Ref. Ares(2025)8289253 - 01/10/2025

Deliverable D15.2
TMS and ATO/C-DAS Timetable Test & Simulation Environment

Project acronym:	MOTIONAL
Starting date:	01/12/2022
Duration (in months):	46
Call (part) identifier:	HORIZON-ER-JU-2022-01
Grant agreement no:	101101973
Due date of deliverable:	Month 24
Actual submission date:	22/11/2024
Code	FP1-WP15-D-PR-002-01
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Dissemination level:	PU
Status:	Issued

Reviewed: yes

This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101101973.

Document history		
Revision	*Date*	*Description*
0.1	15-03-2024	Initial structure
0.5	07-06-2024	First issue (50% version)
0.9	30-08-2024	Version for internal WP15 review
0.95	04-10-2024	Version for FP1 and SP review
1.0	22-11-2024	Final
1.1	04-09-2025	Minor updates based on review by SP and FP2

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1. Executive Summary

This deliverable D15.2 'TMS and ATO/C-DAS timetable test & simulation environment' is the result of the developments carried out in FP1-MOTIONAL WP15 on 'Linking TMS to ATO/C-DAS for optimized operations' based on Tasks 15.3-15.5. This deliverable fills a gap in the state of the art and practice by considering in detail the interactions between the main system components of TMS – ATO-TS – ATO-OB, including C-DAS. WP15 focused on the TMS-ATO operations, processes, feedback control loops, algorithms, data interfaces and human factors to improve operations.

TMS-ATO railway operations can be viewed as a system revolving around three main objects: the Real-Time Traffic Plan (RTTP), the Train Path Envelope (TPE), and the Train Trajectory (TT), focussing on the railway network, railway corridor and single train, respectively. Functional requirements were defined for each of these three objects. The RTTP is the real-time traffic plan that coordinates all operations on the railway network at Timing Points (TPs). It contains the exact train routes, timings at stopping and passing points, and the orders over the (switch) sections. The RTTP is kept up to date in the TMS using functions of traffic state monitoring, traffic state prediction, conflict detection and conflict resolution. The interaction with ATO/C-DAS can be used to improve the accuracy of these functions. Several such components have been developed: the RTTP Updater, Traffic Regulator, TMS–C-DAS Enhanced Operation, and ATO Train Forecast and Operational Plan Update. The TPE is the sequence of TPs with time windows that the ATO-TS sends to the ATO-OB within a journey profile, which is used in the train trajectory generation algorithm. The TPE may enrich the RTTP with extra TPs. A TPE Generator has been developed that computes a TPE for each train by considering multiple driving strategies and the interactions between adjacent TPEs that may generate extra TPs to avoid conflicts.

Four TMS-ATO operational variants have been defined depending on a passive or active role of the ATO-TS and ATO-OB. An active ATO-TS includes a TPE generator that monitors and optimizes TPEs from TMS and ATO-OB updates. An active ATO-OB has a train trajectory generation algorithm onboard. Depending on the combination of passive/active ATO-TS and ATO-OB different feedback control loops arise, with the most flexible configuration the active ATO-TS and ATO-OB resulting in a distributed TMS-ATO solution. An Integration Layer (IL) has been developed based on the Conceptual Data Model (CDM) that provides an enhanced publish/subscribe paradigm for processing messages between the TMS and ATO-TS. In addition, a Journey Profile generator has been developed based on the IL that translates an RTTP into Journey Profiles and Segment Profiles.

A Human-In-The-Loop (HITL) simulation environment has been enhanced with the TPE Generator and a new ATO-OB, to test full TMS/ATO-TS/ATO-OB operation, including feedback control loops and human factors (HF) using HMIs for drivers and traffic management/control operators. HF research requirements and a toolkit have been developed to study train drivers and traffic management/control operators within a TMS–ATO environment. Also, Human Readiness Levels (HRLs) are defined to assess the level of maturity of technology to its readiness for human use.

The annex contains the results of TRL 4 validation in a lab environment of the functions developed.

2. Abbreviations and Acronyms

Abbreviation / Acronym	Description
AoE	ATO over ETCS
API	Application Programming Interface
ARS	Automatic Route Setting
ATO	Automatic Train Operation
ATP	Automatic Train Protection
CCS	Control, Command, and Signalling
C-DAS	Connected Driver Advisory System
CD	Conflict Detection
CDR	Conflict Detection and Resolution
CDM	Conceptual Data Model
CMS	Capacity Management System
CR	Conflict Resolution
CTC	Centralized Traffic Control
DAS	Driver Advisory System
DMI	Driver Machine Interface
DSS	Decision Support System
DV	Dependent Variable
EETC	Energy-Efficient Train Control
EU-Rail	Europe’s Rail Joint Undertaking
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
FB	Feedback
FP	Flagship Project
FRISO	Flexible Rail Infra Simulation Environment
FRMCS	Future Rail Mobile Communication System
GoA	Grade of Automation
HITL	Human-In-The-loop
HMI	Human Machine Interface
HF	Human Factors
HRL	Human Readiness Level
IL	Integration Layer
IM	Infrastructure Manager
JP	Journey Profile
KPI	Key Performance Indicator
LSTM	Long Short-Term Memory
MA	Movement Authority
MAE	Mean Absolute Error
MTTC	Minimum-Time Train Control
MWL	Mental Workload
OB	On-board (system)
OPL	Optimization Programming Language

RCA	Reference CCS Architecture
RMS	Reduced Maximum Speed (train control)
p-RTTP	Proposed Real-Time Traffic Plan
RTTP	Real-Time Traffic Plan
RU	Railway Undertaking
SA	Situation Awareness
SCI-OP	Standard Communication Interface Operational Plan
SFERA	Smart Communications for Efficient Rail Activities
SME	Subject Matter Expert
SMTTC	Shifted Minimum-Time Train Control
SP	Segment Profile
STP	Static Traffic Plan
STR	Status Report
TCMS	Train Control and Monitoring System
TCS	Traffic Control and Supervision System
TD	Train Data
TE	Technical Enabler
TFT	Temporal Fusion Transformers
TMS	Traffic Management System
TP	Timing Point
TPE	Train Path Envelope
TR	Traffic regulation
TRL	Technology Readiness Level
TS	Trackside (system)
TSI	Technical Specifications for Interoperability
TSM	Traffic State Monitoring
TSP	Traffic State Prediction
TSR	Temporary Speed Restriction
TT	Train Trajectory
WP	Work Package

3. Introduction

3.1. Background

Within the framework of the Flagship Project FP1 – MOTIONAL (Mobility management multimodal environment and digital enablers) of Europe's Rail Joint Undertaking (EU-Rail), Work Package 15 (WP15) focuses on Linking the Traffic Management System (TMS) to Automatic Train Operation (ATO) and Connected Driver Advisory Systems (C-DAS) for optimized operations. A seamless integration between TMS and ATO (or C-DAS) is expected to contribute to increased network capacity, punctuality and robustness while reducing energy consumption, for both normal and disturbed conditions. The TMS aspects that are within the scope of WP15 are aspects that are related to C-DAS and ATO.

The TMS replans train schedules in case of delays and disturbances with the aim of optimising performance at the network level. On the other hand, ATO/C-DAS optimizes its own trajectory through the network within the margins of the train path envelope (TPE), i.e., the bandwidths wherein the train may operate. The combination of both leads to a balanced usage of ATO/C-DAS train centric optimisation, which complies with the network optimisation of the TMS.

TMS and ATO/C-DAS are both under development to be put into operation. This requires first ensuring each system works well individually, before combining them and gradually increasing complexity. Next to this, future TMS and ATO functionality must be tested by simulation before they are tested in a live environment. This includes simulation of the interaction between humans, TMS and ATO. To achieve this, we extend existing simulation tools and methodologies with specific TMS-ATO/C-DAS components, including the development of a system that supports testing human factors in the interaction with ATO/C-DAS.

Timetable modelling must take care of the integration of the train path envelopes in network planning. These envelopes will also have specific developed timing points for ATO/C-DAS operation based on microscopic attributes (speed profiles and resulting infrastructure occupation) to allow ATO-over-ETCS train operation. A real-time traffic plan (RTTP) that is dynamically adjusted based on real-time train status and infrastructure monitoring information is required for efficient ATO/C-DAS operations. WP15 delivers guidelines for future (operational) timetable modelling for ATO/C-DAS operation, and in particular for the RTTP and TPEs and their interaction.

The previous deliverable D15.1 'Requirements for the deployment of TMS linked with ATO/C-DAS' described important concepts, the state-of-the-art and the state-of-practice concerning TMS, ATO, C-DAS and their interactions. Moreover, it described the main principles of linking the TMS to ATO/C-DAS and the innovations required to enable a successful TMS – ATO/C-DAS linkage for optimized operations.

The main output of the TMS is the RTTP specifying the exact route for each train with time targets or windows at stopping and passing points. The RTTP is the basis for efficient train operation and timely route setting by the Traffic Control and Supervision System (TCS). The traffic plan must be translated into a train trajectory for each train specifying a reference time and speed profile over the route of the train that can be followed by a train driver in the case of C-DAS or by a train trajectory tracking algorithm in the case of higher Grades of Automation (GoA 2 or higher).

The link between the RTTP from the TMS and the train trajectories onboard all trains is given by the TPEs. The TPE provides time constraints to a train trajectory generation algorithm, such that the latter can generate a punctual, drivable and conflict-free train trajectory, while providing maximal flexibility for energy-efficient driving. Hence, the TMS computes the RTTP for all train traffic at the network level, from which feasible TPEs must be derived for all trains at a corridor level, that can then be used for train trajectory generation at the individual train level. The generation of the TPEs and train trajectories can be executed at the TMS, the ATO Trackside (TS) or the ATO Onboard (OB). Moreover, the three objects (RTTP, TPEs, train trajectories) must be updated continuously depending on the system conditions, dynamics, disturbances and disruptions. The resulting interactions and feedback control loops therefore depend on the allocation of the functions of computing/updating the RTTP, TPEs and train trajectories over the three subsystems TMS, ATO-TS and ATO-OB.

The optimal linking of TMS and ATO/C-DAS for optimized operations is achieved by developing functions concentrated in the following two technical enablers (TE):

- **Technical Enabler 12**: Real-time convergence between planning & feedback loop from operations.
- **Technical Enabler 15**: TMS speed regulation of trains, precise routes, and target times for ATO and dynamic timetables.

The developments in WP15/16 contain two process steps:

1. Feedback loop with traffic simulation (TE 12) verifying the algorithms of TE 15 to test the linkage of TMS to ATO/C-DAS.
2. Testing the future applicability in operations, including human-factors research, by 'real-world' emulation with a human-in- the-loop simulation environment that contains connected simulators of train drivers, signallers and traffic managers linked to a dynamic traffic management system and ATO on-board modules.

The present document constitutes Deliverable D15.2 'TMS and ATO/C-DAS timetable test & simulation environment', which presents the requirements for linking TMS to ATO/C-DAS for optimized operations and the components developed within WP15 to test and simulate TMS – ATO/C-DAS operation. This also includes the human factors and human-in-the-loop simulation. The content is based on the results of tasks T15.3-T15.5. This deliverable includes technology validation in a lab (TRL 4) for the developed components. In WP16 the concepts and components will be validated in a relevant environment (TRL 5).

3.2. Objective/Aim

The aim of this deliverable is to report the results of tasks T15.3-T15.5 from FP1 – MOTIONAL WP15 on "Linking TMS to ATO/C-DAS for Optimized Operations". In short, the scope of those tasks was the development of TMS and ATO/C-DAS timetable test and simulation environments for developing and testing optimisation algorithms, TMS-ATO interaction concepts, data models, and human-factors research. Table 3-1 provides an overview of the various tasks and where they are addressed in this deliverable.

Table 3-1 Contributions of chapters to tasks

Topic	Addressed at
Task 15.3 Requirements for TMS and ATO/C-DAS timetable development	
Definition and outline of requirements to model TMS-ATO/C-DAS operated trains in timetables and simulation.	Chapter 6 on TMS – ATO/C-DAS Requirements Chapter 10 on TMS-ATO Data Models
Identification of types/grades of TMS for optimal linking with ATO/C-DAS and applying algorithms to them.	Chapter 4 on Operational Aspects Chapter 5 on TMS-ATO Functions and Interactions Chapter 7 on Real-Time Traffic Plan Chapter 9 on ATO-Enhanced TMS
Development of guidelines for train path envelopes TMS – ATO/C-DAS, including distribution strategies for dynamic and optimized capacity, punctuality, and energy consumption.	Chapter 8 on Train Path Envelopes
Task 15.4 Development of specific TMS-ATO/C-DAS planning & simulation environment, including HF	
15.4.1. Human-factors research and best-practices overview on TMS and ATO/C-DAS simulation.	Chapter 12 (Sections 12.1-12.2) on Human Factors literature review and state-of-the-art
15.4.2. Human factors testing requirements (methods, machinery) based on academic research. This identifies relevant actors, collects their requirements, and compiles a set of requirements, considering these communities and work-related impacts. Additionally, integration of such requirements into prototype developments.	Chapter 12 (Sections 12.3-12.6) on Human Factors constructs and measurement techniques, comparison of traffic management roles, research requirement, and Human Readiness Levels
15.4.3. Development of a 'human factors full command chain simulator' capable of simulating 'real live traffic' situations with TMS-ATO operated trains that captures ATO/C-DAS characteristics of trains for development and evaluation of enhanced TMS functionality and human-in-the-loop aspects, considering the requirements from Task 15.3.	Chapter 11 on Human-In-The-Loop Simulation Environment
Subtask 15.4.4. Development of TMS-ATO integration platform based on the updated requirements & specifications, following the possible new needs supporting autonomous train operations.	Chapter 10 on TMS-ATO Data Models, with the Integration Layer (Section 10.2) and the Journey Profile Generator (Section 10.3)
Task 15.5 Preparations (requirements) for TMS-ATO 2030 demonstrator in real-time live operations	
Development of traffic regulation strategies (Operational Concept) for improved global behaviour of the traffic under minor timetable disturbances (delays and unfulfilled headways), based on different criteria and taking into account the global situations of the line through TMS – ATO interaction.	Chapter 7 (Section 7.3) on the Traffic Regulator

3.3. Methodology

This deliverable describes the developments carried out within WP15 following the review from D15.1 of the state-of-the-art, state-of-practice, and the standards available and in development concerning the linking of TMS and ATO/C-DAS. This led to the identification of main functions and components by the WP15 partners during the 3rd physical WP15 meeting in March 2024. This was the basis for a logical architecture and classification of scopes for the developments that may apply for different railways/conditions. To better align the various topics, six cross-task thematical groups were formed with partners working on related components and functions. These themes were:

1. TMS-ATO requirements (Chapters 4-6)
2. RTTP updating, traffic regulation and traffic forecasting (Chapters 7 and 9)
3. TPE calculation (Chapter 8)
4. Integration platform and journey profiles (Chapter 10)
5. Human factors (Chapter 12)
6. Simulator environment and feedback control loops (Chapter 11).

Each group had a group leader, contributors and reviewers, where all partners could sign up for. The group leaders coincided with the WP15 (sub)task leaders plus an additional group leader of group 6. Each group had biweekly online group sessions, while the group leaders discussed the progress and possible interactions in the monthly WP15 management team meetings. The groups were assigned to specific chapters of D15.2, including a chapter responsible, contributors and reviewers, to secure alignment between the related chapters. The Development Delivery Plan for D15.2 formalized for each chapter the collaborating persons and their roles (responsible, contributor, reviewer), as well as the focus of the chapter. The alignment between groups was also guaranteed by key persons participating in multiple groups. The draft chapters were completed by the end of August 2024, after which the (internal) reviewers reviewed the content in the first two weeks of September. The remainder of September was used by the contributors to finalize the content based on the reviewer comments.

Group 1 had a special task to define requirements for all the TMS – ATO/C-DAS developments, as well as setting the scene by aligning terminology, and describing the operational aspects and the logical architecture. During the 4th physical WP15 meeting in July 2024, the terminology, system requirements, and logical architecture were discussed in interactive sessions with all partners, after which they were further worked out in Group 1. The result is presented in Chapters 4-6. The other Chapters 7-12 describe the developments by the various partners within WP15. The relations between the developments and the requirements are also presented in Chapter 6.

During September and October 2024, the components/functions developed within WP15 were validated at TRL 4 (Technology validation in lab). The test reports and the detailed test descriptions and test execution results are presented in the Annex (Chapter 15). In WP16 the components/functions will be further developed and validated to reach TRL 5 (Technology validated in relevant environment).

Finally, the concept final deliverable was reviewed by two independent FP1–MOTIONAL reviewers and a System Pillar reviewer in October 2024, which led to minor updates by the contributors.

3.4. Document Outline

D15.2 is built up in a logical sequence of the WP15 developments. The first three chapters consist of the Executive Summary, abbreviations and acronyms, and an introduction with the background, objective/aim, methodology, and this document outline.

Chapter 4 considers the operational aspects of the TMS – ATO/C-DAS system, including the scope/purpose with a description of the typical TMS–ATO processes, actors, benefits, and use cases that will be used in the demonstration phase in WP16. Here the main objects and their interactions within the system are introduced: the real-time traffic plan (RTTP), the train path envelope (TPE), and the train trajectories used by the ATO/C-DAS OB. Chapter 5 considers the main functions within the TMS to keep an up-to-date RTTP, and then proposes four TMS–ATO/C-DAS feedback control architectures depending on an active or passive ATO/C-DAS TS and ATO/C-DAS OB. These variants extend the existing classification based on just a different role of the ATO-OB. The chapter finally provides a high-level logical architecture of the TMS – ATO/C-DAS system and its interactions, also with the direct environment, including the safety layer, and the relevant existing standards that need to be considered. Chapter 6 provides the functional requirements for the three main objects, the data communication between them, and relevant human factors. The developments in the later chapters are based on these requirements.

