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Co-simulation platform for demonstration and testing of moving block systems

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Abstract

This paper presents the design and development of a real-time co-simulation platform for integrated testing and assessment of moving block systems. The platform's main objective is to operate as an evaluation environment for the proof of concept of moving block specifications defined throughout the PERFORMINGRAIL project. The distinguishing feature of the proposed framework relies on the introduction of a GNSS receiver simulator connected to the Birmingham Railway Simulator Suite to represent a real test network for the demonstration of moving-block specifications, train location tools and traffic management models. The results of the implementation of an initial set of operational scenarios are presented to validate the proposed platform.

Keywords: Moving Block Systems, GNSS, Testing, Modelling & Simulation.

1. Introduction

As a reflex of the intensified globalization and population growth, the demand for passenger and freight railway transportation is expected to increase by respectively 50% and 80% by 2050 (Shift2Rail Joint Undertaking, 2015). In a scenario where infrastructure expansions are not always a viable option due to high construction costs and the lack of suitable sites for new tracks, the European railway sector will confront major challenges to significantly amplify the capacity of existing networks, particularly in highly populated regions, which already have been operating in near-to-saturation conditions.

To maximise capacity utilisation of current networks, the railway sector has focused its efforts on an operational paradigm shift that minimises train separation by moving vital trackside equipment on board the trains. Differently from traditional signalling systems, where train detection sections are strategically positioned to divide the line into limited sections, also called fixed blocks (MOVINGRAIL D2.2, 2020). Under the so-called Moving Block Systems (MBS) the separation between two trains is no longer defined by a set of adjacent fixed points on the line. Instead, blocks are dynamic and move with the train as they travel along the network. As a result, the train separation is determined by the absolute braking distance (i.e., the distance required to reach a standstill from current speed) plus a safety margin, based on the train position report accuracy.

In MBS, the minimised train separation is possible because safety-critical tasks such as train location reporting, Train Integrity Monitoring (TIM) and braking supervision are all conducted by onboard devices. However, as reported by (Furness & Bartholomeus, 2017), TIM technologies have not yet reached an acceptable reliability level to monitor the integrity of trains with variable composition (e.g., freight trains) given the absence of trackside train detection equipment. As a result, MBS has been so far only deployed on metro systems, due to its lower infrastructure complexity and uniform traffic composition.

For railway segments featuring greater complexities in topology and traffic (e.g., main-lines and high-speed), the identification of safe and reliable moving-block principles, technologies and methods is still an open research area. Up to now, the use of localisation systems to lead to high-accuracy and reliability of reported train positions, a vital characteristic for moving-block operations, is still to be defined. Among many potential candidates, the use of Global Navigation Satellite Systems (GNSS) for train localisation has been extensively investigated in different European research projects (Marais et al., 2017; PERFORMINGRAIL D3.1, 2021). However, the industry acceptance and the consequent market uptake of MBS and adjacent technologies solely depend on whether concrete developments will be made towards high-accuracy train localisation, reliable position integrity provision, optimised moving-block traffic management systems, and the validation of safe operational procedures.

With that in mind, the PERFORMINGRAIL project aims to implement a holistic system approach to address the open challenges for moving-block concepts. Therefore, the main objectives of the project are to enhance and verify existing specifications for moving-block signalling, while developing formal models, algorithms and proof of concepts to test and validate an integrated future moving-block system architecture that will provide safe and effective operational performances.

Considering the dynamic nature of moving block systems, testing and simulation will play an important role to predict the system behaviour and guarantee that its quality and reliability are being fulfilled. Thus, this paper presents the design and development of the co-simulation platform for the evaluation of the proof of concept of moving block specifications defined throughout the PERFORMINGRAIL project.

