Deliverable D4.2

Guidelines for a Safe and Optimised Moving-Block Traffic Management System Architecture

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Guidelines for a Safe and Optimised Moving-Block Traffic Management System Architecture

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Report contributors		
Name	Beneficiary Short Name	Details of contribution
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Nina Versluis	TUD	• Table of Contents • Conflict Detection and Resolution Model • Early-Warning Hazard Prediction Model • Guidelines for MB TMS Architecture • Recommendations for MB TMS • Review of references
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Executive Summary

This deliverable contains the output of the activities performed for Task 4.3 "Guidelines on integrated traffic management architectures for safe and optimised moving-block operations" of the EC Shift2Rail PERFORMINGRAIL project. A real-time model for Moving Block traffic conflict detection and resolution is mathematically specified based on the formulation introduced in Deliverable D4.1. A mathematical formulation of the RECIFE-MILP rescheduling tool extended for Moving Block rail operations is reported together with a detailed description of the objective function and constraints. The proposed MB traffic conflict detection and resolution model is then verified for a given network layout and compared to the original RECIFE-MILP formulation for fixed-block to assess modelling and performance impacts of introduced MB constraints. A validation has successively investigated the applicability and effectiveness of the proposed MB traffic management algorithm by testing it on two real railway networks in France (Gonesse junction and a portion on the Paris-Le Havre line) for different traffic scenarios. The validation experiment shows that with respect to fixed-block, Moving block can reduce delay propagation especially: i) for junctions where trains are not stopping, ii) in denser peak-hour traffic and iii) when train rerouting decisions are taken.

A detailed description is the provided for the early-warning MB hazard prediction modules introduced in PERFORMINGRAIL Deliverable D4.1. A specification of input/output data and main functionalities is reported together with practical examples illustrating the usefulness of those modules in mitigating potential MB safety risks in the short and medium term.

A functional TMS architecture is then defined for a safe and optimised real-time management of MB traffic operations. Guidelines are outlined for the different functional TMS modules, specifying input/output data, main functionalities and interactions with other components within and without the TMS.

A set of recommendations is eventually provided to support both science and the industry in further development and implementation of functional modules and an advanced TMS architecture for MB rail traffic. Recommendations particularly refer to novel modules introduced in PERFORMINGRAIL, namely the MB conflict detection and resolution and the early-warning MB hazard prediction models. In addition, indications are given for further development and practical implementation of the proposed functional TMS architecture for safe and optimised MB railway operations. The main highlighted points regard the need of interfacing current Traffic Monitoring systems with satellite-based train location systems as the removal of track-side train detection will compromise the use of existing train describers. That also leads to then necessity of the TMS architecture to include proposed modules for early-warning hazard prediction to mitigate safety risks which can arise for MB in locations with compromised GNSS or GSM-R signal availability. Another essential recommendation refers to data interface standardisation to enable seamless communication among functional modules within the TMS and with external supporting systems.

Abbreviations and Acronyms

Abbreviation / Acronyms	Description
BRaSS	Birmingham Railway Simulation Suite
CDR	Conflict Detection and Resolution
D4.1	Deliverable 4.1 – Real-Time Traffic Rescheduling Algorithms for Perturbation Management and Hazard Prevention in Moving-Block Operations
D4.2	Deliverable 4.2 – Guidelines for a Safe and Optimised Moving-Block Traffic Management System Architecture
FB	Fixed Block
GNSS	Global Navigation Satellite System
MB	Moving Block
MILP	Mixed Integer Linear Programming
RECIFE	Recherche sur la Capacité des Infrastructure Ferroviaires
T4.3	Task 4.3 – Guidelines on Integrated Traffic Management Architectures for Safe and Optimised Moving-Block Operations
TRL	Technology Readiness Level
TMS	Traffic Management System
TSM	Traffic State Monitoring
TSP	Traffic State Prediction
WP	Work Package
WP2	Work Package 2 – Modelling and Analysis of Moving-Block Specifications
WP3	Work Package 3 – Fail-Safe Train Locationing
WP4	Work Package 4 – Integrated Moving-Block Architecture for Safe and Optimised Traffic Operations
X2Rail-3	Advanced Signalling, Automation and Communication System (IP2 and IP5) – Prototyping the future by means of capacity increase, autonomy and flexible communication

1 Introduction

The implementation of next-generation train-centric signalling systems such as Moving Block (MB) is set to change current principles, processes and tools for tactical and operational rail traffic planning. The on-board migration of track-side vital equipment and changes in the interfaces between signalling and interlocking will inevitably require an upgrading of the rules and the HW/SW systems currently supporting planning/dispatching decisions. The removal of track vacancy detection sections will for instance have a major impact on current Traffic Management System (TMS) architectures as real-time train position monitoring could no longer rely on existing train describers, using information on track section release/occupation. The upgrade of core TMS functionalities (e.g. traffic monitoring, conflict detection and resolution) is indeed one of the main challenges that the railway industry is facing to enable safe and effective MB train operations. Several industry-led R&D programmes have been initiated at national (e.g. the UK Digital Railway (Network Rail, 2015) and the German Digitale Schiene (Digitale Schiene Deutschland, 2017)) and international level (the EC Shift2Rail Joint Undertaking (2020) and Europe’s Rail Joint Undertaking (2023)) to investigate enabling train-centric operational procedures and technologies. An upgraded functional scheme has been defined by the ERTMS User Group and EULYNX (2020) for the Future Control Command and Signalling (F-CCS) architecture to interface digital and automated technologies for train planning, management and control (e.g. Automatic Train Operation, ATO). Although those programmes have led to a defined TMS configuration for fixed-block radio-based signalling like ETCS Level 2, further research is still needed to outline a TMS functional architecture for MB. Different research questions are still open which include: i) the identification of automated algorithms for MB conflict detection/resolution, ii) the interface with on-board devices for train integrity and position monitoring, iii) the provision of early-warning predictions to prevent the occurrence of hazardous MB traffic situations.

The research in this deliverable contributes to address those questions and bridge existing knowledge gaps in defining a TMS functional architecture for safe and effective MB train operations. An algorithm for automated MB train conflict detection and resolution is here introduced, verified and validated over different real-life railway networks. Specifically, the extended RECIFE-MILP algorithm for MB which has been specified in PERFORMINGRAIL Deliverable D4.1 (PERFORMINGRAIL, 2022) is verified for a given network layout and then validated for different traffic scenarios on two French case studies: Gonesse junction and a stretch of the Paris-Le Havre line. A schematic TMS architecture for MB is then defined which provides main functional modules and mutual input/output relationships, including interactions between Traffic state monitoring and satellite-based GNSS train position and integrity devices. A detailed description is then given about functional TMS modules to support dispatchers in detecting and preventing the occurrence of hazardous MB traffic situations in the short and medium-term. Those modules are based on methods to identify violations of safety-critical operational / signalling design thresholds (e.g. safe driving reaction times, MA update times) or the arising of track conflicts in crucial locations with limited GNSS and/or GSM-R coverage. Based on the research in this document, a set of guidelines and recommendations are provided to support the railway industry in the development of TMS functionalities for MB operations.

Section 3 defines, verifies and validates the proposed RECIFE-MILP algorithm for MB train conflict detection and resolution. Section 4 describes and shows the defined methods for early-warning prediction of hazardous MB traffic conditions. Section 5 gives general guidelines about functional modules and mutual relationships for a TMS architecture enabling MB operations.

Recommendations about implementation and further development of the proposed methods and architectures are illustrated in Section 6. Conclusions are discussed in Section 7.

1.1 Objectives and Scope

This deliverable contains the outcome of Task 4.3 “Guidelines on integrated traffic management architectures for safe and optimised moving-block operations” of the EC Shift2Rail PERFORMINGRAIL project. This task is performed in the frame of Work Package 4 “Integrated Moving Block architecture for safe and optimised traffic operations” and aims at providing a set of guidelines and recommendations on a functional TMS architecture to enable optimised and safe MB operations. Based on functional specifications from deliverable D4.3 “Future Moving Block Architecture” of X2Rail-3 (Task T4.5) and the modelling outputs from PERFORMINGRAIL tasks T4.1 and T.4.2, a traffic management algorithm for MB traffic operations is here defined, verified and validated. In detail, the RECIFE-MILP algorithm extended for MB is mathematically defined and verified for different track layouts and operational conditions. A model validation experiment is also illustrated by applying the extended RECIFE-MILP algorithm to real railway networks in France, namely the Gonesse junction and a stretch of the Paris – Le Havre line. A set of guidelines are later provided to illustrate the practical application of the methods for early-warning prediction of hazardous MB traffic situations, specified for both the short and the medium term in PERFORMINGRAIL deliverable D4.1. A set of guidelines are then reported for developing a functional TMS architecture for safe and optimised MB train service. The main functional TMS components are described together with the input/output data and their mutual interactions. Also, a description is given about the specific implementation of those functional components in the PERFORMINGRAIL simulation-based impact assessment platform. Defined guidelines specifically refer to functional components interacting within the TMS while interfaces of this latter with other external systems such as the interlocking, the signalling, the ATO and the tactical planning environment are out of the scopes of this work. Recommendations are thereafter provided to support scientists and practitioners in the utilisation as well as the further development/improvement of defined traffic management methods and functional components. Hence the main objectives of this deliverable are:

- Verifying and validating an automatic algorithm for train conflict detection and optimised resolution under MB signalling.
- Providing guidelines for the application of defined methods for early-warning prediction of MB traffic situations in the short and medium term.
- Delineating a set of guidelines and recommendations on a functional architecture for an integrated TMS which can enable safe and optimised MB traffic operations.

Those objectives are linked to Technology Demonstrator TD2.9 “TMS Evolution” in IP2 “Advanced Traffic Management and Control Systems” and Work Area 4 “Smart Mobility” of the Shift2Rail MAAP (2020).

1.2 Related Documents

This document relies on inputs provided by deliverables of other PERFORMINGRAIL WPs as well as other Shift2Rail projects. In detail the set of deliverables relative to other tasks and WPs in the PERFORMINGRAIL project are:

- Deliverable D1.1 - Baseline system specification and definition for Moving Block Systems
- Deliverable D2.2 - Moving Block Specification Development
- Deliverable D3.1 - Design document of the Location algorithms
- Deliverable D3.3 - Multi-frequency/constellation GNSS receiver
- Deliverable D4.1 - Real-Time Traffic Rescheduling Algorithms for Perturbation Management and Hazard Prevention in Moving-Block Operations

Further inputs are provided from deliverables of the S2R project X2Rail-3, specifically:

- D4.2 - Moving Block Specification
- D4.3 - Future Moving Block Architecture

Outputs from this document will be instead feed the content of other tasks and WPs in the PERFORMINGRAIL project, namely:

- D1.2 – Best practice, recommendations and standardisation to definition of the railway minimum operational performance standards
- D5.2 - Assessment report

2 Background

The present document constitutes D4.2 “Guidelines for a safe and optimised moving-block traffic management system architecture” which is the second and last deliverable of WP4 “Integrated Moving Block architecture for safe and optimised traffic operations” of the EC Shift2Rail project PERFORMINGRAIL. Referring to the Shift2Rail MAAP (2020), the work described in this document links to Technology Demonstrator TD2.9 “TMS Evolution”, tasks 2.9.3 “Framework for Traffic Management Business Service” and task 2.9.6 ”Functionalities and Interfaces for Dynamic Demand and Information Management” in IP2 “Advanced Traffic Management and Control Systems”. Also, it refers to Work Area WA 4 “Smart Mobility” subtask 4.2 “Integrated mobility management” of the Shift2Rail MAAP (2020).

3 Conflict Detection and Resolution Model for Moving-Block Signalling

The basis of the proposed conflict detection and resolution model for moving-block signalling is RECIFE-MILP. RECIFE-MILP is a conflict detection and resolution model developed by Pellegrini et al. (2014, 2015) for fixed-block signalling. RECIFE-MILP models the infrastructure at a microscopic level and implements the route-lock sectional-release interlocking system. For details about the original mathematical formulation, we refer the reader to Pellegrini et al. (2014, 2015) and Section 4.2 of D4.1 (PERFORMINGRAIL, 2020).

The RECIFE-MILP model formulation is here extended to approximate moving-block rescheduling. Main moving-block signalling system characteristics are: i) that open lines are no longer separated into block sections and ii) the minimum train separation between trains is an absolute braking distance. To this end, the original RECIFE-MILP model is extended with: *a*) a block-independent discretisation of the open line, *b*) a speed dependent headway function (including a discrete set of alternative speed profiles) and *c*) a train blocking time based on absolute braking distances. For more information on how those enhancements are included in the model formulation, we refer to Versluis et al. (2023) and Section 4.3 of D4.1 (PERFORMINGRAIL, 2020).

In the following, we present the mathematical formulation of RECIFE-MILP model enhanced for moving-block signalling (Section 3.1), as well as a verification (Section 3.2) and a validation of the model (Section 3.3).

3.1 Mathematical Model

Here we present the mathematical formulation of the conflict detection and resolution model for moving-block signalling as extension of RECIFE-MILP. Note that not all details of RECIFE-MILP are given here. For that, we refer to Pellegrini et al. (2014, 2015).

3.1.1 Sets, Parameters and Variables

The sets, parameters and variables of the model are listed in Table 1.

Table 1 Sets, parameters and variables of the MILP model.