Chapter 7 to Chapter 12 describe the developments of functions and components that can be used to improve TMS–ATO/C-DAS operations. Chapter 7 focuses on the RTTP with a definition and discussion about its content. Two components are described here: the RTTP Updater and the Traffic Regulator. Chapter 8 focuses on the TPE with a definition and discussion of its purpose. The chapter then describes the TPE Generator that can be used in an active ATO-TS (or in the TMS with a passive ATO-TS) to improve the ATO/C-DAS performance. Chapter 9 considers two developments that use ATO/C-DAS information to advance the TMS functions, and in particular the traffic forecasting, and thus improve the accuracy of the RTTP: the TMS – C-DAS Enhanced Operation and the ATO Train Forecast and Operational Plan Update. Then, Chapter 10 deals with TMS – ATO/C-DAS TS data models, and in particular describes the Integration Layer for data exchange between the TMS and the ATO/C-DAS TS, and the Journey Profile Generator that can generate the Journey Profiles for the data exchange between the ATO/C-DAS TS and ATO/C-DAS OB. Chapter 11 describes a Human-In-The-Loop (HITL) simulation environment and its extensions for testing TMS – ATO/C-DAS operations, which will also provide human factors testing facilities. Finally, Chapter 12 considers Human Factors (HF) for TMS – ATO/C-DAS operations.

Chapter 13 provides the conclusions of the developments within WP15, while the references are listed in Chapter 14. Chapter 15 is the annex and contains the TRL 4 validation results of all the developments described in this deliverable.

4. Operational Aspects

4.1. Introduction

This chapter focuses on the description of what TMS-ATO system users must achieve and outlines the general system (and its components) that performs the TMS-ATO functions. This chapter relates these components to different system users and actors within the system, in terms of how and where they interact. A brief summary of the benefits that users of the system are expected to achieve is also included. Finally, the chapter presents the related demonstration use cases that will be included in the demonstrations of WP16.

We define the general TMS-ATO system as a combination of components performing a set of functions. The main components we consider within the total system architecture are the TMS, ATO-TS, and ATO-OB and their interaction. Within the general system, several users can be differentiated, which interact with or receive information from the system (components). An effective and efficient multi-actor collaboration and coordination is essential. The system users can be defined on several levels. The end users are passengers and freight carriers. Operational users could be defined as the employees performing operational tasks like traffic control, train operation, and incident management. Here, we focus on users involved in normal operation conditions, being the Infrastructure Manager (IM) employees involved in the traffic management or the train drivers.

4.2. Scope/Purpose

This section includes a brief summary of the scope of the general system and the main systems/components that comprise it and are the objective of this report. The main functions of them at operational level are described. Focus is always on the TMS-ATO/C-DAS connection (general system). As part of the scope of this section, the three main objects that are at the base of the TMS-ATO/C-DAS interaction, are described. They are the RTTP, TPE, and train trajectory.

The functions of ATO/C-DAS are divided into a Trackside (TS) and an Onboard (OB) system, with the TMS connected to the ATO/C-DAS TS. The ATO/C-DAS OB of the connected trains get information from the TS and report their status as feedback back to the TS. The ATO-TS could also report this status report information to the TMS but this is not currently specified in the CSS TSI.

The TMS-ATO interaction is based on three main objects: the RTTP, TPE (within the JP and SPs), and train trajectory, see Table 4-1. The RTTP is the outcome of the TMS and sets time targets to trains at main timing points, like stopping and passing points at stations, as well as the exact routes of the trains, and the orders of the trains over the infrastructure. The construction of the RTTP considers the train traffic over the network, i.e., multiple corridors and their interaction. It is based on the traffic plan from the planning system (Capacity Management System) with possible rescheduling actions triggered by a conflict detection and conflict resolution (CD/CR) process given the current state of the trains and infrastructure. Typical rescheduling actions for daily disturbances and delays are retiming, reordering, and local rerouting including re-platforming in stations. For disruptions, even more severe replanning measures can be applied to keep a feasible

RTTP, including stop skipping, stop adding, (partial) service cancellations, short-turning and global rerouting. The objective is typically a mix of optimal capacity allocation, minimizing deviations from the original plan, and a trade-off between short and robust journey times. The constraints should guarantee a feasible time-distance allocation of trains to tracks, including minimum running and dwell times, and safety and capacity constraints.

A TPE specifies time targets and windows to a train over a sequence of timing points on a corridor (i.e., a railway line between two main stations including intermediate stations and junctions with merging/diverging lines). In particular, the TPEs must facilitate conflict-free and energy-efficient driving of the trains, and comply with constraints imposed by the RTTP. Therefore, the TPEs include the timing points and time targets of the RTTP for each train and must be mutually exclusive with sufficient headway at critical points to guide the train operation, while at the same time maximizing flexibility to possible train speed profiles given the uncertainties and variations in static and dynamic train movement characteristics, such as driving behaviour (by a driver or ATO algorithms), train composition, power supply, traction and brake characteristics, resistance coefficients, wind and track adhesion.

A TPE may be specified by a sequence of timing points over each successive track section or block with appropriate time targets or time windows to guide the train in a feasible envelope from target to target. However, to better appreciate the uncertainties in the actual train dynamics or ATO/C-DAS driving behaviour, the number of timing points may be reduced to the absolute necessary number to guide the train operation. These selected timing points are typically placed at the entry of critical blocks, which depend on the specific traffic and infrastructure characteristics. Train trajectory tracking is never perfect due to, for example, noise and reaction times. Therefore, additionally, tolerances in the form of time windows at these timing points must be specified to allow minor deviations from a computed train trajectory. In the case of dense traffic, the time windows at critical blocks may need coordination between the TPEs of successive trains to reduce interference of the optimal trajectories for each train.

The TPEs are part of the Journey Profiles (JPs) and Segment Profiles (SPs) which are sent from the ATO-TS to the ATO-OB as specified by the ERTMS/ATO subset-125 and Subset-126 for ATO in the CCS TSI 2023 and the SFERA protocol for C-DAS. The SPs define the route segments including TPS that are used by the associated JP. The JP contains the TPE with reference to the TPs defined in the SPs, as well as other operational data and dynamic infrastructure data (temporary constraints).

Finally, each train generates a train trajectory over a corridor to a future time target, which is typically an arrival time at a station. This train trajectory corresponds to a speed profile and the corresponding time-distance path. It specifies the driving strategy of successive driving regimes consisting of acceleration, cruising, coasting, and braking and their switching times. The train trajectory must satisfy the time windows from the TPE to avoid any possible conflicts with other trains. The TPE also includes the punctuality goal by specified time targets. The bandwidths contained within the TPE can be exploited to generate a drivable, comfortable and energy-efficient speed profile from the train motion equations given the specific train and track characteristics.

Table 4-1 Typical scope of RTTP, TPE and TT.

	Real-time traffic plan (RTTP)	Train path envelope (TPE)	Train trajectory (TT)
Content	• Routes • Arrival and departure times • Passing times • Train orders	• Timing points • Time targets • Time windows	• Speed profile • Time targets • Traction/brake control
Scope	• Train traffic on rail network	• Train traffic on corridor	• Train on corridor
Decisions	• Retiming • Reordering • Rerouting • Cancelling	• Departure tolerances • Operational tolerances • Extra timing points	• Acceleration • Cruising • Coasting • Braking
Objectives	• Conflict-free train paths • Minimize delays • Cost & travel time efficiency • Robustness	• Feasible train trajectories • Flexibility • Mutually conflict-free TPEs	• Energy efficiency • Punctuality • Drivability • Comfort
Constraints	• Track capacity • Minimum activity times • Maximum activity times • Safety (minimum headways)	• Driving strategies • Train parameter variation • Speed tracking thresholds • RTTP	• Train dynamics • Train characteristics • Track characteristics • TPE

The interaction between RTTP, TPE and TT give benefits in punctuality, energy consumption, network capacity utilization, avoiding unplanned stops, workload for users, resilience, and robustness. Since the TMS and ATO/C-DAS exchange information from the RTTP, TPE and/or TT, a correct and harmonized linkage of the TMS with ATO/C-DAS is required to achieve the benefits.

The performance is measured over all trains in a certain geographical area considering Key Performance Indicators (KPIs), such as mean delay, punctuality and energy consumption. The size and configuration of those areas will be different by country. The railway traffic will operate under normal and disturbed conditions. Next to ATO also C-DAS is part of the use cases. In the scope, C-DAS can be seen as a GoA1 ATO system with manual speed advice tracking.

The scope of the developments in WP15/16 may vary depending on specific network and traffic characteristics. A (non-exhaustive) list of factors is given as follows.

- Geographical scope
  - Single-track line between an origin and destination station with traffic running in both directions on the same track
  - Single-track line between an origin and destination station, and one or more overtaking locations in between
  - Double-track or multi-track line between an origin and destination station, with traffic separated by direction
  - Double-track or multi-track line between an origin and destination station, with crossing/merging/diverging movements at one or more locations.

- TMS-functions (by human operator or system)
  - Rerouting trains (local or global changing allocated tracks)
  - Reordering trains entering a corridor and at critical points
  - Changing train activities, e.g. extra stop or skipping a stop
  - Retiming of train events at stations (and other timing points)
  - Re-platforming, changing platform track in station
- Mix of train types
  - Homogeneous traffic: one train type and same stopping pattern
  - Heterogeneous traffic: several train types with different stopping patterns, speed profiles, and/or driving characteristics
- Train frequency
  - Low frequency, e.g., up to 4 trains per hour
  - High frequency, e.g., exceeding 4 train per hour
- Number of ATO/C-DAS -equipped trains
  - One ATO/C-DAS train, no surrounding trains
  - One ATO/C-DAS train, surrounding trains without ATO/C-DAS
  - One ATO/C-DAS train, some surrounding trains also with ATO/C-DAS
  - Multiple ATO/C-DAS trains, surrounding trains without ATO/C-DAS
  - Multiple ATO/C-DAS trains
- Number of human operators
  - One or multiple traffic operators
  - One or multiple trains
  - One or multiple drivers (or simulated drivers).

We assume one TMS and one ATO/C-DAS TS and no interfaces with neighbouring TMS-areas or ATO/C-DAS TSs. Also, the reallocation of rolling stock and crew is not included in case of disruptions.

4.3. Actors

This section identifies the key actors and/or entities that will interact with the system. For all of them, the roles and responsibilities associated are remarked. When necessary, the dependencies and relationships between them are also identified.

Key actors or entities are

- CTC operator (signaller): responsible for safe route setting in both normal and degraded conditions by commands to interlockings over remote control areas (routes). Note that traffic control centres have several integrated systems and the CTC (Centralized Traffic Control) is one of them.
- TMS operator/local traffic controller (dispatcher): responsible for a feasible Real-Time Traffic Plan (times, orders and routes of trains). He/she is also responsible for contacting train drivers in case of disturbances and disruptions.

- Combined TMS/CTC operator: Different countries have different configurations of CTC and TMS operators, including both roles combined in one person. In that situation, the TMS operator manages the traffic through the CTC.
- TMS operator/network traffic controller (global): in charge of coordinating network traffic (or large traffic control area).
- TMS: this is the system for monitoring and managing the traffic and the signalling system from the control centres. The TMS will be in charge for updating the Real-Time Traffic Plan (RTTP), which is the base for route setting in the TCS and for train operation by ATO/C-DAS.
- ATO-TS (Trackside): part of the ATO system installed on the trackside. This communicates with the TMS and the ATO-OBs of the connected vehicles. Based on the RTTP received from the TMS, the ATO-TS generates segment profiles and journey profiles, and sends these to the ATO-OB of all connected trains (responsible for sending timing points and timing windows to ATO-OB systems). It also receives status reports from the ATO-OB.
- ATO-OB (On-Board): part of the ATO system installed onboard of the vehicles, responsible for calculating train trajectories within the limits provided by the ATO-TS. This translates the information contained in the journey and segment profiles received from the ATO-TS into train trajectories and controls the traction and braking systems for automated train runs.
- C-DAS TS (Trackside): part of the C-DAS system installed on the trackside. This communicates with the TMS and the C-DAS-OB of connected Driver Advisory System (DAS) trains. Based on the RTTP received from the TMS, the C-DAS TS generates segment profiles and journey profiles, and sends these to the C-DAS OB of all connected trains. It also receives status reports from the C-DAS OB.
- C-DAS OB (On-board): part of the C-DAS system installed onboard of the vehicles. It receives the data from the ground (C-DAS TS), performs the calculation for the driving advice (if not done previously on the ground by Railway Undertaking (RU) or IM), and sends the driving advice to the user interface to be displayed. This device can either be integrated into the train or a portable unit.
- Train driver: responsible for starting and driving a train in a safe, punctual, and economic manner over various routes in accordance with operational rules, regulations and procedures (ATO GoA1/2). With ATO GoA3/4, there is no need for a driver onboard the train, or the driver does not need to be at the front of the train to monitor the line for obstacles.
- Person responsible for departure process: this person (who may be a driver, conductor, or a member of station staff, depending on the use case) is responsible for a safe dwell and departure process.

4.4. Benefits for the System Users

In this section, we include some examples of what system users are expected to achieve with the integration and use of TMS – ATO/C-DAS linkage. This means what benefits are expected to be obtained for system users.

- For passengers, some of the benefits are a higher service availability and reliability given that a greater punctuality is sought, more accurate travel information, an improved journey comfort (avoiding unnecessary acceleration/braking of train), and a higher regularity in the driving. Another benefit could be less train cancellations because of TMS.

- For railway undertakings and freight carriers, the expected higher punctuality will also increase reliability such that the railway system will deliver as expected (efficient tools for dispatchers, efficient/automatic route planning and replanning tools at incidents and communication with trains and drivers). Moreover, the RUs benefit from a reduction of energy consumption through more energy-efficient automatic driving and pro-actively avoiding inefficient braking and reacceleration due to conflict-free train operations.
- At IM (planners, traffic control operators, systems, etc), the benefits identified are:
    - Centrally guided automatic train operation from the trackside to avoid conflicts between trains and improve predictability, punctuality and energy efficiency.
    - Running trains more precisely and regularly at the operational level.
    - Operating more trains on the same track at the operational level, especially in cases of disturbances and disruptions.
    - The possibility to increase network capacity at the planning level. With TMS and ATO, trains may be able to consistently run more exact and closer to each other at the operational level. If the infrastructure is maintained at a high enough level that there is a reduction in day-to-day variability in realized trajectories (e.g. due to temporary restrictions) over longer planning periods, then there is a capacity increase at those levels. The IM can then use this capacity increase to schedule more trains on the line.
    - Reduction of energy consumption through more energy-efficient automatic driving and pro-actively avoiding inefficient braking and reacceleration due to conflict-free train operations.
    - Better train forecasts based on more precise information on train position and speed and weather conditions (different braking curves evaluation). Moreover, a better train forecast provides better conflict detection and resolution.
    - A higher accuracy in real-time traffic replanning. Achieving an RTTP of high quality and closer to reality taking advantage of the status and forecast information (Status reports) that the ATO/C-DAS system can provide to the TMS, without introducing extra workload.
    - Trend towards greater automation of operations. To reduce the human responsibility and interaction, and variability of human answers in the system. The reaction time on disturbances is expected to be faster. Additionally, it is expected to reduce the workload of operators, drivers, etc, and achieving greater confidence and reducing stress.
    - Functions and solutions in the TMS and ATO/C-DAS TS facilitate data collection and distribution for a stepwise introduction of higher grades of automation (GoA 1 with C-DAS and GoA 2, and preparing for further steps up to 3 and 4), along with the maturing of necessary technology.

4.5. Demonstration Use Cases

Use Cases were developed for FP1 MOTIONAL D2.5 'Use cases for project demonstrations'. Table 4-2 lists these high-level demonstrations use cases, including both the demonstration number from the GA that were SG specific, and the new demonstrations numbering, which are numbered consecutively by WP16. The sub-demos here have their own demo number. Each demo has one or more use cases. The full descriptions of the use cases are given in FP1-MOTIONAL D2.5.

A use case is understood as the description of a specific interaction between a user or external system and the system developed. In this, the sequence of events that occur when an actor performs a specific task or action using the system is described, including the input and output involved. The current high-level use cases could encompass several actions or tasks on the system as they are described in a general way.

Table 4-2 MOTIONAL WP15/16 high-level use cases

Use Case ID	Use Case Title	Lead Partner	Demo
FP1-DEMO-16.1-UC-01	Train Path Envelope calculation	PR	16.1 (12)
FP1-DEMO-16.1-UC-02	TMS-ATO feedback loop	PR	16.1 (12)
FP1-DEMO-16.2-UC-01	TMS-ATO operation interactions between human actors in different conditions	PR	16.2 (14/12)
FP1-DEMO-16.3-UC-01	RTTP-updates to increase C-DAS efficiency	TRV	16.3 (13.1)
FP1-DEMO-16.4-UC-01	TMS enhancements to support C-DAS operations	INDRA	16.4 (13.2)
FP1-DEMO-16.5-UC-01	C-DAS simulator	CEIT	16.5 (13.3)
FP1-DEMO-16.6-UC-01	Performance comparison between C-DAS-C and C-DAS-O architectures	STS	16.6 (13.4)
FP1-DEMO-16.7-UC-01	ATO-TMS integration	AZD	16.7 (15.1)
FP1-DEMO-16.8-UC-01	Traffic regulation based on the time of the day	CAF	16.8 (15.2)
FP1-DEMO-16.8-UC-02	Traffic regulation based in track areas	CAF	16.8 (15.2)
FP1-DEMO-16.8-UC-03	Traffic regulation considering adhesion factors	CAF	16.8 (15.2)
FP1-DEMO-16.9-UC-01	Operational Plan update through TMS and ATO-TS interaction	MERMEC	16.9 (15.3)

The use cases represent different situations. Table 4-3 shows the combination of scope elements and relevance for each use case. Each use case has a very short reference to the topic in the top row. The use case numbers are taken from Table 4-2.

