Deliverable D1.2: Best Practices, Recommendations and Standardisation to Definition of the Railway Minimum Operations Performance Standards

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Deliverable D1.2

Best Practices, Recommendations and Standardisation to Definition of the Railway Minimum Operations Performance Standards

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		Criteria and Existing Requirements • Conclusions
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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 addresses the definition of specifications for minimum Moving Block (MB) performances. Based on the results obtained from the other PERFORMINGRAIL work packages (specifically WP2, WP3 WP4 and WP5) as well as deliverable D1.1, this document provides Key Performance Indicators (KPIs) and recommendations for defining MB Minimum Operational Performance Standards (MOPS). An extensive literature review on KPIs based on RAMS (Reliability, Availability, Maintainability and Safety) is performed considering standardized criteria and processes adopted in several engineering sectors, including aviation and telecommunication. The outcome from such literature review has allowed identifying possible KPIs which can be used to define MOPS for MB signalling systems. Selected KPIs have been successively implemented in a realistic simulation environment to assess the impact on MB Operational Performances of different design configurations of MB signalling and train positioning components (set out by WP2 and WP3 respectively) as well as traffic management algorithms (defined in WP4). Sensitivity of MB MOPS to signalling, train positioning and traffic management configurations have been evaluated for both nominal (undisturbed) and perturbed traffic conditions. Results of the literature review and the sensitivity analysis have then be used to delineate a set of recommendations for both academia and the railway industry towards the definition of MOPS for Moving block railway operations. Most relevant recommendations are summarised as follows:

- MOPS for MB train operations can be defined in terms of Service Availability KPIs such as train punctuality, total lateness, regularity.
- The definition of MB MOPS shall refer to and include safety and reliability requirements of critical signalling and train positioning components whose configuration is found to compromise minimum MB performance levels even in nominal service conditions.
- A formal analysis of the MB signalling system shall be performed prior the definition of MOPS to identify design configurations of critical sub-components which mostly affect delivered MB performances.
- MB system specification should ensure that real-time variations of subcomponent design parameters is kept within defined thresholds.
- Automatic and optimised traffic management algorithms shall be developed and implemented alongside MB signalling to allow train operations satisfying required MOPS and being less sensitive to signalling parameter variations in both nominal and perturbed service conditions.

Abbreviations and Acronyms

Abbreviation / Acronyms	Description
ACTE	Across Track Errors
AL	Alter Limit
ATPL	Along Track Protection Level
BRaSS	Birmingham Rail Signalling Simulator
CENELEC	European Committee for Electrotechnical Standardization
EC	European Commission
EN	European Standards
ERTMS	European Rail Traffic Management System
EUSPA	European Union Space Programme Agency
ESA	European Space Agency
GNSS	Global Navigation Satellite System
GSM	Global System for Mobile communication
HPL	Horizontal Protection Level
ICAO	International Civil Aviation Organization
IR	Integrity Risk
KPI	Key Performance Indicator
MA	Movement Authority
MAPO	Maximum Accepted Position Overestimation
MAPU	Maximum Accepted Position Underestimation
MB	Moving Block
MOPS	Minimum Operational Performance Standards
MTBF	Mean Time Between Failure
MTTR	Mean Time To Restoration
PE	Position Error
PL	Protection Level
RAMS	Reliability, Availability, Maintainability, and Safety
RBC	Radio Block Centre (processing time)
RIDC	Rail Innovation & Development Centre
RTCA	Radio Technical Commission for Aeronautics
RTTP	Real-Time Traffic Plan
SAN	Stochastic Analysis Network
TM	Traffic Management
TPR	Train Position Report(ing time)
TTA	Time To Alert
VPL	Vertical Protection Level
WP	Work Package
WP	Work Package

1 Introduction

The present document constitutes the Deliverable D1.2 "*Best practices, recommendations and standardisation to definition of the Railway Minimum Operational Performance Standards*" in the framework of the Shift2Rail project PERFORMINGRAIL. This document is the second and last deliverable of WP1, and it incorporates the work undertaken in T1.3 (Task 1.3: Recommendations and standardisation to definition of the Railway MOPS for MB systems).

Referring to the Shift2Rail MAAP (2020), the work described in this document links to Technology Demonstrator TD2.3 "Moving-Block", tasks 2.3.2 "Moving Block System Specifications" in IP2 "Advanced Traffic Management and Control Systems". Also, it refers to Work Area WA 2 "Key Performance Indicators" subtasks 2.1 "Reference scenario" and 2.3 "Sublevel KPI" of the Shift2Rail MAAP (2020).

1.1 Objectives and Scope

This document has been prepared to fulfil Objective 8 of the PERFORMINGRAIL project on defining Recommendations for safe and performing moving-block configurations. The main objective of this deliverable is to define requirements on minimum operation performances for the Moving Block System (MB). The intended goal is to provide recommendations to define railway Minimum Operational Performance Standards (MOPS) for MB systems. Results coming from the other work packages of the PERFORMINGRAIL project will be taken as inputs of this task T1.3 (cf. Subsection 1.2).

First, the metrics that exist in the railway domain to measure the performances associated with a railway line in operation, will be recalled. The operational performance of a railway line depends on the inherent performances of the system used to operate the line which, in turn, depends on the intrinsic performances of each sub-system and equipment. Different metrics exist according to the level of detail for the analysis of the system, when its breakdown structure is scrutinized. Section 2 will present and define metrics that are useful for defining the railway MOPS for MB systems.

In Section 3, the main performance criteria associated with the GNSS-based localisation technologies will be highlighted, given the new breaking features such technologies bring to the MB system. Railway user requirements as expressed today for the GNSS-based localisation function will be also presented. This permits to show which technical performance values are currently formulated for several railway safety applications, including the functions of the control-command and signalling involving localisation.

Section 4 assesses the influence of design configurations of MB signalling components (encompassing characteristics of the GSM-R and GNSS layers) and the inclusion of optimised real-time traffic management strategies on MB operational performances. To this end a simulation-based sensitivity analysis has been performed considering different perturbed MB traffic scenarios. The results provide an indication of system design configuration ranges enabling safe and effective MB operations while showing the significant benefits of optimised traffic management algorithms to keep standard rail service performance levels.

A set of recommendations for keeping minimum operational performance of MB train service is eventually provided in Section 5 based on the results of the sensitivity analysis.

Final conclusions are instead drawn in Section 6.

1.2 Related Document

This document relies on the inputs provided by deliverables of other PERFORMINGRAIL WPs. Specifically, the related deliverables are:

- Deliverable D1.2 - Baseline System Specification and Definition for Moving Block Systems
- Deliverable D2.1 - Modelling guidelines and Moving Block Use Cases characterization
- Deliverable D2.2 - Moving Block Specification Development
- Deliverable D2.3 - Moving Block Verification and Validation
- Deliverable D3.4 Location Algorithm validation report
- Deliverable D4.1 - Real-Time Traffic Rescheduling Algorithms for Perturbation Management and Hazard Prevention in Moving-Block Operations
- Deliverable D4.2 - Guidelines for a Safe and Optimised Moving-Block Traffic Management System Architecture
- Deliverable D5.1 Feasibility Report

D1.2 being the last deliverable of the PERFORMINGRAIL project, it is not foreseen that the document serves as direct input.

2 Review on Metrics for Railway MOPS

MOPS (*Minimum Operational Performance Standards*) are related to principles adopted in guidance documents found in the aeronautical domain, as will be explained in this section. However, defining railway MOPS for MB systems requires focusing first on the metrics existing in railways and coming from the standardized and regulatory background. The TSI-CCS (Technical Specification for Interoperability relating to the `Control-Command and Signalling') (TSI CCS (EU) 2016/919 regulation 2016) is recognized in the railways and mentions the ERTMS Subsets et and the railway safety CENELEC standards (cf. (PERFORMINGRAIL D1.1 2022)). In the last one is defined a global process to control RAMS requirements (*Reliability, Availability, Maintainability, Safety*). RAMS performance criteria and properties will be then addressed, and related operational criteria will be highlighted to identify operational KPI for MB systems. The KPI established in this section 2 will drive the performance and sensitivity analyses carried out in T1.3 (cf. Section 4). The latter will include MB system parameters discussed in (PERFORMINGRAIL D1.1 2022), especially the most influential ones on effectiveness and safety as outlined by WP2, WP3, and WP4 results.

2.1 Considering the Principles of MOPS in the Railway Domain

MOPS is an acronym stemming from the aeronautical domain. It is introduced by RTCA (Radio Technical Commission for Aeronautics), US non-profit organization, that develops technical guidance in the aeronautical domain for use by authorities and industries. RTCA defines MOPS as follows[1]:

> "*MOPS provide standards for specific equipment(s) useful to designers, manufacturers, installers and users of the equipment. The word "equipment" used in a MOPS includes all components and units necessary for the system to properly perform its intended function(s). MOPS provide the information needed to understand the rationale for equipment characteristics and requirements stated. The MOPS describe typical equipment applications and operational goals and establishes the basis for required performance under the standard. Definitions and assumptions essential to proper understanding are provided as well as installed*

1 https://www.rtca.org/standards/standards-guidance-materials/

equipment tests and operational performance characteristics for equipment installations.

Compliance with these standards is recommended as one means of assuring that the equipment will perform its intended function(s) satisfactorily under all conditions normally encountered in routine aeronautical operations. A MOPS may be implemented by one or more regulatory document and/or advisory document and may be implemented in part or in total."

Consequently, MOPS provide standards that are useful to designers, manufacturers, installers and users of a given aeronautical equipment. They provide:

- Information on the equipment characteristics and requirements to perform the functions,
- Typical application,
- Operational goals,
- Establish the basis for required performance under the standard.

In the railway domain, before considering operational performances, it is worth mentioning that, in (EN 50126-part1 2017), requirements are classified according to three main categories: functional, contextual, or technical requirements:

- Functional requirements refer to what the system should do. They might be "*complemented by properties qualifying [system] behaviour (e.g., reliability, safety, accuracy, timing), and by performance requirements expressed in terms of boundary values of functional parameters (e.g., maximum speed, service duration, response time, accuracy, etc.)*"
- Contextual requirements refer to the relation between the system and its environment in terms of logistics, human factors, etc.
- Technical requirements are requirements that do not derive from the system functions but from its technical implementation (e.g., potential threats created by the technology regardless of its intended function).

Consequently, when addressing functional requirements, performance requirements might be needed, and are seen in terms of boundary values of functional parameters of a system.
Besides, different performances metrics exist according to the level of detail for the analysis of the system, when its breakdown structure is scrutinised (cf. Figure 1 showing the different levels for the MB system):

- At the system and subsystem levels are found the quantitative measures related to the RAMS attributes (*Reliability*, *Availability*, *Maintainability*, *Safety*). A process to control RAMS is defined in a more general way in railway critical applications (signalling, rolling stock, and fixed installations), to manage the lifecycle of the related system faced with potential internal and external risks (EN 50126-part1 2017). On the one hand, control of RAM attributes refers to setting conditions for the system to be maintained in a state to deliver a required operational service, despite the possible occurrence of technical failures during the system mission. On the other hand, the control of the S attribute refers to the conditions for avoiding unacceptable risks and for managing the tolerable remaining risks.
- At the equipment or at the component level, other performance criteria can exist, in particular some criteria that are peculiar to specific technologies planned to be used for achieving the intended features of the system. This is especially the case for the GNSS-based and telecommunication technologies that are envisaged to realise the localisation, integrity monitoring, and communication functions of the MB system.