Sets	
T	set of trains
R	set of routes
$\mathrm{R_t} \subset \mathrm{R}$	set of routes available to train $t \in T$
L	set of locations
$L_t \subset L$	set of locations which can be used by train $t \in T$
$L^r \subset L$	set of locations along route $r \in R$
$OL_{t,r,l} \subset L$	set of locations along route $r \in R$ such that if train $t \in T$ starts occupying it, the train has not yet cleared location $l \in L^r$
S	set of stations
$S_t \subset S$	set of stations where train $t \in T$ has a scheduled stop
$LS_{t,s} \subset L$	set of locations that can be used by train $t \in T$ for stopping at station $\mathrm{s} \in \mathrm{S_t}$
$\widehat{L_{t,t',l}} \subset L$	set of locations $l' \in L$ which may be used by trains $t, t' \in T$, i.e., $l' \in L_t \cap L_{t'}$, such that if t precedes t' on l, then t precedes t' on l'
$\mathrm{P} \subset L$	set of locations $l \in L$ such that l is a speed representation location

$\mathrm{P}^r \subset \mathrm{P}$	set of speed representation locations $l \in \mathrm{P}$ along route $r \in R$
Parameters	
$p_{r,l},\ s_{r,l} \in L^r$ $\rho_{r,l} \in \mathrm{P}$ $s(l) \in \{0,1\}$ $l_\infty \in L$ $init_t \in \mathbb{R}_+$ $sched_t \in \mathbb{R}_+$ $dw_{t,s} \in \mathbb{R}_+$ $a_{t,s}, d_{t,s} \in \mathbb{R}_+$	preceding location and succeeding location of location $l \in L$ along route $r \in R$ speed representation location of location $l \in L$ along route $r \in R$ $= 1$ if location $l \in L$ lies in a switch area dummy location considered as destination for all trains earliest time at which train $t \in T$ can be operated scheduled arrival time of train $t \in T$ at dummy destination location $l_\infty \in L$ minimum dwell time for train $t \in T$ at station $s \in S_t$ scheduled arrival/departure time for train $t \in T$ at station $s \in S_t$
$for_{r,l} \in \mathbb{R}_+$ $rel_{r,l} \in \mathbb{R}_+$ $rt_{t,r,l} \in \mathbb{R}_+$ $\Delta rt_{t,r,l} \in \mathbb{R}_+$ $ct_{t,rl} \in \mathbb{R}_+$ $\Delta ct_{t,r,l} \in \mathbb{R}_+$ $ref^{s}_{t,r,l} \in L$ $ref^{sm}_{t,r,l} \in L$ $lag^{s}_{t,r,l} \in \mathbb{R}_+$ $lag^{m}_{t,r,l} \in \mathbb{R}_+$ $w, w_t \in \mathbb{R}_+$ $M \in \mathbb{R}_+$	formation time, i.e., setup and reaction time, of location $l \in L^r$ along route $r \in R$ release time of location $l \in L^r$ along route $r \in R$ minimum running time for train $t \in T$ from location $l \in L_t$ to $s_{r,l}$ along route $r \in R_t$ additional running time for train $t \in T$ from location $l \in L_t$ to $s_{r,l}$ along route $r \in R_t$in case of scheduled speed minimum clearing time for train $t \in T$ of location $l \in L_t$ along route $r \in R_t$ additional clearing time for train $t \in T$ of location $l \in L_t$ along route $r \in R_t$ in case of scheduled speed reference brake location for location $l \in L^r$along route $r \in R$ for train $t \in T$approaching at scheduled speed reference brake location for location $l \in L^r$along route $r \in R$ for train $t \in T$approaching at maximum speed time by which blocking of location time by which blocking of location weights for objective function a large constant
Variables	
$y_{t,t',l} \in \{0,1\}$ $x_{t,r} \in \{0,1\}$ $v^{s}_{t,r,l} \in \{0,1\}$ $v^{m}_{t,r,l} \in \{0,1\}$ $o_{t,r,l} \in \mathbb{R}_+$ $o^{+}_{t,r,l} \in \mathbb{R}_+$ $b^{s}_{t,l}, b^{e}_{t,l} \in \mathbb{R}_+$ $D_t \in \mathbb{R}_+$ $D_{t,s} \in \mathbb{R}_+$	$= 1$ if train $t \in T$ blocks location $l \in L_t \cap L_{t'}$ before train $t' \in T$ $= 1$ if train $t \in T$ uses route $r \in R_t$ $= 1$ if train $t \in T$ passes location $l \in L_t$ along route $r \in R_t$ at scheduled speed $= 1$ if train $t \in T$ passes location $l \in L_t$ along route $r \in R_t$ at maximum speed occupation starting time of train $t \in T$ on location $l \in L_t$ along route $r \in R_t$ extended occupation time of train $t \in T$ on location $l \in L_t$ along route $r \in R_t$ time at which train $t \in T$ starts/ends blocking location $l \in L_t$ delay suffered by train $t \in T$ when exiting the infrastructure and/or arriving at destination delay suffered by train $t \in T$ when stopping at station $s \in S_t$

The sets represent collections of elements that are used for the model notation. The four main sets are the set of trains T, the set of routes R the set of locations L and the set of stations S. Subsets $R_t \subset R$ and $S_t \subset S$ are defined to represent routes and stations relevant to train $t \in T$.

For the set of locations, multiple subsets are defined. First, the subsets indicating the relevant locations per train $L_t \subset L,\ t \in T$ and per route $L^r \subset L,\ r \in R$. Next, the sets of *occupied locations* $OL_{t,rl} \subset L$, containing the locations along route $r \in R_t$ for which it holds that if train $t \in T$ starts occupying it, the train has not yet cleared location $l \in L^r$. $LS_{t,s} \subset L$ is the set of locations that can be used by train $t \in T$ to stop at stations $\in S_t$. $\widehat{L_{t,t',l}} \subset L$ is the set of locations that trains $t, t' \in T$ need to traverse in the same order, i.e., if train t precedes t' on $l \in L$, then t precedes t' on $l' \in \hat{L}_{t,t',l}$. Finally, the set of speed representation locations $\mathrm{P} \subset L$ containing the open line locations to which a speed profile is assigned for the whole open line stretch. Subset $\mathrm{P}^r \subset \mathrm{P}$ contains the speed representation locations along route $r \in R$.

The parameters are provided as input to the model. First, parameters related to the infrastructure. $p_{r,l}$ and $s_{r,l}$ are defined to represent the preceding and succeeding location of location $l \in L^r$ along route $r \in R$, respectively. indicates the speed representation location of (the open line stretch containing) location $l \in L$ along route $r \in R$. Additionally, function $s: l \mapsto \{0,1\}$ indicates whether a location is a switch location, $s(l) = 1$, or an open line location, $s(l) = 0$. Also, dummy location l_∞ represents the fictional destination of all trains, added at the end of each route.

Next, we define the parameters related to the timetable. The initial entry time and the scheduled destination arrival time of train $t \in T$ are given by $init_t$ and $sched_t$, respectively. The dwell time of train $t \in T$ at station $s \in S_t$ is given by $dw_{t,s}$. The arrival and departure time of train $t \in T$ at station $s \in S_t$ is given by $a_{t,s}$ and $d_{t,s}$, respectively.

Then, we define the parameters related to the blocking times. The formation time, which includes the setup and reaction time, and the release time of location $l \in L^r$ along route $r \in R$ are given by $for_{r,l}$ and $rel_{r,l}$, respectively. The running time of train $t \in T$ from location $l \in_t$ to its succeeding location $s_{r,l}$ along route $r \in R_t$ is described by two parameters. $rt_{t,r,l}$ gives the minimum running time corresponding to running at maximum speed. $\Delta rt_{t,r,l}$ gives the additional running time in case the train follows a scheduled speed profile. Similarly, the clearing time of train $t \in T$ of location $l \in L_t$ along route $r \in R_t$ is given by the minimum clearing time $ct_{t,rl}$ and the possible additional clearing time $\Delta ct_{t,r,l}$.

A second group of parameters is related to the approach time: the reference locations and the reservation lags. Locations $ref^{\mathrm{s}}_{t,r,l}, ref^{\mathrm{m}}_{t,r,l} \in L$ represent the reference brake locations for location $l \in L^r$along route $r \in R_t$ for train $t \in T$ approaching at scheduled or maximum speed, respectively. Reservation lag parameters $lag^{\mathrm{s}}_{t,r,l}$ and $lag^{\mathrm{m}}_{t,r,l}$ are defined to indicate the time by which the reservation of location $l \in L^r$ along route $r \in R_t$ for train $t \in T$ can be postponed after passing the corresponding reference brake location.

Finally, we define the weights w and $w_t, t \in T$, for the objective function, and M to be a large constant.

The model variables are either continuous timing variables or binary decision variables. The binary decision variables capture the scheduling and speed profile decisions. The passing order of two trains $t, t' \in T$ at common location $l \in L_t \cap L_{t'}$ is determined by variable $y_{t,t',l}$. The order variables are only defined for one representative location per $\hat{L}_{t,t',l}$ set. The route assignment of train $t \in T$ is captured by variable $x_{t,r}$, indicating for route $r \in R_t$ whether or not the route is used by train t. The assignment of speed profiles is described by two different sets of variables. $v^{\mathrm{s}}_{t,r,l}$ indicates whether or not train $t \in T$ runs at scheduled speed over speed representation location $l \in \mathrm{P}^r$ along route $r \in R_t$, while $v^{\mathrm{m}}_{t,r,l}$ indicates whether or not train $t \in T$ runs at maximum speed over speed representation location $l \in \mathrm{P}^r$ along route $r \in R_t$.
The timing variables include the decision variables indicating the physical occupation starting time: $o_{t,r,l}$ with $t \in T$, $r \in R_t$ and $l \in L_t$. The other timing variables depend on them in combination with the binary decision variables. These auxiliary variables represent the extended physical occupation times due to dwell time, delay and/or scheduling decisions ($o^{+}_{t,r,l}$ with $t \in T$, $r \in R_t$ and $l \in L_t$), the blocking starting and ending times ($b^{\mathrm{s}}_{t,l}$ and $b^{\mathrm{e}}_{t,l}$ with $t \in T$ and $l \in L_t$), the final delays (D_t with $t \in T$), and the delays at scheduled stops ($D_{t,s}$ with $t \in T$ and $s \in S_t$).

3.1.2 Objective Function

The main objective of the model is to minimise the total delay. Additionally, we want to enforce the assignment of scheduled speed profiles where possible. This results in the following objective function:

$$\text{minimise } \textstyle\sum_{t\in T}(w_t(D_t + \sum_{s\in S_t} D_{t,s}) + w \sum_{w\in R_t:\, l\in \mathrm{P}^r} v^{\mathrm{m}}_{t,r,l})) \,. \qquad (1)$$

The first term includes the weighted cumulative delay, i.e., the weighted sum of train delays upon arriving at scheduled stops ($\mathrm{D}_{t,s}$ with $t \in T$ and $s \in S_t$) or upon exiting the infrastructure, either by leaving the area of by reaching its terminus (D_t with $t \in T$). The weights can, for example, be interpreted as priority factors.

The second term counts the number of maximum speed profiles assigned. Minimising the number of maximum speed profile assignments balanced with the delay minimisation ensures the assignment of scheduled speed unless it decreases the total delay with more than w seconds.

3.1.3 Constraints

The constraints describing the moving-block version of RECIFE-MILP are given by Equations (2) to (17).

$$o_{t,r,l} \geq init_t\, x_{t,r} \qquad \forall t \in T,\ r \in R_t,\ l \in L^r, \qquad (2)$$

$$o_{t,r,l} \leq M\, x_{t,r} \qquad \forall t \in T,\ r \in R_t,\ l \in L^r, \qquad (3)$$

$$\sum_{r\in R_t} x_{t,r} = 1 \qquad \forall t \in T, \qquad (4)$$

$$v^{\mathrm{m}}_{t,r,l} + v^{\mathrm{s}}_{t,r,l} = x_{t,r} \qquad \forall t \in T,\ r \in R_t,\ l \in \mathrm{P}^r, \qquad (5)$$

$$o_{t,r,s_{r,l}} = o_{t,r,l} + o^{+}_{t,r,l} + rl_{t,r,l}\, x_{t,r} + \Delta rl_{t,r,l} v^{\mathrm{s}}_{t,r,\rho_{r,l}}$$

$$\forall t \in T,\ r \in R_t,\ l \in L^r, \qquad (6)$$

$$o^{+}_{t,r,s_{r,l}} \geq \sum_{\substack{s\in S_t:\\ l\in S_{t,s}\cap L^r}} dw_{t,s}\, x_{t,r} \qquad \forall t \in T,\ r \in R_t,\ l \in \bigcup_{s\in S_t} S_{t,s}, \qquad (7)$$

$$o_{t,r,s_{r,l}} \geq \sum_{\substack{s\in S_t:\\ l\in S_{t,s}\cap L^r}} d_{t,s}\, x_{t,r} \qquad \forall t \in T,\ r \in R_t,\ l \in \bigcup_{s\in S_t} S_{t,s}, \qquad (8)$$

$$D_{t,s} \geq \sum_{r\in R_t} \sum_{l\in L^r\cap LS_{t,s}} o_{t,r,l} - a_{t,s} \qquad \forall t \in T, s \in S_t, \qquad (9)$$

$$D_t \geq \sum_{r\in R_t} o_{t,r,l_\infty} - sched_t \qquad \forall t \in T, \qquad (10)$$

$$b^{\mathrm{s}}_{t,l} \leq \sum_{\substack{r \in R_t: \\ l \in L^r}} \left(o_{t,r,ref^{\mathrm{s}}_{t,r,l}} + \left(lag^{\mathrm{s}}_{t,r,l} - for_{r,l} \right) x_{t,r} \right)$$

$$\forall t \in T,\ l \in L_t : s(l) = 0 \vee \nexists r \in R_t : s(p_{r,l}) = 1, \qquad (11)$$

$$b^{\mathrm{s}}_{t,l} \leq \sum_{\substack{r \in R_t: \\ l \in L^r}} \left(o_{t,r,ref^{\mathrm{m}}_{t,r,l}} + \left(lag^{\mathrm{m}}_{t,r,l} - for_{r,l} \right) x_{t,r} + M\, v^{\mathrm{s}}_{t,r,p_{r,ref^{\mathrm{s}}_{t,r,l}}} \right)$$

$$\forall t \in T,\ l \in L_t : s(l) = 0 \vee \nexists r \in R_t : s(p_{r,l}) = 1, \qquad (12)$$

$$b^{\mathrm{s}}_{t,l} = b^{\mathrm{s}}_{t,p_{r,l}} \qquad \forall t \in T,\ l \in L_t : s(l) = 1 \wedge \exists r \in R_t : s(p_{r,l}) = 1, \qquad (13)$$

$$b^{\mathrm{e}}_{t,l} = \sum_{\substack{r \in R_t: \\ l \in L^r}} \left(o_{t,r,l} + \left(cl_{t,r,l} + rel_{r,l} \right) x_{t,r} + \Delta cl_{t,r,l} v^{\mathrm{s}}_{t,r,p_{r,l}} + \sum_{\substack{l' \in L^r: \\ l' \in OL_{t,r,l}}} o^{+}_{t,r,l'} \right)$$

$$\forall t \in T,\ l \in L : s(l) = 0 \vee \nexists r \in R_t : s(s_{r,l}) = 1, \qquad (14)$$

$$b^{\mathrm{e}}_{t,l} = b^{\mathrm{e}}_{t,s_{r,l}} \qquad \forall t \in T,\ l \in L_t : s(l) = 1 \wedge \exists r \in R_t : s(s_{r,l}) = 1, \qquad (15)$$

$$b^{\mathrm{e}}_{t,l} - M \left(1 - y_{t,t',\hat{l}}\right) \leq b^{\mathrm{s}}_{t',l} \qquad \forall t, t' \in T, \text{index } t < \text{index } t',\ l, \hat{l} \in L_t \cap L_{t'} : l \in \hat{L}_{t,t',\hat{l}}, \qquad (16)$$

$$b^{\mathrm{e}}_{t',l} - M\, y_{t,t',\hat{l}} \leq b^{\mathrm{s}}_{t,l} \qquad \forall t, t' \in T, \text{index } t < \text{index } t',\ l, \hat{l} \in L_t \cap L_{t'} : l \in \hat{L}_{t,t',\hat{l}} \qquad (17)$$

Constraints (2) force train t to start operating no earlier than its initial entry time $init_t$ on its assigned route, while Constraints (3) set the occupation starting time of all locations along the train's alternative routes to zero. Constraints (4) ensure that a single route is assigned to each train.