Table 4-3 MOTIONAL WP15/16 high-level use cases list with scope elements

FP1-DEMO	TPE	FB	HITL	RTTP	TMS	CDAS	CDAS	INT	TR	TR	TR	TMS
	16.1	16.1	16.2	16.3	16.4	16.5	16.6	16.7	16.8	16.8	16.8	16.9
Use case	1	2	1	1	1	1	1	1	1	2	3	1
Geographical scope												
Single-track line						x						x
Single-track line with overtaking				x	x		x	x				
Multi-track line, directional tracks	x	x							x	x	x	
Multi-track line with crossings		x	x									
TMS-functions (human or system)												
Rerouting			x					x				
Reordering		x	x		x							x
Extra/skip stop			x		x		x	x				x
Retiming at timing points	x	x	x	x	x		x	x	x	x	x	
Re-platforming			x		x			x				x
Mix of train types												
Homogeneous traffic						x	x		x	x	x	x
Heterogeneous traffic	x	x	x	x	x							
Train frequency												
Low frequent (≤ 4 trains/h)	x			x			x	x				x
High frequent (> 4 trains/h)		x	x		x				x	x	x	
Number of ATO/C-DAS trains												
One train ATO/C-DAS								x				
One train, adjacent unequipped				x								
One train, adjacent equipped				x					x	x	x	
More trains, adjacent unequipped			x		x							
More trains, all with ATO/C-DAS	x	x	x			x	x		x	x	x	x
Number of human operators												
One traffic operator				x				x	x	x	x	x
Multiple traffic operators			x		x							
One ATO/C-DAS OB								x				
Multiple ATO/C-DAS OB	x	x	x		x	x	x		x	x	x	x
One (simulated) driver			x				x	x				
Multiple (simulated) drivers	x	x		x		x			x	x	x	

4.6. Conclusions

Chapter 4 considered the operational aspects for the TMS-ATO system, and described the general system and its components, to be understood as a system that involves three main objects: the Real-Time Traffic Plan (RTTP), the Train Path Envelope (TPE), and the Train Trajectory (TT). The chapter also included the scope of the general TMS-ATO system and of the three different objects. Additionally, the actors and entities involved in the TMS-ATO system were described, such as the TMS Operator, CTC operator, and Train driver. The different benefits for the System Users, i.e., passengers, railway undertakings, freight carriers, and infrastructure managers were also collected. Lastly, demonstration use cases, which will be used in the developments in WP16, were listed taking into account the scope elements.

5. TMS – ATO/C-DAS Functions and Interactions

5.1. Introduction

This chapter introduces the various TMS functions needed to keep an up-to-date RTTP and proposes four variants of TMS – ATO feedback-control loops depending on a passive or active ATO-TS and ATO-OB. It then provides a high-level logical architecture of the main components and functions of a TMS – ATO/C-DAS system, and their interactions. Finally, the existing relevant standards are listed relevant to the development of TMS – ATO/C-DAS systems. This chapter thus provides the general framework to understand all the components/functions developed in WP15 and their interactions.

5.2. TMS Functions for Updating RTTP

The TMS receives a railway traffic plan developed at the Capacity Management System (CMS) before operations. This (static) traffic plan contains the infrastructure capacity allocation in terms of routes, train orders over the route sections, and time targets or windows at stopping points and selected passing points for all trains running on the network for a given time period; typically a given day. It is assumed that this plan is realizable and conflict-free, such that it can be executed when all trains adhere to their scheduled train paths as detailed within this traffic plan. This plan is used as the initial version of the real-time traffic plan within the TMS that coordinates the train movements and timely route setting over the network. A main task of the TMS is to keep this RTTP up to date during the day of operation considering disturbances and disruptions that may cause deviations from the plan (Quaglietta et al., 2016).

Five main TMS functions can be identified that work together to keep an up-to-date RTTP (Quaglietta et al., 2016):

1. Traffic State Monitoring (TSM),
2. Traffic State Prediction (TSP),
3. Conflict Detection (CD),
4. Conflict Resolution (CR), and
5. RTTP Updating.

Each TMS function can be executed by a human operator, partially automated, or fully automated depending on ability, authority, and responsibility. A TMS can involve automation of all five functions at different levels (Parasuraman et al., 2000). Below is a description of each TMS function and the typical level of precision and automation in current practice. Afterwards, possible improvements in connection to ATO are discussed.

The *TSM function* provides the current traffic state, i.e., the position and speed of all trains on the network. It is based on data collected from the infrastructure (e.g., track-clear detection, train describer system) and the trains (e.g., train position and speed) via the traffic control and supervision system (TCS). The TSM function is usually highly automated based on input from the TCS. Typical examples of TSM information are track-layout screens showing set and occupied track sections with the corresponding train description, and lists of current (or last measured) train delays. The data is typically automatically received from interlocking and train describer systems. A typical manual action is a phone call between dispatcher and train driver to inform each other in case of exceptional conditions.

The *TSP function* (also known as train forecasting) predicts the train movements over the planned routes for a defined prediction horizon given the current traffic state, the current RTTP, and the current infrastructure state (e.g. temporary speed restrictions). In addition, it uses this information to predict the deviations from the current RTTP. The TSP function is often automated, although the accuracy depends on the available data and model/algorithm. A simple delay prediction method is given by extrapolating the current delays to the next stopping points. If information about running time supplements is available, then a more precise method subtracts the running time supplements from the current delay to model delay recovery by faster running. This is already becoming tedious to do manually but can easily be automated. More advanced methods compute the microscopic train movements by solving the dynamic equations of motion, which provides the entire (time and speed) train trajectory over the successive track sections given the current train and infrastructure state. The accuracy of these microscopic calculations depends on the accuracy of the used parameter values of the train and track characteristics. Nevertheless, the TSP focuses on predicting the train paths without considering the impact of any possible conflicts between delayed trains (or timetable conflicts). Typical examples of TSP information are lists of predicted train delays at specific locations or predicted train paths in time-distance diagrams, which are typically automatically generated based on the TSM data. However, most important task of the TSP is to provide input to the conflict detection function.

The *CD function* detects conflicts between predicted (free-flow) train paths based on the current traffic state, the current RTTP, and the predictions from the TSP. In particular, train path conflicts can be detected by overlapping train paths over shared track sections, either at macroscopic or microscopic detail. A complication is the detection of secondary conflicts after the first conflict between two trains, since the predicted train paths are no longer accurate after a first conflict unless the impact of that conflict is taken into account. Typical conflict detection models extend the free-flow train prediction models by incorporating information about shared routes and buffer times between train paths. This results in *train delay propagation* models where delays are propagated to other trains when a delay exceeds the buffer time to an adjacent train. Such models can be macroscopic based on given activity times between train evens, such as running, dwell and minimum headway times (Goverde, 2010) or microscopic with more advanced blocking time calculations that predict track occupation conflicts and resulting delays (Kecman and Goverde, 2014). At this stage, these algorithms do not include advanced conflict resolution measures, but assume that the planned routes and train orders are maintained, while train event times are pushed forward in time following delayed conflicting train paths. These models thus detect conflicts and provide a prediction of the impact of the conflicts including following conflicts. While the first conflicts can be predicted quite accurately, the following conflicts may be less accurate depending on how well any time loss at a conflict is modelled.

Typical examples of CD information in control centres are platform track occupation diagrams with overlapping trains at platform tracks, lists of endangered connections, and predicted train paths in dynamic time-distance diagrams. These dynamic time-distance diagrams are split into two parts divided by the current time, with the realized train paths from the monitoring information shown up to the current time, and the predicted train paths after the current time. If the predicted train paths are computed without consideration of track conflicts (free-flow train state predictions) then the time-distance diagram shows train path conflicts by overlapping train paths that could be highlighted as information to the traffic managers. If the future train paths are computed including the delay propagation between conflicting train paths then the time-distance diagram shows the predicted traffic when no rescheduling actions are executed (except retiming). Besides the predicted train paths, also the planned train paths from the current RTTP can be shown to highlight deviations from the planned train paths.

The *CR function* aims at resolving the detected conflicts using rescheduling measures, such as retiming, reordering and rerouting. Mostly, the CD and CR functions are combined in a Conflict Detection and Resolution (CDR) function, since any change in the timetable may cause conflicts elsewhere which should be detected and resolved as well (D'Ariano et al., 2014). The CDR takes the current RTTP and current train path deviations as input and computes a set of rescheduling measures that together provides a new feasible timetable. The resolution process can be guided by objective functions, such as minimizing train delays (deviation from the original timetable) or passenger delays (incorporating passenger flows and missed connections). The CD/CR interaction can be implemented interactively by solving one conflict at a time while maintaining a list of new conflicts and possible backtracking decisions to explore different search directions. Another option is to model the CDR problem as an optimization problem where the constraints model the activities between train events and decision variables model the rescheduling measures. An algorithm then tries to find a feasible solution such that all constraints are satisfied, while optimizing the objective function to improve the solution. Such optimization algorithms try out many solutions in a structured way and return an optimal solution or best solution found within a given time budget. Train rescheduling is an active field of research and many models, algorithms and methods have been developed to automatically reschedule trains in the best way possible (Cacchiani et al., 2014). Still, current practice is still based on manually solving conflicts by traffic managers using experience, best practices and predefined measures, while the automation is limited to supporting functions such as the CD function and interactive time-distance and track occupation diagrams where trains can be retimed, reordered and rerouted.

Finally, the RTTP is updated based on the CR results, which may change the train routes, train orders and timings of trains at TPs. The updated RTTP is then used to feed the route setting, train operation, and passenger information. Hence, the RTTP proactively resolves predicted conflicts by adjusting time targets/windows, train orders, routes, and/or platform tracks. This TMS cycle from TSM to RTTP updating is repeated at regular intervals or every time when new monitoring data is available depending on the network characteristics (Quaglietta et al., 2016). Updating the RTTP can be automated when the output of the CR is digitally available. In case of a manual CR process this may not be the case, by which dispatchers have to adapt the RTTP manually, i.e., change train routes, orders over routes, and timing at TPs in the plan, before it can be executed. This is still the current practice in most railways, which also hampers a rapid TMS cycle to feed railway operations with the most up-to-date plan.

The RTTP is updated using the TMS cycle to manage the railway operations, but disturbances are unavoidable. For instance, train departures may not occur as scheduled due to an extended dwell time or departure procedure, which also may lead to a delayed route setting for another train on a conflicting route causing a secondary delay for that train as well. Such delays cannot be predicted well in advance, and therefore will affect operations while a new TMS cycle is executed to update the RTTP with the latest monitoring information. In contrast, train runs are quite predictable and, therefore, deviations of arrival or passing times, and possible conflicts with other trains, can be predicted and resolved proactively based on current infrastructure and train status data. The faster the TMS cycle can be executed and the more accurate the results of each of the steps, the better the response to disturbances and the performance of railway operations. Here, automation is the key, in each of the TMS functions.

The CD/CR process works both for disturbances, i.e., relative small deviations from the timetable, and for disruptions, i.e., major changes to the timetable due to unavailability of (infrastructure, rolling stock, crew) resources (Cacchiani et al., 2014). In the latter case, the rescheduling measures may also include short-turning, train cancellations, rerouting over different railway lines, and other changes to the train services, as well as rolling stock and crew rescheduling. Disruptions essentially lead to a (locally) new timetable with changed train paths and resources, which provides a completely new RTTP. This RTTP is then a new basis for route setting and train operation, and the entire chain of TMS functions. Rescheduling for disruption management is more involved than for traffic management of disturbances, and typically takes more time. Rescheduling models, algorithms and methods for disruption management have also been developed that can support to speed up disruption management (Zhu and Goverde, 2019, 2020). However, here the role of human traffic managers will remain essential due the complex interaction of various stakeholders involved and the large impact on the traffic plan and different resources. In the remainder, the focus will be on disturbances since this is the main real-time control interaction with ATO. However, the TMS-ATO automated functions may also affect the human factors during disruptions.

In the case of ATO (including C-DAS), the RTTP must be translated into a TPE for each train which provides the essential constraints for train trajectory generation. The TPE generation can be another function of the TMS, or it can be executed by the ATO-TS. This will be explored in the next section. The introduction of ATO could also improve the performance of TMS functions by providing more accurate train data from the ATO-OB (or C-DAS OB), including predictions of the estimated time of arrival at TPs based on the generated train trajectory onboard. In particular, this may improve traffic state monitoring, traffic state prediction and conflict detection. This will be considered in Chapter 9. Also, the TMS-ATO communication will accelerate and standardize time target and route updates to the train onboard, which will result in faster response times between updates in the TMS and execution in the train (Chapter 10). This may have beneficial effects to operational performance, which will be explored in Chapter 7 and 8. Finally, more automated functions in the TMS-ATO interaction will also change the roles of human operators, including traffic managers, traffic controllers and train drivers, as well as their interaction. This will be considered in Chapter 11 and 12.

5.3. TMS-ATO Architectures and Feedback Loops

This section proposes different variants of TMS-ATO interactions and the impact of this choice on the resulting feedback control loops. Specific details and cases will be addressed in subsequent sections, highlighting how different configurations can impact the distribution of functions over trackside and onboard components, in particular the RTTP and train trajectory generation.

Updating the RTTP is a functionality of the TMS, but generating/updating the corresponding TPEs on a corridor and the train trajectories per train can in principle be a functionality of different components. The TPE may be generated by the TMS or by the ATO-TS, while the train trajectories may be generated by any of the three components of the TMS, ATO-TS or ATO-OB. In this view, four levels for the TMS - ATO interaction can be identified as in Table 5-1 depending on a passive or active ATO-TS and ATO-OB.

Table 5-1 TMS – ATO interactions for passive and active functions in the ATO-TS and ATO-OB.

	Passive Onboard	Active Onboard
Passive Trackside	**Remote Control** TS: Train trajectory from RTTP OB: Train trajectory from TS	**Onboard Intelligence** TS: TPE from RTTP OB: Train trajectory optimization
Active Trackside	**Centralized Intelligence** TS: Train trajectory optimization OB: Train trajectory from TS	**Distributed Intelligence** TS: TPE optimization OB: Train trajectory optimization

A passive ATO-TS assumes that the RTTP computed by the TMS includes accurate TPs and associated time targets or windows, such that the ATO-TS only needs to translate it into SPs and JPs for each train and send them to the ATO-OB. The handling of feedback from the ATO-OB is also limited in this case, as this will be a function of the TMS. It will be restricted mainly to passing information from the OBs when targets or constraints are infeasible, such as a deviating Expected Time of Arrival at a TP. The TMS then has to adjust the RTTP to facilitate feasible train trajectories or TPEs.

The ERTMS/ATO Subsets assume an active ATO-OB that generates the train trajectory based on a TPE that is received from the ATO-TS within the Journey and Segment Profiles. On the other hand, the ATO variants with a passive ATO-OB must essentially receive a fixed train trajectory from the ATO-TS. Hence, to enable a passive ATO-OB the ERTMS ATO-TS / ATO-OB interface should be extended to include speed information, like in the SFERA C-DAS-Central architecture.

Each of the four variants will generate different feedback control loop dynamics, which all can be advantageous depending on the circumstances. The four variants and their feedback control loops will be explained next.

5.3.1. Passive Trackside – Passive Onboard

Figure 5-1 shows the situation of a TMS – ATO variant with both a passive trackside and onboard. The picture shows four functionalities located at the three systems, including the two functionalities of train trajectory generation and tracking at the ATO Onboard. In this specific case, the functionalities are composed of RTTP optimization at the TMS, the extraction of train trajectories from the RTTP at the ATO Trackside, the application of these fixed train trajectories at the ATO Onboard of each train, and finally the tracking of the train trajectory at the ATO Onboards. The solid arrows indicate active feedback control loops, while the dashed arrows indicate information flow only.

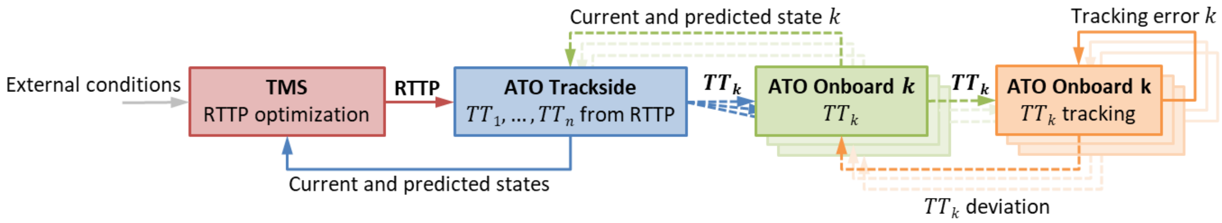


Figure 5-1 TMS-ATO feedback control-loops with passive TS and passive OB

In this TMS – ATO variant, the TMS generates the train trajectories of all trains and sends them to the ATO Trackside within the RTTP. This requires that the RTTP has to be extended to facilitate speed information. The ATO Trackside extracts the train trajectories from the RTTP and sends them to the ATO Onboard of the various trains. The ATO Onboard just uses the received train trajectory to derive the (traction/brake) control commands that track the reference train trajectory. For C-DAS this is a function of the driver, while from ATO GoA2 onwards this is a tracking algorithm, such as a cruise control for the cruising regime. Tracking a train trajectory is never fully accurate due to reaction times after deviations. As long as the tracking error stays within a preset tolerance the ATO/C-DAS onboard is able to follow the train trajectory and a status report can be sent back to the ATO trackside with (amongst others) the current and predicted state. The ATO trackside can also forward the status reports from all trains to the TMS to keep it informed about the progress. However, if the tracking error exceeds an acceptable bound (either measured in time deviation or position deviation from the reference train trajectory) then the train trajectory is no longer applicable, and a new one has to be determined. In this situation, a request for a new train trajectory is sent within the status report via the ATO Trackside to the TMS. The TMS then has to calculate a new feasible train trajectory for this train, which is then sent back via the ATO trackside to the ATO onboard.

This variant thus has two feedback control loops: one between the ATO trackside and the TMS considering train trajectory updates, and one within the ATO onboard (and the actual state monitoring within the train) to track the train trajectory. The ATO trackside and ATO onboard are passive in the sense that they cannot adjust the train trajectory. This has to be done by the TMS. Therefore, this variant can be viewed as a Remote Control with the intelligent functions located at the TMS. Note that the TMS does not directly command the traction and brake system onboard, but the (reference) train trajectory that should be tracked by the train via either the driver or ATO tracking algorithm. So, we always assume an active actor in the train that translates a reference speed profile to the required traction or brake commands.

5.3.2. Passive Trackside – Active Onboard

Figure 5-2 shows the TMS – ATO variant with a passive ATO trackside but an active ATO onboard. In this case, the ATO onboard generates the train trajectories that are being tracked. Since the ATO trackside is passive, the RTTP from the TMS should contain the TPEs that are extracted by the ATO trackside and send in Journey Profiles to the train ATO onboards. The ATO onboard will then generate a train trajectory satisfying the constraints and targets contained within the TPE. The tracking algorithm (or driver) will then track this train trajectory. If the tracking error exceeds the preset tolerance, then the ATO onboard will generate a new train trajectory that will be tracked from then onwards. If no feasible train trajectory can be generated within the TPE, then a request for a new TPE is sent in the status report via the ATO trackside to the TMS. The TMS then has to compute an updated TPE that is conflict-free with respect to the other traffic, which is then send via the ATO trackside to the ATO onboard.

