNIT (External)</b>		
Train Position Request	Train Position Reporting	Request the position/speed information to the TLU.
<b>DRIVER (External)</b>		
Acknowledgment Request	Manage Dynamic Speed Profile	Request of Ack.
Integrity Information Report	Integrity Information Management	The Driver receives train integrity information on the DMI.
Speed Supervision Information	Speed and Distance Supervision	The Driver receives speed and supervision info on the DMI.
<b>TRAIN / ENGINE (External)</b>		
Command To Train	Speed and Distance Supervision	Traction and braking commands to the train mechanisms.



<b>TRAFFIC MANAGEMENT SYSTEM (External)</b>		
Alert From TTD Management	Trackside Train Detection Management	“TTD Management” alerts the TMS in case of TTD/TPR synchronization problems.
Report Issued MA	MA Management	Reporting of the MAs sent to the trains to the TMS.
Report Reserved Status Area to TMS	Reserved Status Management	Reporting of the Reserved Status Areas to the TMS.
Report Track Status Area	Track Status Management	Reporting of the Track Status Areas to the TMS.
Report Train Location	Trains Management	Reporting of the Trains Location to the TMS.

## 11. Annex B: Synthesis of MB Requirements, Operational and Engineering rules

The "PERFORMINGRAIL D1.1-v1-Annex B.xlsx" worksheet contains the following data taken from X2Rail3 project (D4.2 X2Rail-3, 2020) using several tabs:

- the MB system requirements (from MB system specifications - D4.2 part 3)
- the operational rules (D4.2 part 4)
- the engineering rules (D4.2 part 5)

## 12. Annex C: Advanced Technologies for Moving Blocks and Virtual Coupling Systems

### 12.1. Localization Options for MB Systems

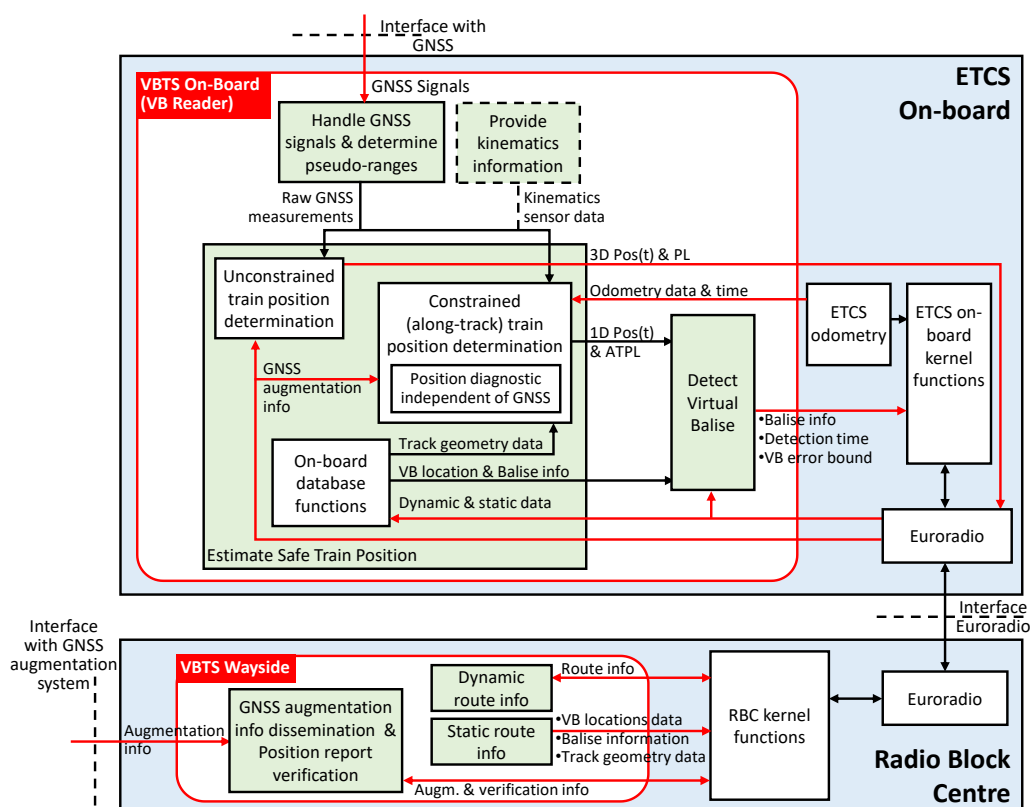
#### 12.1.1. On-board system including satellite positioning

Readjusting the long-term drift of the current odometry device no longer by balises on track but by a GNSS receiver (Global Navigation Satellite System) embedded in train is entirely possible, providing thus positioning markers at higher frequency. In such a way, GNSS receiver play the role of a virtual balise (VB), functionally equivalent to a physical one (or to a balise group).