Constraints (5) ensure that a speed profile is assigned to speed representation locations along the route of a train. No speed profile is assigned to locations along routes that are not assigned to the train ($v^{\mathrm{m}}_{t,r,l} = v^{\mathrm{s}}_{t,r,l} = 0$).

Constraints (6) describe the difference in occupation starting time between successive locations in terms of extended occupation time and running time. By Constraints (7), the extended occupation time $o^{+}_{t,r,l}$ includes the dwell time at scheduled stops. Additionally, it includes the difference in running time in case the assigned speed profile cannot be followed due to a delayed train in front. In a post-processing step, the extended occupation time can be used to obtain a smoother speed profile with a lower target/cruising speed.

The running time of a train from a location to the succeeding one depends on the assigned speed. If train t runs over location l along route r according to the maximum speed profile, i.e., $v^{\mathrm{m}}_{t,r,p_{r,l}} = 1$ and hence $v^{\mathrm{s}}_{t,r,p_{r,l}} = 0$, then only the minimum running time $rt_{t,r,l}$ is considered. If train t runs over location l along route r according to the scheduled speed profile, i.e., $v^{\mathrm{s}}_{t,r,p_{r,l}} = 1$, then the additional running time $\Delta rt_{t,r,l}$ is also included.

Constraints (7) ensure that the station dwell times are included in the extended occupation time, while Constraints (8) ensure that train$t$ does not leave its stopping location $l \in LS_{t,s}$ before its scheduled departure time from station s.

Constraints (9) and (10) quantify non-negative delay at each station where train t has a scheduled stop and at its exit from the infrastructure and/or when reaching its final destination. In Constraints (9), the occupation starting time of train t on the stopping location along route r at station s is compared with the scheduled arrival time at station s. In Constraints (10), the occupation starting time of train t on the dummy destination location is compared with the scheduled exit time.

Constraints (11) to (13) set the blocking starting times. Constraints (11) and (12) describe the blocking starting times of open line locations, i.e., location l such that $s(l) = 0$, and of locations that can be the first of a switch area for a specific train, i.e., location l such that $\nexists r \in R_t: s_{p_{r,l}} = 1$.

Constraints (11) ensure that the blocking of open line location l by train t starts at the latest the formation time before the train passes the brake application point corresponding to the scheduled speed profile, that is the moment the train starts occupying the scheduled-speed reference location $ref^{s}_{t,r,l}$ along the assigned route, postponed with the reservation lag $lag^{s}_{t,r,l}$. Indeed, blocking of a track location starts earlier when a train is approaching at maximum speed than at scheduled speed because of the longer braking curve.

Constraints (12) ensure that in case the approaching train is running at maximum speed, the blocking starts earlier. Namely, at the moment the train passes the maximum-speed brake application point ($\mathrm{o}_{\mathrm{t,r,ref^{m}_{t,r,l}}} + lag^{\mathrm{m}}_{\mathrm{t,r,l}}$) along the assigned route, minus the formation time. However, the blocking starting time in case of a train approaching at scheduled speed must not be restricted. For that purpose, a big-M term is added. The value of M should be high enough to include the running time from the maximum-speed brake application point to the scheduled-speed brake application point and the possible longer stay at the locations in between.

Constraints (13) deal with the locations in switch areas that are not the first switch location for a specific train, i.e., with l such that $s(l) = 1$ while $\exists r \in \mathrm{R_t}: \mathrm{s}(\mathrm{p}_{r,l}) = 1$. The blocking of such a switch location starts as soon as the preceding location starts being blocked. With this, the locations in the same switch area are being blocked at the same time.

Constraints (14) and (15) set the blocking ending times. The blocking time of a location lasts until the train exists it along any route, plus the release time. Constraints (14) are dedicated to the blocking ending times of open line locations ($l \in L: s(l) = 0$) and of locations that are the last location of a switch area for a specific train ($\nexists r \in R_t: s(s_{r,l}) = 1$). On the open line, the locations, which have no length, are blocked separately. Hence, at open line locations the running time component is excluded to better approximate moving-block blocking times.

In Constraints (15), the blocking ending times of switch locations that are not the last of a switch area ($l \in L: s(l) = 1$ and $\exists r \in \mathrm{R_t}: \mathrm{s}(\mathrm{s}_{r,l}) = 1$) are set. In switch areas, locations are considered as the entry point of a track circuit. Hence, a switch location remains occupied until the last location in its switch area, is released.

Independently of switch areas or open line stretches, the location clearing time is included in the blocking time. In case of a maximum speed profile, only the minimum clearing time is considered, while in case of a scheduled speed profile an additional clearing time component is included. In switch areas, the additional clearing time is zero.

Additionally, if the train is long enough to keep occupying a location when its head is at the end of the following ones (included in set $OL_{t,r,l}$), also the extended occupation times of the train on these locations has to be accounted for.

Finally, disjunctive Constraints (16) and (17) ensure that the location blocking times of two trains do not overlap, depending on train orderings. The passing order of a pair of trains is defined per set of locations that the two trains need to pass in the same order.

3.2 Model Verification

In this section, we present the computational setup in which the model has been verified, including the results of the model verification.

3.2.1 Initialisation

For the initialisation of the model, we rely on input data available for the fixed-block version of RECIFE-MILP. Since this does not provide all the information we need, we make the following assumptions.

- The discretisation of the open line corresponds to the track circuits.
- A location is a switch location if it corresponds to the boundary of a track circuit containing a switch. Any other location is an open line location.
- The locations at the end of an open line stretch along any route are selected as speed assignment locations. A location's associated speed assignment location along a route is the first speed assignment location along that route.
- The maximum speed of a train at a location is the minimum of the maximum line speed at the location and the maximum train speed.
- The scheduled speed equals the maximum speed in switch areas.
- The scheduled speed is 80% of the maximum speed on the open line.
- The additional running and clearing times are zero in switch areas and 25% of the minimum times on the open line.
- The formation time is fifteen seconds for all locations.
- The release time is five seconds for all locations.
- The train braking rates are constant (0.8 m/s^2).
- The track gradients are zero.
- The running resistance coefficients are zero.
- The rotation mass factors are one.
- The safety margin is 50 meters.
- The trains have no alternative routes.
- The objective function minimises the entrance and exit delay, as well as the number of maximum speed profile assignments ($w_t = 1$ for all trains $t \in T$, $w = 10$).

In the fixed-block model, we use running and clearing times computed considering maximum speed profiles. By doing so, we are being conservative. If a bias on delay assessment is introduced, it will be in favour of the fixed-speed model rather than of the moving-block model that we aim to verify.

3.2.2 Scenario

The scenario considered for the verification of the model is as follows. The infrastructure consists of two open line stretches, merging at a switch, see Figure 1. The two open line stretches before the switch contain 19 and 21 track circuits, respectively. The open line stretch after the switch contains six track circuits.

Two trains, train A and train B, traverse the infrastructure along partially overlapping routes, route 1 and route 2, respectively. The trains enter the infrastructure using different open line stretches, and their routes merge at the switch, as indicated in Figure 1. Train A is scheduled to traverse the infrastructure in 397 seconds, while the minimum total running time is 327 seconds. The scheduled and minimum total running time of train B are 339 seconds and 281 seconds, respectively. Train A is scheduled to enter the infrastructure 180 seconds earlier than train B does, to pass the switch and to exit the infrastructure first.

Given the described infrastructure and timetable, we specifically consider a scenario in which train A is entering the infrastructure with a delay of 190 seconds.

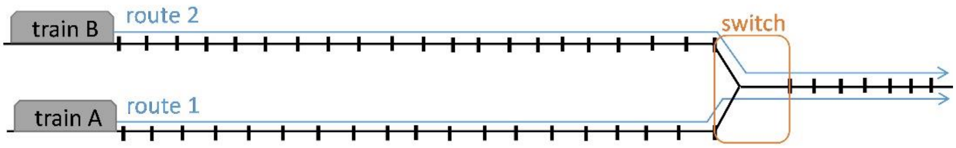

Figure 1 Considered infrastructure with train routes and switch and open line locations.

3.2.3 Results

Here we present the results obtained with the fixed-block and moving-block versions of RECIFE-MILP.

Blocking Time Diagrams

The solutions of the fixed-block and moving-block models are represented by blocking time diagrams in Figure 2. The figures show the time window in which track circuits (fixed block) or locations (moving block) along a route are exclusively allocated to train A and to train B, respectively. The total blocking times are decomposed into the following components: formation time, approach time, occupation time, extended occupation time, and release time.

The blocking time diagram resulting from the RECIFE-MILP model for fixed-block signalling is given in Figure 2a. Figure 2a features route 1, used by train A, and shows the blocking times of train B only for the common track circuits. We focus on route 1 because train A is the most affected by delay in the fixed-block solution, as described in the following section.

The blocking time diagram clearly shows the sectional-release interlocking system, in which the track circuits within one block are reserved at the same moment and released one by one. The total blocking times include the formation time of the reference block, the running time from the reference block to the track circuit entry, the physical occupation time, and the release time of the track circuit. The physical occupation time includes the running time over the track circuit and the clearing time. Extended occupation time is included in case the train cannot run at the assigned speed due to having to slow down due to traffic ahead.

The blocking time diagram resulting from the RECIFE-MILP model for moving-block signalling is given in Figure 2b. Figure 2b features route 2, used by train B, and shows the blocking times of train A only for the common locations. We focus on route 2 because train B is the most affected by delay in the moving-block solution, as described in the following section. The blocking time diagram shows that the open line locations are reserved and released one by one, while the switch locations, i.e., locations 22 and 23, are reserved and released together. Here, the blocking times include the formation time, the running time over the absolute braking distance and safety margin, the occupation time, possibly the extended occupation time, and the release time. For open line locations, the occupation time corresponds to the clearing time. The blocking times of these locations only reflect the blocking of the discrete locations themselves, rather than the section between two locations. The blocking times of the track between discrete locations can be approximated by interpolating the blocking times by the two neighbouring locations, as is illustrated by the black lines in Figure 2b.

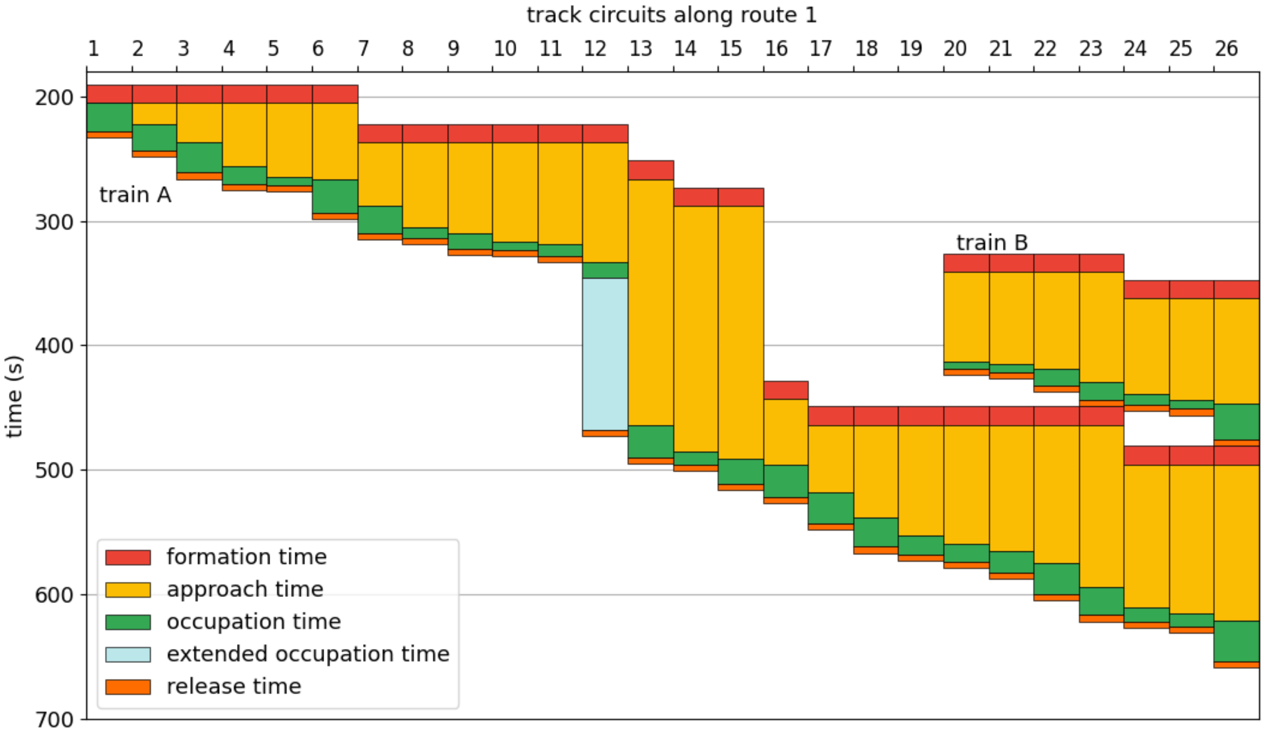

Figure 2a Blocking time diagram of fixed-block solution. Track circuit 20 contains the switch.

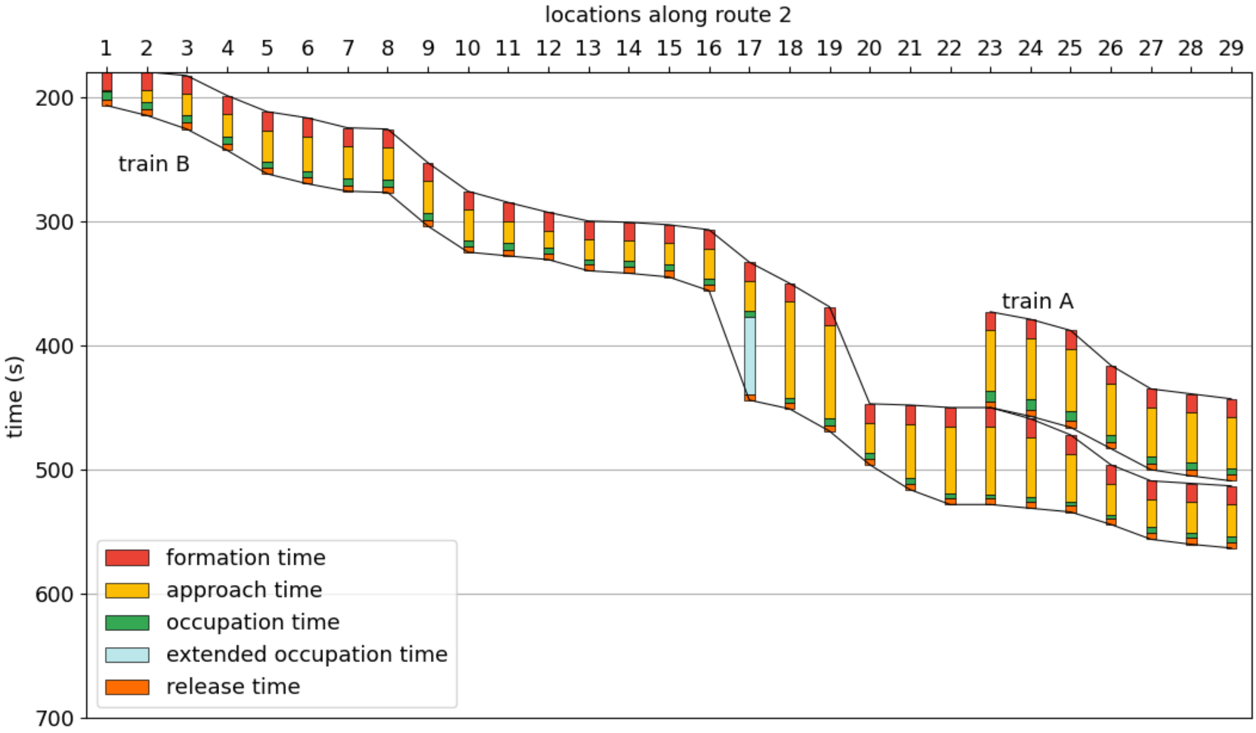

Figure 2b Blocking time diagram of moving-block solution. Locations 22 and 23 are switch locations.