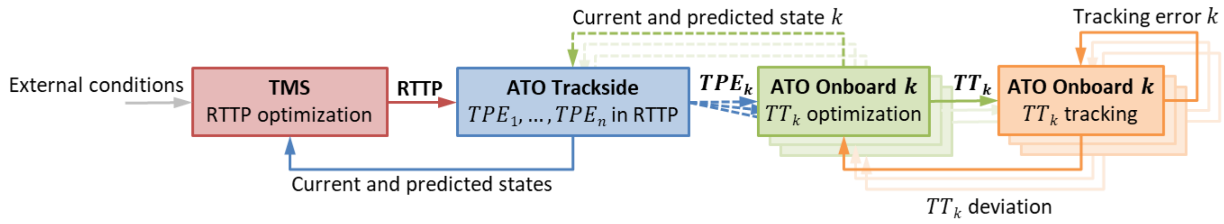


Figure 5-2 TMS-ATO feedback control-loops with passive TS and active OB

This TMS – ATO variant has three feedback control loops with an active update mechanism of the RTTP in the TMS, and active train trajectory generation and tracking at the ATO onboard. The ATO trackside is passive and cannot adjust the TPEs that it receives from the TMS encoded within the RTTP. Hence, the TMS is responsible to respond to feasible TPE update requests from the ATO. This variant can be framed as onboard intelligence with the adaptive train trajectory generation onboard.

5.3.3. Active Trackside – Passive Onboard

Figure 5-3 shows the TMS – ATO variant with an active ATO trackside but a passive train trajectory generation on the ATO onboard. In this case, the ATO trackside jointly generates the train trajectories for all trains sharing infrastructure based on the RTTP, where any conflicts can be resolved by adding extra timing points. The train trajectories are sent to the ATO onboards of the various trains, where they will be used directly by the tracking algorithm (or driver). If the tracking error exceeds a preset tolerance, then the ATO onboard sends a new train trajectory request to the ATO trackside. In calculating a new train trajectory, the ATO trackside can also adjust the trajectories of neighbouring trains to jointly optimize the train trajectories, where the current positions are taken into account. The updated train trajectories are then sent to the ATO onboards of the relevant trains to be used as updated reference train trajectory for the tracking algorithms (or driver) in each train. If the ATO trackside cannot find a feasible train trajectory for one or more trains, it sends an operational plan execution response to the TMS rejecting the operational plans of the associated trains. This message may include information about the infeasible TP(s) or combinations of TPs in the RTTP although this is not yet foreseen in the TMS-CCS interface specification in development by the System Pillar. Note that the ATO trackside can only use intermediate timing and speed adjustments while sticking to the time targets and windows specified in the RTTP to resolve any infeasible train trajectories. If this is not possible then the TMS can resolve feasibilities by retiming targets at stopping or passing points, or use even more drastic measures such as reordering or rerouting. The new RTTP with possible adjusted routes and time targets for some trains are then send to the ATO trackside for computing new train trajectories.

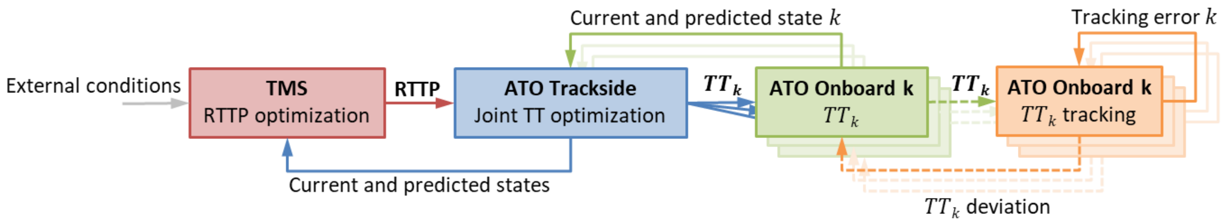


Figure 5-3 TMS-ATO feedback control-loops with active TS and passive OB

This TMS – ATO variant also has three feedback control loops. The control loop around the TMS-ATO trackside keep the RTTP up to date such that the ATO trackside can optimize the train trajectories. The control loop around the ATO trackside and the ATO onboard reoptimizes the train trajectories when a train deviated too much from the train trajectory, and third the tracking control loop in the ATO onboard between the actual and reference states (position or time deviations). This variant can be framed as centralized intelligence, since the ATO trackside can jointly optimize the train trajectories of sets of adjacent trains given the RTTP. The ATO onboard is passive in the sense that it just tracks the received train trajectory and requests a new one when tracking failed.

5.3.4. Active Trackside – Active Onboard

Figure 5-4 shows the final TMS – ATO variant with both active ATO trackside and onboard. This variant is the most advanced and can adapt its objects at all components. In this case, the ATO trackside optimizes the TPEs of all trains based on the RTTP received from the TMS. Here, the ATO trackside can decide to give more bandwidths to some train at the cost of a following train based on the current positions to optimize, for instance, to optimize the overall energy consumption. The TPEs are then send to the ATO onboards of the various trains, where each ATO onboard optimizes the train trajectory within the given TPE. When the tracking error exceeds the given tolerance, first the ATO onboard will generate a new train trajectory given the current position. If no train trajectory within the TPE can be found, this means that the train will violate the TPE and may therefore get into the TPE of another train. Therefore, the ATO onboard will request a new TPE to the ATO trackside that will generate new TPEs for the relevant trains. Based on the latest status reports of the trains, the TPE for the train that is not able to stay within its old TPE will be relaxed, which may lead to a restricted TPE to the following train, but possible also a relaxed TPE to its preceding train. If no conflict-free TPEs can be found or a train is not able to arrive on time at the next time target dictated by the RTTP, then the ATO trackside will request a new RTTP from the TMS and provide information about the conflicts in terms of infeasible TPs or groups of TPs.

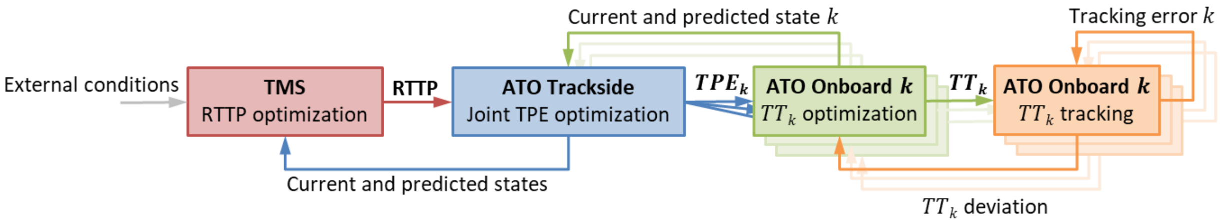


Figure 5-4 TMS-ATO feedback control-loops with active TS and active OB

This TMS – ATO variant has four feedback control loops, with correction mechanisms at all components to maximize resilience to disturbances and parameter variations. This variant can be framed as distributed intelligence. Each train optimizes its own train trajectory given a TPE that is coordinated with all other trains at a higher level at the ATO trackside.

5.4. TMS – ATO/C-DAS Logical Architecture

The TMS-ATO system should be able to provide any data necessary for ERTMS/ATO system operation by creating an interoperable interface for seamless and continuous data exchange between TMS and ATO systems. The TMS must provide the ATO-TS component with the following set of data:

- The train schedules for all trains running in the control area, at least to the extent for given ATO-TS to be able to fulfil the requirements of ERTMS/ATO Subset-125 (JP generation).
- List of stopping points including their characteristics and actions to be performed by trains after reaching given points.
- Information about set train routes for running trains, or RTTP of train paths for trains not yet running.
- List of temporary restrictions belonging to the control area of given ATO-TS.

In addition, according to the system architecture developed by the System Pillar another source publishes the description of the network topology belonging to the control area of a specific ATO-TS, at least to the extent of every data needed for Segment Profile creation, described in CCS TSI 2023 ERTMS/ATO Subset-126 (SP generation).

In the reverse direction, the ATO-TS must provide the TMS with the following information:

- Current location of running trains and their state description (ATO status, speed, etc.), as contained in the train status reports specified in the CCS TSI Subset-126.
- Estimation of future train movement timing provided by the ATO-OB to the ATO-TS for the TMS for traffic forecasting and conflict detection. This feedback is currently not envisaged by the System Pillar TMS-CCS design and would therefore need adjustments.

Figure 5-5 shows the high-level architecture of the TMS-ATO used as part of WP15/16. In this, the main components/functions of the system and interactions are identified. This has been created based on the input of the partners involved in WP15 and taking into account the TMS-CCS interface from the RCA and updates from the System Pillar. Within the diagram it is possible to differentiate between system components and system peripherals. The key system components are the TMS, ATO-TS, TMS <-> ATO-TS integration layer, ATO-OB, ETCS-TS and ETCS-OB.

The TMS is responsible for planning and management of train movements on the railway infrastructure. It should provide ATO with an RTTP specifying for each train the track description and TPs which the train should pass or stop at given times. These TPs should be positioned in such matter, that they are relevant for the train journey and operational planning only (i.e., stopping points), so that it does not interfere with ATO-OB's computed train trajectory incl. energy savings.

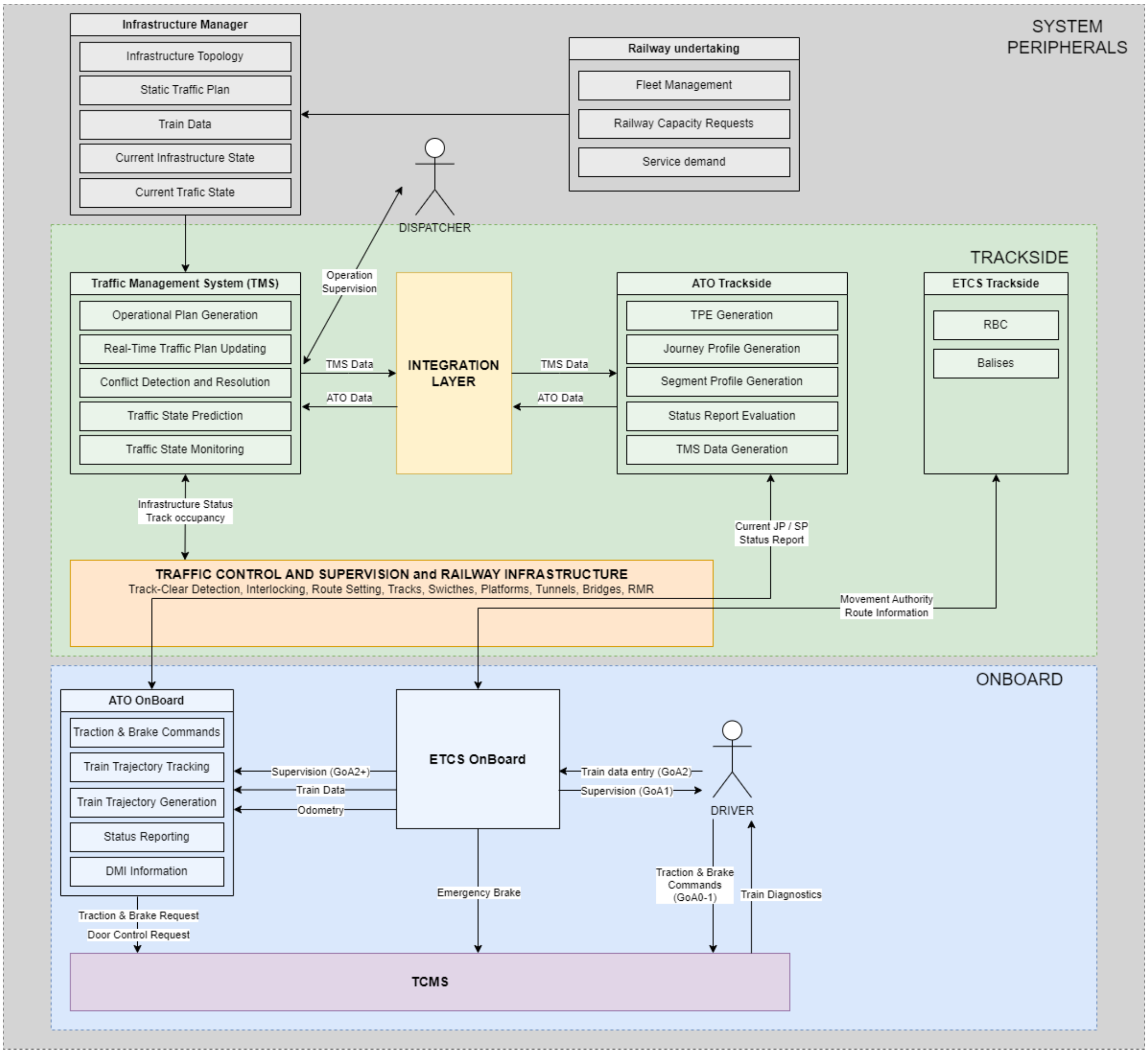


Figure 5-5 TMS-ATO high-level architecture

The TMS <-> ATO-TS Integration Layer (IL) is an interoperable platform providing the interface between the TMS and ATO. It is based on the Conceptual Data Model (CDM). For ERTMS/ATO in GoA2, ETCS provides ATO with a location reference, braking curves to respect, etc, using the interface defined by ERTMS/ATO Subset-126. The ATO-OB controls the train speed profile according to the restrictions provided from the ATO-TS by interfacing with the Train Control and Monitoring System (TCMS). Its purpose is to follow the received timetable by driving and stopping the train (requesting traction and brake), while optimizing energy efficiency given the (specific) circumstances. At stopping points, the ATO-OB performs requested actions, such as releasing the doors. Depending on the GoA, its operation may be initiated and supervised by the driver, other

on-board staff, or be fully autonomous. The ATO-OB also generates a Status Report (STR) and sends it to the ATO-TS. This is all specified in ERTMS/ATO Subset-125 and Subset-126.
The key system peripherals include the IM, TMS operator, interlocking, Railway Mobile Radio (RMR, such as GSM-R or FRMCS), train and driver. The IM possesses a dynamic database of all trains (scheduled, inactive, or running) and a database containing description of static elements of the infrastructure, while keeping dynamic information on any scheduled or occurring restrictions affecting the traffic flow or the usability of given parts of the infrastructure. The IM provides these data to the TMS, although implementing such an interface is provider specific.

The RMR (GSM-R, FRMCS) is a wireless data transmission system connecting ETCS-OB <-> ETCS-TS and ATO-OB <-> ATO-TS. This system could be proxied by a public mobile network or local ethernet network for the purpose of laboratory testing.

A train is a vehicle equipped with at least GoA2 ATO, ETCS and TCMS, to demonstrate train movement after successful TMS -> IL -> ATO data transmission. This could be simulated for laboratory testing. Under GoA2, the ATO is supervised and controlled by the driver. This includes operations such as commanding the activation of the ATO driving function. Then, if the conditions for activation are fulfilled, the ATO takes control of the train and automatically drives the train to the next stopping point.

5.5. Interfaces and Standards

The following (interface) standards from the CCS TSI 2023 are relevant to TMS-ATO.

- ERTMS/ATO Subset-125 – System Requirements Specification
- ERTMS/ATO Subset-126 – ATO-OB / ATO-TS FFFIS Application Layer
- ERTMS/ATO Subset-130 – ETCS-OB / ATO-OB FFFIS Application Layer
- ERTMS/ATO Subset-139 – ATO-OB / Rolling Stock FFFIS Application Layer
- ERTMS/ATO Subset-143 – Communication Layers for On-board communication
- ERTMS/ATO Subset-148 – ATO-OB / ATO-TS FFFIS – Transport and Security Layers.

In addition, the Reference CCS Architecture (RCA) and SFERA protocols are important references, as well as the Conceptual Data Model (CDM).

5.6. Conclusions

This chapter discussed the various TMS functions from monitoring to conflict resolution to keep an up-to-date RTTP. After that, four variants of TMS – ATO/C-DAS architectures were proposed together with their implications for feedback control loops between the main objects of the RTTP and TPEs. These variants depend on the choice of passive or active ATO-TS and ATO-OB. The ERTMS/ATO specifications assume an active ATO-OB with onboard train trajectory generation, which can be implemented with either a passive or active ATO-TS. In the active ATO-TS, fine-tuning of the TPEs is executed by the ATO-TS resulting in a distributed intelligence. With a passive ATO-TS this function should be executed by the TMS. Finally, a logical architecture of the various TMS – ATO/C-DAS components and their interactions is given, as well as pointers to the existing specifications related to the TMS – ATO/C-DAS architectures.

6. TMS – ATO/C-DAS System Requirements

6.1. Introduction

This chapter specifies the TMS – ATO/C-DAS functional requirements of the main functions and interactions explained in chapter 4 and 5. These requirements are used in the development of the components and functions within WP15.

The focus of WP15/16 is the TMS – ATO-TS interaction (including C-DAS). The ATO-OB and the train trajectory generation are an integral part of the TMS–ATO system but are not part of the developments. The interface ATO-TS / ATO-OB is already specified in the CCS TSI 2023 within the ERTMS/ATO Subsets, and likewise for C-DAS in the SFERA protocols. In contrast, the interface specification and interactions between the TMS and ATO-TS are still in development. WP15/16 therefore focuses on this latter part with an emphasis on the functional interactions to improve system performance.

6.2. Functional Requirements

The focus of the TMS–ATO functional requirements is to specify the requirements needed for the TMS – ATO/C-DAS interactions. The requirements are grouped into different parts. First, requirements are presented for the information objects that are used in the subsystems TMS, ATO-TS, and ATO-OB, namely the Real-Time Traffic Plan (RTTP), Train Path Envelope (TPE), and Train Trajectory (TT). In addition, functional requirements are given for the data communication and human factors. The details of the RTTP and TPE will be given in later chapters based on the requirements given in the sections below, and likewise for the data communication and human factors.

6.2.1. Real-Time Traffic Plan

ID	RTTP-1
Requirement	The TMS shall provide a Real-Time Traffic Plan (RTTP) that specifies for all trains the exact route, time targets or time windows at specific (stopping and passing) timing points along the route, and the passing orders at switches and crossings.
Comment	The exact route for each train must be known for both route setting and train operation. The RTTP must specify the event times at timing points (TPs) relevant for coordinating all trains on a network level, either by specific time targets or by time windows. Also, the order of trains over routes must be specified to guarantee a consistent execution of route setting and train operation.

ID	RTTP-2
Requirement	An RTTP shall facilitate robust feasible train paths for all trains.
Comment	The RTTP must enable conflict-free train paths for all train operations, taking into account process time variations that occur in normal operations.