System level	Sub-System level	Component level (equipment)
• Infrastructure + trains	• On-board ETCS • Trackside ETCS (including interlocking) • Telecom	• ETCS components excluding odometry • Odometry/Localisation components • RBC • Object controller for points • Trackside train detection components • …

Figure 1: Different levels for quantifying performances of the MB system.

Given these considerations, the RAMS performance criteria will be addressed in the next subsection, especially the properties that are related to the operational conditions. Moreover, some main indicators qualifying the global performance of a railway line, i.e., KPIs at system level, will be expressed from the presented criteria.

2.2 RAMS Performance Criteria

As mentioned previously, RAMS (*Reliability*, *Availability*, *Maintainability*, and *Safety*) are railway dependability attributes that are referred to in EN 50126, EN 50128 and EN 50129 railway safety standards. Their definitions are inherited from the IEC 60050-192 standards and can be stated as follows (EN 50126-part1 2017).

Definition of RAMS attributes:

'*Reliability*' is the ability that an item can perform a required function, without failure, for a given time interval, and under given conditions.

'*Availability*' is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.

'*Maintainability*' is the ability to be retained in (or restored to) a state to perform as required under given conditions of use and maintenance.

'*Safety*' is the freedom from unacceptable risk of harm. The harm refers to the physical injury or damage to the health of people or damage to property or the environment. Accordingly, the safety-related functions are any functions whose purpose is to achieve or maintain a safe state for the system in respect of a specific hazardous event.

Moreover, the '*Safety Integrity*' is further defined as the ability of a safety-related system to satisfactorily achieve its required safety functions under all the stated conditions within a stated operational environment and a stated period of time.

In Figure 2 are shown some properties and parameters related to RAMS attributes. Such properties and parameters can be found in Annex B of (EN 50126-part1 2017), in (Signoret J.-P. 2021), as well as in the IEC 60050-192, IEC 61703, and IEC 61508 international standards. A distinction is made between probabilistic and operational concepts. Given the goal of this deliverable, we will focus on the operational properties, leaving out the probabilistic ones, which are dedicated to the system failure characterization when RAMS analyses are carried out during the system development phases. Nevertheless, the definitions of most of the terms included in Figure 2 can be looked online when firstly accessing the mind-map (cf. link at the top left of the figure), and secondly, reaching the hyperlinks in blue.

This figure is available online [here](#), each hyperlink in blue brings to an IEC definition.

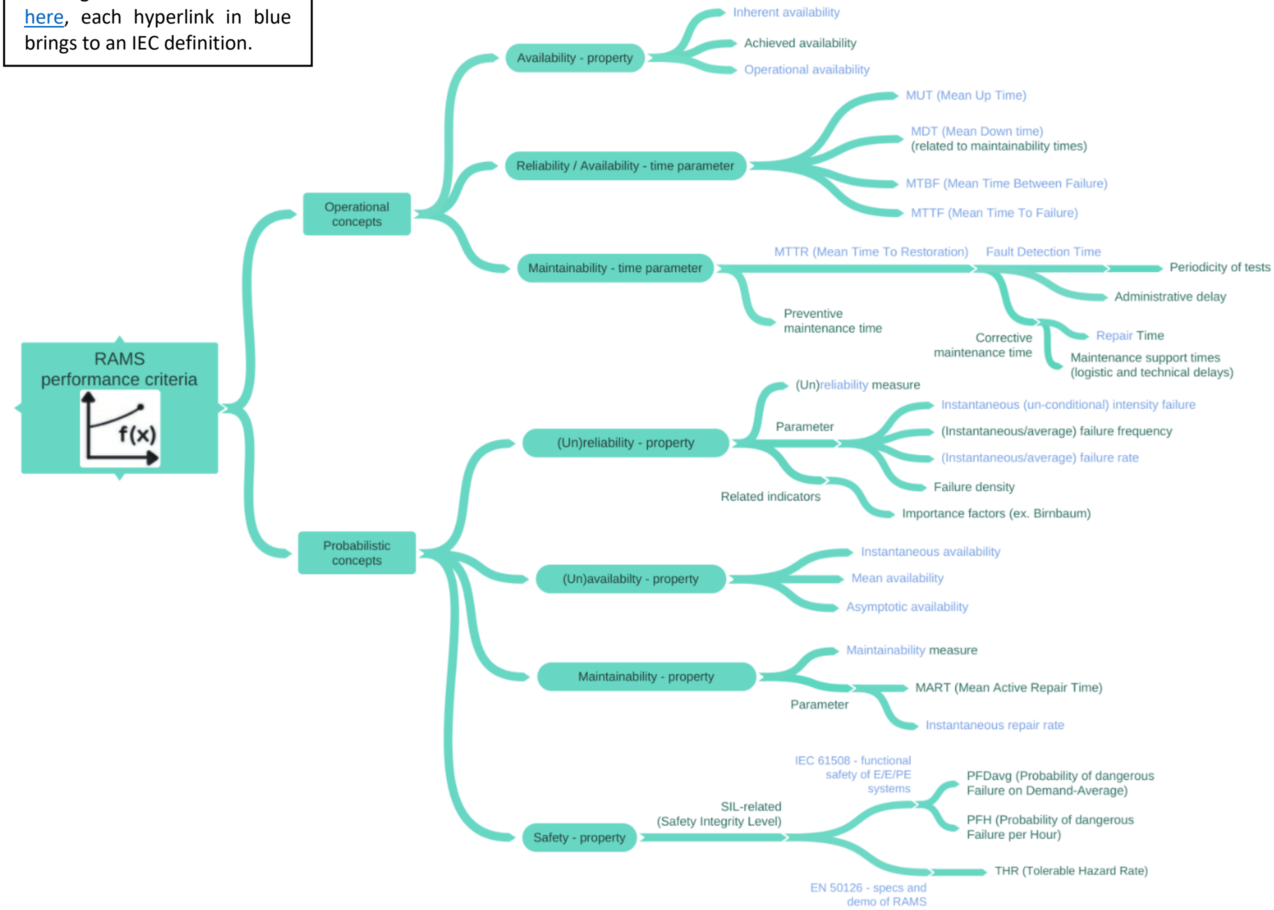

Figure 2: RAMS performance properties and parameters.

RAMS operational properties:

The main parameter that allows RAMS operational properties to be evaluated is the system "*down time*", more precisely the different periods of down time the system encounters. The down time is defined by the time interval for which the system is *unavailable*, i.e., the system is unable to perform its mission as required. This applies regardless of the considered level. Finally, the availability is simply expressed as follows:

$$Availability = \frac{MeanUpTime}{MeanUpTime + MeanDownTime}$$

When analyzing the availability of a system, the point of view is failure-oriented and parameters such as MTTR (*Mean Time To Restoration*) or MTBF (*Mean Time Between Failure*) are employed. Also, different types of availability are found (Pandey, Goyal et Agarwal 2015): '*inherent availability*', '*achieved availability*', and '*operational availability*'. For the inherent availability, times due to corrective maintenance are only considered in the system down time. For the achieved availability, times due to corrective and preventive maintenance are considered in the down time. For the operational availability, times due to logistic delays, supply delays and administrative delays along with corrective and preventive maintenance are included in the down time.

Generally speaking, the operational availability is the "availability experienced [by the system user] under actual conditions of operation and maintenance" (cf. IEC 60050-192). From this point of view, down times coming from operating conditions can be also taken into account. Assuming this, the different conditions influencing the availability are depicted in Figure 3. They are due either to operating conditions, system/equipment conditions, or maintenance conditions. It is worth noticing that requirements on RAMS are interrelated. Indeed, attainment of in-service availability targets is achieved by optimising reliability and maintainability whilst considering the influence of maintaining safety (EN 50126-part1 2017).

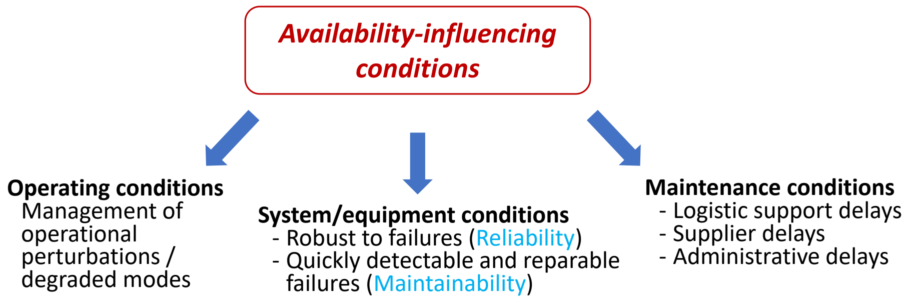

Figure 3: Different conditions influencing the availability of a system

To select key indicators, which express the performances of a railway line, and which are tightly coupled with RAMS properties as defined in the railway domain, the focus will be placed on the operating conditions at the system level, while considering possible perturbations.

2.3 Performances of a Railway Line: Selected Key Indicators at System Level

In the railway domain, the operational availability experienced by the system user is, actually, the availability that customers experience. The customers are either at the infrastructure side, namely the infrastructure manager, or at the train side, namely the train operators and passengers. In (Stenström, Parida et Kumar 2016), the operational availability experienced at the train side, i.e., the availability based on train-delaying failures, is called "Service-Affecting Availability". In (Pandey, Goyal et Agarwal 2015), failures in the core subsystems disrupting the system service are service affecting failures. They are deemed to occur when the arrival of the train at the terminal station is delayed by more than one minute against its scheduled timetable or missed trip as per timetable. To summarize, it can be observed that the "service availability" criterion emerges from the operational availability criterion. The "service availability" concept is implicitly included into the EN 50126 standard with criteria such as "fleet availability" or "schedule adherence" (cf. Annex B of (EN 50126-part1 2017)). These criteria are normally defined only according to what a contracting authority expects and are subject of contractual negotiations; this can explain why such criteria are not standardized.

In this work, the "service availability" concept will be retained and the intended idea is to study events creating perturbations of the railway traffic with the assumption that such events create train delay, whatever the source of perturbation. The latter can be external to the system with, for example, object on track or weather events, or internal to the system because of equipment failures. These ones cannot be treated in this work because of the absence of failure data.

Moreover, equipment features that can impact the train run on a line, as highlighted during WP4 work, will be analysed using parameters characterizing their technical performances. These

parameters are constraints identified for both MB signalling within WP2, and the GNSS localisation and train integrity monitoring devices within WP3.
Service availability measures can pertain to (Stenström, Parida et Kumar 2016):

- Punctuality - the percentage of train arrivals in which the difference between actual and planned times is less than a threshold of, e.g., 3 minutes.
- Total lateness - the cumulative difference between actual and planned arrival times of all trains at all stops.
- Journey time - the total travelling time of a train (or passenger).
- Regularity - the difference in intervals between train services.
- Capacity - the number of train services on the network.