Rescheduling Decisions and Delays

The main results of the RECIFE-MILP model are the rescheduling decisions that are taken in order to minimise the total train delay. For the considered scenario, in which no alternative train routes are included, it comes down to the (re)ordering of the two trains at the switch.
The entry delay suffered by train A leads to different reordering decisions in the fixed-block and the moving-block model. In the fixed-block model, it is decided to reorder the trains and let train B pass the switch before train A. In the moving-block model, no reordering is applied and train A passes the switch first, as scheduled.

The reordering decision is based on the evaluation of total train delay. We consider entry delay and exit delay as no scheduled stops are considered in the scenario. Table 2 reports these delays for the two trains in the optimal (in bold) and alternative solution for the fixed-block and the moving-block model. In addition, it shows the delay with which the trains reach the switch. Note that only positive delays contribute to the objective function.

As defined in the scenario, train A enters the infrastructure with a delay of 190 seconds, while train B enters on time. The fixed-block model assumes minimum running times, so both trains are modelled to run according to the maximum speed profile. With this model, train A accumulates additional delay in the infrastructure: its exit delay is higher than its entry delay. This is due to the reordering decision: train A reserves and passes the switch after train B has passed and released it. Hence, extended occupation time is included between the entry of the infrastructure and the entry of the block containing the switch (Figure 2a, track circuit 12). The extended occupation time is 65 seconds longer than the difference in scheduled and minimum times before the switch. So, the delay increases from 190 seconds at the entry to 255 seconds at the switch. From the switch on, train A follows train B at the minimum separation distance. With this, train A recovers 13 seconds, exiting the infrastructure with a delay of 242 seconds. The modelling of minimum running times results in train B running ahead of schedule, passing the switch and exiting the infrastructure ahead of scheduled (with a negative delay of -44 seconds and -57 seconds, respectively).

The alternative fixed-block solution does not consider the reordering of the trains. In that case, train A traverses the infrastructure spending the minimum running time in each track circuit, passing the switch with a delay of 141 seconds and exiting the infrastructure with 120 seconds. Hence, train A recovers 70 seconds of delay. Train B has to wait for train A to pass and release the switch, resulting in a 144 seconds later passing of the switch than scheduled and an exit delay of 132 seconds. Indeed, the decision to reorder the trains is beneficial to the total train delay considered in the objective function due to the difference in total exit delay: 242 seconds versus 252 seconds.

In the moving-block model, the decision to run according to a scheduled or a maximum speed profile is part of the solution. Train A is assigned a maximum speed profile on both open line stretches of its route, to reduce its delay as much as possible. Since the trains are not reordered, train A can freely run at maximum speed and recovers 70 seconds of delay, of which 49 seconds on the first open line stretch: train A passes the switch with a delay of 141 seconds and exits the infrastructure with a delay of 120 seconds. Train B is significantly affected by the delay of train A. On the first open line stretch, train B is set to run at scheduled speed with an extended occupation time of 62 seconds (Figure 2b, location 17): it has to wait for train A to pass the switch first. This results in a delay of 62 seconds at the switch. After the switch, train B follows train A using the maximum speed profile and respecting minimum separation distance. By doing so, it recovers 13 seconds of delay and exits the infrastructure with a delay of 49 seconds.

The alternative moving-block solution considers the reordering of the trains. In that case, train B traverses the infrastructure with minimum running times, passing the switch and exiting the infrastructure ahead of schedule (with a negative delay of -44 seconds and -57 seconds, respectively). Train A runs over the first open line stretch at scheduled speed due to the minimal gain in exit delay of 2 seconds in case of maximum speed. Hence, train A passes the switch with a delay of 190 seconds. After the switch, it recovers 13 seconds by following train B at the minimum distance, exiting the infrastructure with a delay of 177 seconds. Indeed, the decision not to reorder the trains leads to a lower value of the objective function, with a total exit delay of 169 seconds versus 177 seconds (175 seconds if train A is only assigned maximum speed profiles). For sake of brevity, we do not describe in detail the alternative solutions in which different speed profiles are assigned to the trains. They result in longer total delays anyway.

Table 2 Train delays in fixed-block and moving-block model. In bold the optimal solutions.

Fixed Block	Not Reordered		**Reordered**	
Delay (s)	Train A	Train B	Train A	Train B
At entry	190	0	**190**	**0**
At switch	141	144	**255**	**-44**
At exit	120	132	**242**	**-57**
Moving Block	**Not Reordered**		Reordered	
Delay (s)	Train A	Train B	Train A	Train B
At entry	**190**	**0**	190	0
At switch	**141**	**62**	190	-44
At exit	**120**	**49**	177	-57

Discussion

The presented results illustrate the features of the enhancement of the fixed-block model, and their possible influence on the rescheduling decisions. The decision whether to reorder the trains or not depends on the difference in blocking times. Indeed, the moving-block blocking times are shorter than the fixed-block blocking times due to the reduced approach and occupation time. The blocking times around the switch are particularly relevant. Actually, the difference in blocking times of the switch (77 and 78 seconds in the moving-block model and 173 and 123 seconds in the fixed-block model) is roughly the same as the difference in total exit delay.

The difference in blocking time of the switch is significant due to the long blocks containing the switch in the fixed-block model and the small switch area containing only the three switch boundary locations in the moving-block model, as illustrated in Figure 3. Additionally, the trains have better braking capabilities than the worst-case for which the block structure is defined. Together this leads to a significant difference in length of track which a train can only occupy if the switch is blocked for it.

Figure 3 indicates these *switch blocking areas* under fixed-block and under moving-block signalling. Under fixed-block signalling, it is the area between the entry of the reference block to the end of the block containing the switch. Under moving-block signalling, it is the area between the brake starting point (which depends on the speed) and the exit of the switch. The smaller such an area, the shorter the blocking times. So indeed, moving-block blocking times can be much shorter than the fixed-block blocking times, providing the opportunity to evaluate the ordering alternatives differently.

The inclusion of speed profile alternatives in the moving-block model allows to better approximate the actual capacity consumption of train movements. Besides a minimal difference in the clearing time, the main effect of the speed profile on the capacity consumption is due to the difference in approach time. As hinted at in Figure 2b, the approach time of a train running at scheduled speed is shorter than the approach time at maximum speed. Indeed, given the assumptions on the values of the terms of the train approach distance formula, a maximum speed higher than 10 m/s leads to a longer approach time for maximum speed than for scheduled speed. For example, if we consider a maximum speed of 40 m/s, then the approach distance is $\frac{{v^m}^2}{2b+R} + sm = \frac{40^2}{2 \cdot 0.8} + 50 = 1050$ m, and the time it takes to run over this distance, the approach time, equals $\frac{1050}{40} = 26.25$ s. For the scheduled speed, which is $0.8 \cdot 40 = 32$ m/s, the approach distance is $\frac{{v^s}^2}{2b+R} + sm = \frac{32^2}{2 \cdot 0.8} + 50 = 690$ m, and the approach time is $\frac{690}{32} = 21.5625$ s.

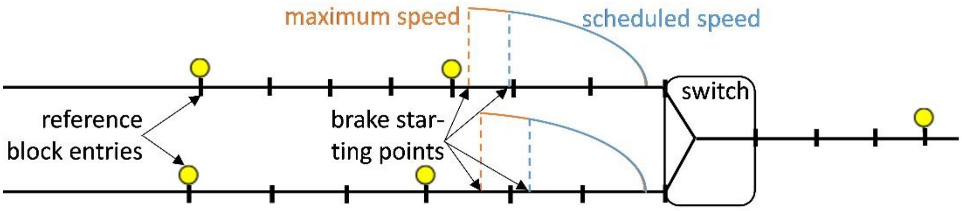

Figure 3 Switch blocking areas for fixed-block and moving-block signalling.

3.3 Model Validation

In this section, we present the computational experiments which are done to validate the presented moving-block rescheduling model.

3.3.1 Experimental Setup

The computation experiments are performed on two case studies. The first case study resembles the French junction of Gonesse, featuring an 18 km long junction area with intense mixed traffic. Figure 4a provides a schematic representation of its track layout. The daily timetable includes 336 trains, of which 116 high-speed, 129 conventional passenger trains and 19 freight trains, with 5 to 13 route alternatives per train.

The second case study resembles instead a portion of the Paris-Le Havres line in France, which is an 80 km-long corridor with intermediate stops and mixed traffic. Figure 4b shows a schematic representation of its track layout. The daily timetable includes 215 trains, of which 2 high-speed, 140 conventional passenger, 59 freight and 14 other trains, with 1 to 24 route alternatives.

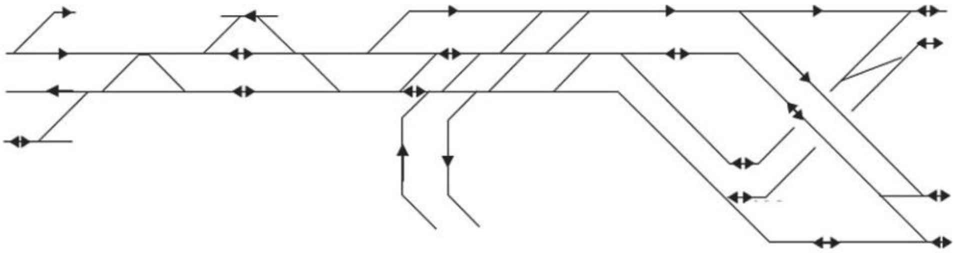

Figure 4a Schematic representation of track layout of considered junction area.

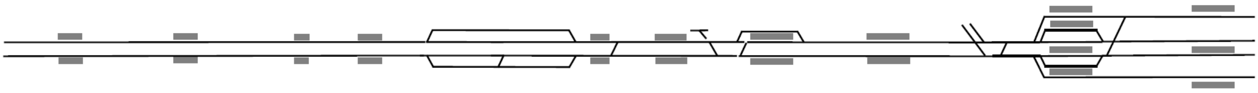

Figure 4b Schematic representation of track layout of considered long line.

For both case studies, 100 delay scenarios are considered. In each scenario, 20% of the trains have an entry delay of 5 to 15 minutes. The delay scenarios are applied to different cases; for each case study two one-hour instances (a pre-peak and a peak hour) are considered with two rescheduling strategies (with and without rerouting). An overview of the resulting eight cases is given in Table 3.

Table 3 Overview of experimental cases.

Case	Track Layout	Hour	Rescheduling Strategy
1	Junction	Pre-Peak	Without Rerouting
2	Junction	Pre-Peak	With Rerouting
3	Junction	Peak	Without Rerouting
4	Junction	Peak	With Rerouting
5	Line	Pre-Peak	Without Rerouting
6	Line	Pre-Peak	With Rerouting
7	Line	Peak	Without Rerouting
8	Line	Peak	With Rerouting

3.3.2 Experimental Analysis

Here, we present the results of the comparison between the moving-block and the fixed-block optimal solutions. First, we obtained the objective values of the fixed-block and the moving-block model. Cases 1 to 4 on the junction case study were solved optimally or close to optimally, with an optimality gap of at most 0.05%. Cases 5 to 8 on the open line case study were all solved optimally. Then, we obtained the objective values of the fixed-block solution in the moving-block model and vice versa.

We identified the scenarios for which both the moving-block solution performed better than the fixed-block solution in the moving-block model and the fixed-block solution outperformed the moving-block solution in the moving-block model as the scenarios with moving-block impact.

Per case, we obtained the relative gain in objective value of the moving-block solution over the fixed-block solution in the moving-block model, as well as the number of different ordering decisions and number of different routing decisions, if applicable, between the two solutions. Both the maximum and the mean value of the relative gain, different routing and different ordering decisions are provided. The maximum value is always obtained by a scenario with moving-block impact, while in the calculation of the mean value all the zero values of the scenarios without moving-block impact are included. In this way, the results can be compared at case-level.

Note that we performed the comparison based on the solutions provided by the model. These solutions are however in many, if not all, scenarios not unique. Hence, the results are indicative rather than accurate.

Table 4 presents for each of the cases the number of scheduled trains, the number of scenarios with a moving-block impact, the relative gain in objective value in the moving-block model and the different routing and ordering decisions between the moving-block and fixed-block solutions.

Table 4 Experimental results per case.

Case	# Trains	# Scenarios with MB Impact	Relative Gain in Objective (%)	# Different Routing Decisions	# Different Ordering Decisions
1	16	7	max: 3.63% mean: 0.09%	-	max: 2 mean: 0.08
2	16	45	max: 4.41% mean: 0.33%	max: 3 mean: 0.72	max: 1 mean: 0.01
3	30	44	max: 5.54% mean: 1.09%	-	max: 6 mean: 0.79
4	30	82	max: 17.5% mean: 1.01%	max: 10 mean: 2.94	max: 3 mean: 0.37
5	12	2	max: 1.45% mean: 0.00%	-	max: 1 mean: 0.02
6	12	21	max: 1.30% mean: 0.07%	max: 5 mean: 0.58	max: 1 mean: 0.03
7	17	20	max: 15.77% mean: 0.89%	-	max: 7 mean: 0.47
8	17	37	max: 1.63% mean: 0.12%	max: 6 mean: 1.45	max: 3 mean: 0.08

Preliminary Conclusions

- Moving block rescheduling strategies are found to reduce total delays in 44.5% of all the scenarios for the junction area without stops (cases 1 to 4), and in 20% of all the scenarios on the open line with stops (cases 5 to 8).
- When train rerouting is considered, moving block rescheduling strategies reduce total delays in 46.25% of all the analysed scenarios (cases 2, 4, 6 and 8), and in 18.25% of the scenarios when rerouting is instead excluded (cases 1, 3, 5 and 7).
- Moving block rescheduling strategies reduce total delays in 45.75% of the scenarios when considering the peak hour (cases 3, 4, 7 and 8), and in 18.75% of the scenarios in the off-peak hour (cases 1, 2, 5 and 6).
- The number of train reordering decisions taken by the moving block and the fixed-block strategies differs on average by 0.12 if rerouting is included (cases 2, 4, 6, and 8), and by 0.34 if rerouting is excluded (cases 1, 3, 5 and 7).
- The number of routing decisions taken by the MB and the FB strategies differs by 2.20 in the peak hour (cases 4 and 8), and 0.65 in the off-peak hour (cases 2 and 6).
- The max relative reduction in total delays achieved by MB strategies over the FB ones is 17.5%, obtained for the junction area in the peak hour, when rerouting is included (case 4).