ID	RTTP-3
Requirement	An RTTP shall facilitate energy-efficient train operation.
Comment	One of the objectives of ATO/C-DAS is to stimulate energy-efficient train operation. However, energy-efficient driving is largely affected by the RTTP. If no running time supplement is provided then the ATO/C-DAS algorithm cannot save energy, and likewise when excessive running time is given on short distances then the ATO algorithm must run at a slow speed without much options to save energy. In addition, a sequence of time targets or misplaced time windows at passage points may cause unstable driving behaviour where the speed has to be adapted after each passage point, which must be avoided. In case of delays, the TMS may decide to recover from delays as fast as possible or up to some TP to avoid high energy consumption, if possible, regarding other criteria.

ID	RTTP-4
Requirement	The TMS shall maintain a robust conflict-free RTTP by monitoring and forecasting train traffic, and proactively detecting and resolving conflicts due to disturbances based on infrastructure and train status reports.
Comment	Both route setting and train operation rely on a conflict-free RTTP, so any potential conflicts must be detected and resolved proactively before they occur in reality to avoid disturbances. Still, some delays cannot be predicted in advance, such as an extended departure process, in which case the RTTP must be updated as soon as possible after the departure to resolve any possible conflicts from the departure delay.

ID	RTTP-5
Requirement	The TMS shall reschedule the RTTP to resolve conflicts due to disruptions.
Comment	During disruptions, routes and train circulations may change. The RTTP must always represent an actual traffic plan to guide accurate route setting and train operation. This includes the impact of, e.g., temporary speed restrictions, rerouting, and short-turning. It could be impossible to (immediately) find a RTTP without non-commercial stops. Conflict-free could mean that trains have to wait at some point, or have to drive slowly, but that should be an exception.

6.2.2. Train Path Envelope

ID	TPE-1
Requirement	A Train Path Envelope (TPE) consists of a list of TPs with time targets or time windows over the train route for a train.
Comment	The TPE represents time constraints at given successive locations on the route of a train that must be satisfied by the train trajectory generation algorithm.

ID	TPE-2
Requirement	A TPE is embedded in Journey Profiles (JPs) and Segment Profiles (SPs) for communication between the ATO-TS and the ATO-OB.
Comment	JPs and SPs are defined in the CCS TSI ERTMS/ATO Subset-125 and Subset-126 as the message structure for communication between the ATO-TS and ATO-OB. Likewise, the SFERA protocol adapted the same standard for communication between the C-DAS TS and OB. The SPs include the route and TPs, while the JPs include time targets or windows associated to TPs.

ID	TPE-3
Requirement	A TPE shall comply with targets and constraints imposed by the RTTP.
Comment	TPEs must comply with timing, routing and ordering decisions in the RTTP to ensure that routes are set up in a timely manner as the train progresses through the network. Moreover, time targets at stopping points specified in the RTTP must be consistent with the TPE to enable on-time running according to the RTTP.

ID	TPE-4
Requirement	The TPE may include additional TPs with time targets and windows to those imposed by the RTTP, and restrict time windows at TPs imposed by the RTTP.
Comment	The capacity benefits of ATO/C-DAS-enabled operations stem from the ability to more accurately coordinate train trajectories through the network. To achieve these capacity gains extra TPs can be added to the TPE of a train to control the train trajectory at critical locations, while the RTTP considers a higher-level grid of main stopping and passing points. The TPE may also decrease time windows at TPs from the RTTP to avoid conflicts.

ID	TPE-5
Requirement	A TPE shall facilitate drivable train trajectories while remaining robust to variations in train parameters and small delays that could occur in the course of normal operations.
Comment	The computation of the train trajectory is defined by the TPE and associated constraints based on the train’s own performance characteristics and the driving mode (manual or ATO). The TPE (including the time targets and windows imposed by the RTTP) should avoid unnecessary time constraints that would lead to irregular speed behaviour, uncomfortable jerks, or (in GoA2) unacceptable train movements for the train driver.

ID	TPE-6
Requirement	TPEs shall be mutually exclusive to guarantee a conflict-free train trajectory for each train.
Comment	The primary objective of ATO/C-DAS is to operate trains in a conflict-free manner in accordance with the RTTP. To that end, the TPEs of any two trains should not permit both trains to reserve the same section of track at the same time, unless needed for e.g. coupling.

ID	TPE-7
Requirement	TPEs shall provide maximal freedom to optimize each train's trajectory, given the RTTP-imposed constraints and the need for conflict-free operation.
Comment	TPs must be provided with care to avoid overspecifying the constraints for train trajectory generation. Train generation algorithms are capable of computing energy-efficient speed profiles for given time targets (scheduled departure and arrival times) but are influenced by additional TPs. Any additional restriction decided at the trackside may lead to increased energy consumption and drivability issues at the onboard.

ID	TPE-8
Requirement	The TPE time targets and time windows shall allow for tracking errors, i.e., some buffer time around the TPE.
Comment	Train trajectory tracking algorithms in ATO and train drivers in C-DAS may not be able to accurately follow the given time targets and time windows from the TPE. Therefore, some tolerance should be allowed around the time targets and the time window bounds without causing conflicts. These buffer times are not included within the feasible driving area of the TPE but outside the TPE contours.

ID	TPE-9
Requirement	The TPEs shall be kept up-to-date based on the latest RTTP and train status reports.
Comment	The TPEs must comply with constraints imposed by the RTTP at all times, the driving mode used by each train (manual or ATO) and the positions and speeds of trains currently moving between stopping locations. If there is an inconsistency, there is a risk of a train's OB failing to find a drivable trajectory or failing to drive in a conflict-free manner.

ID	TPE-10
Requirement	Information about infeasible TPEs shall be reported to the TMS.
Comment	During train operation, a deviation from the trajectory may occur such that an updated train trajectory satisfying the TPE is no longer possible. When this occurs, and the conflict cannot be resolved by re-calculating the TPEs involved, the TMS must compute a new RTTP. This process can be improved by providing relevant information about infeasible running times, or conflict locations and the trains involved. Meanwhile, the TPEs that are possible to generate should be sent to the trains without conflicts.

6.2.3. Train Trajectories

ID	TT-1
Requirement	Up-to-date train trajectories (TTs) shall be generated for the driving mode currently in use.
Comment	The train trajectory is an input to the process that generates speed advice for the driver (C-DAS) or the traction/brake commands made by the ATO system. If a train trajectory cannot be computed for the driving mode in use (ATO or manual driving), it cannot be guaranteed that the train will run in a conflict-free manner. For instance, for ATO under ETCS Full Supervision, the train may operate to the warning braking curve (if implemented), whereas the permitted braking curve is used for manual driving.

ID	TT-2
Requirement	A train trajectory shall satisfy the constraints defined in the TPE.
Comment	The time targets at the stopping points provide the punctuality targets to the train trajectories, and the requirement that TPEs must be mutually conflict-free ensures that if each train respects its TPE then they will not experience unplanned braking due to conflicts. In C-DAS applications, drivers' acceptance of the provided advice also depends on the degree to which they trust that the system will provide them a conflict-free trajectory to follow.

ID	TT-3
Requirement	Train trajectory generation shall aim at energy-efficient driving.
Comment	Punctuality is incorporated in the TPE by specifying arrival time targets at stopping points (or departure times in case of departure time punctuality). Safety and capacity can be incorporated implicitly by providing time windows at timing points in bottlenecks. The remaining freedom within the TPE can be used for energy-efficient train operation. Unnecessary acceleration and braking should be avoided. Note that ATO is supervised by ATP (Automatic Train Protection, e.g., ETCS), which monitors and possibly intervenes when the speed exceeds the supervised speed or braking curves, similar to manual driving. The train trajectory should therefore respect the dynamic speed profile supervised by the ATP to avoid braking by ATP intervention.

6.2.4. Data Communication

ID	DC-1
Requirement	The communication module between TMS and ATO/C-DAS TS shall grant communication between systems from different owners through a common data structure, the Conceptual Data Model.
Comment	In the interest of maintaining interoperability within Europe, the information exchange for ATO/C-DAS, and their link to the TMS, need to be standardized. In order to do this, systems shall communicate using a common data structure, the Conceptual Data Model, which simplifies the integration of systems from different countries or different owners. This will allow infrastructure managers to easily exchange data on routes that cross national borders, improving the quality of the traffic management. Standardization also avoids the need for trains on cross-border routes to be equipped with multiple country-specific ATO/C-DAS systems, such as is the case with the many ATP systems in Europe. The data communication between the ATO-TS and ATO-OB, as well as between ATO-OB and ETCS-OB is specified in the CCS TSI ERTMS. SFERA also adopted this standard for C-DAS.

ID	DC-2
Requirement	The communication module between TMS and ATO/C-DAS TS shall support a modular architecture.
Comment	With the aim of an integration of systems within Europe, the architecture of the Railway System is modular: systems from different countries and different owners, especially across national borders, have to communicate with each other. To avoid having multiple interfaces, one for each system to be integrated with, the communication module used between TMS and ATO/C-DAS TS shall support a modular architecture by implementing a common data structure and a standard communication protocol.

6.2.5. Human Factors

ID	HF-1
Requirement	The system shall demonstrably have an equivalent Technology Readiness Level (TRL) as the Human Readiness Level (HRL).
Comment	The HRL and TRL scales align directly and similarly aim to structure the steps required to demonstrate the readiness of a technology for operational use. By aligning activities to achieve a certain TRL level and the associated HRL level, it is ensured that critical choices can be made with knowledge of both technology and human technology interaction. This requirement ensures that the technological components of the system are mature and prepared for technical deployment as well as demonstrated to be safe and efficient for operational use. In this way, repair costs later in the project, or problems in the operation, are avoided.

ID	HF-2
Requirement	The system shall be evaluated on its impact/interaction with human operator(s) through human factors research.
Comment	In its assessment, research requirements and human factors constructs and related measurement techniques will be considered and applied, in conjunction with the research question.

6.3. Mapping Requirements to Developments

Table 6-1 gives an overview of the requirements mapped to the various WP15 component/function developments. The developments are indicated by descriptive abbreviations (first row) and the chapter or section where they are described (second row). As can be seen, all requirements are considered at least once.

Table 6-1 Requirements used by the various component/function developments

	RTTP	TR	TPE	TMS C-DAS	TMS ATO	IL	JP	HITL	HF
	7.2	7.3	8.3	9.2	9.3	10.2	10.3	11	12
RTTP-1	x	x		x	x	x	x	x	
RTTP-2	x			x				x	
RTTP-3	x								
RTTP-4	x	x		x	x		x	x	
RTTP-5	x							x	
TPE-1			x				x	x	
TPE-2							x	x	
TPE-3			x					x	
TPE-4			x					x	
TPE-5			x					x	
TPE-6			x					x	
TPE-7			x					x	
TPE-8			x					x	
TPE-9			x					x	
TPE-10			x					x	
TT-1								x	
TT-2								x	
TT-3								x	
DC-1				x		x	x		
DC-2				x		x	x		
HF-1									x
HF-2									x

6.4. Conclusions

This chapter has listed the high-level functional requirements that relates to the components that are developed within WP15 and will be demonstrated in WP16. The requirements focused on the different information objects that are used in the process of linking TMS to ATO/C-DAS, as well as data communication and human factors. In the comments for each requirement the idea and purpose of the requirement are explained to give a better context and understanding. The requirements are used in the development of components and functions of the later chapters.

7. Real-Time Traffic Plan

7.1. Introduction

The TMS is responsible for producing an RTTP to minimize the impact of disturbances and disruptions on network-level performance. The RTTP is the tool by which the TMS coordinates the actions of the infrastructure, train operation, staff, and other operational processes to achieve conflict-free operations. For each train in the network, the RTTP contains its exact route through the network and the time targets or windows at all stopping points and selected passing points. At switches and crossings, the RTTP also specifies the passing orders of trains with conflicting routes. The RTTP is sent (via the operational plan) to the TCS for route setting and ATO/C-DAS (if present) to empower the TPE computation and train trajectory generation functions (FP1-MOTIONAL, 2024).

The routes, orders, and times specified in the RTTP are imposed as strict constraints in the feasibility or optimization problems solved by the ATO/C-DAS. The RTTP's route and time information also empower the railway's passenger information systems (e.g. indicating the assigned platform at a station stops, or modifications to departure and arrival times).

The TMS' objective is to minimize deviations from the planned timetable due to primary delays. This goal is achieved through the specification of an RTTP to coordinate the actions of the route-setting function(s), the ATO/C-DAS speed regulation functions, the staff in stations and on the trains, and to update the traffic information systems used by passengers to plan their journeys. The RTTP must specify the times of all events relevant to measuring network-level performance. Their inclusion in the RTTP ensures that execution-layer systems (which take the RTTP as an input) act in a manner that allows the measured performance (at the TMS-level) to be realized. To that end, the TMS also must continually verify whether the times in the current plan are still realizable, and that the operations-level systems' actions are sufficiently coordinated to achieve its plan. If the currently implemented RTTP is not realizable given the current traffic state and the actions of the different operations-level systems, it is said to contain a conflict. When this occurs, the TMS needs produce a new RTTP that is realizable given current traffic conditions, and the capabilities and limitations of the staff and systems at the operational level.

The TMS needs to maintain a conflict-free RTTP to guarantee proper generation of drivable trajectories for trains to follow. For an RTTP to be conflict-free, the ATO/C-DAS TS must be able to generate a set of conflict-free, drivable and robust TPEs complying with the RTTP-imposed routes, orders and timing constraints. Failure to compute conflict-free TPEs would result in the ATO/C-DAS trajectory generation algorithm not receiving required inputs to work. To avoid this situation, the TMS needs to continually verify that the RTTP is conflict-free (given the traffic state), and to propose and provide a new RTTP if the current one is considered infeasible. The requirement to maintain a conflict-free RTTP (where all performance-relevant times can be realized) is what allows the TMS to compare the impact of different RTTPs on network-level performance.

7.1.1. RTTP Required Content

The RTTP needs to include all information required to coordinate the different systems and staff at the operations level, and to measure network-level performance indicators. While the exact RTTP specification depends on the architecture of the operations-level systems, some elements are necessary in any system to allow the TMS to minimize the impact of primary delays on network-level performance, and to coordinate the different operations functions to achieve conflict-free operation.

In environments where C-DAS or ATO are used, the RTTP must specify (at minimum):

- Each train's exact route through the network (including scheduled stopping locations),
- Train order sequence at switches and crossings,
- Earliest permitted departure times at scheduled stopping points,
- Planned arrival times (as specific time targets) at scheduled station stops,
- Any other arrival, departure, or passing times relevant to coordinate traffic specified by either time targets or time windows.

For each individual train service, the RTTP must specify its exact routing through the network. The route must be specified with enough precision that there is no ambiguity as to which infrastructure elements are traversed by the train, or the position the movable elements are in when they are traversed. The train routing is also used to determine which platform the train will stop at in each station. The route specification is necessary:

- To ensure the correct route is set up for the train as it approaches each switch/crossing,
- To determine the infrastructure data (e.g. speed limits, grades, and temporary restrictions) necessary for performing the TPE generation and trajectory calculation,
- To indicate where staff need to wait at a scheduled stop (e.g. for a driver/conductor break, to assist passengers getting on/off, or to service the train),
- To assess whether a timed transfer is still possible if the RTTP is implemented (if transfer reliability is relevant for measuring network performance).

The specification of trains' exact routing through the network allows the TMS to identify which trains have conflicting routes at each interlocking. To ensure that the plan is properly implemented, the RTTP needs to include a strict order specification. This can be specified directly, or by providing approximate passing times from which a unique train order can be deduced at every route. At the plan execution layer, the order specification is used:

- By the route-setting function to determine the order the routes should be set up at each switch or crossing.
- To operate the direction locking system for bidirectional open track between adjacent route-setting areas (if there is geographical decentralization of the route set-up process).
- By the ATO/C-DAS TPE generator, to determine which trains' TPEs are adjacent (and thus could have a blocking time overlap).

If the train orders used for route setting are different from the one used for TPE generation, the ATO/C-DAS may fail to compute drivable and conflict-free trajectories. On single-track sections, where the receiving interlocking can unilaterally release the direction lock to a state with no direction set up, a deadlock will occur if the two adjacent interlockings cannot agree on the direction of the next train to enter the line. To prevent this, the TMS needs to dictate the orders to both systems through the RTTP.

The RTTP must include trains' earliest-permitted departure times at all scheduled station stops to coordinate the actions of the plan execution layer. In passenger operations, it is usually forbidden to depart early from a scheduled station stop, because it can cause passengers who rely on the published timetable to miss the service. Passengers' journey times also could be extended if a timed connection is missed because of changes to arrival and departure times, or changes to the platform assignments in the station. The earliest-permitted departure times are also used to check if missed timed transfers could occur in the RTTP, and to assess the impact on network performance. These departure times are also used by:

- The ATO/C-DAS TPE generator to check for conflicts of outbound routes after a station stop (because the train needs a movement authority to exit the station).
- All on-train staff (in GoA1-3) and, if applicable, platform staff, to determine when they need to be ready to obtain the starting conditions and start moving the train.

At short stops on open tracks departure times could also be rounded down to avoid unnecessary waiting by the train on its scheduled departure. In this case, the actual earliest departure time is the arrival time plus the dwell time.

7.2. RTTP Updater for Single-Track Lines

7.2.1. Description

A TMS might include a digitalized tool for making a time-space diagram representing the RTTP. Still, in many TMSs the RTTP is planned “manually” in the sense that there is no advanced automation or optimization that supports the TMS operator in the construction of the RTTP. This is the situation in, e.g., Sweden. The use of ATO or C-DAS will put new requirements on the TMS operator. There will be specific requirements when there is a mix of trains: some trains that have ATO/C-DAS and other trains that are unequipped. Some experience related to this from a Swedish large-scale test of C-DAS is reported in Fr8Rail II (2020). A few relevant conclusions are:

- When there is a mix of trains with both, equipped and unequipped trains, the advantages of C-DAS can be seriously reduced, challenging the motivation in investing in C-DAS.
- A mix of equipped and unequipped trains can increase the workload of the TMS-operators, as there is increased demand for always having a high-quality RTTP with good forecasting.