The analysis of the existing literature on RAMS and service performance indicators performed in this (Section 2.2) and the previous section (2.1) leads to the following conclusions:

- MOPS principles originating from the aeronautical field can be adopted in the railway sector for the analysis of reliability and safety of the Moving Block signalling.
- Service availability is considered a valid measure to assess minimum operational performances of MB.
- Train punctuality and total lateness are representative KPIs for service availability and can be practically used to evaluate whether delivered MB service satisfies the minimum operational performance levels.

3 GNSS for Railways: Performance Criteria and Existing Requirements

Albeit GNSS cannot be used as-is in railway due, in part, to insufficient availability requirements (i.e., train position fixes should be delivered at least 99.9% of the time without gaps nor interruptions), the trend to remove physical components and equipment from the track is gaining momentum. A relevant example of this trend is the adoption of virtual balise as potential replacement for physical balise. In terms of GNSS, the goal is to adopt satellite navigation as a relevant component for the train localization system (albeit not the only one). In this context, the usage of GNSS has been promoted by several public institutions and a clear adoption roadmap has been put in place since 2015 through the funding vehicles granted by institutions such as ESA, EUSPA or EC (FP6 and FP7 Framework Programmes, Horizon 2020, Shift2Rail). A comprehensive list of such projects can be found in the Annex of D3.1 (PERFORMINGRAIL D3.1 2021) .

The following sections include the basic performance criteria and requirements in terms of location to address Tasks 1.2 and Tasks 1.3 of WP1. The information and findings hereby described serve as baseline to establish a set of specifications as well as recommendations for systems aiming at implement or provide with moving block capabilities. Therefore, the guidelines and definitions established in these sections will drive the developments to be performed in later stages of the project (in particular in WP3).

3.1 Performance Criteria Characterising GNSS

GNSS performance criteria are introduced in international aeronautical standards. In these standards, the concepts of *accuracy*, *continuity*, *availability* and *integrity* are defined to characterize the performances of satellite navigation systems. Based on (ICAO 2018) and (RTCA 2006), and the metrology standard for the *accuracy* criterion (ISO/IEC Guide 99 2007), the aforementioned criteria can be defined such as:

'*Accuracy*' (positioning accuracy) is the degree of conformance of the estimated position with the true position. Accuracy is a statistical measure of performance and indicates *trueness* and *precision* in terms of confidence level with respect to a confidence interval. The accuracy of a GNSS system is usually presented as a statistical measure of the system error (e.g., position error ≤ 5m in 95% of cases).

'*Continuity*' of service is the capability of the system to achieve its function without unscheduled interruptions during the intended operation. More specifically, it represents the probability associated with the capability of the navigation system to provide a navigation output with the specified accuracy and integrity (cf. below) throughout the intended operation, assuming that the information was available at the start of the operation. Therefore, the occurrence of navigation system alerts (e.g., due to failures) constitutes continuity failures.

'Availability' (service availability) of a GNSS system is characterized by the portion of time that the positioning services of the system are usable (e.g., the position estimation can be computed in 99 % of time with an error ≤ 1m-95% threshold). Hence, the availability is an indication of the ability of the system to provide reliable navigation information within a specified coverage area. It should be noted that the availability is dependent on both the physical characteristics of the environment, and the technical capabilities of the localization system.

'*Integrity*' (position integrity) is the measure of the trust that can be placed in the correctness of the information provided by a navigation system. In addition, the integrity includes the ability of the system (endowed with a monitoring/warning system) to provide timely warnings to users when the system should not be used for navigation. Integrity requirements are expressed for each operation (or mission phase) in terms of horizontal and vertical and 'Integrity Risk', *'Alert Limits'*, and *'Times To Alert'*. This triplet of requirements, expressed by the ICAO for each phase of flight of an aircraft, is defined in detail as follows:

- The '*Integrity Risk*' (IR) refers to the probability of providing localization information that is out of some tolerance margin without warning the user in a given period of time (cf. *Time to Alert*).
- The *'Alert Limit'* (AL) is established to represent the largest *'Position Error'* that is allowable for a safe operation. It particularly defines the error tolerance that cannot be exceeded without issuing a warning. Therefore, AL is considered as an application-dependent safety requirement.
- '*Time To Alert*' (TTA) is the maximum allowable time elapsed from the onset of the navigation system being out of tolerance until the equipment enunciates the alert. Accordingly, an integrity failure is an integrity event that lasts longer than the time to alert with no raised alarm within the TTA. For GNSS, TTA is an operational time that includes the aggregated time spans taken by each monitoring part to detect an unsafe condition.

Besides, the estimation of IR is based on a set of parameters, PE and PL defined below:

- The '*Position Error*' (PE), which is the difference between the measured position and the actual position (also known as ground truth).
- As it is not possible to know the actual position error during normal operation, a statistical bound, called '*Protection Level*' (PL), is associated with the position error. Accordingly, the computed PL is associated with the risk that the alert limit is exceeded.

In practice, the expected nominal operation mode implies having a PE to be smaller than the calculated PL that bounds PE. Besides, the system is declared unavailable if the PL exceeds the AL fixed value.

3.2 Existing Requirements for GNSS-Based Localisation systems in Railways

Beforehand, it should be noticed that the *train localization* function is employed for calculating the train position (the head of the train, which is associated with a Protection Level (PL) if a monitoring system is used) in a track-based coordinate system, and is considered equivalent to the *train positioning* notion. On the other hand, the *train location* function refers to the track occupancy as seen by the trackside system, i.e., from the head to the tail of the train in order to determine the different free/occupied track status areas.

Due to the harsh railway environments with tunnels, rail canyons, stations, foliage, etc., GNSS technology is often not used alone in railways (i.e., in a standalone mode). It is instead integrated into technical architectures combining additional sensors and digital means (ex. map matching, augmentations), which can compensate GNSS signal perturbations (signal blockage, attenuation, reflection or diffraction, multipath, interference). In that case, *accuracy*, *continuity*, *availability* and *integrity* also characterise the GNSS-based train localization system.

Even if the ICAO standard distinguishes two PL components, the '*Horizontal Protection Level*' (HPL) and the '*Vertical Protection Level*' (VPL) in order to bound the horizontal and vertical position errors, HPL is sufficient for land transportation applications. Indeed, the position of users is restricted on the earth's surface. To go further, as the railway track constrains the train position, only a one-dimensional component of the PL, called the '*Along Track Protection Level'* (ATPL) can be used.

For TTA, it is stated in (EUSPA 2019) that "*when a failure occurs a train has to immediately stop. The railway community wants to take no risk. Therefore, the notion of Time-To-Alarm in the railway domain dissents from the aeronautical one*". In (Beugin, et al. 2017), it is stated that the TTA notion is difficult to understand by railway safety analysts for whom a failure or an error is present or it is not. A probability is assigned to a failure occurrence but not to its duration. Probability per hour exists; however, it does not deal with an event that lasts one hour, but with an event that can appear during this period.

In the railway domain, positioning performances have been defined in different projects (Marais, Beugin et Berbineau 2017). Currently, the most recent rail user performance requirements for a representative sample of safety relevant GNSS applications for rail are expressed in (EUSPA 2019). In annex 1 of (EUSPA 2019) are summarized the requirements coming from past initiatives, in particular performance requirements coming from the GNSS rail advisory forum (2000), the GRAIL project focusing on enhanced odometry (2008), and the SUGAST project (2012). In all these initiatives, GNSS-based solution requirements were translated into an ERTMS context (cf. Tables 2, 3, and 4). However, performances for safety-relevant applications of GNSS are still discussed in users' group, such as in the Rail users' group consulted by the EUSPA[2] (aeronautical-oriented), and the EUG Localisation working group[3] (railway-oriented) supported by several railway operators. This last group indicates online several recent documents of interest regarding the localisation under the OCORA (Open CCS On-board Reference Architecture) and the RCA (Reference CCS Architecture) projects. Some new criteria appear such as MAPU / MAPO (Max Accepted Position Underestimation / Overestimation).

2 https://www.euspa.europa.eu/euspace-applications/euspace-users/user-consultation-platform-2020#Rail
3 https://ertms.be/workgroups/localisation_working_group

Application	Accuracy (2Sigma)	Availability	Integrity	SIL	TTA*	Category
Cold Movement Detection	HNSE < 1 m	High	Very High	4	TTA < 10s	Safety relevant
Level Crossing Protection	1 m < HNSE < 10 m	High	Very High	4	TTA < 10s (TBC)	Safety relevant
Train Integrity and train length monitoring	1 m < HNSE < 10 m (TBC)	High	Very High	4	10s < TTA < 30s	Safety relevant
Track Identification	ACTE < 1.9 m	High	Very High	2-4	10s < TTA < 30s	Safety relevant
Door Control Supervision	1 m < HNSE < 10 m	High	High	TBD	10s < TTA < 30s	Safety relevant
Door Control Supervision in ATO	HNSE < 1 m	High	High	2	10s < TTA < 30s	Safety relevant
Trackside Personnel Protection	1 m < HNSE < 10 m Track discrimination	High	High	TBD	10s < TTA < 30s	Safety relevant

Table 1: Rail GNSS user requirements in **(EUSPA 2019).**

Horizontal accuracy, i.e., HNSE (Horizontal Navigation System Error) is divided into along-track (ALTE) and across-track (ACTE) errors for some applications. Across-track requirement is defined by “track discrimination” for some applications in the table.

Application	Horizontal accuracy (m)	Integrity		Interruption (% of mission time)	Interruption of service (s)	Continuity of service (%)
		Alert limit (m)	Time to alarm (s)			
Safety related applications						
ATC on high density line/station/parallel track	1	2.5	<1.0	>99.98	<5	>99.98
Train Control on medium density lines	10	20	<1.0	>99.98	<5	>99.98
Train Control on low density lines	25	50	<1.0	>99.98	<5	>99.98
Mass commercial/information and management – operational applications						
Tracing & Tracking of vehicules	50	125	<10	>99.9	N/A	N/A
Cargo monitoring	100	250	<30	>99.5	N/A	N/A
Dispatching	50	125	<5	>99.9	N/A	N/A
Passenger information	100	250	<30	>99.5	N/A	N/A
Infrastructures & civil engineering, professional applications						
Positioning of machines	1 cm	N/A	<5	99.5	N/A	N/A
Infrastructure survey	1 cm	0.1 cm	<10	99	N/A	N/A
Fix point applications	5 mm	N/A	<30	99	N/A	N/A

Table 2: GNSS requirements for rail from the GNSS Rail Advisory Forum, using an aeronautical perspective.