The remainder of this paper is structured as follows: The first part of the work gives an overview regarding co-simulation. The following section describes the requirements for the co-simulation platform, in addition to its applicability and configuration. Afterwards, the overall architecture of the framework is presented, followed by the description of the subsystems, including the behaviour and interaction between the simulators. In the next section, the performance of the platform is analysed based on the implementation of the PERFORMINGRAIL case study. Finally, in the last part, the simulation results for an initial set of operational scenarios are discussed.

2. Background

Co-simulation is defined as the coupled of one or more simulators that have been developed and implemented independently. In other words, co-simulation is the connection of multiple simulators to provide a global representation of complex multi-domain systems.

The main advantage of coupling multiple simulators is the fact that it allows the introduction of tools from different developers and different levels of maturity. As a result, simulators can be independently upgrade by the respective developers, benefiting from the improvements provided by each simulator.

On the other hand, connecting multiple simulators can lead to challenges associated with synchronization between the many domains, stability, and might require previous knowledge and extensive training in all the different tools being used. A review of research and developments in co-simulation, including the discussion on the topic of stability and accuracy are given elsewhere (Trcka and Wetter, 2007).

Up to now, co-simulation approaches have been extensively used in industry and academia. From the energy and automotive industry to even the military, various co-simulation systems already exist, achieving different levels of maturity, usability, and popularity. More details regarding co-simulation for different areas, including main principles, strategies, and research challenges can be found in a thorough survey focused on co-simulations performed by (Gomes et al., 2018).

3. Requirements of the co-simulation platform

The design of the platform is based on the following requirements which cover co-simulation, applicability and configuration in the context of the PERFORMINGRAIL project and further applications.

3.1. Co-simulation requirements

The co-simulation environment shall have the primary capability to support the demonstration of formal specification for Moving Block system and various railway infrastructure and operational scenarios. Moreover, the platform is expected to support the optimisation of traffic management for Moving Block systems and support the automation and analysis of test results providing the necessary KPIs for safety approval.

Furthermore, the environment should also be easily upgradeability to reduce the need of re-assessments due to the upgrade of GNSS application hardware and software and be able to support the simulation of GNSS characteristics (availability and coverage) and failure modes (i.e., GNSS hazards, mostly due to multipath, interferences/jammings, spoofing and limited satellite visibility) defined by software simulation, and field test results on GNSS application to train localisation defined and implemented in the PERFORMINGRAIL project.

3.2. Applicability requirements

One main requirement is that the platform must be modular and have well-defined interfaces to allow the integration of future techniques and components. Moreover, the platform must facilitate the demonstration and assessment of train location tools and traffic management algorithms. Furthermore, the formal models, use cases and operational scenarios defined in the PERFORMINGRAIL project must be, when possible, executed in the platform.

3.3. Configuration requirements

The co-simulation framework should be easy to use and provide an interface that facilitates the setup of different parameters. The platform should be configured to represent the test track of Melton, Leicestershire (Melton Rail Innovation & Development Centre, 2022), where the GNSS on-site data collection will take place, so the data and the operational scenarios could later on be included and validated in the platform.

4. Co-simulation platform design

This section is divided in two parts. First, the overall architecture of the co-simulation framework is presented. Followed by the description of the platform's subsystems, including the behaviour and interaction between the simulators.

4.1. Overall architecture

Figure 1 represents the overall architecture of the co-simulation platform.

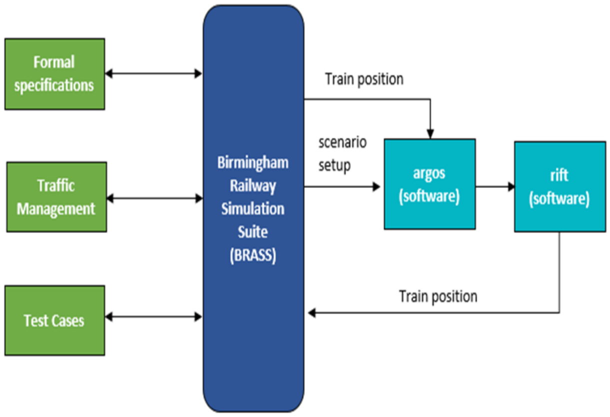


Figure 1. Architecture and process flow of the co-simulation platform

The platform consists of the following two parts:

- The **B**irmingham **Ra**ilway **S**imulation **S**uite (**BRaSS**), which simulates a wide range of elements of train control systems and reports the actual train trajectory represented as a series of locations (longitude, latitude, height) associated with their calling times.
- **G**NSS **L**ocation **S**imulator **(GLS)**, which accepts the synthetic position and epoch as input, generate GNSS raw measurements (i.e., pseudo-ranges and carrier phases) based on scenarios that may include GNSS hazards and forwards them to the positioning engine to generate a position estimate that will be fed back to BRaSS.

By integrating BRaSS and the GNSS simulators, a novel co-simulation platform is built. In this environment, every position estimate derived from the GLS is transmitted and received by BRaSS, which is used to simulate the real-world train localisation.

To the best of the authors' knowledge, this is the first time a railway simulator has been integrated with a GNSS simulator. Hence, a much more realistic demonstration and evaluation of train operation and localisation can be carried out in this environment.

4.2. Platform subsystems

A platform for the evaluation of MBS and train localisation algorithms requires a tight integration among its subsystems. To provide a better understanding of the architectural aspects of each individual component, the two simulators are presented in the following subsections.

4.2.1. *Birmingham Railway Simulation Suite*

The Birmingham Railway Simulation Suite is a tool written in Java that has been developed by the Birmingham Railway Research and Education Centre at the University of Birmingham over a period of more than seven years. BRaSS allows the simulation of different railway systems e.g., mainline railways, high speed railways, metros etc, at a microscopic level. Using the library provided by BRaSS (as shown in **Figure 2**), a wide range of elements of train control systems can be simulated, including onboard, radio block centre, and infrastructure components.

Figure 2. Birmingham Railway Simulation Suite environment

Within the tool, users can set various parameters, such as vehicle type and specification, railway infrastructure, signalling systems, control systems components and timetables.

In the context of PERFORMINGRAIL project, an additional module has been implemented to represent the RBC and allow the simulation of the case studies that will be discussed in section 4. In addition, a special events file that highlights the existence of tunnels, bridges, forests, and anything else that would generate the GNSS hazards mentioned before.

BRaSS features a component-based architecture, as shown in **Figure 3**. Each of the components in the system performs an independent set of functions. Components are divided into three main groups:

- Static – This data is described as static because it does not change during the simulation process.
- Dynamic – entities that modify the state of other entities: i.e., Interlocking changes the state of signalling, traffic changes the state of trains and clock changes state of time.
- Actors – Components that represent human behaviour (that can be replaced with real people interfaces).

The microscopic simulator also provides an API interface that enables the integration with other modules/tools such as performance analysis module, Traffic Management (TM) modules, power and traction modules, communications network simulator (OMNET), timed automata machine model (UPPAAL), and many others. It is through this API interface that the following GNSS simulator/emulator is linked to BRaSS.

4.2.2. GNSS location simulator

The GNSS location simulator (GLS) is a tool design and developed by ROKUBUN in the context of the PERFORMINGRAIL project (PERFORMINGRAIL D3.1, 2021; PERFORMINGRAIL D3.2, 2021; PERFORMINGRAIL D3.3, 2021). The GLS main objective is to simulate a multi-frequency and multi-constellation GNSS receiver for railway operation, as well as cope with any anticipated adverse events (i.e., GNSS hazards).