Virtual balises are georeferenced points recorded in a database embedded in train computer. They can replace physical balises (PB) by keeping existing ETCS Levels 1 and 2 specifications and reference architecture unchanged. As PB can be removed, costs can be saved.

The VB function is planned to be accomplished using the on-board GNSS receiver as follows: a VB reader periodically computes the train GNSS position and compares it with the locations associated with the VBs. The VB function is activated when the estimated train position matches the stored VB position in the database. The balise information (the telegram) is then obtained also from the on-board database.

This VB concept has been investigated in various European research projects related to ETCS and their safety aspects was explored in recent works (Marais, Beugin, & Berbineau, 2017). However, VB functionalities with GNSS are not available in areas where satellite signals are blocked like in tunnels and will still need physical balises in specific locations where GNSS positioning does not ensure adequate performances (accuracy, availability, continuity, localization integrity). Figure 29 shows a hypothetical architecture of VBTS (Virtual Balise Transmission System) attempting to synthesize project works on VB (Sassi, Beugin, Sallak, & Ait Tmazirte, 2020).



**Figure 29: VBTS functional architecture**

MB systems without trackside train detection (FMB type, not FVB type) and with virtual balises were investigated in the ASTRail Shift2Rail project (interlocking functions for route management are out of scope) (D2.1 ASTRAIL, 2019). In such configuration, LRBG becomes LRVB (Last Relevant Virtual Balise).

Using virtual balises permits to keep existing ETCS Odometry equipment and to remove track balises by realizing the resetting operation with absolute position coming from a GNSS receiver. Two other train localization options using a GNSS-based subsystem (i.e., using a GNSS receiver and other kinematics sensors) are possible:

- purely and solely replacing Odometer equipment and balises with an on-board solution using GNSS;
- Replacing the existing Odometer equipment with an Odometry whose quality is improved by the use of GNSS, fewer balises to reset the drift are then necessary.

These 3 options are conceivable and various research projects have addressed them (Marais, Beugin, & Berbineau, 2017). However, to go beyond prototype solutions and obtain an Authorization for Placing Into Service (APIS) the new signalling subsystem benefiting from the GNSS advantages, developments are often guided according to the European logic already adopted with ERTMS. Any solution that would completely change the way of controlling trains would have more difficulty to be established in Europe but are not excluded in terms of

innovation. In this context, the X2Rail-2 project has addressed the virtual balise option (D3.1 X2Rail-2, 2017), which emanates from past works showing the interest, in terms of interoperability, of using this concept rather than using an enhanced odometry. The replacement of odometry equipment and balises has also been investigated (D3.8 X2Rail-2, 2019). Both options will be investigated deeper in the X2Rail-5 project.

### 12.1.2. Technological options in combination with satellite positioning

In combination with satellite positioning, sensors for environmental recognition on-board (e.g., camera, radar, Lidar), as well as a high-definition (HD) digital map, make possible to locate trains with improved performances.