Application	Accuracy	Speed Accuracy	Availability	Continuity	Integrity	TTA	Alert Limit	Train Length Confidence Interval Accuracy
Enhanced Odometry	Travelled Distance Accuracy for main lines (urban and rural scenarios) and for low visibility scenarios (tunnels, covered stations) REQ-GNSSUT-EO-PER-170	Independently of operational conditions REQ-GNSSUT-EO-PER-190	In any place within the Service Volume, when operating in the Nominal SIS Constellation state REQ-GNSSUT-EO-PER-200	Assuming the SoL core system performance requirements (without receiver contribution) of $8x10^{-6}$/15s. REQ-GNSSUT-EO-PER-210	>TBD% REQ-GNSSUT-EO-PER-220	< 5s REQ-GNSSUT-EO-PER-230		
	Appr.1: ± (5m + 5% of the distance since last beacon)	2 km/h	95%	< $8x10^{-5}$/15s.				
	Appr.2: ± (5m + 2% of the distance since last beacon)	1 km/h						
Cold Movement Detection & Train Awakening	Position Accuracy: 1m REQ-GNSSUT-EE-TA-250		In any place within the Service Volume, when operating in the Nominal SIS Constellation state REQ-GNSSUT-EE-TA-280	Assuming the SoL core system performance requirements (without receiver contribution) of $8x10^{-6}$/15s. REQ-GNSSUT-EE-TA-290	Independently from environmental influences topography and buildings (REQ-GNSSUT-EE-TA-320)			
			95%	< $8x10^{-5}$/15s.	SIL 4 (final report)			
Absolute Positioning	Position accuracy with a SIL 4 integrity level REQ-GNSS-EE-AP-490 REQ-GNSS-EE-AP-500	Velocity accuracy with a SIL 4 REQ-GNSS-EE-AP-510 REQ-GNSS-EE-AP-520	In any place within the Service Volume, when operating in the Nominal SIS Constellation state REQ-GNSSUT-EE-AP-530		SIL 4 (final report)			
	Zone 1 / Short term / Rural / ≤ 100m	≤ 1.5 m/s	99%					
	Zone 1 / Short term / Urban / ≤ 150m	≤ 3 m/s						
	Zone 1 / Long term / Rural / ≤ 50m	≤ 1m/s						
	Zone 1 / Long term / Urban / ≤ 100m	≤ 2 m/s						
	Zone 2 / Short term / Rural / ≤ 30m	≤ 1.5m/s						
	Zone 2 / Short term / Urban / ≤ 40m	≤ 3 m/s						
	Zone 2 / Long term / Rural / ≤ 20m	≤ 1 m/s						
	Zone 2 / Long term / Urban / ≤ 25m	≤ 2 m/s						
Train Integrity Length Monitor	Train Length confirmation Accuracy: ≤ 10m REQ-GNSSUT-EE-TI-370		99.98% main lines 95% low traffic lines (final report)	Assuming the SoL core system performance requirements (without receiver contribution) of $8x10^{-6}$/15s. REQ-GNSSUT-EE-TI-390	Independently from environmental influences topography and buildings (REQ-GNSSUT-EE-TI-440)		≤ 2L for high speed lines (headway 3') ≤ 37.8%L for mixed traffic lines (headway 4') REQ-GNSSUT-EE-TI-370	
				< $8x10^{-5}$/15s.	SIL 4 (final report)			

Table 3: User requirements coming from the GRAIL project.

	Locator Unit Class A	Locator Unit Class B	Locator Unit Class C	Locator Unit Class D
Functions	• Provide valid position to the train when the stored position is invalid or unknown • Detect train movement when ETCS on-board equipment is powered off • RBC ID • Compute PVT • Train orientation • Standstill (absence of movement) • Translation of coordinates • Absolute Positioning Reference Point (APRP) • Track ID • DM manage	• Provide valid position to the train when the stored position is invalid or unknown • Detect train movement when ETCS on-board equipment is powered off • RBC ID • Compute PVT • Train orientation • Standstill (absence of movement) • Translation of coordinates • Absolute Positioning Reference Point (APRP) • Train Integrity status • Train length confirmation • Level Crossing status (ID, distance to level crossing) • Generate flags/ alarm (optional) • DM manage (if needed)	• Provide PVT • Generate flags/alarm (optional)	• Provide PVT
I/F	PROFIBUS	PROFIBUS	TBD	TBD
Horizontal accuracy	1m	10m	25m	50m
AL	2,5m	25m	62,5m	125m
SIL	4	4	TBD	0
Availability	99,98%	99,98%	99%	95%
TTFF	120s	120s	TBD	TBD
TTA	<7s	<7s	<20s	<30s

TTFF = Time To First Fix, DM = Digital Map
PVT = Position, Velocity, and Time

Table 4: User requirements coming from the SUGAST projects.

Type of Area	MAPO, MAPU	Safety relevant
Mainline / Dense traffic line	Max(30m, Distance run in 1s at the track speed)	Yes
Train traffic node	10m	
Precise positioning area	10m	

Table 5: Performance of the function "Provide safe Train Front End 1D Position" (OCORA 2022).

The identified KPIs in Subsection 2.3 will be analysed in the following sections for a line operated under MB principles. The factors that may influence the value of the selected KPIs, will also be investigated when considering equipment features (component level), especially GNSS-related factors underlined in Section 3. These factors are called later "MB parameters".

4 Sensitivity of MB operational performances to signalling configuration and automated traffic management

A sensitivity analysis is performed to assess the influence of signalling component configurations and automatic traffic management on MB train service performances. MB operational performances are measured in terms of service availability KPIs such as punctuality and total train lateness. Several design configurations are analysed for the "*TPR communication latency*" and the "*RBC processing time*" to issue a MA, which resulted as two of the most influential MB signalling design parameters from the formal analysis performed in (PERFORMINGRAIL D4.1, 2022). For each combination of values of those two MB design parameters, service punctuality and lateness are assessed in 4 different delayed scenarios (respectively ranging from 5 min, 10 min, 15 min and 20 min of train entrance delay) both in presence and absence of an automated traffic rescheduling algorithm. The traffic rescheduling algorithm used in the analysis is the extended RECIFE-MILP tool developed in WP4 and described in (PERFORMINGRAIL D4.2, 2023). The assessment is carried out for the real case study of the Melton RIDC in the UK.

4.1 Experimental Setup

Case study

A model of Melton RIDC test track is simulated, with a timetable consisting of 12 trains running over a period of 65 minutes. The test timetable consists of three cycles of four trains: two per direction, meeting in the middle on the double track part. Trains run over yellow highlighted part in Figure 4. The trains are numbered 1 to 12, with odd numbered trains running in the northbound direction from Melton to Tollerton. Even numbered trains run southbound from Tollerton to Melton. All trains make a scheduled stop in the central section at Old Dalby. Table 6 shows the planned times in the test timetable.

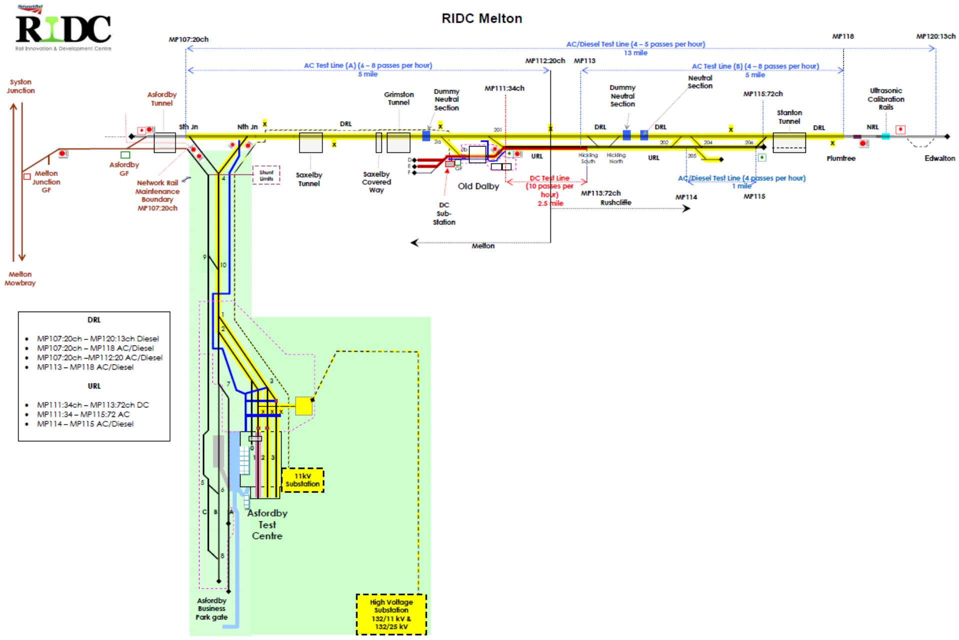

Figure 4 Melton RIDC test track.

Northbound Train		1	3	5	7	9	11
Melton	Arr	08:58:00	09:01:00	09:20:00	09:23:00	09:42:00	09:45:00
	Dep	08:59:00	09:02:00	09:21:00	09:24:00	09:43:00	09:46:00
Old Dalby	Arr	09:04:44	09:07:44	09:26:44	09:29:44	9:48:44	09:51:44
	Dep	09:05:14	09:08:14	09:27:14	09:30:14	9:49:14	09:52:14
Tollerton	Arr	-	-	-	-	-	-
	Dep	-	-	-	-	-	-
Southbound Train		2	4	6	8	10	12
Tollerton	Arr	08:57:00	09:01:00	09:19:00	09:23:00	09:41:00	09:45:00
	Dep	08:58:00	09:02:00	09:20:00	09:24:00	09:42:00	09:46:00
Old Dalby	Arr	09:09:57	09:13:57	09:31:57	09:35:57	09:53:57	09:57:57
	Dep	09:10:57	09:14:57	09:32:57	09:36:57	09:54:57	09:58:57
Melton	Arr	09:16:06	09:20:06	09:38:06	09:42:06	10:00:06	10:04:06
	Dep	09:17:06	09:21:06	09:39:06	09:43:06	10:01:06	10:05:06

Table 6: Timetable of the 12 simulated trains.

Scenarios
The (undisturbed) test timetable is the baseline scenario. In addition to the baseline scenario, four scenarios are tested in which trains 1 and 8 are imposed an entrance day:

- Scenario 1, in which trains 1 and 8 are imposed an entrance delay of 5 minutes;
- Scenario 2, in which trains 1 and 8 are imposed an entrance delay of 10 minutes;
- Scenario 3, in which trains 1 and 8 are imposed an entrance delay of 15 minutes; and
- Scenario 4, in which trains 1 and 8 are imposed an entrance delay of 20 minutes.

In the simulation-based analysis, scenarios 1 to 4 are first considered without intervention from traffic management (Section 4.2.1) and then with traffic management intervention (Section 4.2.2)

Figure 5 shows the train blocking times in a time-distance graph in line with the test timetable. Entrance locations of trains suffering entrance delays are indicated with arrows; at the start of the journey of train 1's journey, which is the first train to run northbound and at the start of train 8's journey, which is the second southbound train in the second group.

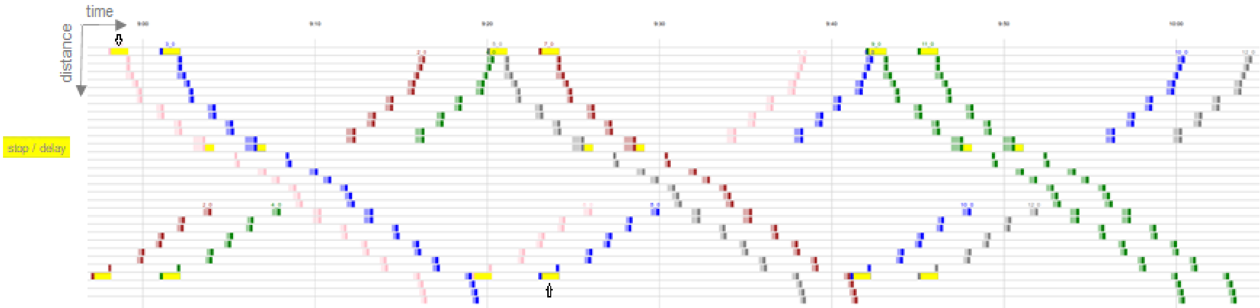

Figure 5: Time-distance diagram of tested timetable with entrance locations of delayed trains.