4 Early-Warning Hazard Prediction Model

Preliminary frameworks for short-term and medium-term early-warning hazard prediction models have been previously introduced in Deliverable D4.1 (PERFORMINGRAIL, 2022, Section 5.4). In the document, the focus is on describing the functional process which those models will implement to identify MB hazardous traffic conditions. Although the models have been formally specified their actual implementation at a higher Technology Readiness Level (TRL) is out of the scopes of PERFORMINGRAIL.

4.1 Short-Term Hazard Prediction

The objective of the short-term hazard prediction model is to provide early-warnings based on the real-time violation of safe thresholds of moving-block signalling variables. An initial framework for short-term hazard prediction is presented in Section 5.4.1 of D4.2 (PERFORMINGRAIL, 2022). In the following, we illustrate the sequential steps for the initialisation of the model until the delivery of MB safety warning messages to the dispatcher:

1) The model is fed with static data about safety-critical thresholds for variables of MB onboard and track-side signalling components (e.g. RBC processing time, MA and TPR update times), as well as the rolling stock and latencies/errors of the GNSS and GSM-R signals. Critical thresholds of those design variables can be identified thanks to sensitivity analysis of formal MB signalling models or even Hardware-in-the-loop testing. In PERFORMINGRAIL a Stochastic Activity Networks (SAN) model of MB signalling has been applied to assess those safe threshold values. More details of that analysis are reported in Section 5.3 of PERFORMINGRAIL Deliverable D4.1 (2022).
2) The model is also initialised with dynamic data from the real (or simulated) railway field about current values of the variables indicated at point 1) for the MB signalling components, the GNSS, the GSM-R and the rolling stock. For example, as reported in PERFORMINGRAIL Deliverable D1.1 (2021) ETCS Level 3 MB has a mute timer to measure the time elapsed from the last received TPR message. The value of such timer should hence stay within the identified safe threshold values to enable safe MB operations.
3) Based on received dynamic information (which can be at regular time intervals on an event-driven basis) the short-term hazard prediction model compares real-time values of the considered system variables versus the static critical thresholds.
4) In case one or more variables are detected to exceed the corresponding safe thresholds the model records data about the system variables overshooting safety limits, the IDs of the trains involved and their current location.
5) A warning message is then issued to the dispatcher, containing information on cause of the safety warning as well as the train services and locations involved such that the dispatcher can intervene accordingly.
6) As a result of the short-term safety warning, the dispatcher can hence mitigate the predicted safety risks by e.g. stopping affected trains and/or not allowing other trains in the critical area.

Example. The short-term hazard prediction module detects that the mute-timer for a train has assumed a value of 10 s and violated the maximum tolerable threshold of 0.5 s. As in those 10 s train integrity and position of that train will be unknown, there are safety risks for other trains approaching that track location. Based on that information the dispatcher can hence intervene by either rerouting or even by imposing a stop to any train approaching the critical track location. That mitigation action can of course be implemented until a new TPR is received by the lost train which confirms its position and integrity status.

4.2 Medium-Term Hazard Prediction

The objective of the medium-term hazard prediction model is to provide early-warnings based on the predicted traffic state close to areas with limited GNSS and/or GSM-R visibility. An initial framework for medium-term hazard prediction is presented in Section 5.4.2 of PERFORMINGRAIL Deliverable D4.2 (2022). In the following the sequential steps are reported for the initialisation of the model until the delivery of MB safety warning messages to the dispatcher

1) The medium-term hazard prediction model is initialised with static geographical data about coverage availability of GNSS and GSM-R signals. Those maps are necessary to the model to have information about areas with limited/disturbed GNSS signals (due to e.g. multipath, limited visibility) and GSM-R communication (due to e.g. lack of bandwidth).
2) The model is also fed with dynamic data deriving from the conflict detection and resolution model regarding detected track conflicts within a given time horizon ahead.
3) When receiving information about detected track conflicts, the medium-term hazard prediction model cross-checks the conflict locations against the geographical GNSS and GSM-R coverage maps.
4) In case one or more conflict locations lie in areas with compromised availability of the GNSS or the GSM-R signals, the prediction module records the information about the corresponding conflicting train IDs, the conflict location and the criticality relative to the GNSS and/or GSM-R signal coverage.
5) When a safety hazard is detected a safety warning message is issued to the dispatcher of with information about IDs of involved trains, time and location of the conflict and the type of GNSS /GSM-R criticality. The dispatcher can receive such a warning message some time before the occurrence of the predicted conflict, depending on the length of the prediction horizon of the conflict detection and resolution model (e.g. 30 min to 1 hour before).
6) Based on the received information the dispatcher can timely decide on a suitable strategy to prevent the safety-critical conflict by e.g. assigning alternative routes or retiming the involved trains.

Example. In the railway network represented in Figure 5, a CDR model predicts at time 18:30 that a track conflict will occur at time 19:13:53 between trains A and B at around track location no. 7 (highlighted in the orange circle). Upon receiving this information, the medium-term hazard prediction model identifies that track location no.7 falls in an area with low GNSS visibility. As limited GNSS visibility might compromise the reliability of train location and integrity reports, track occupation conflicts in that area might potentially result in dangerous train movements. Hence, the hazard prediction model generates (about 45 minutes before the conflict occurs) a safety-warning, containing information on involved train IDs, location, time and causes of the GNSS criticality. The dispatcher intervenes to mitigate the predicted hazard by for instance retiming the trains: train B is asked to run with a lower target speed, while train A is instructed to skip the coasting phase in approach to a stop.

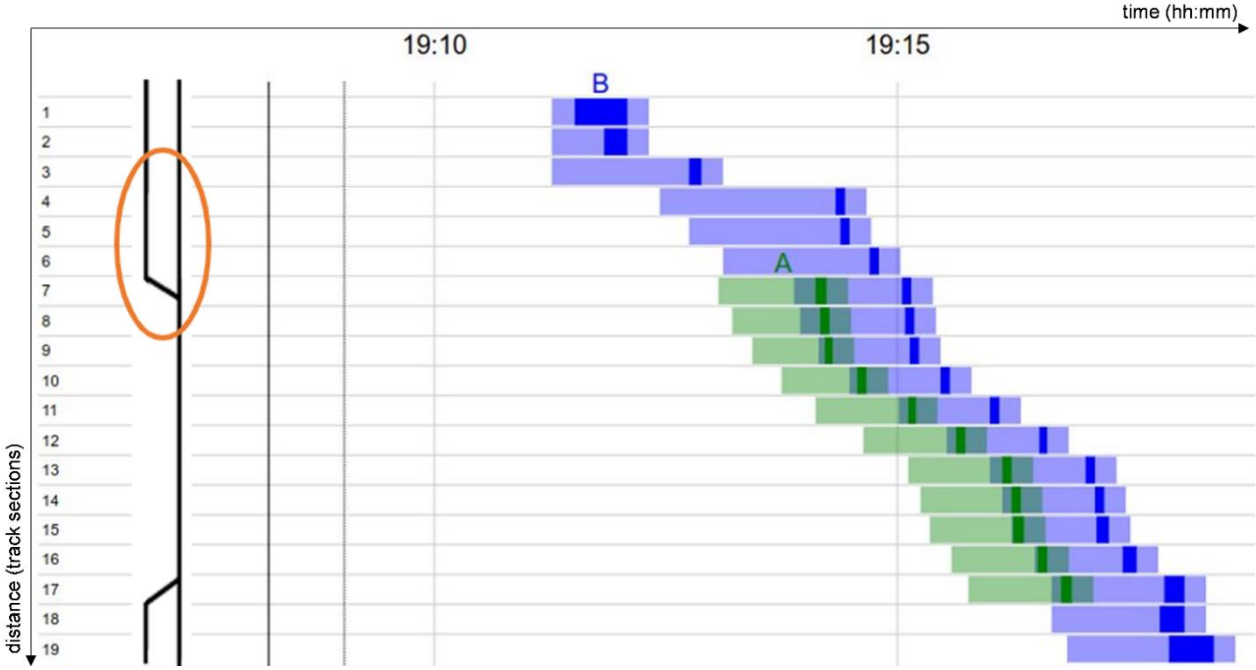

Figure 5 Overlapping blocking time diagrams on track with low GNSS visibility area.

5 Guidelines for Moving-Block Traffic Management System Architecture

In this section, we provide guidelines on the functional architecture for the moving-block traffic management system. Figure 6 illustrates the main functional modules and the set of mutual data interactions which are required by the TMS to enable safe and effective moving-block rail traffic operations. The reported architecture is limited to necessary functionalities for supporting operational/real-time traffic planning and prediction of potentially hazardous MB traffic conditions. Interfaces and interactions of those TMS functionalities with other external systems such as the interlocking, the ATO, and the tactical planning environment are instead out of the scope of this document.

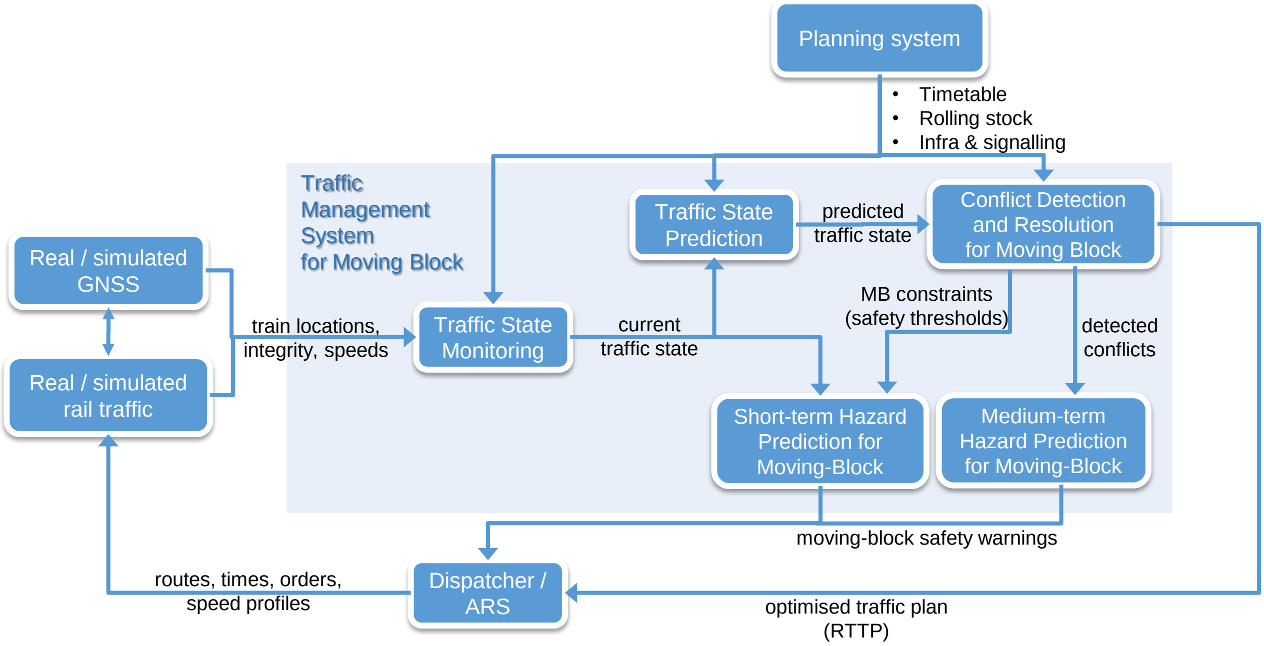

Figure 6 Functional TMS architecture for moving-block operations.

As can be seen the main core of the functional TMS architecture (light blue rectangle) is fed static information regarding the characteristics of the infrastructure, the signalling and the circulating rolling stock as well as the service timetable. That information is directly derived from the tactical "planning system" to ensure data consistency between the tactical planning environment and functional modules supporting real-time/operational planning such as the Traffic State Monitoring and Prediction as well as the Conflict Detection and Resolution. On the other hand, the TMS is also receiving real-time information from the real-life (or simulated) rail traffic field as well as the satellite-based GNSS train location and integrity system (or simulator). Traffic information about estimated train locations, speeds, accelerations are sent at regular time intervals (or an event-driven basis) to the Traffic State Monitoring module. This latter has the main functionality of collecting real-time field information and transfer it to other TMS modules based on their needs. Railway field information can be however not just limited to current traffic information but depending on the specific TMS architecture implementation, can also include the current status of crucial system variables which might affect MB safety. Those variables are for instance GNSS location errors, GSM-R latencies, extended RBC and/or EVC processing times and reduced train braking performances.

The Traffic State Prediction module receives current traffic information from the Traffic

State Monitoring to forecast time-distance profiles of the trains within a present time window ahead, called prediction horizon. Forecasted time-distance profiles are broadcasted to the Conflict Detection and Resolution (CDR) to detect potential track conflicts which might occur in the prediction horizon. If any conflict is detected a corresponding rescheduling strategy is automatically computed which solves or mitigates the conflict such that its impact on the service is minimised. Usually, conflict resolution is formulated as an optimisation problem where an optimisation algorithm attempts to identify a set of train orders, routes and arrival/departure times which minimise a pre-set objective function (e.g. total delay, max consecutive delays). The output of the CDR is hence a real-time traffic plan which contains the optimised set of rerouting, retiming and reordering actions computed by the conflict resolution algorithm. The real-time traffic plan is then sent to the dispatcher or the Automatic Route Setting (ARS) and implemented via instructions to trains and the interlocking in the real-life (simulated) railway field. Beside the real-time traffic plan, the dispatcher also receives warning about hazardous MB traffic conditions which might occur either in the short or the medium term. The short-term hazard prediction module can detect potential real-time violations of safety-critical values of moving-block system design variables relative for example to tolerated MA or TPR update times, GNSS location and integrity errors or train braking performances. To detect such violations the module is fed with real-time system information by the Traffic State Monitoring (or directly from the GNSS system and the track-side / on-board signalling equipment) and with static safety-critical thresholds of system design variable from the CDR module. The medium-term hazard prediction module is instead responsible for detecting hazardous MB traffic condition in a longer time horizon ahead. Specifically, the module triggers a warning message whenever the CDR detects a track conflict in an area of the railway network characterised by limited or disturbed availability of the GSM-R communication and/or the GNSS signal. To this end the module shall receive information about detected conflicts from the CDR as well as be setup with geographical data pertaining to the availability of the GNSS and the GSM-R signal coverage. If a hazard warning message is prompted by the short-term or the medium-term hazard prediction modules, the dispatcher (or the ARS) can accordingly instruct the interlocking or the potentially involved trains such that the hazardous MB traffic situation is avoided. That could for instance be done by reducing train speeds, asking them to stop or setting alternative routes which prevent the train to cross locations identified in the hazard warning messages.