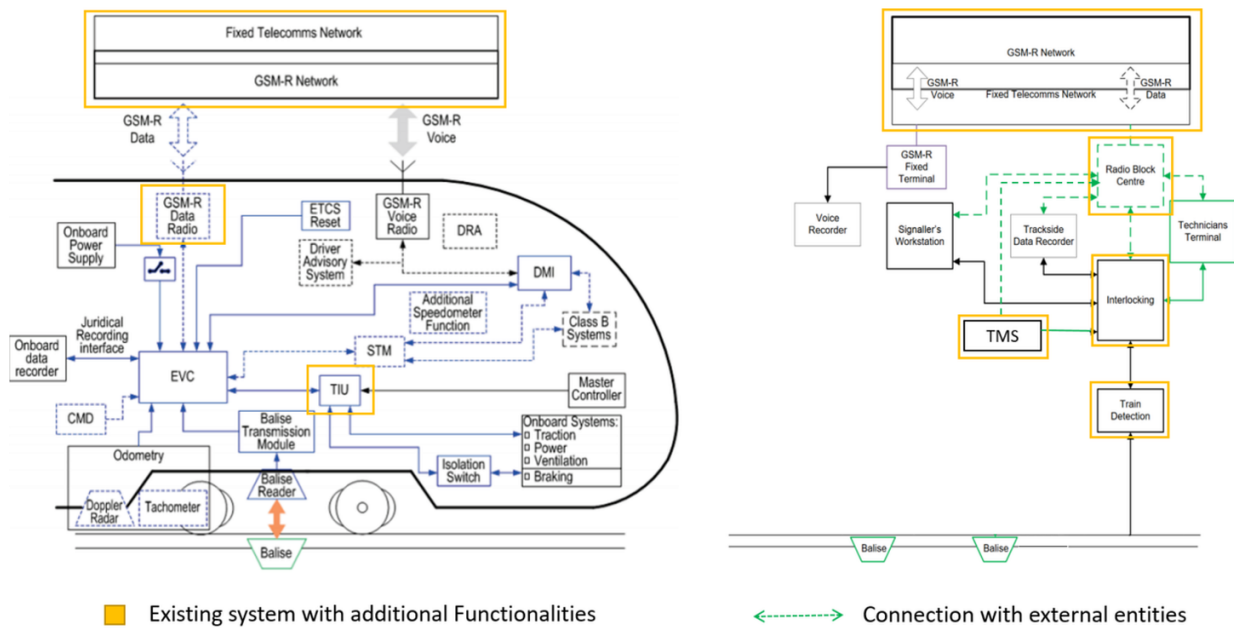
In addition to the track-accurate position, train speed, acceleration and train integrity can also be determined accurately with an integrated satellite-based positioning system. The digital map is the central repository for static and dynamic infrastructure data. A large part of the data is needed for automated driving and train location. For these purposes, the HD map depicts reality in a much higher level of detail than conventional navigation maps.<sup>7</sup>

## 12.2. Communication Options for MB systems

The train-to-ground communication system in ETCS L2 and L3 are expected to have the same on-board functional requirements according to (D3.3 X2Rail-1, 2019). However, in a Moving Block signalling system (i.e. ETCS L3), some additional functionalities for the trackside Radio Block Centre (RBC) are expected due to the raise of new scenarios. These scenarios include loss of communication, movement of a non-communicating train, recovery management after loss of communication, and the management of a radio hole. Figure 30 highlights (in orange) the blocks that exist for ETCS L3 and L2 with newly added functionalities in ETCS L3.

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<sup>7</sup> Adapted from <https://www.digitale-schiene-deutschland.de/en/technologies>



**Figure 30:** ETCS L2 and L3 blocks with newly added functionalities in ETCS L3

GSM-R is the responsible radio link for train-to-ground communication in ETCS L2 signalling system and it offers a rich set of features addressing the specific needs of railway operators. However, due to interference and capacity challenges of GSM-R, there is an industrial willingness to adopt an alternative communication system architecture that supports transparency of networks in use (i.e., the type of network in use is transparent to the application), concurrent use of communication bearers, vertical handover management between bearers, support of end-to-end application security, and capability to use and select a bearer based on the application requirements.

It is worth mentioning that the Future Railway Mobile Communication System (FRMCS) will be based on 5G technology as an alternative to the GSM-R for train-to-ground communications. The 5G technology offers very high throughput, low latency, flexible communication architecture, improved security, and better interference management compared to the preceding technologies. Table 11 summarizes all the candidate wireless technologies proposed for train-to-ground communications in ETCS L2 and L3 systems.