MB parameters

The MB parameters considered in the sensitivity analysis are the *RBC processing time* to issue a valid MA to the trains as well as the communication latency for a train to provide its position report to the RBC (*TPR net delay*). These parameters are selected based on the results of the SAN analysis provided in Section 5 of D4.1. Table 7 reports the parameters and their value ranges that were used. From the SAN analysis, the RBC processing time and the TPR net delay were found to be the two parameters critical for the MB system. In the analysed scenario, for both parameters values higher than the baseline of 0.5 s has negative impact.

Parameter	Range	Step
RBC processing time	[0.5: 4] s	0.5 s
TPR net delay	[0.5: 2.5] s	0.5 s
MA net delay	[0.5: 2.5] s	0.5 s
Driver reaction time	[4: 12] s	0.5 s
TPR update period	[1: 5] s	0.5 s

Table 7. Parameter variation range used in the SAN analysis (D4.1).

In the BRaSS simulator, the RBC and the TPR time effectively become the time that it takes for the movement of one train to affect the movement authority of another train. The simulation is run at timesteps of 0.1 seconds. For every scenario, including the non-disturbed baseline scenario 0, the simulation is run for 30 possible parameter setting combinations: 6 RBC times and 5 TPR times. The range of RBC times are configured from 0.5 s to 4 s, in steps of 0.7 s; TPR train position reporting times are configured from 0.5 s to 2.5 s in steps of 0.5 s.

Service availability KPIs

The service availability KPIs of punctuality and total lateness are considered for the evaluation of the operational performance. Punctuality is measured as the percentage of train arrivals at the planned stops (three for the southbound trains, two for the northbound trains) with an actual arrival time within 5 minutes from the planned arrival time. Total lateness is measured as the cumulative number of seconds that trains arrive later at the planned stopping points.

4.2 Simulation-Based Analysis

To perform the sensitivity analysis, the BRaSS simulator is extended to include the following additional components:

- **Scenario** component performs Monte Carlo runs with the simulator with RBC processing times and TPR times.
- **KPI** component collects the total lateness and punctuality of each Monte Carlo run and outputs the results at the end of the simulation session.

In the following, the results of the sensitivity analysis are given for the baseline scenario (below), without traffic management (Section 4.2.1) and with traffic management (Section 4.2.2). Appendix A contains graphs that show the results with and without traffic management to compare the difference.

Baseline scenario

In the baseline scenario, a small amount of total lateness was observed, which increases by varying both the RBC and TPR times. The range of total lateness observed was from 24 seconds with both RBC and TRP times set to 0.5 seconds, up to 60 seconds total lateness with RBC time of 4 seconds and TPR time of 2.5 seconds.

All trains were 100% punctual. Varying parameter values in the baseline scenario had no effect on punctuality, therefore no critical values are found. This result is as expected because the small amount of delay imposed by the RBC and TPR timings is relatively small compared to the punctuality threshold, which is 5 minutes.

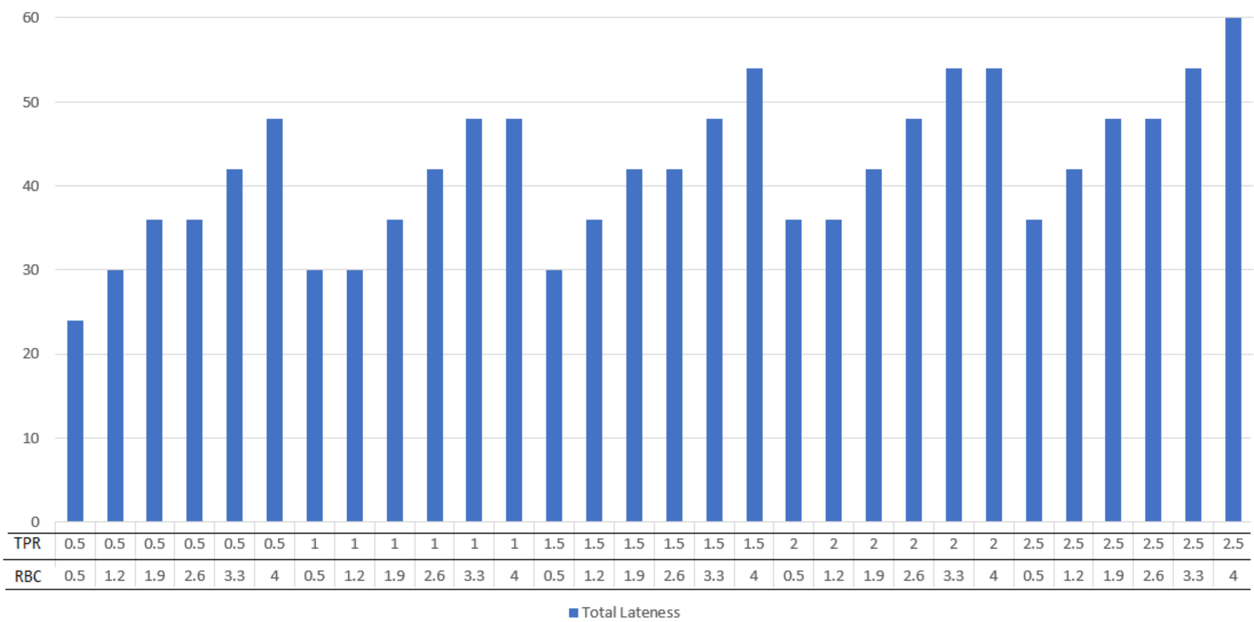

Figure 6 Baseline scenario total lateness in seconds.

4.2.1 Simulation Results without Traffic Management

This section describes the simulation results when the delay scenarios are run without traffic management. The simulator is configured to route the trains in timetable-order, meaning that at critical junctions, the dispatcher will route the trains in the order that they appear in the original (undisrupted) timetable. Delays are applied to trains 1 and 8.

In the 5-minute delay scenario, the total lateness is increased because 2 trains have 300 seconds of lateness applied to them. Additional secondary delay is also recorded resulting in total lateness in the range of 1506 to 1722 seconds. The effect of increasing RBC and TPR times is also more significant than in the baseline scenario, as the increase in total lateness is steeper than the increase observed in the baseline scenario. The range of values covers 216 seconds, whereas the baseline scenario range was 36 seconds. Punctuality is 100% throughout because the punctuality threshold is 5 minutes and despite there being secondary delay, it does not exceed the punctuality threshold.

In the 10-minute scenario the total lateness recorded ranges from 5793 to 6150. This shows that significant secondary delay has occurred. The TPR and RBC times are also more significant than in scenario 1. This time the range increases by 357 seconds. The punctuality is 60%, dropping slightly to 57% when the RBC and TPR times total 6 seconds or more.

In the 15-minute scenario the range of values for total lateness range from 10893 to 11250. The range of values is 357 seconds, which is the same as the 10-minute scenario. In scenario 3, the punctuality is a constant 43% and is not affected by the RBC and TPR times.

In scenario 4, the lateness ranges from 15993 to 16350, which is a difference of 357 seconds and is the same difference observed in scenarios 2 and 3. In scenario 4, the punctuality is a constant 43% and is not affected by the RBC and TPR times. This is the same as the result recorded for scenario 3.

Summary of results without traffic management

Table 7 shows the ranges of lateness and punctuality recorded for the four scenarios. Where punctuality is affected, the critical values are the sum of the RBC and TPR times required to result in a change of punctuality.

Scenario	*Min Lateness*	*Max Lateness*	*Lateness Range*	*Min Punctuality*	*Max Punctuality*	*Punctuality Range*	*Critical values*
Baseline	24s	60s	36s	100%	100%	-	-
Scenario 1	1506s	1722s	216s	100%	100%	-	-
Scenario 2	5793s	6150s	357s	60%	57%	3%	6.0s
Scenario 3	10893s	11250s	357s	43%	43%	-	-
Scenario 4	15993s	16350s	357s	43%	43%	-	-

Table 7: Summary of results without traffic management.

4.2.2 Simulation Results with Traffic Management

This section describes the simulation results with the involvement of traffic management. Traffic management is represented by the moving-block rescheduling model from WP4 (see D4.1 and D4.2). The necessary input data, including infrastructure, rolling stock and timetable data, is obtained by converting the data available in BRaSS to the format required by RECIFE-MILP, the rescheduling model extended to moving block. The data converter has been developed within Task 1.3.

The rescheduling model provides optimised retiming and reordering strategies, for each delay scenario. This solution is effective in terms of total train delay, i.e., cumulative of the delays of all trains at entry, stops and exit. The rescheduling solution is described in a real-time traffic plan, which serves input for BRaSS to evaluate the impact of automated traffic rescheduling strategies. To realise this setup, the following component was added to BRaSS:

- **RTTP** component optionally applies a Real-Time-Traffic-Plan that is produced by RECIFE.

Note that the RTTP is optimised for total train delay, I.e., cumulative delays of all trains at entry, stops and exit.
Appendix B contains the time-distance diagrams of the RTTPs for the four delay scenarios.

In the 5-minute scenario, the range of values of total lateness with the traffic management applied is between 1695 and 1821 seconds, which is a range of 126 seconds. The performance of total lateness is slightly reduced on the scenario when using TM. The reason for this is still to be explained. However, the range of values is reduced, meaning that the importance of RBC and TPR times is slightly reduced when using TM. The punctuality is also reduced to a range of 97% down to 93% when the RBC and TPR times total 3.7 seconds. This suggests that secondary delay has been reduced by the traffic management.

For the 10-minute scenario, the traffic management has significantly reduced the secondary delay, improving the total lateness to a range of 3603-3743 seconds. The punctuality is also improved to a consistent 90%.

In the 15-minute scenario, the total delay is reduced significantly down to a range of 4282 to 4466 seconds and the punctuality is a constant 90%. This is the same punctuality level as the 10-minute scenario, demonstrating that the traffic management has eliminated additional secondary delay.

The most significant improvement of traffic management application is seen in the 20-minute scenario where the total lateness is reduced by 2/3rd down to a range of 4318 to 4476 seconds. The punctuality is maintained at 90% demonstrating further that traffic management is strongly reducing propagation of secondary delays.

Summary of results with traffic management
Table 8 shows the ranges of lateness and punctuality recorded for the four scenarios with traffic management applied. Where punctuality is affected, the critical values are the sum of the RBC and TPR times required to result in a change of punctuality.

Scenario	*Min Lateness*	*Max Lateness*	*Lateness Range*	*Min Punctuality*	*Max Punctuality*	*Punctuality Range*	*Critical values*
Baseline	24s	60s	36s	100%	100%	-	-
Scenario 1	1695	1821s	126s	97%	93%	4%	3.7s
Scenario 2	3603s	3743s	140s	90%	90%	-	-
Scenario 3	4282s	4466s	184s	90%	90%	-	-
Scenario 4	4318s	4476s	158s	90%	90%	-	-

Table 8: Summary of results with traffic management.