A background for the conclusions is shown in Figure 7-1, which illustrates a meeting on a single-track line between a C-DAS-train and an unequipped train, where the unequipped train is supposed to stop for the C-DAS-train. There is a timing point for the C-DAS-train at the meeting point (station C), which ensures that that train really follows the RTTP. However, there is an uncertainty of the exact arrival time to C for the non-equipped train. The TMS operator does not know if the train will arrive according to the RTTP (driving profile x), a bit later (driving profile y), or a bit earlier (driving profile z). Depending on the true arrival time at C of the non-equipped train, the timing point for the C-DAS-train should be adjusted. In the worst case, if the non-equipped train arrives a bit late, there will be an extra stop for the C-DAS-train which causes the train loses both time and energy, destroying the expected benefits of having a C-DAS. In order to keep the meeting and timing point in good shape, there might be many small adjustments on the RTTP, increasing the workload for the TMS operator.

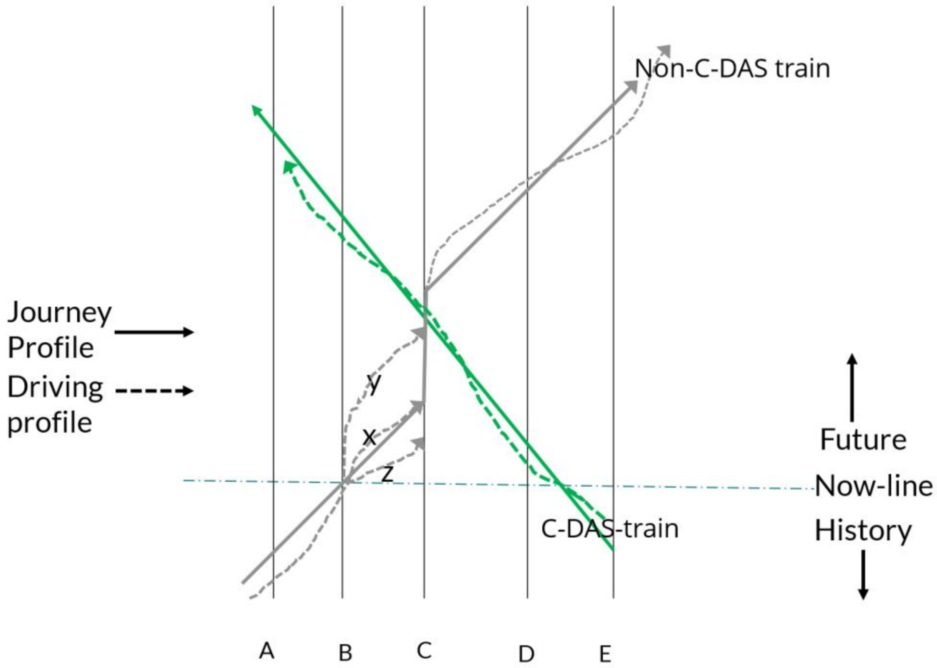


Figure 7-1 Illustration of the meeting between a C-DAS train and an unequipped train

These conclusions motivate the development of the support tool aimed at assisting the TMS operator in keeping the RTTP in good condition. Even though the Swedish experience is based on the use of C-DAS, the situation could be very similar also when using ATO. The support tool is further motivated in D15.1 (MOTIONAL, 2024) and is denoted *RTTP Updater*. The demonstration use case FP1-DEMO-16.2-UC-01 puts the *RTTP Updater* in a setting and describes its usage in relation to the TMS system. The *RTTP Updater* will be demonstrated in Demonstration 16.3 of WP16 (task 16.3).

The *RTTP Updater* has the following main functionalities:

- Performing short-term runtime forecasts for trains not equipped with ATO/C-DAS. The forecasted distance is from one interaction point to the next, assuming that the distance is conflict free. An interaction point is where the train has a planned start, stop, overtake or (on single line tracks) meeting. The module creating the forecast is denoted *Runtime estimator*.
- Performing (minor) time adjustments of the RTTP in the module *RTTP Finetuner*. A basic assumption is that the TMS-operator makes the decisions regarding train order and train paths while the *RTTP Finetuner* can determine the times in the RTTP based on TMS-operator's decisions. The idea is that these small timely adjustments can be made

automatically by the system without challenging the operator from being in control. The runtime forecasts from *Runtime estimator* are input to the *RTTP Finetuner*.

Trains equipped with ATO/C-DAS are expected to follow their JP, and consequently their RTTP. If an ATO/C-DAS train deviate from its JP and cannot follow it, there should be a feedback loop from ATO/C-DAS TS to TMS implying that the RTTP should be changed to make the JP feasible. Such changes are not the focus of the current developments of the *RTTP Updater* module. Instead, the developments aim to increase the quality of an RTTP that is runnable for the ATO/C-DAS-train.

The *RTTP Updater* gives the following advantages:

- Relieves the operator from making minor adaptions to the RTTP when train (non-C-DAS train) makes minor deviations from RTTP.
- Keeps the TMS-operator in control, letting him/her make the important decisions.
- Creates an optimal RTTP for C-DAS-trains, considering and balancing the timetable requirements, energy cost and operational robustness.
- Important component to secure the advantages of C-DAS (and ATO) also when a limited number of trains are equipped.

A tool like *RTTP Updater* is relevant in several different settings: for both C-DAS and ATO, double track and single track, freight traffic and passenger traffic. However, the focus of the developments of it in WP15/WP16 is for handling mixed traffic with both C-DAS and non-C-DAS trains, operating on single-track line, since this is the operating case where an improved RTTP would make most improvements in the Swedish rail traffic situation. Many of the principles would be similar in a generalized situation including double-track lines and/or ATO.

Table 7-1 summarizes the input and output data of *RTTP Updater*. The column class refers to validity-span of the data: static refers to that data does not change during one operational day, while dynamic refers to that data may change in a real-time manner, and the parameters are related to the control scope, result and performance of the modules. In addition, there is a data need for training of the deep learning algorithms in the *Runtime estimator*-module, not included in the table.

In WP15, the focus is on the development of first versions of the modules *Runtime estimator* and *RTTP Finetuner* and on the communication channel from Digital graf (see Section 7.2.2) to the *RTTP Updater*. The integration between modules, including data flow, will be limited. The primary test and evaluation case in WP15 will correspond to a case including:

- Three adjacent stations on a single-track line.
- Two trains, one equipped with C-DAS and one without, running in different directions, meeting on the intermediate station.
- Both trains of same class (regional passenger trains).

Table 7-1 Summary of data for RTTP Updater

Data type	Description	Class	I/O Data
RTTP	Real Time Traffic Plan	Dynamic	Input
Train positions	Latest know positions of relevant trains.	Dynamic	Input
Infrastructure	Macro level description of stations and tracks.	Static	Input
Static Traffic Plan (STP)	"Original" RTTP, corresponding to the timetable that the RTTP aims to minimize deviations from.	Static	Input
Train data	Operational weight and length of trains. Changes in engine power, acceleration or brake capabilities (in comparison to nominal capabilities)	Static	Input
Minimum and maximum runtimes	Shortest possible runtime and longest allowed runtime on each trip for each train.	Static	Input
Runtime-energy-correlation	Piecewise linear approximation/estimation of the correlation between energy consumption and runtime. One such function for each trip for each train.	Static	Input
Event separation time parameters	Time parameters, primarily from signalling system, regarding the traffic flow, e.g., minimum time between two arrivals from different directions.	Static	Input
Case parameters	Description of which trains that are in focus, which trains have C-DAS, etc.	Dynamic	Input
Robustness parameters	Settings for robustness aspects	Parameter	Input
Delay parameters	Settings for delay valuation aspects	Parameter	Input
Estimated arrival times	Runtime estimates to upcoming interactions for non-C-DAS-trains.	Dynamic	Output
p-RTTP	Proposed RTTP, i.e., the incoming RTTP with adjusted times (no change of train ordering)	Dynamic	Output

- None of the trains have yet departed from each respective first station of the three considered stations, i.e., the runtime estimations will start from one station (and not from an intermediate position along the line).
- Both trains have run more than five stations from their original departure station.

Complications and speed restrictions connected to pre-signals ahead of meeting stations are ignored and assumed to be handled by time separation between events (Lidén and Rydberg, 2014).

From a user perspective, this primary case is also the most important case. From this primary case, there are a number of generalizations to be handled in later versions of the system:

- Both trains are equipped with C-DAS.
- Trains have started their first considered trips (i.e., runtime estimations are made from an intermediate point along the line).
- Other classes of trains (other types of passenger trains, freight trains).
- One of the trains is less than five stations from its starting station.
- Other stations.
- Several meetings (without stopping) for one C-DAS-train during one start-stop cycle.

7.2.2. High-Level Architecture

The architecture setup used in the WP15 related to *RTTP Updater* is illustrated in Figure 7-2. The architecture consists of four major components, placed in both Trafikverket and RISE computer environments. The figure also illustrates the most important data flows. The data flow represented by black arrows will be developed and evaluated in WP15, while red arrows will be developed in WP16. Demonstration specific enhancements of Digital graf will be made in WP16.

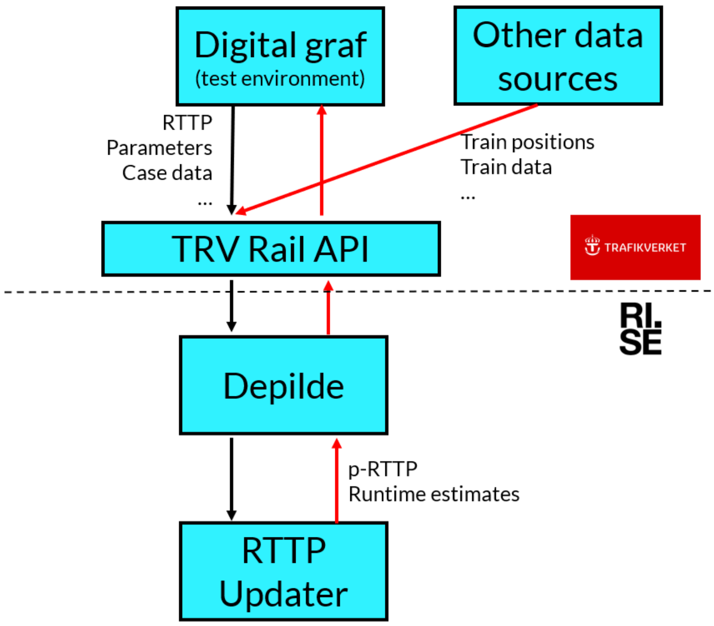


Figure 7-2 Conceptual architecture of RTTP Updater and surrounding systems

- *Digital graf* is the Human Machine Interface (HMI) of the TMS at Trafikverket. Digital graf includes a graphical interface for planning and updating the RTTP. In the setup for WP15, the test environment of Digital graf is used. The test environment uses the same base timetable as the production environment, but changes to the RTTP made in the production environment are not reflected in the test environment. Occasionally, the test environment has been used also to test connections to C-DAS trains, but in test for WP15, no actual C-DAS trains will be connected.
- *Trafikverket's Railway-API (Application Programming Interface)* is the data gateway at Trafikverket. Many different data types are handled in this API, e.g., RTTP and train position data. The API can handle data flow in both directions, in and out of Trafikverket.
- *Deplide* is RISE's generic platform for data sharing. Deplide listens to Trafikverket Railway-API (and other data sources) and different data consumers can subscribe to selected data streams.
- *RTTP Updater* is the component in which the main developments for WP15 are made. It consists of two modules, the *Runtime estimator* and the *RTTP Finetuner*.

In future versions of the architecture setup (not in MOTIONAL), the RTTP Updater could be an integrated module direct in the TMS (Digital graf).

7.2.2.1. Runtime Estimator

The module *Runtime estimator* makes short-term estimations of a non-C-DAS-train's runtime up to the train's next relevant interaction. A relevant interaction in this sense is either a planned (mandatory or technical) stop or a meeting or a take-over - as defined by the current RTTP. (For double-track lines, meetings should normally not be considered as a relevant interaction.) The aim is both to relieve the TMS operator from making minor time adjustments to the RTTP and to increase the precision in the estimations compared to manual estimations. The starting point of the estimation is the previous relevant interaction before the end of the estimation.

In WP15, all historical data used for training the models is truncated to minute level. In WP16, the precision of the estimations will be improved by both finer granularity of the time data and by utilizing the current position as starting point for the estimation.

7.2.2.1.1. Method

For estimating the runtimes, we apply machine learning models. The estimation problem can be seen as a time series where the content is continuous variation of time information. To handle this, we use the method known as Temporal Fusion Transformers (Lim et al., 2021). Temporal Fusion Transformers (TFT) is a neural network architecture specifically designed for time-series forecasting. TFT has the capability to make multi-horizon forecasting, enabling it to predict train delays at various future time points rather than just the next step. The method's interpretability is a significant advantage, as it provides clear insights into the factors influencing predictions, helping to identify the root causes of delays. The attention mechanism within TFT allows it to weigh the importance of different time steps and features, ensuring a focus on the most relevant information. Additionally, TFTs are able to handle mixed data types, including numerical features like historical delays and categorical features like train types and station attributes. The method of the Runtime estimator is further described in (Pichardo Vicencio, 2024).

The process involves combining historical and static data, using LSTM (Long Short-Term Memory) layers to capture sequential patterns, and attention layers to highlight crucial time points and features, ultimately generating better predictions for future delays. LSTM is a type of artificial neural network specifically designed for processing sequences of data, such as time series. It excels at remembering important information and discarding irrelevant details over long periods. It features memory cells that maintain information over time, hence the term "long-term memory."

The name "Transformers" in the context of TFT originates from the Transformer model introduced by Vaswani et al., (2017). This model is built around the self-attention mechanism, which allows it to weigh the importance of different elements in a sequence, regardless of their positions. This mechanism transforms the handling of sequential data by focusing on relationships between all elements simultaneously, rather than sequentially. It enables dynamic weighting, where each element can adjust its importance based on other elements, and allows for parallel processing, making computations faster compared to traditional sequential models like LSTMs. In TFTs, the self-attention mechanism captures temporal relationships and patterns in time-series data more effectively than traditional methods. It also transforms the fusion of different types of features (historical, future, and static) for forecasting, emphasizing the most relevant information.

7.2.2.1.2. Training Data

To build the runtime estimation model, we start by using historical data from 2023 including planned times, actual times, delays, station names and information about events. Train-specific information, such as train type, trip ID, and departure and arrival stations, is included to capture operational details. This data originates from Trafikverket's database for traffic data (LUPP), in which time data has a granularity of one minute.

Additionally, meteorological data like temperature during the trip is sourced from the Swedish Meteorological and Hydrological Institute (SMHI).

7.2.2.2. RTTP Finetuner

The module *RTTP Finetuner* makes minor adjustments to the RTTP. The result is a proposed new RTTP (p-RTTP) which the user of the TMS-system can accept or deny. The functional requirements on *RTTP Finetuner* are summarized as follows.

- The time aspects of the RTTP can be changed.
- Geographical aspects of train interactions must not be changed.
- The order of trains must not be changed.
- No stops are added or removed.
- Adjustments should balance three aspects of the RTTP: minimize delay, minimize energy consumption, maximize robustness.
- For trains without C-DAS, runtime estimates are used (input data from *Runtime estimator*). The runtime estimate may overrule the RTTP for non-equipped trains.
- The response time of the calculations should be fast enough to be used in a real-time setting.
- The quality of the resulting p-RTTP should be good enough for a TMS operator to accept the solutions without modifications.

The main technique used in the RTTP Updater is mathematical optimization (mixed integer linear programming). The mathematical model is based on (Lidén, 2013; Lidén and Rydberg, 2014) with some enhancements. It will be further developed in WP16, both regarding scope (the type of cases it handles) and integration in the surrounding environment.

The RTTP for a train is divided into trips, where each trip corresponds to a conflict-free run between two adjacent train interaction points. An interaction point is where trains have some kind of interaction in the RTTP, either a planned stop (according to the RTTP) or to a meeting or take-over (with or without a stop in the RTTP). For each trip, input data gives a piecewise linear estimation of the energy-runtime-correlation (see Figure 7-3), given the start/stop pattern in the RTTP. The energy consumption of the trains considered is the sum of the energy consumption of the trips. The data to construct energy-runtime correlations can either be provided by the C-DAS-system, or alternatively be collected from the energy measurement instruments on the trains. However, methods for calculating energy-runtime-correlations are outside the scope of WP15/16.

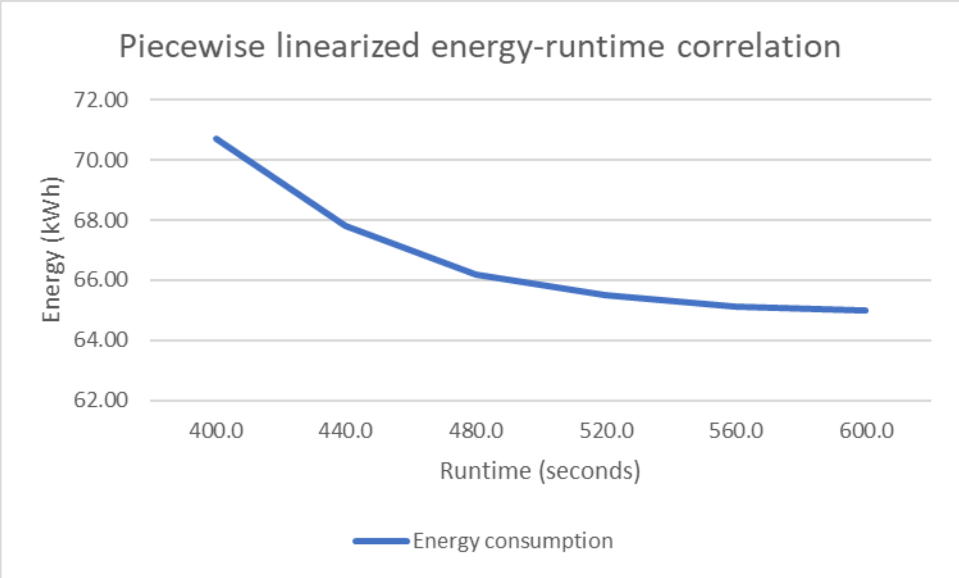


Figure 7-3 Conceptual energy-runtime correlation considered in the RTTP Finetuner algorithm

The RTTP includes information whether stops correspond to delivery commitments or are technical times. Delivery commitments are typically stops for exchange of passengers, but can also be exchange of driver or wagons, while the technical stops are added to regulate the traffic flow. Technical stops are typically meetings at passing loops on single-track lines, or overtakes on both single- and double-track lines. The times of technical stops can be changed as long as they have no negative impact, but the times of delivery commitments should be respected as far as possible. The *RTTP Finetuner* minimizes the delay in two ways at the delivery commitments; primarily, the deviation towards the RTTP is minimized and, secondly, if there is delay in the RTTP compared to the STP (Static Traffic Plan), the delay towards the STP is minimized.