In the following, each component is discussed in terms of required input, internal functionalities and provided output. Additionally, the implementation of the component is described in the context of the PERFORMINGRAIL project.

5.1 GNSS

Albeit Global Positioning Satellite Systems (GNSS) are the de-facto provider of navigation solutions for transportation and outdoor, its application in safety-of-life applications such as air and road navigation are still elusive. The officially defined minimum requirements of railway navigation applications for Positive Train Control (PTC) are 1 meter in 2D Root mean square with an availability of 99.9% (Specht et al., 2020). These requirements are among the strictest (as a reference, Air Transport CAT I type demands the same accuracy level with an availability of 99.99%).

Because of these requirements, navigation systems that depend only on GNSS cannot be used as there are multiple scenarios in a railway environment where GNSS is not available (underground, tunnel, …). Even if trains are equipped with high-grade GNSS receivers that are able to provide decimetric accuracy, these areas with limited visibility forces navigation solutions to integrate (hybridize) various systems. The most common approach is to use inertial navigation systems (INS) such as accelerometers and gyroscopes, that can provide position estimates in areas without GNSS visibility.

Despite this limitation, big efforts are being made to standardize the usage of GNSS in rail application. For instance, GNSS is applied in rails by means of the Virtual Balise concept, as proposed in projects such as Gate4Rail (2019) where the GNSS position of the train is reported to a central processing facility (the Radio Block Center or RBC) that makes the matching of this position against a database of track virtual points, stored in the facility database. The Virtual Balise is a concept inherited from the physical Balise concept.

A necessary step to apply GNSS positioning and assess its possible bottlenecks and failures in a railway environment, especially in train signalling systems, is a specification and execution of real or simulated tests. Albeit hardware simulators from manufacturers such as Spirent or Oriola already exist, there is no Software-in-the-loop (SIL) simulator for GNSS hazards. For this reason, such a GNSS SIL Simulator was developed in WP3 of Performing Rail as an alternative. This approach allows for a more flexible and customizable tool for GNSS simulation. In particular, the different inputs (Section 5.1.1) and functionalities (Section 5.1.2) detailed in the following sections can be exercised with the GNSS simulator repeatedly with a much shorter time duration than using an e.g., hardware simulator. Moreover, it allows to flexibly change the configuration parameters to extend the analysis and verify the impact in the outputs, also specified below, in Section 5.1.3.

This section includes the main guidelines and aspects that might be required for a proper simulation of GNSS hazards, that could be used as standalone tools or embedded in more complex systems such as the BRaSS signalling simulator tool (discussed later in this document).

5.1.1 Input

This section includes the necessary inputs that might be needed to set-up and define a simulation of a GNSS system (either hardware or software based, as done in PERFORMINGRAIL). Two types of inputs have been defined:

1. **Static**: set of configuration options that do not vary during the execution of the simulation
   a. *Hazards* to simulate, which includes typology and places/epochs of occurrence. This includes satellite visibility limitation (configured by defining blocked directions as well as applicable geographical areas), multipath areas (whose configuration depend on parameters to define multipath as well as applicable geographical areas), signal degradation due to interference (whose configuration depend on parameters to define multipath as well as applicable geographical areas)
   b. Error due to ionosphere
   c. *Error due to ephemeris*: GNSS satellite orbits and clocks
   d. *Processing strategy*: different approaches could be used to estimate the position of the train such as single-frequency code only, multi-frequency, code and phase, differential (Real Time Kinematic, if nearby reference stations are available), Precise Point Position (if corrections are available).

   e. *Elevation mask* (minimum elevation used to discard satellites, usually 10 to 15 degrees)
   f. *Data weighting scheme* (usually based on the Signal to Noise Ratio or SNR)
2. **Dynamic:**
   a. *Train location* (i.e., position, “ground truth”), which will trigger the GNSS signal model (i.e., measurement engine) to generate the GNSS raw measurements that will be later used in the positioning engine to compute the filter as given by a GNSS receiver (containing all simulated characteristics and hazards defined in the static settings).
   b. *GNSS broadcast ephemeris* (orbits and clocks) which are typically provided along with the GNSS measurements but in PERFORMINGRAIL they are provided to the simulator by means of navigation files in RINEX format (International GNSS service, 2020).

5.1.2 Functionalities

The main functionality of the GNSS system simulation consists of assessing:

1. The **estimated train location** on different scenarios, in order to assess the impact that the different hazards can have into the train positioning
2. The **formal error** of the estimated locations on different scenarios. This formal error is critical in order to establish potential warnings (i.e., presence of GNSS hazards) as well as establishing potential protection levels in integrity monitoring systems.

At a minimum, the following scenarios should be simulated:

1. **Nominal** scenario: with no hazards. This represents the standalone GNSS system, which uses broadcast ephemeris (orbits and clocks) as well as broadcast ionospheric model
2. **Limited visibility** scenario: mimics narrow canyons where low elevation satellites are typically unavailable
3. **Multipath** scenario: where an increased level of noise in the GNSS raw measurements due to nearby buildings or urban canyons is expected
4. **Signal degradation** due to e.g., adverse environment such as vegetation and canopy. This scenario is particularly critical when using GNSS phase measurements due to the increased number of cycle slips.

Note that most of the hazards to be simulated (e.g., limited GNSS coverage or availability) do not depend on the train itself but they are mostly depending on the surrounding: topology, geography and conformation of the ground or by the presence of barriers such as tunnels or canyons.

5.1.3 Output

The output expected for the GNSS system simulation should contain, at a minimum:

1. **Estimated train location** (i.e., geographical coordinates), delivered at the same rate as the location being fed into the simulator.

2. **Formal error** of the estimated location. Note that the actual error (not available in operations) can be obtained by subtracting the train location reported by the simulator from the location that has been fed into the simulator (i.e., “ground truth”). This actual error could be compared to the formal error to refine the computation of the formal error. It is expected that the formal errors increase in areas that contain specific hazard events (multipath, limited visibility, ...)

5.1.4 Implementation in PERFORMINGRAIL

As stated before, In PERFORMINGRAIL, the GNSS system simulator component is represented by the GNSS simulator of ROKUBUN. Currently, the GNSS simulation segment is dominated by hardware simulators (Spirent, Orolia), but the main drawback of these devices is that the configuration has to be made mostly manually (difficult to automate) and the tests need to be done in real time. For this reason, a Software-in-the-Loop (SIL) simulation strategy is required in Performing Rail in order to efficiently simulate all the possible configuration combinations of inputs and functionalities stated before. As far as the author’s knowledge, there is no software solution that allows performing such simulation and hence the GNSS simulator developed in WP3 has been used. This simulator supports the inputs and functionalities described above and, being software based, it allows batch processing (I.e., automatic configuration and trigger simulation sessions) as well as executing the simulations in shorter time frames (compared to hardware solutions). Moreover, the GNSS simulator can be run in a virtualized environment so that it can be combined with external components that launch simulation sessions and consume the output of the simulation (such as e.g., University of Birmingham’s BRaSS simulator)

Rokubun GNSS simulator is in fact a combination of two modules:

1. The measurement engine (argos), that computes synthetic GNSS raw measurements (pseudorange, phase, Doppler) using a given input location as well as the static configuration options stated above
2. The positioning engine (rift), which computes the train location using GNSS raw measurements as well as ancillary data (i.e., broadcast ephemeris with orbits and clocks)

The interrelation of these two modules with external simulator is shown later in Figure 7. BRaSS feeds the position to simulate and argos generate a set of GNSS measurements based on a configuration (provided at the start of the simulation via e.g., a file in INI format). These GNSS raw measurements are fed to the positioning engine that estimates a position based on a configuration (also passed to the engine through a file in INI format). The configuration files establish the static configuration parameters mentioned above. More details on the architecture of the GNSS simulator can be found in the deliverable D3.1 (PERFORMINGRAIL, 2021b).

5.2 Real-Life / Simulated Railway Traffic

5.2.1 Input

The input for the real-life or simulated railway traffic module consists of static and dynamic data, as follows:

- **Static:**

  - *Infrastructure*: detailed data for the track layout with lengths, gradients and positions for switches, speed limits, station locations.
  - *Signalling system*, e.g., block sections, signal positions (for fixed-block systems), safety margins, track vacancy detection sections on movable infrastructure elements (for moving block).
  - *Rolling stock*: vehicle type and specifications, e.g., acceleration and braking characteristics
  - *Timetable*: scheduled trains, defined origins and destinations as well as routes, set departure and arrival times at stations, scheduled stops and routes within stations
  - *Interlocking*: route setting rules ensuring safe train movements at junction and stations.
- **Dynamic:**
  - *Updated real-time traffic plans*
  - *Entry and Initial delays:* a set of delays for trains entering the network or stopping at stations to represent disturbed traffic operations.

5.2.2 Functionalities

The railway traffic module is a system built on a single, integrated, and consistent collection of operational data, enabling high levels of rail operations. The main functionality of the railway traffic module consists of supporting railway operations processes and procedures, as well as representing and executing the real-life or simulating rail traffic components, such as infrastructure, signalling, control systems, operational timetable, rolling stocks. Simulation models can describe train time-distance profiles by integrating the Newton's motion formula over time. Based on the movement of trains the signalling system can be modelled as an event-driven system providing safe Movement Authorities or signal aspect sequences (in case of multi-aspect fixed-block signalling) when a train occupies a given track portion. The interaction between the signalling and interlocking models will then ensure that safe routes are set for trains when their simulated position approaches interlocking areas such as stations and junctions.

In case of nominal traffic operations, set routes and train entry/release times at stations and/or track sections follow the time scheduled in the original timetable. In case of delayed traffic conditions, the real/simulated traffic environment shall be able to receive an implement an updated real-time traffic plan (computed by a dispatcher or an automatic Conflict Detection and Resolution tool) by accordingly changing planned train routes, platform/track entry and release times as well as train running times and passing orders at junctions.

5.2.3 Output

The real-life or simulated railway traffic module provides as output the following data:

- Current train positions, speed, accelerations
- Current status of train integrity and GSM-R communication signal
- Train delays at stations and other timetabling points
- Track occupation/release times
- Time-distance and speed-distance train profiles
- Consumed power/energy diagrams over time per train.

5.2.4 Implementation in PERFORMINGRAIL

In the context of PERFORMINGRAIL project, the railway traffic is simulated by BRaSS. BRaSS

(Birmingham Railway Simulation Suite) is an application written in Java that has been developed for more than seven years by the Birmingham Railway Research and Education Centre at the University of Birmingham. BRaSS allows the simulation of different railway systems, such as mainline railways, high speed railways, metros etc, at a microscopic level. Within the simulator, users can select various parameters, such as vehicle type and specification, railway infrastructure, signalling systems, control systems components and timetables and specified a different elements of train control systems, including onboard, radio block centre, and infrastructure components.

For the PERFORMINGRAIL project, additional configurations were implemented on BRaSS to represent the RBC and allow the user to simulate hazardous scenarios such as loss of communication and integrity. Moreover, a special events file, that highlights the existence of tunnels, bridges, forests, etc. were included to allow the simulation of the GNSS hazards scenarios mentioned in Section 5.1.2.

5.3 Traffic State Monitoring

5.3.1 Input

The input for the traffic state monitoring module consists of static and dynamic data:

- **Static:**
  - *Infrastructure***:** track layout including switches and stations, running directions, track gradients, track curves, maximum track speed, temporary speed limits, temporary track unavailability, setup times, reaction times, running times, clearing times, release times
  - *Rolling stock*: (compositions of) vehicle types, maximum train speeds, train braking rates, tractive effort-speed diagrams
  - *Timetable:* scheduled entrance and exit times, arrival and departure times at scheduled stops, scheduled and alternative routes, scheduled speed profiles
  - *Signalling system***:**
    1. Signal positions, signal aspects, block sections, track detection sections for fixed-block systems
    2. Special safety margins, track sections on movable track elements for MB.
- **Dynamic:**
  - *Current traffic state*: train positions and speeds
  - *Previously implemented real-time traffic plan.*

The dynamic traffic data originate from the real-life or simulated railway traffic module, in combination with the GNSS module. Note that this data is provided at discrete time intervals due to the system commination times. For example, the location of a train is received through GNSS and issued in a TPR to the RBC, so it depends on the TPR update period which include the GNSS update rate and the communication time from train to the RBC. Due to this discreteness, real-time data consists of the information of a short period, e.g., of the last five seconds (Quaglietta et al., 2016).

5.3.2 Functionalities

The main functionality of the traffic state monitoring module is to translate the available real-time data into a format fitted for the traffic state prediction module. This involves two steps:

- The train locations, typically expressed in coordinates, are mapped onto the infrastructure.
- The train locations and corresponding train speeds at a specific time are estimated based on the discrete data, possibly supported by trackside train detection and/or the computation of speed profiles.

5.3.3 Output

The traffic state monitoring provides as output the current traffic state, in terms of train positions, speeds and accelerations.

5.3.4 Implementation in PERFORMINGRAIL

In the context of the PERFORMINGRAIL project, the data originates from the simulated railway traffic module BRaSS in combination with the GNSS simulation module, according to the functional architecture described in detail in Deliverable D3.1 (PERFORMINGRAIL, 2021) and reported for convenience of the reader in Figure 7.

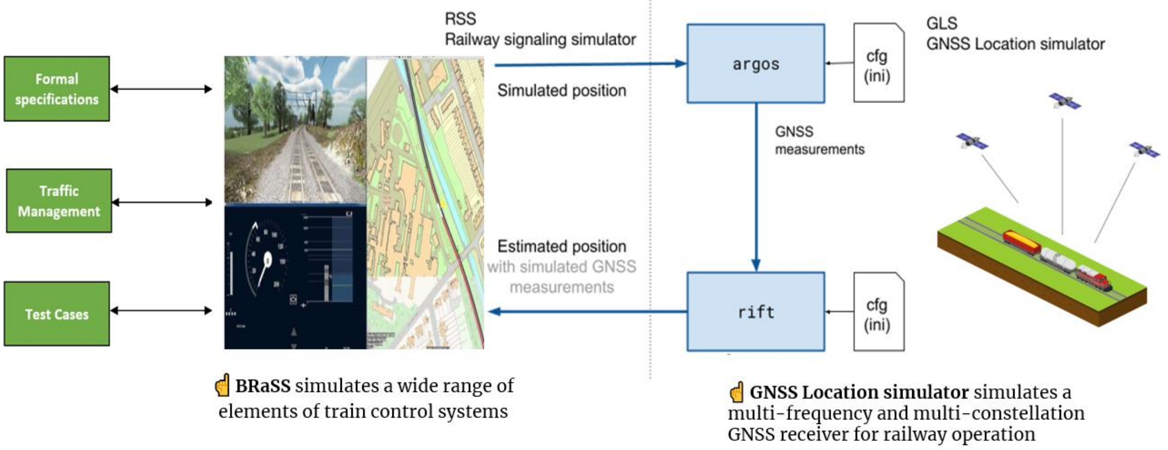

Figure 7 Interaction between railway traffic simulator BRaSS and GNSS location simulator.