4.2.3 Sensitivity analysis conclusions

The main conclusions which can be drawn from the sensitivity analysis performed in this deliverable section are reported as follows:

- MS signalling parameters such as the Train Position Report communication delay and the RBC processing times are identified as critical to MB service availability, as provided by the SAN modelling made in PERFORMINGRAIL Deliverable D4.1.

- For the analysed case study, it is shown that when the values of both TPR net delay and the RBC processing time exceed the recommended max thresholds (i.e. 2.5s and 4s, respectively), MB service availability levels decrease even in case of undisturbed traffic conditions. On the contrary, MB service availability in undisturbed traffic conditions is not affected if those signalling parameters are kept within recommended thresholds.
- In case of delayed traffic conditions, MB service availability (in terms of punctuality) can further decrease when the sum of TPR net delay and RBC processing time exceeds a critical threshold.
- For a disturbed traffic scenario, automatic optimised Traffic Management algorithms greatly improve MB service availability and makes it less sensitive to variations in TPR net delay and RBC processing time.
- The beneficial impact of the application of automatic optimised Traffic Management (TM) algorithms on MB service availability is illustrated in Table 9 with the detail of critical thresholds of TPR net delay and RBC processing times which cause a further punctuality drop in the situation of delayed traffic scenarios

Scenario	*Best Punctuality*	*TPR*	*RBC*	*Reduced Punctuality*
5-min with TM	97%	0.5s	3.8s	93%
		1.0s	4.3s	93%
		1.5s	2.6s	93%
		2.0s	1.9s	93%
		2.5s	1.2s	93%
10-min without TM	60%	2.0s	4.0s	57%
		2.5s	3.5s	57%

Table 9: Overview of critical TPR and RBC values for punctuality.

5 Recommendations on MOPS for Moving-Block Systems

10Based on the outcomes from the analyses performed in the previous sections (2, 3 and 4), the following set of recommendations is provided to support the railway sector in defining Minimum Operational Performance Standards for MB train operations:

- Minimum operational performance standards for MB train operations can be validly defined in terms of KPIs for Service availability (e.g. train punctuality, total lateness, regularity).
- The definition of MB MOPS shall relate to and include safety and reliability requirements at the level of signalling subsystem and/or component to ensure safe and effective train supervision in nominal and hazardous traffic situations.
- A formal analysis of critical signalling and train positioning parameters (e.g. RBC process times, MA delay, GNSS latency) shall be made prior minimum operational performance standards can be defined for a rail network where MB will be deployed.
- The definition of MOPS for MB signalling shall refer to and include determination of a range of threshold values for the most critical signalling and train positioning parameters (see PERFORMINGRAIL Deliverable D4.1 for an overview of those parameters) found to be the most influential on MB operational performances.

- MB system specifications shall ensure that real-time variations in the value of signalling and train positioning parameters are always kept within defined critical thresholds to achieve required MB MOPS in nominal (undisturbed) service conditions.
- Automatic and optimised rail traffic management algorithms shall be developed and implemented to provide MB operational performances which are in line with required minimum performance standards and less sensitive to real-time variations in the value of signalling and train positioning parameters.

6 Conclusions

With the objective to support the definition of future Railway MOPS (Minimum Operational Performances Standards) for the Moving Block system, this document has allowed identifying indicators for qualifying MB system performances and analysing them, given different contexts of operation (normal and disturbed traffic). For this to be achieved, the document is divided into four main sections. Sections 2 and 3 reviewed the metrics for railway MOPS with a focus on criteria associated with the GNSS-based localisation technologies, given the new breaking features such technologies bring to the MB system. As for Section 4 and 5, they presented the analysis of identified key performances indicators (KPIs) in order to finally provide a set of recommendations for developing MOPS.

Section 2 reviewed the metrics that exist in the railway domain to measure the performances associated with a railway line in operation. They pertain to quantitative measures related to the RAMS attributes (*Reliability*, *Availability*, *Maintainability*, *Safety*) as required in the existing railway safety standards. KPIs related to the service availability of a railway line were identified for qualifying the global performance of MB systems.

Section 3 presented GNSS performance criteria as introduced in international aeronautical standards for the localisation. It summarised existing requirements for GNSS-Based Localisation systems in Railways.

Section 4 conducts a simulation-based sensitivity analysis to analyse the influence of relevant MB signalling design parameters on train service performances expressed in terms of service availability-related indicators. Simulation results obtained for the MELTON RIDC in the UK show that the use of optimised traffic management tools can significantly mitigate the impact of train entrance delays even in critical cases of prolonged communication times of both the train position report and the MA from the RBC.

Section 5 finally gives a set of recommendations in line with main results obtained from the previous sections to support scientists and/or the railway industry in developing MOPS for MB systems.

The main outcomes of this work are that the definition of MOPS for MB train operations can refer to KPIs currently used for Service Availability such as train punctuality, total lateness or service regularity. Additionally the definition of MB MOPS should also include the determination of critical design configurations of signalling and train positioning components which mostly affect MB service performances. Results from the simulation based sensitivity analysis (in Section 4) shows indeed that when critical design parameters of signalling and train positioning components exceed given threshold values, MB performance levels are significantly compromised even in nominal service conditions. A formal analysis of MB signalling system is hence recommended before the definition of MB MOPS in order to determine critical design values of most influential signalling and train positioning components. Specification of MB signalling components shall therefore ensure that real-time variations of signalling and train positioning parameters are always kept within defined critical thresholds to satisfy required MOPS. A relevant outcome of the overall PERFORMINGRAIL project regards the use of automatic and optimised Traffic Management which is found to be essential in providing MB train operations which satisfy required MOPS while being less sensitive to real-time variations of critical signalling and train positioning parameters. The development and implementation of automated and optimised Traffic Management systems is a main recommendation to allow an effective deployment of MB signalling.

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Appendix A. Simulation-Based Analysis Results

This section contains the results of the simulation-based analysis, for the four scenarios described in Section 4. On the x-axis, we have a combination of values for the TPR net delay and the RBC processing time, both in seconds. The 'total lateness' figures feature the total lateness in seconds on the y-axis. The 'punctuality' figures feature the 5-minute punctuality in percentages. All figures show the results with (orange) and without (blue) the involvement of traffic management.

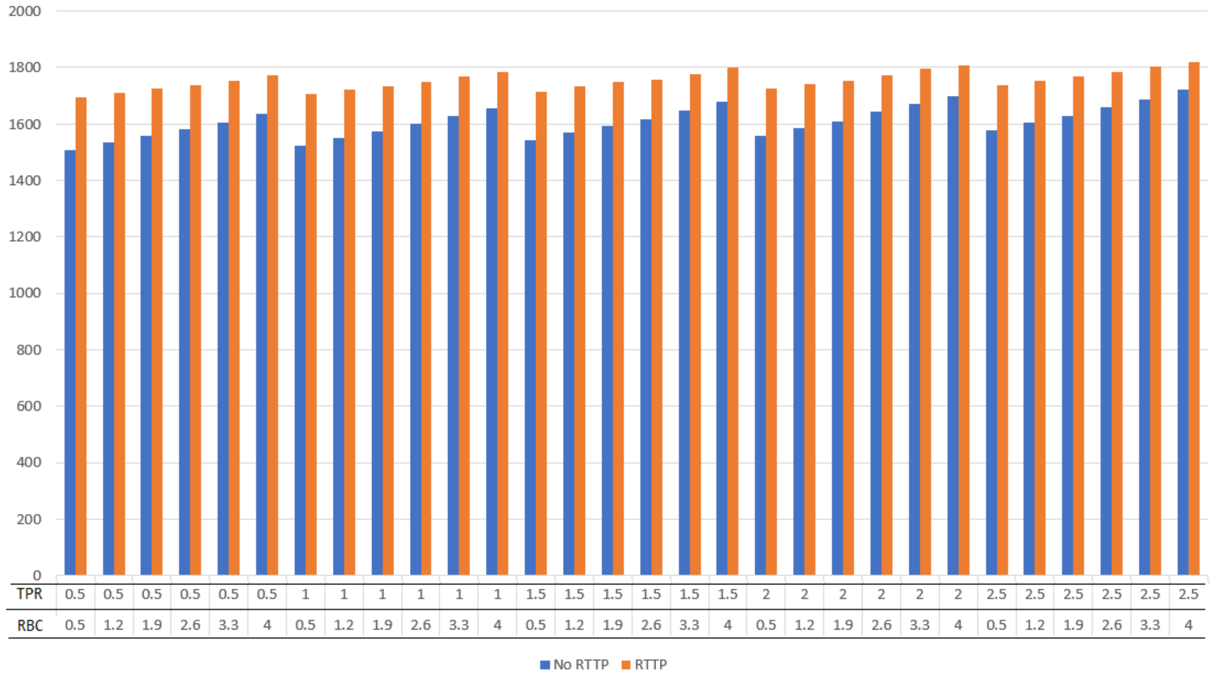

Figure 7: Scenario 1 (5 min delays) total lateness with and without traffic management (RTTP).

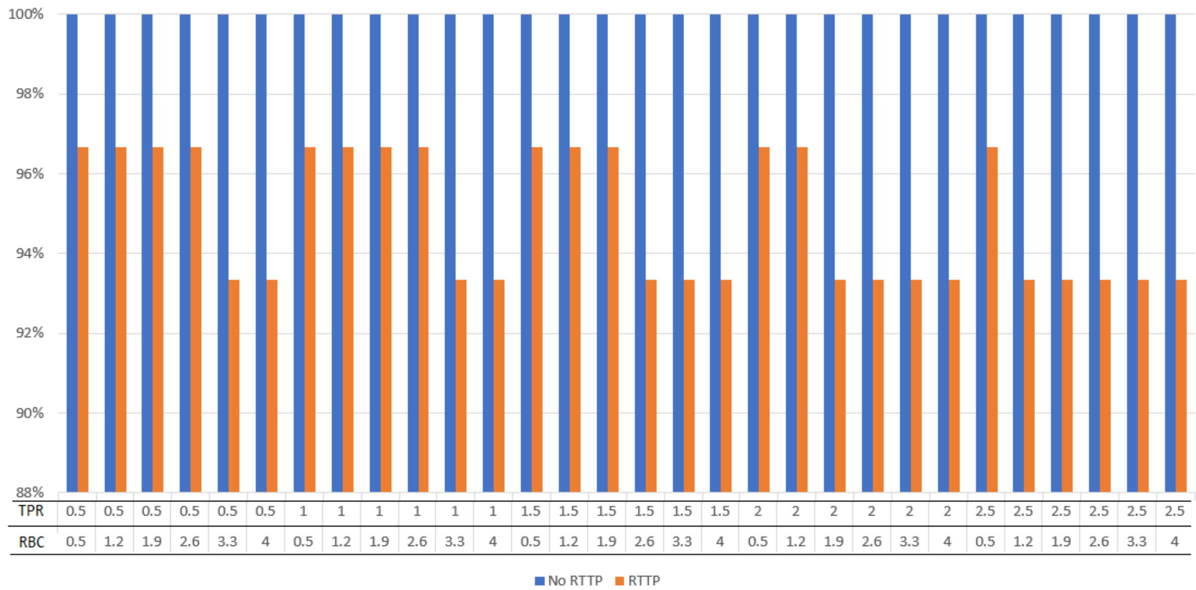

Figure 8: Scenario 1 (5 min delays) punctuality with and without traffic management (RTTP).