Robustness is considered in two ways. Firstly, there is a fixed minimum time separation between adjacent events at a station, e.g., two arrivals of trains from different directions are separated by at least a minimum time. Secondly, a flexible buffer time is separating each event from its earliest or latest possible occurrence. The energy, delay and robustness objectives are contradictory, and the objective function in the optimization model weighs these aspects against each other to find an overall solution that balances all three aspects.

In WP15, the *RTTP Finetuner* is implemented using IBM ILOG CPLEX and the modelling language OPL.

7.2.3. Considered Cases and Illustrative Example

Two Swedish single-track lines are selected to be the focus of Motional WP15/16, and test cases will be selected for these lines. Figure 7-4 illustrates a map of the Swedish railway network and the two selected lines. The selected lines have different traffic situations. Important criteria in the selection of lines have been C-DAS-practical aspects, like the likelihood that there will be C-DAS-trains operating on the line. The traffic situation (like the number of trains and capacity utilization) varies along the lines.

Table 7-2 summarize some aspects of the selected lines. Here, a “traffic system” refers to a set of trains with similar operating conditions; in one traffic system the traffic is more or less homogeneous. Typically, freight traffic systems are more heterogenous than passenger traffic systems.

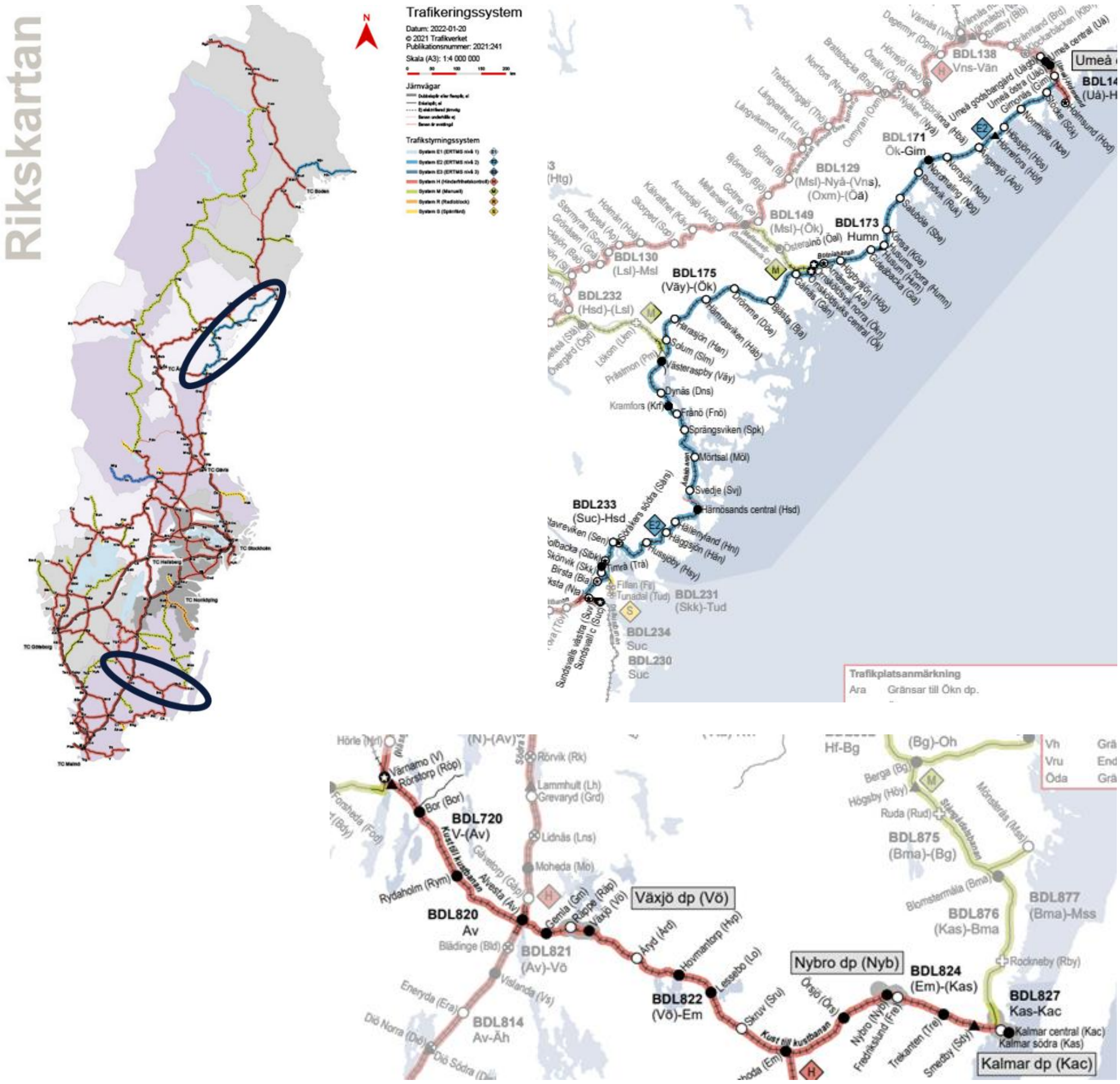


Figure 7-4 Swedish railway network maps with selected lines circled (left), the line Sundsvall-Umeå (top-right) and the line Kalmar-Värnamo (bottom-right). Source: Trafikverket

Table 7-2 Summary of some aspects of the selected Swedish lines

Aspect	Kalmar-Värnamo	Sundsvall-Umeå
Length (km)	180	310
Number of meeting stations	18	41
Traffic control centre	Malmö	Ånge
Signalling system	Swedish ATP	ETCS
Approximate number of trains per day for high utilization section	93	83
Approximate number of trains per day for average utilization section	50	45
Capacity utilization	Alvesta-Växjö: high, otherwise low	low
Number of traffic systems operating the line	3 passenger, 2 freight	2 passenger, > 5 freight
Highest speed (km/h)	180	200
Electrification	Yes	Yes
Other	Crosses southern mainline in Alvesta	

To illustrate the functionality of the RTTP Updater, we consider the scheduled meeting between the trains 1056 and 1097 on the Kalmar-Värnamo track line. Train 1056 goes (Malmö-)Alvesta-Kalmar and train 1097 goes Kalmar-Alvesta(-Malmö). The section Alvesta-Malmö is outside the considered single-track line. Both trains have planned stops for passenger exchange in, e.g., Växjö (Vö) and Hovmantorp (Hvp) and they are planned to meet at Åryd (Ård), see Figure 7-5. According to the RTTP, train 1056 has a planned stop to let 1097 pass (without stopping). Further, we assume that 1097 is equipped with C-DAS, while 1056 is not. In this example, train 1056 departs Vö with a minor delay. Given this, the *Runtime estimator* calculates an estimated arrival time for train 1056 at Ård. Given the estimated arrival time, the *RTTP Finetuner* calculates a p-RTTP. The p-RTTP is illustrated in the TMS, and the TMS Operator can choose to automatically update the RTTP according to the p-RTTP.

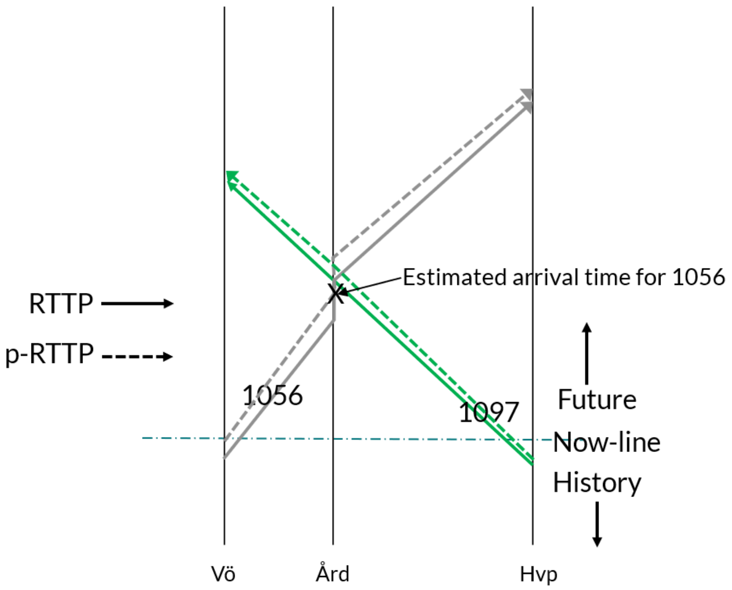


Figure 7-5 Illustration of the changes to RTTP that RTTP Updater makes

7.3. Traffic Regulator

7.3.1. Introduction

This section describes the first approach to the traffic regulation on a commuter line with continuous communication, focused on a double-track line with two terminal stations. This work is developed by IIT for CAF Signalling in the framework of the WP15 FP1-Motional project.

7.3.2. Requirements

Nowadays, traffic regulation systems are based on the centralized calculation of control actions and their dispatch at the stations arrivals and departures, which are the moments at which train delays are calculated. To take advantage of continuous communications, a traffic regulation model is proposed with the following requirements. This algorithm will be inside the regulator that belongs to the TMS.

The proposed traffic regulation model is intended for commuter lines with continuous communication. In this way, the trains delay can be supervised continuously, and the control actions can be recalculated at any moment. Considered is a two-track commuter line with two terminal stations, see Figure 7-6. Traffic is modelled as a set of N trains ($i = 1$ to N) circulating along M platforms ($k = 1$ to M), where each train follows train and stops at stations for passenger to get on and off. The considered number of trains is constant during the model execution.

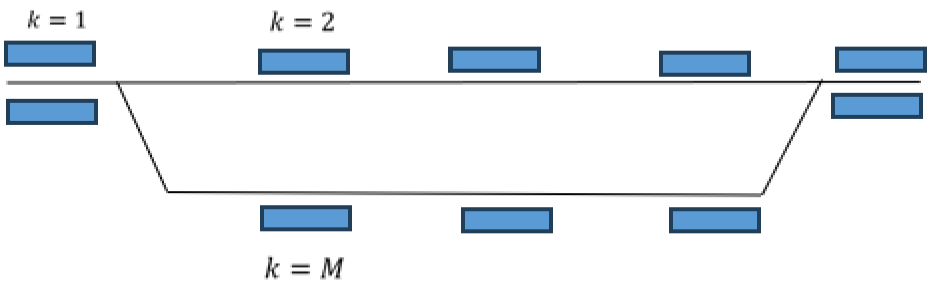


Figure 7-6 Line with terminal stations.

The target of a centralized traffic regulation system is to recover the schedule when delays arise, balancing the importance of timetable punctuality and headways regularity. The traffic regulation system supervises the traffic measuring the trains delays and calculates the control actions to be sent to each train in the line.

The proposed model can regulate lines with published and unpublished timetables. In other words, working with lines where the train can depart ahead the scheduled departure or not. The proposed model does not consider reordering, rerouting or rescheduling, only considers retiming.

The input data for the model are:

- Static Traffic Plan and nominal speed profiles to act as a reference.
- Real time traffic information (current position and speed of each train) to calculate delays.

- Operational constraints to be observed (minimum interval, minimum dwell times, early departure allowed).
- Line and train data (stop positions, gradients, speed limitations, train mass, train length, etc.) to predict train performance.

As a summary, a centralized predictive traffic regulation model for a railway mass transit line equipped with continuous communication technology is proposed, where the TMS can continuously quantify delays in all the trains and send target departure and arrival times via the ATO-TS through a radio communication system at any moment, see Figure 7-7. The model executes at regular time intervals a predictive control algorithm to recalculate the control actions.

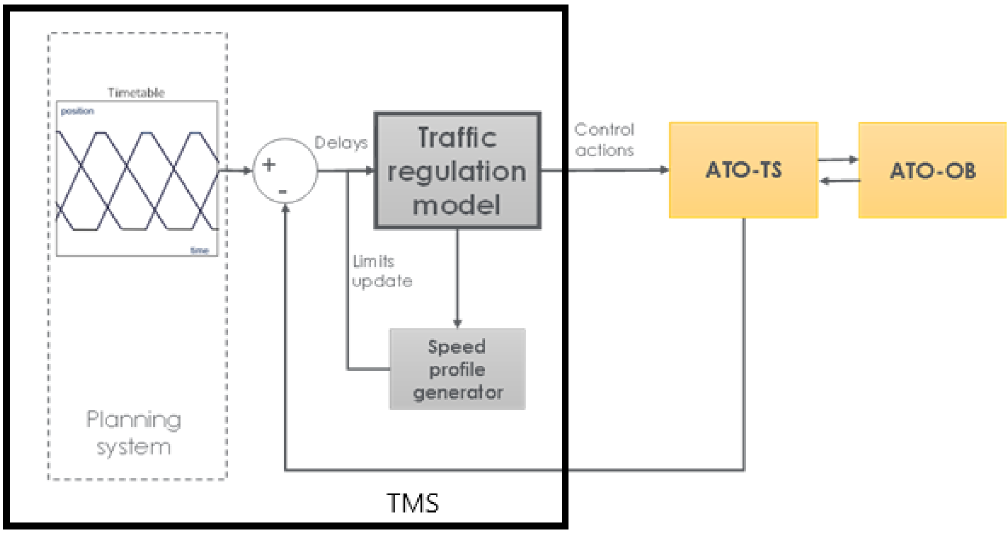


Figure 7-7 Traffic control scheme

7.3.3. Predictive Control Algorithm

The predictive control algorithm calculates the run and dwell control actions based on the quantification of train delays using a quadratic programming optimization model. This model takes advantages of the communication capabilities to control trains continuously according to traffic state.

The objective of the model is to minimize timetable and headway deviations of trains along a prediction horizon defined as the next L stations for each train. The control actions of the model are time corrections on the nominal running time and dwell time for each train and each station along the prediction horizon.

7.3.3.1. Cost Function

A prediction horizon is defined, which contains the next L stations for which the arrival and departure delays (Xa_k^i Xd_k^i) are to be calculated for each train i and station k, as well as the run and dwell control commands for each station (ur_k^i and up_k^i), see Figure 7-8.

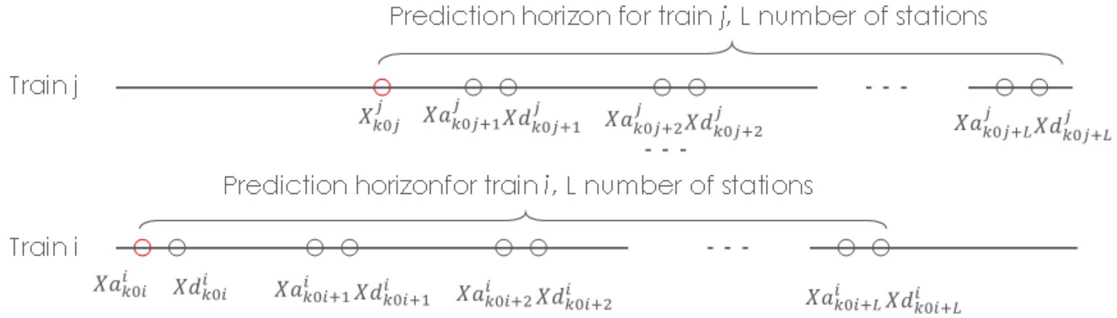


Figure 7-8 Traffic regulation prediction horizon

The cost function that minimizes delay and regularity criteria during the prediction horizon and the magnitude of control actions is defined as:

$$J = p * \sum_{i=1}^{N} \sum_{k=k_{0i}}^{k_{0i}+L} \left(Xd_k^i\right)^2 + q * \sum_{i=1}^{N} \sum_{k=k_{0i}}^{k_{0i}+L} \left(Xd_k^i - Xd_k^{i-1}\right)^2 + a * \sum_{i=1}^{N} \sum_{k=k_{0i}}^{k_{0i}+L} \left(ur_k^i\right)^2 + b * \sum_{i=1}^{N} \sum_{k=k_{0i}}^{k_{0i}+L} \left(up_k^i\right)^2$$

for each train i $(1 \leq i \leq N)$ and for each station k $(k_0 i \leq k \leq k_0 i + L)$, where $k_0 i$ is the next departure station of train i and L is the number of stations included in the optimization horizon. Additionally, constants p and q represent the weight of the deviation from the nominal schedule and the deviation from the nominal interval, respectively. Similarly, constants a and b represent the weight of the control actions for running time and dwell time, respectively.

Once the regulation strategy is decided, it is necessary to adjust values for the weights and that allow the system and the transient evolution to be stable. High value of p gives priority to observe the timetable and the commercial speed while high value of q gives priority to maintain the nominal headway.

Additionally, it is important to consider that the stability of predictive controls increases when the optimization horizon is longer. For this reason, it is necessary to choose a sufficiently large value for this horizon L.

7.3.3.2. Timetable and Headway Deviation

Different delays are calculated by the traffic regulation system to supervise the deviations from the schedule of every train. The delay of the scheduled departure time of a train is its measured departure time minus the published departure time. The delay of the scheduled arrival time of a train is its measured arrival time minus the nominal arrival time. Finally, the deviation from the nominal headway is calculated as the headway of a train minus its nominal headway. The departure headway of each train is calculated as the departure time from a station minus the departure time of the previous train from the same station. Consequently, the headway deviation can be calculated at each station as the delay of the departure time of a train minus the delay of the departure time of the previous train.

7.3.3.3. Traffic Model

The traffic regulator corrects the timetable and headway deviations modifying the trains' nominal running time between two consecutive platforms and the nominal dwell time at platforms. The optimization model includes the main operational constraints as explained next.

The running time of train i from platform k to $k+1$ satisfies

$$ta^i_{(k+1)} - td^i_k = R^i_k + ur^i_k,$$

where ur^i_k is the train i control action that modifies its nominal running time from platform k to $k+1$, R^i_k is the nominal travel time from the timetable of train i from platform k to $k+1$, td^i_k and ta^i_k are the measured departure time of the train from the platform and at the arrival time.

The lower bound of the control action ur^i_k is the difference between the fastest and the nominal running time, and the upper bound is the difference between the slowest and the nominal running time. The upper bound of ur^i_k is a configurable value and it is related to operational decisions. It can be the result of minimum running speed on track curves and/or of passenger comfort criteria.