Within the GNSS location simulator, there are two main components: **argos** and **rift**, that are part of the core software for GNSS data processing:

- **argos** is the software tool that simulates the GNSS range measurements (i.e., pseudo ranges and carrier phases measurements), for a given point or trajectory. This tool allows a flexible configuration in order to model various atmospheric effects (troposphere, ionosphere), errors in the GNSS satellites orbits and clocks, and increase of signal noise due to multipath, interference or lack of satellite visibility, among others.
- **rift** is the navigation filter that converts the data from GNSS range measurement to actual position estimates. This software is the

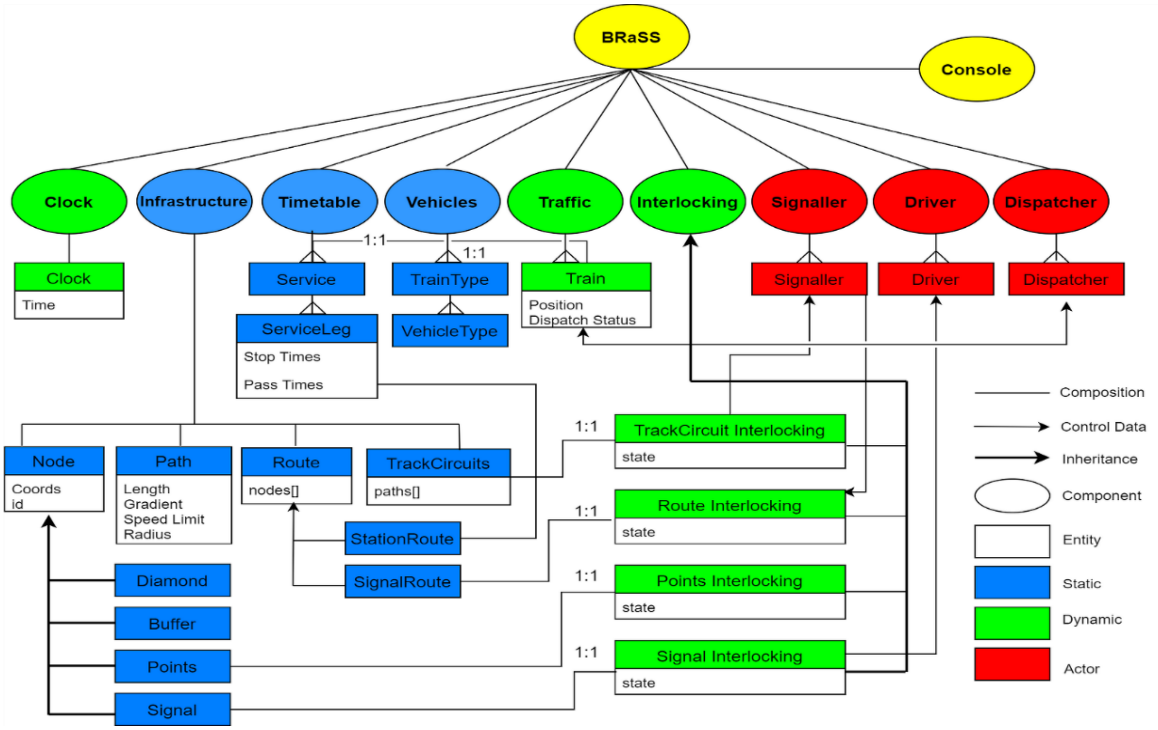


Figure 3. BRaSS main components and entities

positioning engine that will later be embedded into a GNSS receiver and it is based on the undifferenced and uncombined (zero-baseline) processing engine (Odijk et al., 2015). This strategy allows to perform both Single Point Positioning (SPP) as well as its more accurate Precise Point Positioning (PPP) or differential-like techniques similar to Real Time Kinematic (RTK).

Besides the GNSS simulator, Rokubun is also developing a GNSS receiver for the execution of an on-site testing on the Melton, Leicestershire test track. The GNSS receiver (MEDEA) is based on the u-blox (*ZED-F9P Module*, 2018) chipset and hosts the **rift** processing engine designed and implemented to cope with the main and most critical sources of errors in GNSS signals within a railway environment (GNSS hazards).