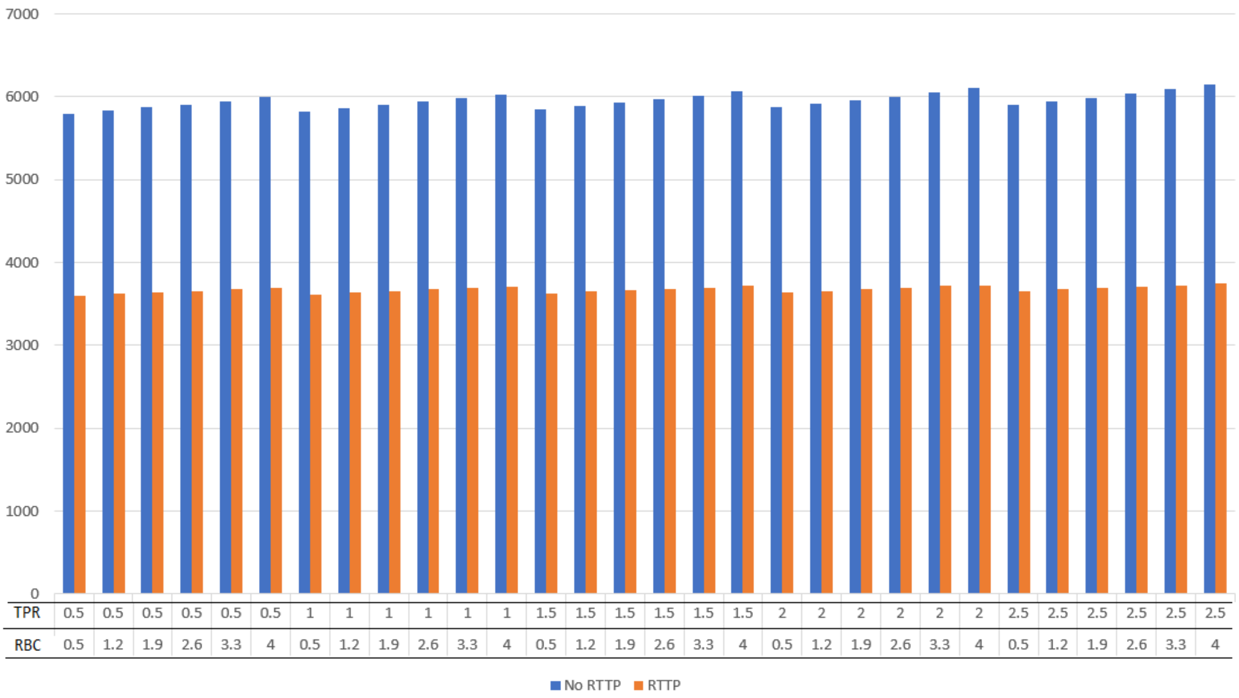

Figure 9: Scenario 2 (10 min delays) total lateness with and without traffic management (RTTP).

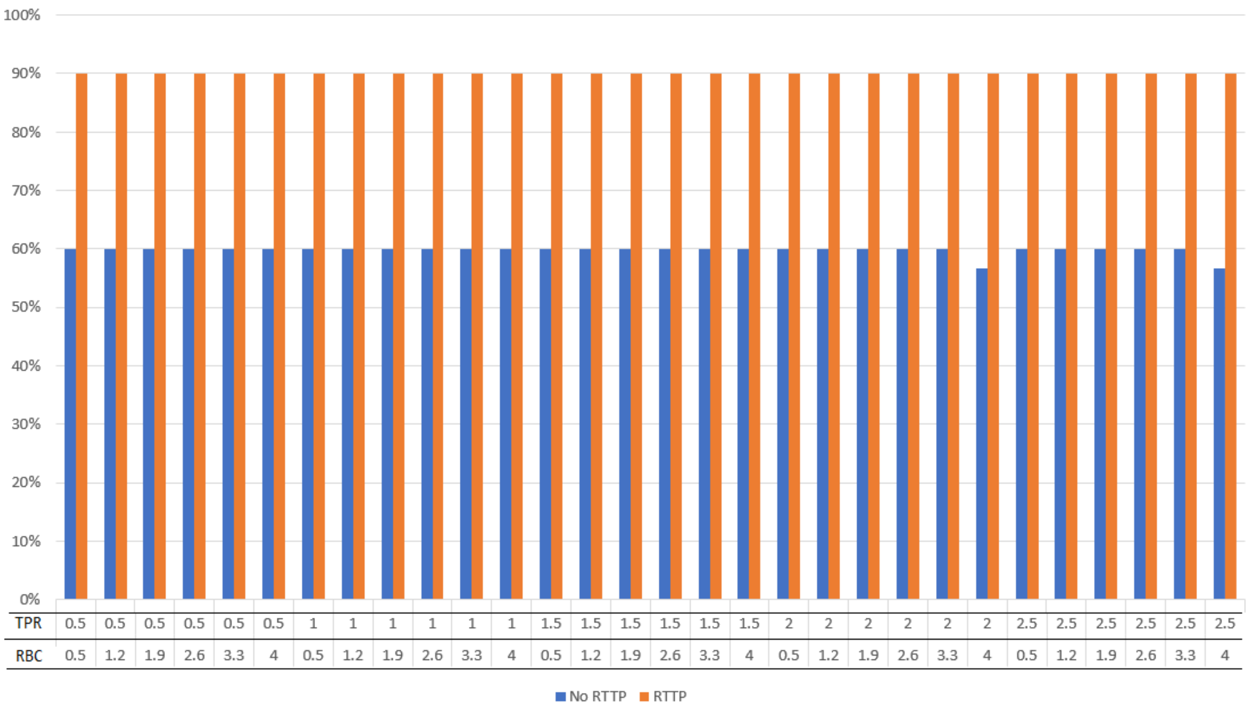

Figure 10: Scenario 2 (10 min delays) punctuality with and without traffic management (RTTP).

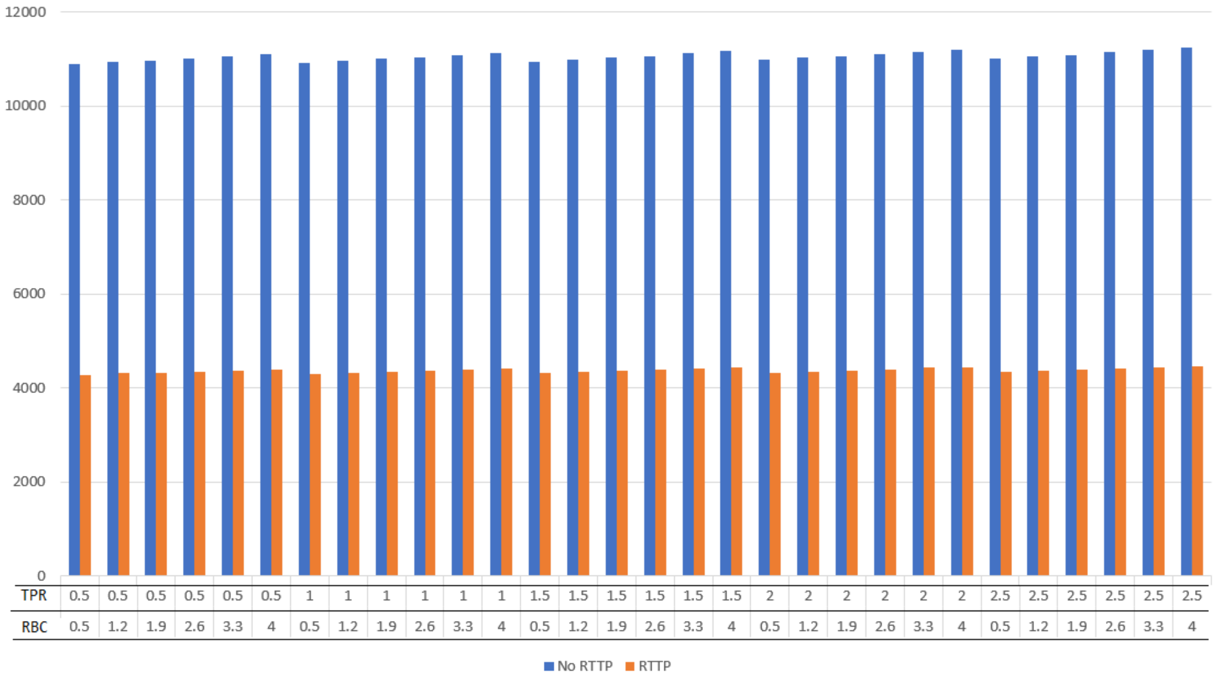

Figure 11: Scenario 3 (15 min delays) total lateness with and without traffic management (RTTP).

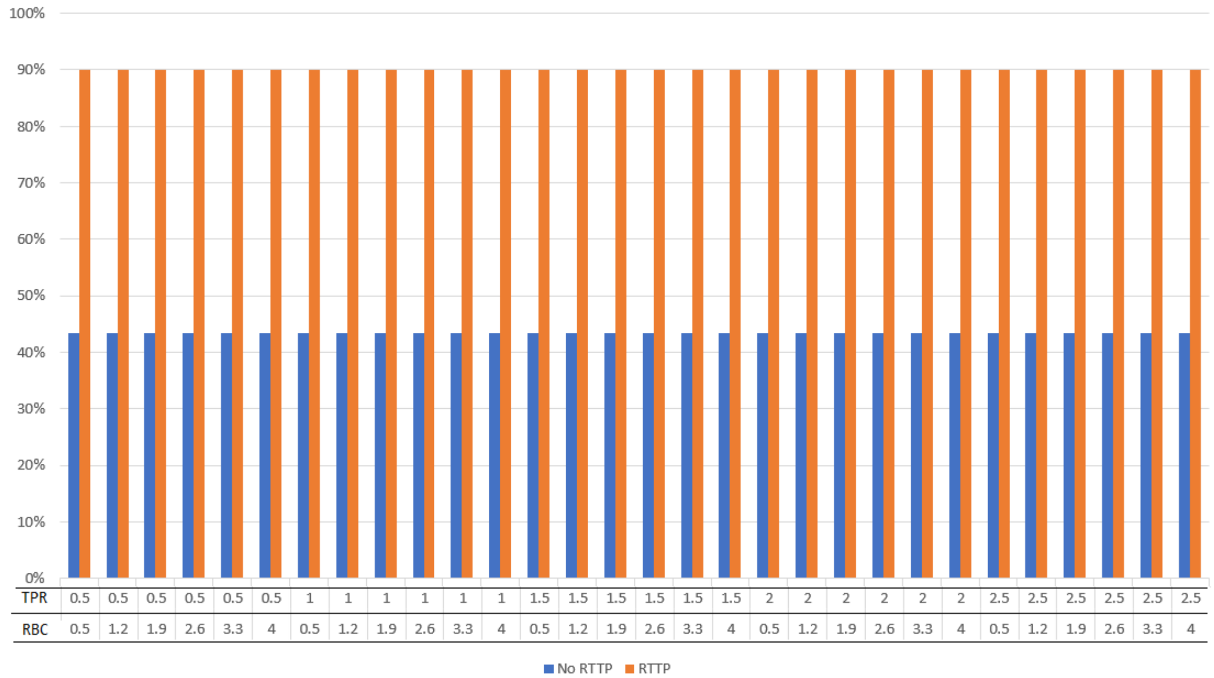

Figure 12: Scenario 3 (15 min delays) punctuality with and without traffic management (RTTP).