**Table 11: Communication Options for MB system**

	KPI/Requirement	GSM-R (GPRS)		LTE (R8)		LTE-A (R12)		5G (R15)	
		values	remarks	values	remarks	values	remarks	values	remarks
Frequency	Frequency Band	876-880 / 921-925 MHz		700, 900, 1800, 2100, 2600 MHz		700, 900, 1800, 2100, 2600 MHz		600, 700, 800, 900, 1400, 1800, 2100, 2600 MHz, 3.3 - 4.2 GHz, 26.5 - 29.5 GHz, 24.25 - 27.5 GHz, 27-40 GHz	
	Support of GSM-R band	yes							
	Use of paired/unpaired spectrum	paired		Both		Both		Both	
	Channel Bandwidth	0.2 MHz		1.4, 3, 5, 10, 15, 20 MHz		1.4, 3, 5, 10, 15, 20 MHz		100 MHz, 400 MHz	
	Possibility of Carrier Aggregation	no		no		yes		yes	
	Maximum Aggregated Bandwidth								1600 MHz below 6 GHz in 2GPP RAN-1 Physical Layer, 3200 MHz in RAN2 - MAC Layer, 6400 MHz above 6 GHz (12800 MHz in RAN2)
	Typical Frequency Re-use	0		NA	up to 100 MHz in R10		100 MHz		
PHY Characteristics	Transmission Transfer Interval (TTI)	1:3		1:1		1:1		1:1	
	TTI Bundling	20 ms		1 ms		1 ms		1 ms	<1 ms
	Downlink Multiple Access	no		yes		yes		yes	
	Uplink Multiple Access	TDMA		OFDMA		OFDMA		OFDMA	
	Duplex Mode	TDMA		SC-FDMA		SC-FDMA		OFDMA / SC-FDMA	
	Support of Hybrid ARQ	FDD		FDD & TDD		FDD & TDD		FDD & TDD	
	Support of Incremental Redundancy	no		yes		yes		yes	
	Support of Adaptive coding & Modulation	no		yes		yes		yes	
	Support of MIMO	no		yes		yes		yes	
	Support of Dynamic Scheduling	no		yes		yes		yes	
	Peak Downlink Data Rate *	0.08 Mbps		150 Mbps	2*2 MIMO, @20 MHz		1000 Mbps		25000 Mbps
	Peak Uplink Data Rate *	0.08 Mbps		75 Mbps			500 Mbps		13600 Mbps
	Mobility	Minimum Supported Speed			350 Km/h				
Measures against Doppler		yes	tail bits	yes	reference signal/preamb	yes	reference signal/preamb	yes	
Measures against Multipath Propagation		yes	tail bits	yes	cyclic prefix	yes	cyclic prefix	yes	
Additional KPIs	Railway-compatible Propagation Profiles	yes		yes		yes		yes	
	Minimum User Plane Latency	600 ms		10 ms		1 ms		1 ms	
	Connection Setup Time								
	Connection Setup Success Rate								
	Connection Drop Rate								
	Packet Error Rate		refer to EIRENE						
	Packet Transfer Delay/ Latency								
	Handover Latency								
	Handover Success Rate								
	Jitter								
	Support Interoperability to GSM-R	yes	Signals from mobile operators	yes	FRMCS using LTE technology will be interfered with GSM-R narrow band signals	yes	FRMCS using LTE technology will be interfered with GSM-R narrow band signals		
Interfere with others in same band	yes		yes		yes				
Interfere with others in neighbouring bands	yes		yes		yes				
General Support of Railway Functionality	yes		yes		yes				

Another feature that distinguishes ETCS L3 from ETCS L2 is the fact that the train detection is no more ensured by the trackside but by the on-board system. This is principally achieved by the addition of a Train Integrity Monitoring System (TIMS). The TIMS device is fitted on-board the train and is used to ensure that the train is still complete and that the individual vehicles have not separated from one another. To achieve this functionality, there is a need for a continuous communication link between the tail and the front cabin. Table 12 summarises the telecommunication requirements for the TIMS, as captured in (D3.1 X2Rail-1, 2018) and FRMCS user requirements (UIC, 2020).