A system-level overview of the GNSS Location simulator is shown in **Figure 4** (interfacing with BRaSS).

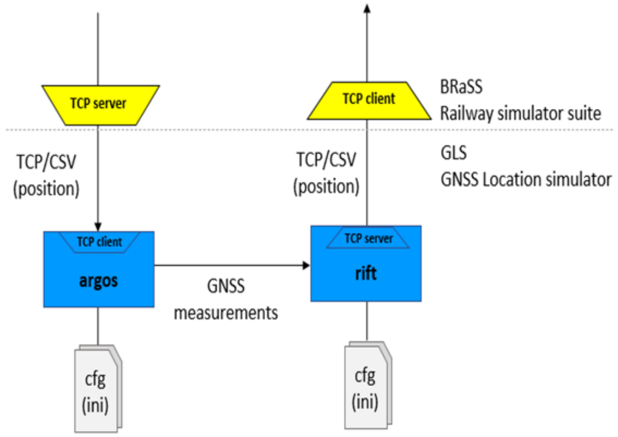


Figure 4. Block diagram of interfaces between GLS and BRaSS

The process for the simulation of the position initiates when BRaSS sends a synthetic position to GLS via TCP protocol and in CSV format. Given a valid TCP/CSV position and certain scenario (defined by GNSS orbits and clocks as well atmospheric conditions) **argos** simulates a range measurement for the input position. Next, the GNSS ranges are then processed by **rift,** that delivers a valid TCP/CSV position (described in Table 1) to BRaSS.

Table 1. TCP/CSV position

Format:	Example:
yyyy-MM-dd,HH:mm:ss.SSS,latitude,longitude,height,rx_name	2021-03-01,09:40:00.000,41.402434220,2.194859688,53.9370,RX1

As the multiple receivers are available in the different cars of the train, they are processed simultaneously and their baselines (i.e., receiver-to-receiver distance) are continuously monitored to detect suspicious deviations, such as an unintentional train split or the presence of jamming or interference, in the occurrence of any feared event the mitigation actions can be executed by the system to avoid any safety risks.

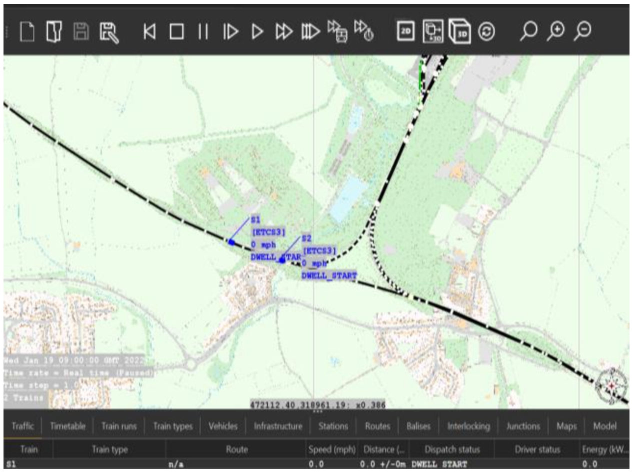
Ideally, if no GNSS hazard is simulated by GLS, the position given by BRaSS and the one delivered by GLS should match. However, as GNSS hazards are simulated, the position of GLS (as it would be seen by an actual GNSS receiver) will start to differ (relative to the "actual" train position given by BRaSS). This feature will allow assessing the impact of the different GNSS hazards in a train simulation environment.

From the onboard's perspective, the train localisation is based on the positions received from the GNSS server and may differ from the actual simulated position. Each time a simulated train position changes, BRaSS sends the front and rear GPS positions to the GNSS server and the GLS responds with recalculated train positions.

5. Performance analysis

For demonstration of the co-simulation platform, an initial set of operational scenarios are simulated and reported in this section.