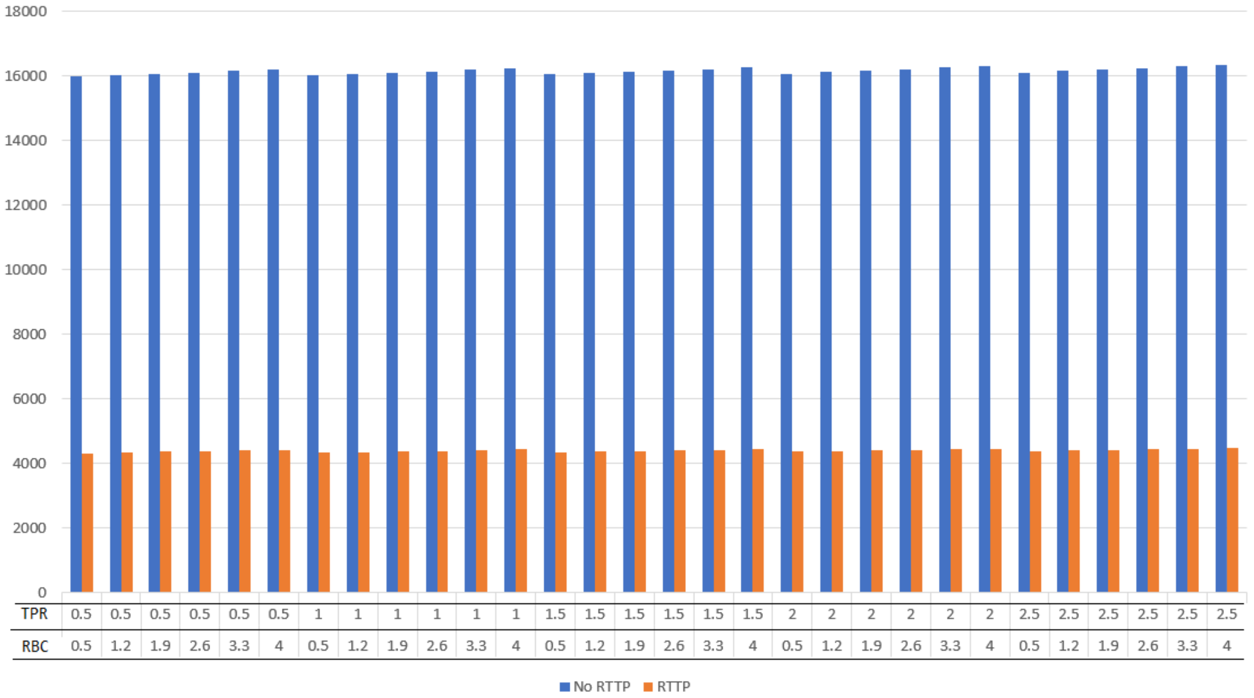

Figure 13: Scenario 4 (20 min delays) total lateness with and without traffic management (RTTP).

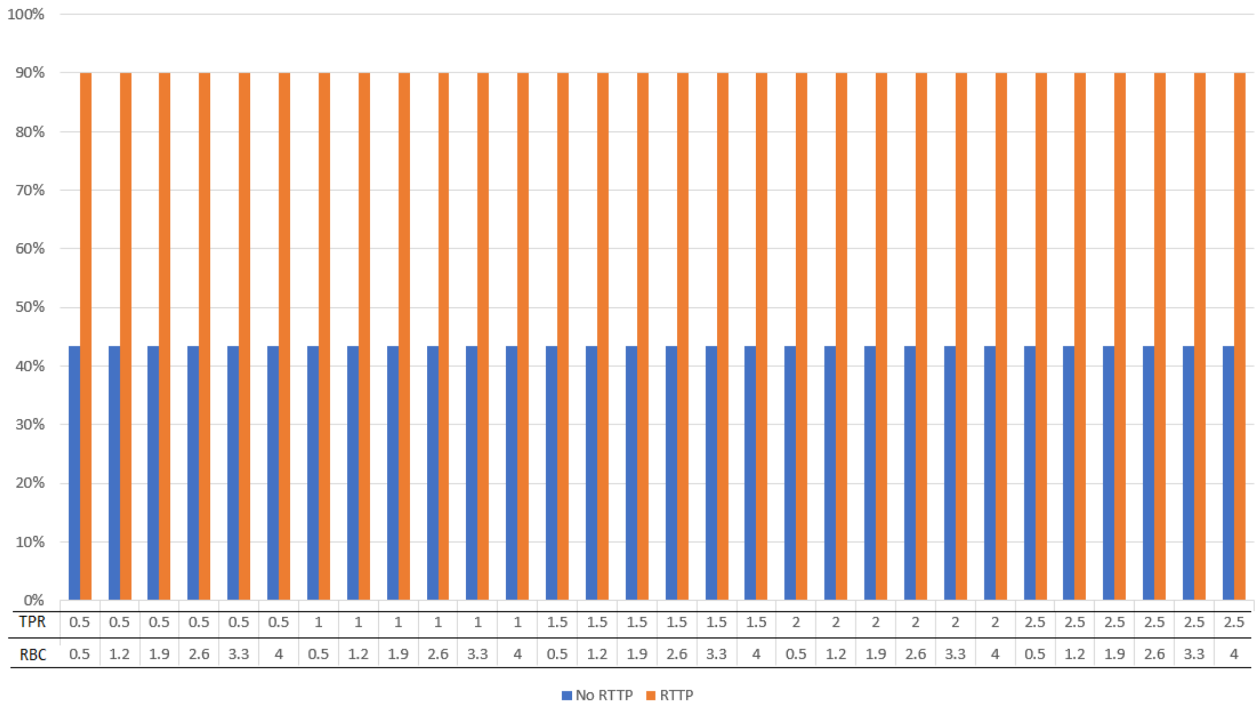

Figure 14**:** Scenario 4 (20 min delays) punctuality with and without traffic management (RTTP).

Appendix B. Blocking Time Diagrams of Real-Time Traffic Plan (RTTP)

This section contains the visualisation of the real-time traffic plans (RTTP) of the optimal rescheduling solution of the traffic management model. In each figure, the blocking time diagrams of all the trains are shown - with horizontally the time and vertically the distance. The darker colours indicate the time is physically occupying a certain point on the track, as part of the full blocking time including the setup, reaction, approach, clearing and release time.

Figure 15 shows the RTTP for scenario 1, in which train 1 and train 8 have an entry delay of 5 minutes. Due to the delay of train 1, train 1 is reordered with train 3 along their joint route, which imposes an entry delay on train 6. The delay of train 8 leads to an exit delay for train 5, as well as a further delay of train 8 itself.

Figure 15 Blocking time diagram of optimised traffic plan for scenario 1.

Figure 16 shows the RTTP for scenario 2, in which train 1 and train 8 have an entry delay of 10 minutes. Due to the delay of train 1, train 1 is reordered with train 3, as well as with train 5 (partly). Because train 1 is to wait for train 5, no other trains are affected. Train 8 is reordered with trains 5 and 7, increasing its own delay and imposing a slight delay on train 10.

Figure 16 Blocking time diagram of optimised traffic plan for scenario 2.

Figure 17 shows the RTTP for scenario 3, in which train 1 and train 8 have an entry delay of 15 minutes. Due to the delay of train 1, train 1 is reordered with trains 2, 3 and 4, imposing a slight delay on train 5. Train 8 is reordered with trains 5 and 7, imposing a slight delay on train 10.

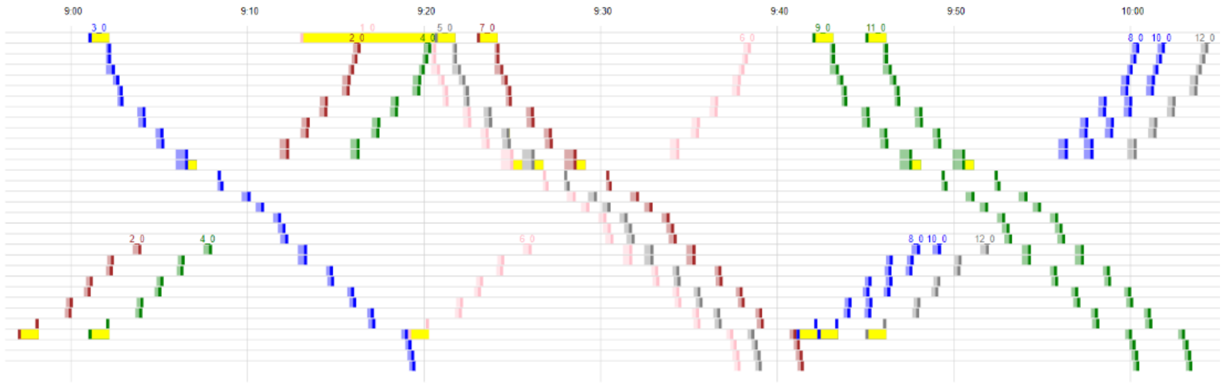

Figure 17 Blocking time diagram of optimised traffic plan for scenario 3.

Figure 18 shows the RTTP for scenario 4, in which train 1 and train 8 have an entry delay of 20 minutes. Due to the delay of train 1, train 1 is reordered with trains 2, 3 and 4, imposing a slight delay on train 5. Train 8 is reordered with trains 5, 7 and 10 with minimal effects on other trains.

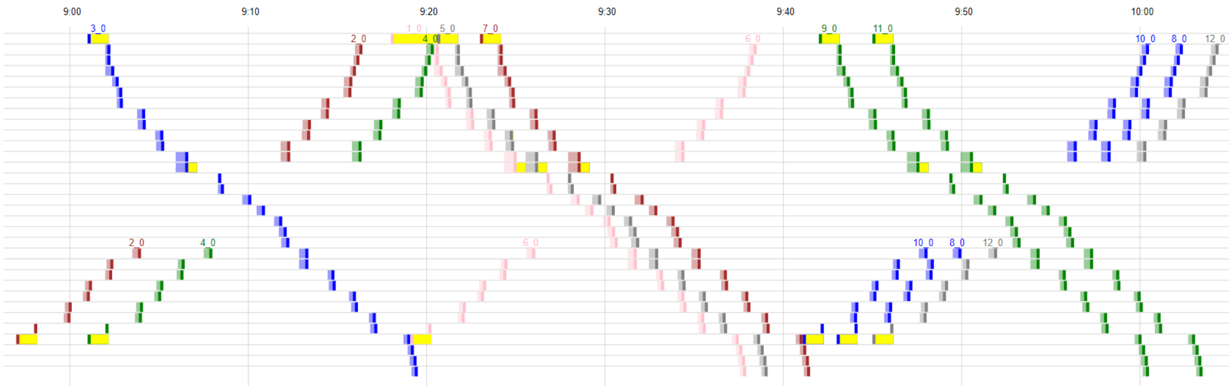

Figure 18 Blocking time diagram of optimised traffic plan for scenario 4.