At discrete time steps, train speeds and positions are computed based on time-integration of the Newton's motion equations and the status of the signalling and interlocking systems are accordingly updated. The simulated train position from BraSS is sent to the two GNSS simulator submodules "argos" and "rift" which add location errors to return an estimated GNSS-based train location and integrity information back to the rail traffic simulation environment. Such GNSS-based train location and integrity estimation is used to compute estimated train speed and accelerations, which realistically account for GNSS measurement errors. Those estimate values of train positions, speeds and accelerations are then stored in the BraSS backend database which acts as traffic state monitoring. That estimated traffic state information can then be sent to the short-term hazard prediction and the CDR modules either at regular time intervals or on an event-driven basis. In the specific PERFORMINGRAIL implementation, beside traffic information the traffic state monitoring can also transfer information from the BraSS simulator to the short-term hazard prediction module. Specifically, that extra information refers to current status of the GNSS signal, the GSM-R communication, MA and TPR update times as well as RBC and EVC processing times.

5.4 Traffic State Prediction

5.4.1 Input

The traffic state prediction requires three types of input: static data, on infrastructure, rolling stock and timetable, dynamic data and modelling parameters (Quaglietta et al., 2016).

- **Static:**
  - *Infrastructure***:** track layout including switches and stations, running directions, track gradients, track curves, maximum track speed, temporary speed limits, temporary track unavailability, setup times, reaction times, running times, clearing times, release times.
  - *Rolling stock*: (compositions of) vehicle types, maximum train speeds, train braking rates, tractive effort-speed diagrams.
  - *Timetable:* scheduled entrance and exit times, arrival and departure times at scheduled stops, scheduled and alternative routes, scheduled speed profiles.
  - *Signalling system***:**
    iii. Signal positions, signal aspects, block sections, track detection sections for fixed-block systems,
    iv. Special safety margins, track sections on movable track elements for MB.
- **Dynamic:**
  - *Current traffic state*: train positions and speeds.
  - *Previously implemented real-time traffic plan*
- **Traffic prediction model parameters:** prediction interval (in case the traffic prediction is performed at regular time intervals), prediction horizon.

The modelling parameters prediction interval and prediction horizon indicate when and for which period the traffic state prediction is performed. For example, every 5 minutes the traffic state for the next hour is predicted. The values of the modelling parameters are predetermined based on the network size, the traffic density and the type of perturbation (Quaglietta et al, 2016).

5.4.2 Functionalities

The main functionality of the traffic state prediction module is to forecast the traffic state during the prediction horizon. A simple approach could be simply starting from the current traffic state and projecting it in the prediction horizon window by means of the planned headways and running times. This means that predicted departure and arrival times of the trains within the prediction horizon are simply computed by linearly shifting those originally planned by the amount of delay / deviation affecting the current traffic state. A more advanced approach is to translate current train locations and speeds into time-distance and speed-distance train trajectories based on Newton’s equation of motion (Quaglietta et al., 2016).

5.4.3 Output

The output of the traffic state prediction module is twofold:

1) Time-distance trajectories for each train within the prediction horizon
2) Speed-distance trajectories for each train within the prediction horizon.

5.4.4 Implementation in PERFORMINGRAIL

In PERFORMINGRAIL, no separate traffic state prediction module is implemented, as this is an integral part of the RECIFE_MILP conflict detection functionality for moving-block (described in Section 3).

RECIFE-MILP predicts future traffic states by a linear projection of the scheduled train running times; scheduled arrival, departure and passing times are shifted in time by the monitored train delays provided by the current traffic state information.

5.5 Conflict Detection and Resolution (CDR)

5.5.1 Input

For an accurate representation of railway operations, Conflict Detection and Resolution (CDR) models require essential input information from the Planning system about the timetable the rolling stock features as well as the infrastructure layout and the signalling (Quaglietta et al., 2016). It is relevant for the CDR also to receive information about safe signalling design parameters regarding maximum tolerable GNSS update times, or GSM-R communication latencies. Those design parameters are indeed required to feed the variables of the blocking time model which is at the basis of the CDR algorithm (see Section 5.3.2 in PERFORMINGRAIL Deliverable D4.1, 2022). Also, maximum tolerable thresholds should be provided for critical signalling design parameters including GNSS and GSM-R latencies and errors as that are necessary to constrain rescheduled train operations within safe a MB configuration. Those tolerable thresholds can derive for instance from a formal sensitivity analysis on signalling system functions as reported in PERFORMINGRAIL Deliverable D4.1 (PERFORMINGRAIL, 2022).

Additional dynamic information is also required to be received from the Traffic State Prediction module about predicted train delays and time-distance profiles within a pre-set time window ahead (so-called prediction horizon). Predicted delays may refer to the nominal timetable or to the previously implemented real-time traffic plan computed by the CDR module itself. Main input data for a conflict detection and resolution module are hence:

- **Static:**
  - *Infrastructure***:** track layout including switches and stations, running directions, track gradients, track curves, maximum track speed, temporary speed limits, temporary track unavailability, setup times, reaction times, running times, clearing times, release times.
  - *Rolling stock*: (compositions of) vehicle types, maximum train speeds, train braking rates
  - *Timetable:* scheduled entrance and exit times, arrival and departure times at scheduled stops, scheduled and alternative routes, scheduled speed profiles.
  - *Signalling system***:**
    v. Signal positions, signal aspects, block sections, track detection sections for fixed-block systems,
    vi. Special safety margins, track sections on movable track elements for MB.
    vii. Signalling design parameters and safe thresholds for braking rates (e.g. ETCS braking curves), GSM-R communication time, latencies and errors, and GNSS updating times and errors.
  - *CDR algorithm parameters***:** scheduling time period, objective function, maximum computation time threshold, constraint values.

- **Dynamic:**
  - *Predicted train Delays and time-distance profiles* from the Traffic State Prediction module.
  - *Previously implemented real-time traffic plan* which might be stored/archived in the CDR module itself or sent by the traffic state prediction module.

5.5.2 Functionalities

The conflict detection and resolution module have two main functionalities: conflict detection and resolution. For both submodules, the computation time is crucial as they are envisaged to be applicable in a real-time environment. Specifically, the main tasks performed by those submodules are reported as follows:

- **Conflict detection:**
  - The blocking times of all trains on all locations within the time period are computed given predicted time-distance profiles sent by the traffic state prediction module.
  - Conflicts are detected based on overlapping blocking times.
  - For each detected conflict, the location, the time, and the IDs of involved conflicting trains are listed.
- **Conflict resolution:**
  - The conflict resolution model is initialised based on the real-time input data.
  - The optimisation model considers retiming, reordering and/or (local) rerouting possibilities in finding a real-time traffic plan based which is optimised for a chosen objective function.
  - The optimised real-time traffic plan identified by the model within a given computation time threshold are stored in a data archive.

5.5.3 Output

The output of the conflict detection and resolution module has different levels of details and different perspectives.

- **Conflict detection:**
  - A list of detected conflicts within time period with the location and time of the conflict, as well as the ID of the trains involved in the conflict.
  - A visualisation of the detected conflicts, e.g., time-distance profiles and corresponding blocking time stairways.
- **Conflict resolution:**
  - The rescheduling decision taken: an overview of the trains affected, whether retimed, reordered and/or rerouted.
  - Value of the objective function for the identified rescheduling solution, e.g. value of the total delay, maximum consecutive delay.
  - Real-time traffic plan: Updated train arrivals/departure/passing times and routes corresponding to the optimised rescheduling solution.

5.5.4 Implementation in PERFORMINGRAIL

Within the PERFORMINGRAIL project, the conflict detection and resolution module rely on the extended moving-block formulation of the RECIFE-MILP rescheduling algorithm, described in Section 3.

Input data required to initialise the RECIFE-MILP algorithms need to be contained in a proprietary xml files, respectively specifying details of the infrastructure, rolling stock, the timetable and current traffic information (i.e. train delays, speeds and positions). Specifically, the information necessary to setup the model is:

- **Infrastructure:** locations of track sections and length, running direction(s), maximum track speed, gradient and curve, speed limits, routes.
- **Signalling:** block sections and signal positions (in case of fixed-block signalling), safety margins, discretised track intervals and track sections over moving infrastructure elements (in case of Moving Block), route reservation and clearance parameters such as setup and reaction time, release times, clearing times.
- **Rolling stock:** vehicle types with length, rotation mass factor, mass, tractive effort, rolling stock with composition of vehicle types, braking rates, resistance factors
- **Timetable:** trains with type, e.g., freight or high-speed, default routes, alternative routes, scheduled running times, scheduled stops with scheduled arrival and departure times.
- **Traffic information:** current train positions, speeds and delays.
- **Optimisation model parameters:** start and end time of the conflict detection and resolution horizon, maximum computation time threshold to find an optimised solution, Objective function (total train delay, maximum train delay, number of delayed trains)

When rescheduling traffic under MB, the input signalling information include the times necessary to update the Train Position Report (TPR), or the Movement Authority (MA) as those times influence the reservation and clearance of a route. For instance the TPR update time coincides with the release time while the MA update time represents the setup time. Also, signalling constraints in RECIFE-MILP include maximum safe thresholds for those variables as well as other related parameters like RBC update and processing times which are functional to identify potentially hazardous MB traffic situations in the short-term. Those safety critical-thresholds are indeed sent to the Short-term early-warning MB hazard prediction module to detect real-time violation of safety-critical MB signalling constraints. As already illustrated in Section 5.3 of PERFORMINGRAIL Deliverable D4.1 (2022) those safety-critical thresholds of MB signalling parameters derive from a dedicated sensitivity analysis performed by a Stochastic Activity Network of MB signalling.

RECIFE-MILP detects conflicts by computing blocking time stairways corresponding to planned time-distance train profiles. Those planned train profiles refer to the service plan currently in operation in the real/simulated railway network and can hence be provided by the original timetable or by a real-time traffic plan implemented to manage previously occurred disturbances. RECIFE-MILP identifies a conflict whenever blocking time stairways of two (or more) trains overlap. Figure 8 shows an example output of RECIFE-MILP track conflict detection. The blocking times of the two trains (respectively represented with a blue and green colours) are overlapping at the start of the shared route. Together with blocking time stairway representation RECIFE-MILP also visualises the initial delay of trains which are depicted by a yellow blocking time indicating a delayed occupation of the track with respect to the current plan. The output of the conflict detection function in RECIFE-MILP can hence provide information on location of detected conflicts as well as the IDs of the involved conflicting trains.

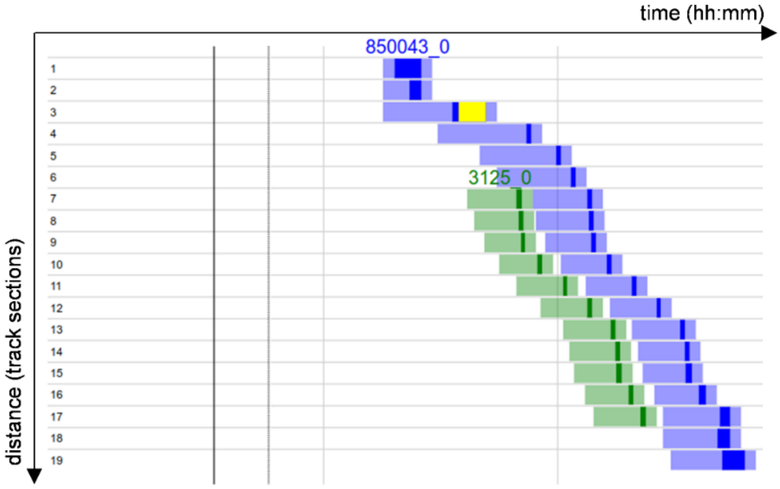

Figure 8 Output after conflict detection.

Whenever a track conflict is detected, the RECIFE-MILP conflict resolution function is activated to solve the identified conflict by reordering, retiming and/or rerouting trains such that the impact on service is minimised. The outputs of the optimisation part of the conflict resolution model are:

- Real-time traffic plan: updated traffic plan with arrival and departure times, train orders and train routes based on the optimised rescheduling strategies identified by the algorithm.
- Value of the objective function corresponding to the optimised real-time traffic plan, together with the corresponding optimality gap, the computation time, the total delays per train and the list of rerouted trains.
- Route table: list of train occupation events over time and corresponding blocking time stairways for the optimised real-time traffic plan.

5.6 Short-Term MB Hazard Prediction

5.6.1 Input

The input data for the short-term MB hazard prediction module consists of both static and dynamic information about design variables of the GNSS and GSM-R signals, the MB signalling systems and the rolling stock. Specifically, the required set of information is provided as follows:

- **Static:**
  - *Safety-critical threshold values of GNSS signal*: max tolerated GNSS latency, max tolerated position errors (as reported in Section 5.1.3).
  - *Safety-critical threshold values of GSM-R:* latency and errors affecting critical train to track-side communication, namely: Max tolerated MA update time, Max tolerated TPR update times
  - *Safety-critical MB signalling variables*: Max safe EVC processing time, Max RBC processing times, min End of Authority safety margin.

  - *Safety-critical rolling stock characteristics*: max and min braking rates, max tolerated train driving reaction times
- **Dynamic:**
  - *Current status GNSS signal*: current GNSS latency and measurement errors (as reported in Section 5.1.3).
  - *Current status of GSM-R communication between train and track-side:* current MA update time, current TPR update times
  - *Current MB signalling variables*: current EVC processing time, RBC processing times, supervised EoA safety margin.
  - *Current rolling stock characteristics*: applied braking rates, current train driving reaction times

The static safety-critical thresholds of GNSS, GSM-R, rolling stock and MB signalling variables are received from the CDR module, which incorporates those safe thresholds in the signalling and operational constraints. The dynamic information about the current status of those systems should come instead from timers and monitoring devices onboard of the train (for instance for measuring the train reaction times, the EVC processing time and the TPR update time) as well as on the track-side (for the RBC processing time, the GNSS position errors). Different timers are defined for ETCS L3 Moving Block specifications, see also Deliverable D1.1 (PERFORMINGRAIL, 2021a). An example is the 'mute timer' that measures the time passed since the last train position report.