As a case study, the scenarios are based at the representative section from the RIDC testing site at Melton, Leicestershire (*Melton Rail Innovation & Development Centre*, 2022). The test track is modelled in BRaSS, as illustrated in **Figure 5**, and consists of 4.6miles (7400m) of track, starting from Old Dalby to the end of Stanton Tunnel.



Train	Train type	Route	Speed (mph)	Distance (...	Dispatch status	Driver status	Energy (kW...
S1	n/a		0.0	0.0 +/-0m	DWELL START		0.0

Figure 5. Scheme of Melton track network

To assess the platform functionalities, the relationship of two trains operating in the sample network is defined. For that, two rolling stocks with the same physical characteristics and configurations are defined. The system always starts from a safe condition and that the separation between two trains should be greater than the safety margin. Hence, the Train-1 (front) is set to initiate at the location 200m, while Train-2 (following) is located at 0m. With Train-2 following Train-1 closely behind.

In this case study, the Radio Block Centre (RBC) handover process was ignored and only one RBC is considered for the entire test track. In the simulation, messages sent between the RBC and the trains take 1 second each to send and are processed instantaneously. To simulate the selected operational scenarios, a loss/restore of communication functionality was added to BRaSS control panel to allow the user to determine the communication status between the subsystems.

To validate the platform, the scenarios were selected based on the operational scenarios and use cases respectively defined in (PERFORMINGRAIL D1.1, 2021; PERFORMINGRAIL D2.1, 2021). The principal criteria for the selection of the initial scenario set were based on industrial relevance, complexity in terms of number of Requirements, Operational Rules and Engineering Rules, Presence of safety hazards and potential GNSS operational issues.

From the 22 operational scenarios described in (PERFORMINGRAIL D2.1, 2021), three scenarios were selected: (i) Normal train movement, (ii) Loss of integrity and (iii) loss of communication. **Figure 6** illustrates the results of the simulations for the aforementioned scenarios and their variations.

In the Normal movement scenario, two trains depart from the initial stations and move along the track under the control of BRaSS. With both trains operating under the moving block approach, Train-2 is able to move closer to Train-1, while maintaining the specified safe distance from each other up to the end of the test track. The result of this scenario is shown in **Fig 6(a).**

Afterwards, the loss of communication scenario is simulated. In this scenario, the link between the train-1 and the RBC is disconnected by the user. Therefore, the Railway Simulation Suite is no longer able to identify the exact location and speed of the train. In such circumstances, three possible cases can happen:

- In the first case, the connection between the train and the RBC is re-established before session timeout. As shown in **Fig 6(b)**, both trains start to decelerate as soon as BRaSS identified the loss of communication repercussions. Soon after the connection is restored and both trains resume movement up to the end of the test track.
- In the second case, Train-2 fails to re-connect with RBC before session timeout and the train is required to apply the emergency brake. The result of this scenario is represented in **Fig 6(c)** with both trains stopped and remaining in the same location after the Train-2 could not recover from the loss of communication.
- Finally, the third and last scenario represents the behaviour of the two trains when the connection between the subsystems is re-established before session timeout. However, the previous loss of communication caused changes of the train position/id/length. In this case, BRaSS recognises that train-1 has now lost its integrity and has failed to recover before time-out. **Fig 6(d)** presents the results of this case, which shows that Train-1 restored the communication with the RBC, but fails to recover its integrity, the front train still reaches the end of the test track.