**Table 12:** Telecommunication requirements for the Train Integrity Monitoring System

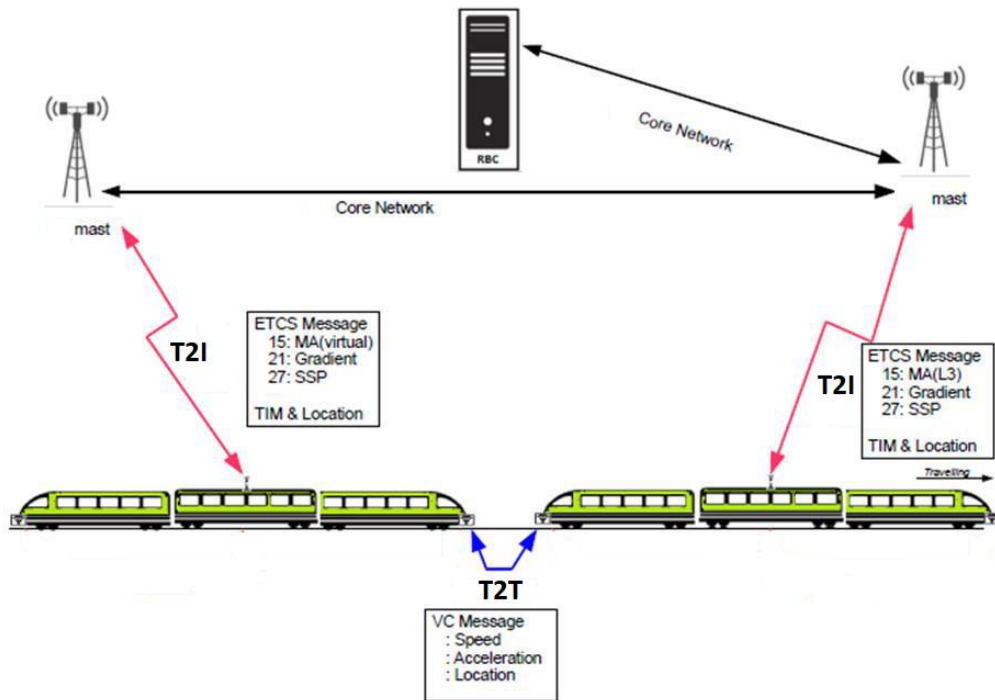
Requirements	Value
Use Classification	Critical
Content Type	Bi-directional data
Symmetry Up/Down	50/50
Data Rate	1 kbps
Latency	< 100ms
Link Reliability	High
Setup Time	1s
Priority	High
Frequent Use at different operational modes	High

### 12.3. Communication Options for VC systems

The virtual coupling concept aims to improve the network capacity further by running trains much closer from each other. The virtual coupling is built on the assumption that the leading train will not halt instantly, but it will brake gradually until it stops. If the following train has a similar braking rate as the leading train, the two trains can run with a separation distance that is less than the full braking distance of the following train.

A distinct requirement in the VC signalling systems is the existence of a reliable communication link between the successive trains (i.e., Train-to-Train (T2T) communications). The link is essential to ensure the braking behaviour of the leading train is reported continuously to the following train so as it can act accordingly and always maintain a separation distance. In other words, while the headway in a moving block system is based on absolute braking distance between trains, the virtual coupling headway depends on a relative braking distance that allows the following train to incorporate the braking behaviour of the leading train. Figure 31, reproduced from (D3.1 MOVINGRAIL, 2020), demonstrates the T2T and the Train-to-Infrastructure (T2I) communication links that constitute the communication architecture for VC systems.





**Figure 31:** Train-to-Train and the Train-to-Infrastructure communication links for VC systems

To compare the communication options for the VC systems, it is crucial to list their communication requirements. Table 13 summarises all the communication requirements as captured from (D3.1 MOVINGRAIL, 2020).

**Table 13:** Telecommunication requirements for the VC systems

Requirements	Value
Use Classification	Critical
Content Type	Bi-directional data with direct T2T and T2I capability
Symmetry Up/Down	50/50
Data Rate (bit/s)	Low (150 – 900 Bytes)
Latency	< 100ms (Low/Immediate)
Link Reliability	High (99.99% of the time)
Setup Time	Very Low (Immediate)
Priority	High
Frequent Use at different operational modes	High

It is worth mentioning that the train-to-ground communications for MB and VC systems are identical. Hence, the comparison of MB communication options in **Table 11** is still valid for VC T2I communications. However, (D3.1 MOVINGRAIL, 2020) listed two additional technologies to the table above, which are the IEEE 802.11 and TETRA.