5.6.2 Functionalities

The main functionality of the short-term hazard prediction module is to identify potentially hazardous MB traffic conditions due to the real-time violation of safety-critical design variables pertaining to the GNSS signal, the GSM-R communication, the MB signalling and the rolling stock. The short-term hazard prediction model detects such violation by simply comparing the current status of those systems received from corresponding monitoring devices versus the safe thresholds provided by the CDR module. In case of detected threshold violations, a warning message is generated to inform the dispatcher about potential hazardous MB traffic conditions in the short-term such that suitable mitigation actions can be timely implemented (for instance imposing the speed reduction or even the stop of a train when it violated some conditions).

5.6.3 Output

The main output of the short-term hazard prediction module is a warning message for the dispatcher containing details about the type of design variables which are detected to violate safety-critical thresholds and the ID of the involved train services.

5.6.4 Implementation in PERFORMINGRAIL

A full software implementation of the short-term hazard prediction model is out of the scopes of PERFORMINGRAIL, as only a mathematical and functional specification of the module was originally planned in the project. However, a functional verification of the module could be performed in later research by means of a software script interfaced with the RECIFE-MILP tool to receive static information about safety-critical thresholds of the GNSS signal, the GSM-R communication, the MB signalling and the rolling stock. The short-term hazard prediction module is also fed with dynamic information from the Traffic State Monitoring, represented in this case by the BraSS simulation database. As mentioned, such information refers to estimation of current train positions, accelerations/decelerations and reaction times, GNSS location errors, current MA and TPR updated times, as well as RBC and EVC processing times. An illustrative example of the functional procedures and the practical utilisation of the outputs from this module is provided in Section 4.1.

5.7 Medium-Term MB Hazard Prediction

5.7.1 Input

The input data for the medium-term hazard prediction module consists of static data on system level and the dynamic information deriving from the CDR module.

- **Static:**
  - Geographical locations/areas of the railway network affected by limited/disturbed GNSS signal availability due to e.g. limited visibility, multipath, signal degradation, spoofing and/or interference
  - Geographical locations/areas of the railway network affected by limited/disturbed GSM-R availability due to e.g. interference, lack of bandwidth.
- **Dynamic:** Times and locations of detected track conflicts (within a prediction horizon) and IDs of conflicting train services.

5.7.2 Functionalities

The main functionality of the medium-term hazard prediction module is to identify whether track conflicts detected by the CDR module fall in locations/areas of the railway network which are characterised by a compromised availability of the GNSS signal and/or the GSM-R communication. If a track occupation conflict is predicted to occur in areas with compromised GNSS or GSM-R availability, unsafe MB train movements can arise with larger likelihood due to probable faults in broadcasting vital signalling information (e.g. TPR or MA messages).

The medium-term early warning hazard prediction module is initialised with static information about geographical data of the GNSS and the GSM-R signal coverage. Such an information can derive directly from the system providers or even from the “planning system” in case that information is available to asset management or capacity planning departments of the rail infrastructure managers. The main function of the module is to match the track conflict location identified by the CDR with the geographical map of the GNSS and GSM-R signal coverage. In case the track conflict is detected to occur in an area with compromised radio or satellite signal availability then a warning message is prompt with the information about the IDs of the conflicting trains, the critical track locations and the type of criticality (e.g. reduce GNSS visibility, lack of GSMR- bandwidth).

5.7.3 Output

The output data of the medium-term hazard prediction module are MB safety hazard warning messages which include:

- **Detected track conflict:** with details about track locations, estimated times of occurrence, and IDs of the train services involved

- **Type of associated criticality:** Cause for the compromised GNSS or GSM-R signal availability (e.g. GNSS multipath, limited visibility, GSM-R interferences) in the area where the conflict has been detected.

5.7.4 Implementation in PERFORMINGRAIL

A software implementation of the medium-term hazard prediction model goes out of the scopes of PERFORMINGRAIL as only a mathematical and functional specification of the module was originally planned in the project. A preliminary functional verification of such a module can be performed in later research in the form of a software script interfaced with the RECIFE-MILP tool to receive information about detected track conflicts. In an initial version the module could be simply initialised by static information about areas of a specific railway case study with known GNSS or GSM-R availability issues. That will greatly reduce the complexity in mapping the identified track conflict location against a GNSS or GSM-R geographical coverage map, thereby increasing reliability of the model verification. When the module identifies that a track conflict falls in an area with a compromised GNSS or GSM-R signal coverage a message is generated containing the IDs of the involved train services, the location of the conflict and the type of criticality related to the GNSS or GSM-R availability. An illustrative example of the functional procedures and the practical utilisation of the outputs from this module is provided in Section 4.2.

5.8 Dispatcher / Automatic Route Setting (ARS)

5.8.1 Input

The dispatcher (or the Automatic Route Setting) receives information from different types of data from different sources:

- **Static:** data on infrastructure, rolling stock, timetable, and the signalling system
- **Dynamic:**
  - *Current traffic information*: train speeds and positions
  - *Moving-block safety hazard warning messages*: warnings concerning the short-term and medium-term, including specifications on reason, location and involved train(s)

    MB safety warnings from short-term and medium-term hazard prediction modules
  - *Updated real-time traffic plan*: optimised traffic plan including train arrival, departure and passing times.

5.8.2 Functionalities

The main role of the dispatcher is to interpret the real-time traffic plans proposed by the conflict detection resolution module and implement them in the real (simulated) railway field by accordingly instructing trains and/or the interlocking system. The dispatchers could be given for instance a set of different suboptimal plans among which they could choose based on their own knowledge and perception of the current traffic situation. In such a case the expertise and critical thinking skills of the human dispatcher might still significantly influence traffic management decisions despite the presence of an automated CDR module mainly acting as a decision support tool. Different is instead the case of an Automatic Route Setting which would for instance automatically implement the real-time traffic plan identified by the CDR to be the most effective for a specific traffic scenario. In such a situation, the quality of taken traffic management decision will only depend on the effectiveness of the automated CDR algorithm.

Another responsibility of the dispatcher will be to take decisions based on safety warnings provided by the short- and medium-term MB hazard prediction modules. In case of short-term hazard messages human dispatchers might directly contact drivers of the involved trains asking them to reduce their speeds or even stop depending on the situation. In the event of medium-term MB hazard instead train could be retimed or rerouted in order to avoid track conflicts in areas with limited GNSS or GSM-R availability.

MB safety warning messages could also be handled by an ARS albeit that might not always be possible depending on the hazard scenario. For instance, an ARS would hardly be able to handle short-term MB safety hazards unless the involved trains are in the vicinity of an interlocking area and can be stopped by simply not setting the routes (after having received a restricted MA). On the contrary not much can the ARS do is the short-term safety hazards were predicted to happen on the open line. Medium-term MB safety hazards would instead be more likely to be effectively managed as the ARS might for instance set a different route for the involved trains to prevent conflicts from occurring in GNSS or GSM-R critical areas.

5.8.3 Output

The output of the dispatcher (or the ARS) is the real-time implementation of decisions to reduce propagation of traffic disturbances or mitigate safety risks. Those decisions translate into a set of instruction to the operating trains which can be:

- Updated arrival, departure and passing times
- Updated train routes and orders
- Updated speed profiles.
- Updated Movement Authorities.

5.8.4 Implementation in PERFORMINGRAIL

The PERFORMINGRAIL project does not address the role of a human dispatcher in relation with the moving-block traffic management framework. That would require human-in-the-loop testing which are out of the scopes of this project. The role of dispatcher is, however, important in order to close the loop in the railway system. Conflict resolution and hazard prediction modules do take over some of the traditional tasks of human dispatchers, but for now, dispatchers remain crucial for the implementation of the outputs of the railway traffic management system in real-life. In PERFORMINGRAIL real-time traffic plans computed by the RECIFE-MILP extended for MB are implemented via an API module which instructs the interlocking module of the BraSS simulator as an ARS would do in the real life.

6 Recommendations for Moving-Block Traffic Management System

6.1 Recommendations for Conflict Detection and Resolution Models

A set of recommendations is provided to support scientists and/or the railway industry in further developing moving-block conflict detection and resolution models and implementing decision support tools for moving-block railway traffic management.

- Positioning errors can be incorporated in the safety margin. The positioning errors are the only moving-block parameter expressed in distance rather than in time and they do not depend on specific train types or speeds.
- A consensus needs be reached in the definition of switch protection zones in moving-block systems: In which cases do switches need to be blocked as a group, and what are sufficient conditions to let switches be blocked one-by-one?
- In discrete-space models, the aim should be to use a discretisation in line with the time-discretisation inherent to moving-block systems due to discontinuous communication. For example, during the train position report update time trains running at 160 km/h can traverse more than 200 meters (Furness et al., 2017).
- An interesting research direction would be to develop a continuous-spaced moving-block conflict detection and resolution model. A continuous-space approach is expected to accurately describe the continuous headway-speed relation on which moving-block operations rely. So far, the added value of a continuous-spaced approach is unknown due to non-existence of these type of models.
- First implementations of conflict detection and resolution models should be in areas with dense and heterogeneous traffic without (too many) stops. These areas can expect the highest impact of a specific moving-block model.
- Conflict detection and resolution models used as decision support tools should include (local) rerouting. The gain of a moving-block conflict resolution model with respect to a fixed-block one may not necessary be better when including rerouting, but the chances of positive impact are higher. More importantly, in practice, dispatchers do apply rerouting.

6.2 Recommendations for Early-Warning Hazard Prediction Models

A set of recommendation is provided as follows to support scientists and/or the railway industry in further developing/implementing the early-warning MB hazard prediction modules functionally specified in this document.

- To support a safe and effective management of Moving Block traffic operations, core TMS functionalities for conflict detection and resolution are recommended to be interfaced with modules for short-term and medium-term MB hazard prediction.
- As the scope of PERFORMINGRAIL is limited to a functional specification the early-warning hazard prediction module, the development of prototypes at higher TRLs are needed to assess the impact on overall MB safety.
- To feed necessary static data, the short-term hazard prediction module shall be interfaced with a Conflict Detection and Resolution model which contains/stores safety-

critical threshold values of variables of the MB signalling (e.g. min EoA safety margin, max EVC processing time), the GNSS location errors/latencies, the GSM-R communication delays and the rolling stock braking performances.

- Static data about safety-critical thresholds of MB signalling variables, GNSS location errors, GSM-R latencies, and train braking performances should derive from a dedicated sensitivity analysis performed by means of formal MB signalling models or even hardware-in-the-loop testing.
- To feed necessary dynamic data, the short-term hazard prediction module should be interfaced directly or indirectly (e.g. via the Traffic State Monitoring) with on-board and track-side signalling components such as the EVC, the On-Train Monitoring Recorder, GNSS receivers, GSM-R antennas, the RBC.
- To feed necessary static data, the medium-term early warning hazard prediction module should be initialised with geographical data about GNSS and GSM-R signal coverage provided by signalling/communication suppliers or available at the asset management department of railway infrastructure managers.
- Static geographical data about GNSS and GSM-R coverage can be provided in the form of an interactive digital maps or a database.
- Dynamic data feeding the early-warning MB hazard module should be received by the Conflict Detection and Resolution module.
- The medium-term early-warning hazard module should contain procedures to consistently match geographical coordinates of detected track conflict locations (from the CDR) with those of the GNSS and GSM-R coverage maps.
- Early-warning hazard messages produced by the short-term and medium-term hazard prediction modules should contain the IDs of the involved trains as well as the type and descriptive characteristics of the hazard which can guide the dispatcher in taking a risk mitigation action.
- The content of the early-warning MB hazard messages could also be graphically visualised on the HMI of the TMS to support an unambiguous reception/understanding of the warning message and facilitate a prompt action of the dispatcher.

6.3 Recommendations for a TMS architecture for Moving Block

A set of recommendations are provided to support further development and implementation of the proposed TMS architecture for safe and effective MB rail operations.

- Communication among functional modules within the TMS and with external systems shall rely on standardised data formats (e.g. EULYNX DP, UIC RailTopoModel) and interfaces for automatic, reliable and unambiguous exchange of static and dynamic information.
- Functional TMS modules for traffic monitoring, prediction and re-planning shall be dynamically interfaced and fed with static data from the Planning system to ensure data consistency for reliable service performance evaluation and effective MB traffic management.

- Data interfaces with the planning system shall enable that any change/update to infrastructure and signalling layout, train planning rules, timetables and rolling stock made at the planning level is automatically and consistently implemented in the TMS.
- Existing Traffic State Monitoring should be interfaced and fed with data from satellite-based train location systems for MB, as the removal of track vacancy detection sections will compromise the use of train describers relying on track section occupation/release events.
- Future evolutions of the Reference CCS architecture for MB could consider including functional modules for early-warning hazard prediction to mitigate safety risks that the removal of track-side train detection would raise in areas with compromised GNSS or GSM-R coverage.
- Real-time traffic plans and early-warning MB hazard messages are recommended to be visualised on the HMI to facilitate unambiguity in understanding and timely intervention of the dispatcher.
- Further development and testing of the proposed functional TMS architecture for MB is recommended to accurately evaluate the impacts on safety and effectiveness of MB traffic operations.
- The practical deployment of a TMS architecture for MB will require specific training sessions and re-skilling of drivers and dispatchers to align with upgraded safety and operational procedures, signalling technologies and decision support systems.

7 Conclusions

This deliverable reports the outcome PERFORMINGRAIL Task 4.3 “Guidelines on integrated traffic management architectures for safe and optimised moving-block operations”. A model for optimised conflict detection and resolution for MB signalling has been specified based on the mathematical formulation provided in PERFORMINGRAIL Deliverable D4.1. Such a model relies on a version of the RECIFE-MILP rescheduling algorithm which has been specifically extended for MB traffic operations. A model verification has been performed by testing the extended RECIFE-MILP for MB on a simple infrastructure layout. The verification stage has also included a comparison of the developed MB formulation versus the original fixed-block formulation of RECIFE-MILP to assess modelling and performance impacts of MB traffic operations. The model has then been validated by applying it to two real railway case studies in France and evaluating its performances for different network topologies and disturbed scenarios.

A functional specification and practical cases have been then provided for functional TMS modules to predict hazardous MB traffic conditions in both the short- and medium-term. Based on the definition of those modules in Deliverable D4.1, a detailed representation is here given of input/output data, main functionalities and their interactions with other components/systems within and without the TMS.

A TMS functional architecture for safe and optimised MB rail traffic operations is then defined together with guidelines about input/output data, module functionalities and mutual information exchange. For each of the module it is also illustrated the corresponding implementation within the PERFORMINGRAIL project.

Eventually a set of recommendations are outlined to support scientists and practitioners in further research and development of novel TMS functionalities introduced in PERFORMINGRAIL, namely the CDR and the early-warning MB hazard prediction modules. An additional set of recommendations is then given to assist the industry in the future deployment of the proposed functional TMS architecture for safe and effective MB rail operations.

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