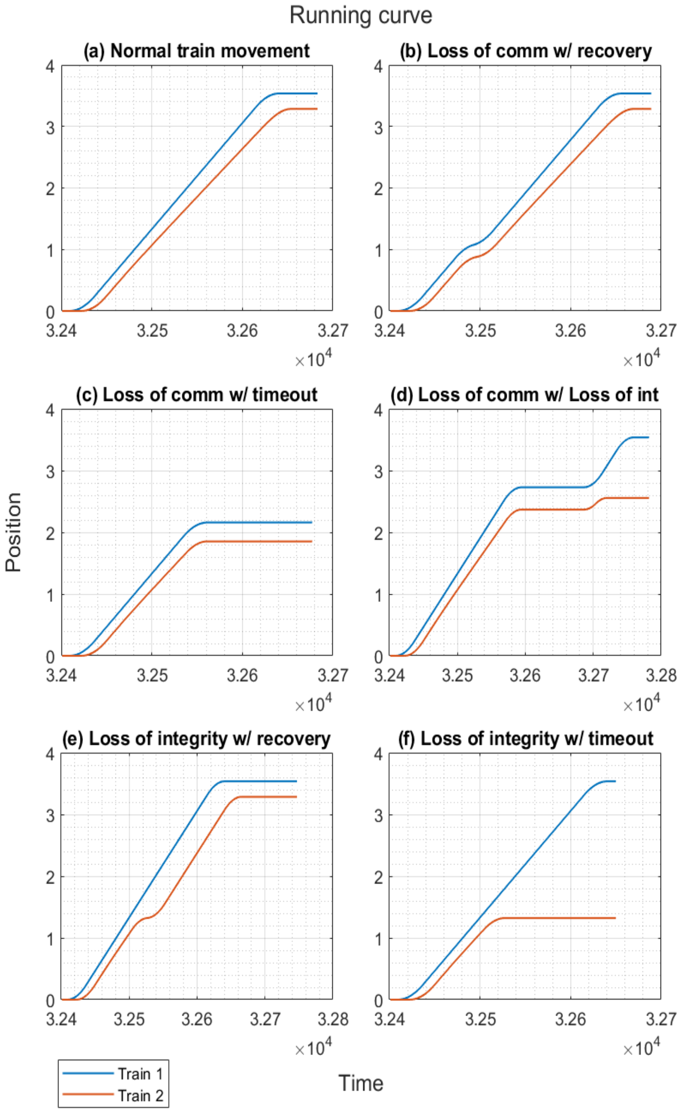


Figure 6. Simulation results

The remainder graphs represent the two instances of the loss of integrity scenario. As the lack of Train Integrity information has a significant impact on the performance of the line and the safety of the operation. As soon as Loss of Integrity occurs, the decision-making part of the BRaSS algorithm acts, and the train starts braking.

- In the first instance, if Train Integrity is restored before timeout, and the train length is unchanged after recovery, the operation can be resumed. As represented in **Fig 6(e)**, train-1 is able to continue movement up to the end station as the loss of integrity is restored promptly and without any impacts for the operation. Train-2, on the other hand, takes extra time to start moving, as the system safety is checked before the train is released to continue travel behind the front train. As a result, the separation between the two trains is greater than the other cases.
- In the second instance, when a train splits unintentionally, and the train integrity is not restored before Timeout, the Track Status Area for the train remains as an Unknown Track Status Area. In this case, as seen in **Fig 6(f)**, Train-1 is still able to resume movement up to the end of the test track, but as it failed to restore the integrity before timeout, until the track status is not checked and cleared manually, the following train must remain in its current location.

6. Conclusions

This paper discusses the development of a co-simulation platform set up using the Birmingham Railway Simulator Suite and GNSS Location Simulator, for the proof of concept of the PERFORMINGRAIL project. The requirements for the design of the platform, the overall architecture, and details regarding both simulators are presented. An initial set of operational scenarios are simulated to assess the performance and functionalities of the co-simulation platform. Based on the results of the case study, this platform can provide an environment for the demonstration, testing and analysis of moving block systems. Future work will concentrate on the inclusion of additional configurations to provide a better representation of train localisation. As part of the scope of the project, real GNSS data will be gathered during on-site testing, processed and then used in the platform to better represent the behaviour of the system. Furthermore, testing routines will be implemented to verify the compliance of defined moving block specifications, as well as to assess and investigate the system behaviours in the occurrence of GNSS feared events and hazard scenarios.

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