The dwell time s^i_k of train i at platform k is calculated as the nominal dwell time S^i_k and the dwell control action up^i_k,

$$s^i_k = S^i_k + up^i_k.$$

The lower bound of the dwell control action up^i_k is the difference between the nominal dwell time and the minimum dwell time when the train has to recover delays.

If the operation rules establish that trains cannot depart before the scheduled time, a restriction is included limiting every departure timetable delay to be positive,

$$Xd^i_k \geq 0.$$

The signalling system is included in the traffic control model considering the minimum headway constraint. The interval calculated as the difference between the arrival time of a train minus the departure time of the previous train from the same station, must be greater than the minimum interval associated to the signalling system between an accelerating departing train and a braking arriving train, which ensures that the braking train is not perturbated by the signalling system. This also holds for the departure headway as well as at each block. Since the stop will be the critical block, it will be sufficient to consider only the departure headway and the departure-arrival headway.

7.3.3.4. Initialisation of Control Algorithm

It is possible to recalculate the control actions (up^i_k and ur^i_k) in any moment during the run with the proposed control algorithm. Therefore, the optimization problem could be initiated while a train is traveling between stations. The model includes this situation considering, for the first station of the simulation horizon $k_0 i$, the current delay of these trains, $X_k 0 i^i$, rather than their delay at the station departure Xd_k^i. The current delay of a train running between stations can be calculated knowing the nominal speed profile associated to the timetable.

Additionally, for these trains it is necessary to update the control actions limits $UR\max_{k0i}$ and $UR\min_{k0i}$. This is because the capability to recover and lose time is reduced during the train run with respect to the initial situation at the departure from the previous station.

As a clarification, the following figure shows a graph where, after the start of a run of any interstation, the velocity of that interstation is presented from a current time T against time. In this representation, it has been assumed that the train follows a faster speed profile than the nominal speed profile. Besides, as it was mentioned before, it is necessary to compute the fastest, slowest and nominal speed profile from the current spatial point where the train is for the recalculation of the control limits to be valid.

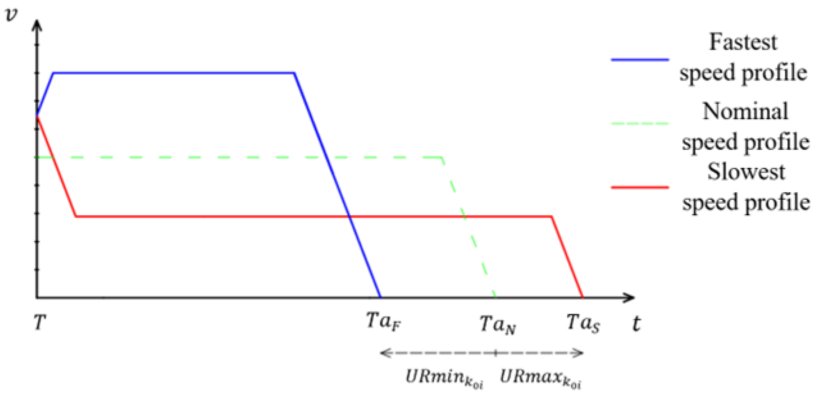


Figure 7-9 Schematical representation of the run control action limits

When the current time of the train is T according to previous figure, the arrival time at the next station according to the nominal speed profile is Ta_N. Similarly, the shortest interstation run time from that current time T is obtained if the train adopts the fastest speed profile which is marked by the solid blue line, arriving at the station at time Ta_F. On the other hand, the longest interstation run time from that current time T is obtained if the train adopts the slowest speed profile which is marked, arriving at the next station at time Ta_S. The slowest speed profile is related to operational decisions. It can be the result of minimum running speed on track curves to limit the wear in the wheels. Additionally, minimum speed limitations can be stablished for passenger comfort to avoid low cruising speeds that can be perceived unpleasant by passengers.

When a train i is stopped at the optimization initialization, the last delay measured is the delay at the last station arrival. Moreover, the limits for the control actions $UPmin_k$ and $UPmax_k$ must be updated at the first station k_0i of the optimization horizon. These limits are updated depending on if the time spent at the stations is greater or not than the minimum dwell time and the maximum one.

7.3.4. Expected Results

The proposed traffic regulation model will be tested in two traffic scenarios:

- Small disturbances. In this case, small delays will be randomly generated at each station departure. The performance of the traffic regulation model will be assessed in terms of timetable punctuality and headway regularity. Several metrics can be applied as the mean value and standard deviation of the timetable and headway delay.
- Big disturbance. In this case, a relevant delay is introduced to a single train to study the transient of the delay recovery process in the line. The expected result is shown in Figure 7-10.

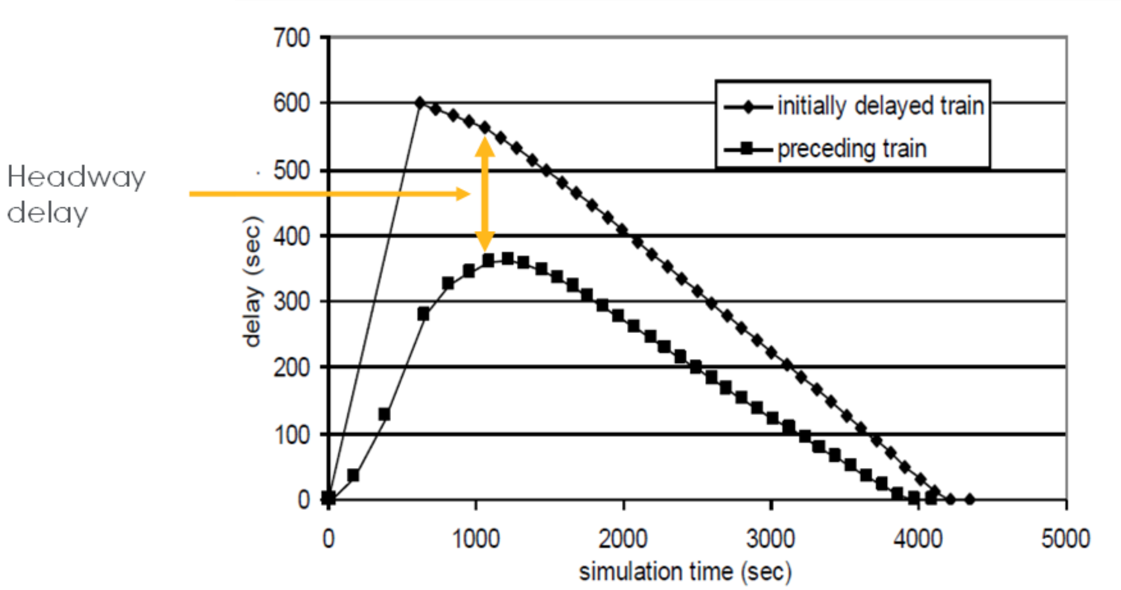


Figure 7-10 Expected results traffic regulation model

As can be seen, once a train suffers a big disturbance, the traffic model should delay the preceding and the following trains in order to improve the headway regularity during the transient. In the absence of new perturbations, the delays have to be completely recovered.

With the incorporation of the algorithm described in this section within the regulator (developed by CAF), we will be able to meet the needs of regulating rail traffic when small disturbances appear on the planned timetable. These regulations will allow us to deal with either frequency-based or time-base schedules. These timetables will depend on the area through which the train runs (urban core or branch lines) or the time of the day (rush hour or off-peak hour).

7.3.5. Communication between TMS and ATO-OB

Between the TMS and ATO-OB, communication is considered as in Figure 7-11. As illustrated in the diagram, the Traffic Regulator within the TMS communicates with the ATO-TS by sending an RTTP with the new timings of all trains. This RTTP will satisfy the requirements RTTP-1 and RTTP-5.

The ATO-TS will send the new timings of each train in an updated JP and SPs based on ERTMS/ATO Subset-126 to the ATO-OB. In the other direction, the ATO-OB shall send train status information in an SR to the ATO-TS. The ATO-TS will then communicate with the TMS in order to update the information available in the TMS. The algorithm that has been explained in the sections above will be included inside the TMS regulator developed also by CAF.

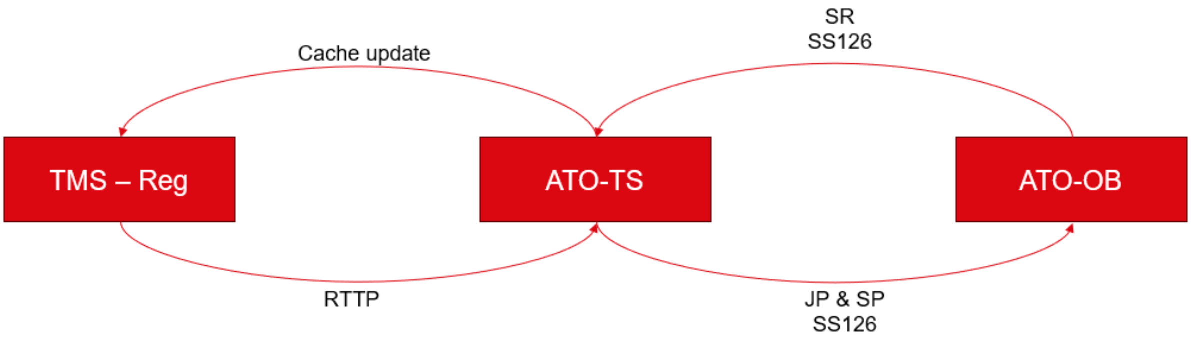


Figure 7-11 Diagram communication

7.4. Conclusions

This chapter discussed the RTTP concept and described two WP15 developments: an RTTP Updater for single-track lines, and a Traffic Regulator for commuter lines. Both aim at maintaining an up-to-date RTTP for different types of railways. The TRL4 validation of these developments can be found in Annex 15.2 and 15.3.

8. Train Path Envelopes

8.1. Introduction

The TPE provides the targets and constraints for a sequence of TPs for the train trajectory generation. The TPEs for all trains are generated at either the TMS or the ATO-TS and are part of the JPs and SPs that are sent to the ATO-OB of each train. We assume that the ATO-TS includes the functionalities of the C-DAS-TS, i.e., the data exchanges with the TMS and the Onboard are the same for C-DAS and for ATO GoA2 and higher.

This chapter starts with a definition of the TPE and several design choices. Then a TPE generator is described assuming a distributed TMS-ATO system with both an active ATO-TS and ATO-OB (see Section 5.3), which is valid for dense heterogenous mainline traffic operating under ERTMS/ATO, as well as generic railway traffic networks/corridors with closely following or crossing trains.

8.2. TPE Definition

A TPE is an ordered sequence of TPs over the route of a train, where each TP has as attribute a time target or time window, and possibly a speed window. A time window specifies the allowed range with a lower and upper bound for the timed event at the TP. The TPs provided by the RTTP should be contained within the TPEs, including the arrival and departure for stopping points, and a passage for passing points. The TPEs may contain extra TPs for guiding the track trajectories and avoiding track occupation conflicts, or restrict time windows at TPs defined in the RTTP. A TPE is the mathematical structure of the timing point restrictions that a train should follow. It is communicated using the journey profile and segment profiles as defined in the ERTMS/ATO Subset-125 and Subset-126.

The TPs are specified by their location and time attributes. The locations can be distinguished in

- Static: TPs are specified at given fixed locations,
- Flexible: TPs can be specified for a selection of fixed locations,
- Dynamic: TPs can be defined everywhere along a track depending on the actual situation.

Typical fixed locations are stop locations at platform tracks and block section entries at marker boards (or lineside signals in case of Class B systems). While the dynamic option is currently considered somewhat distant in terms of feasibility, theoretically it holds the potential to be the optimal choice. However, the primary focus will be on exploring the static and flexible types. The flexible option is particularly relevant from Dutch, Swedish, and Spanish perspectives, given their specific operational contexts and requirements. Therefore, prioritising the investigation of the flexible approach within these contexts is highly beneficial.

8.3. Train Path Envelope Generator

8.3.1. Objectives and Assumptions

This section describes an algorithm to generate TPEs for successive trains on a corridor. A TPE is used by a train trajectory generation algorithm for setting time targets and windows, ensuring the generation of a conflict-free train trajectory. TPEs should therefore be mutually exclusive while also allowing flexibility to accommodate various driving strategies and be robust to parameter uncertainties. This section assumes an Active ATO-TS and Active ATO-OB (including C-DAS). The typical application case is a double-track line with heterogeneous train traffic per direction, overtaking sidings at stations, and possibly short headways that may cause conflicts when trains deviate from their (planned) paths. Opposite and crossing movements are out of scope here.

The input to the TPE generator is an RTTP for the train traffic on a corridor and the output is a TPE for each train. The TPEs must comply with timing constraints imposed by the RTTP but may have additional TPs to avoid train path conflicts between RTTP stopping and passing points. We assume here flexible TPs at block entries, i.e., a TP may be added to each block entry with some additional time target or window. It is assumed that the RTTP is conflict-free and contains sufficient running time supplement for some assumed driving behaviour and train characteristics at the TMS, i.e., it facilitates conflict-free train movements. However, in practice, the train trajectory (speed profile and associated time-distance path) of a train may deviate from the precalculated speed profile calculations, even though the departure and arrival times are the same. For dense train traffic this may result in train trajectory conflicts at critical blocks where the headway is shortest, i.e., a following train has to slow down due to a restricted movement authority (MA). Such late braking is not energy-efficient, so this should be avoided. Therefore, robust TPEs should be derived that allow some variations in driving behaviour without creating conflicts. The required bandwidths and assumed driving behaviours should be the result of simulation studies. In general, different optimization goals for computing the RTTP and the TPE might cause restricted solution space.

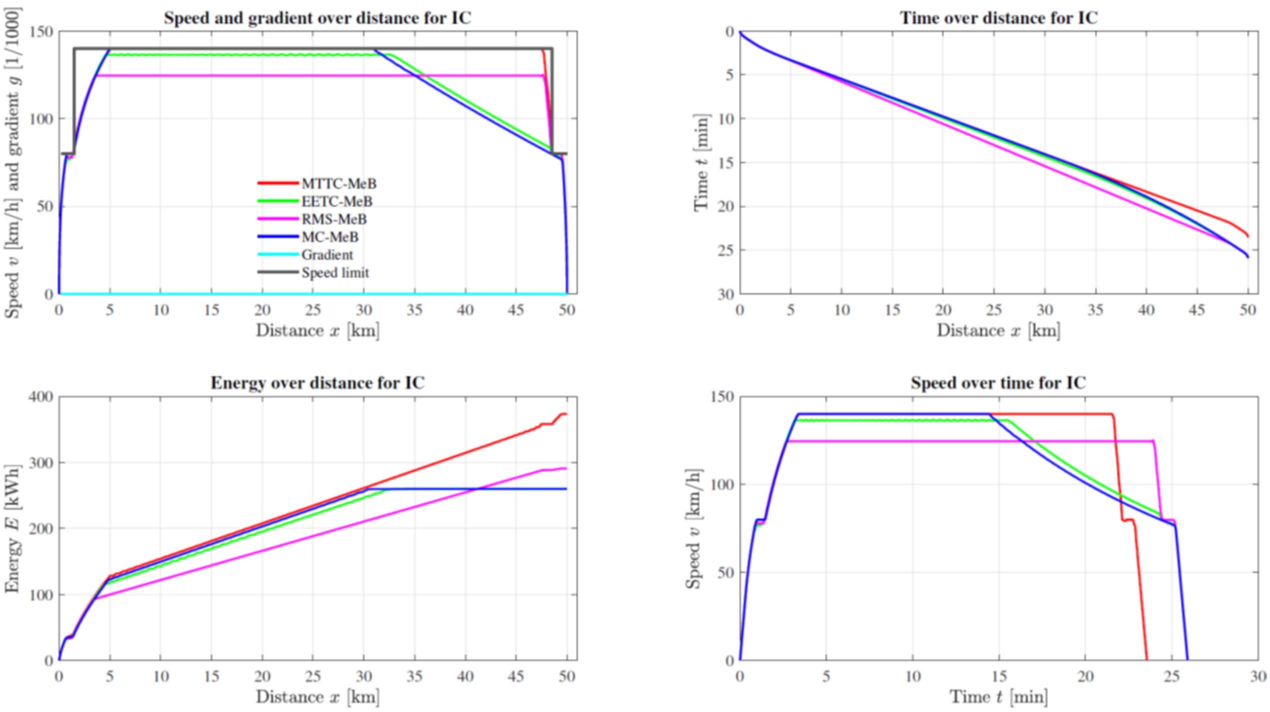
The aim of the TPE generator is to find the optimal TP locations and time windows such that successive trains will run conflict-free while maintaining as much flexibility as possible for energy-efficient train operation. If trains depart with large departure headways including large buffer times between the train runs, then extra TPs are not needed and the TPEs can just adopt the RTTP TPs leaving as much freedom to the train trajectory algorithm as possible. Similarly, on single-track lines where trains meet at meeting stations with time targets, the TPEs can just adopt the RTTP TPs, while the train trajectory remains flexible between the meeting stations. The interesting situation is for train traffic on double-track corridors with short headways between successive trains that may cause train path conflicts depending on the actual train trajectories of the successive trains. This will therefore be the focus of this section.

It is assumed that the RTTP contains a minimal number of TPs, i.e., the stopping points and possibly scheduled passing points at line junctions or non-stop stations. This condition is the most effective situation for the TPE generation. The TPE generator will then determine any additional TPs with the associated time windows needed for conflict-free train operation. The TPE generator jointly optimizes the TPEs for adjacent trains on a corridor by adding TPs with optimized time windows at critical points. These critical points are locations where train trajectories are too close to each other. Restricting train trajectories at these points will avoid conflicts, while leaving maximal flexibility to the ATO-OB train trajectory generation algorithms to compute energy-efficient train trajectories. The critical points vary depending on the actual train trajectories and are typically different for various pairs of train types, e.g., slow after fast, fast after slow, or more homogeneous trains. The TPE generator should therefore optimize the distribution of TPs and associated time targets or windows for all pairs of successive trains over corridors.

The TPE generation approach follows the following general scheme (see Section 8.3.4 for the full procedure). First, a corridor is defined between two stopping (or passing) points with time targets for all trains according to the RTTP. The typical corridor is a double-track line with one track used per direction and possibly different routings over intermediate and terminal stations that allows overtaking, merging or diverging. Then, a latest and earliest train trajectory are computed for each train on the corridor consistent with the RTTP. Next, any blocking time conflicts are computed between the latest and earliest train trajectories of successive trains, which are resolved by restricting the flexibility of the train trajectories by reducing time windows or adding extra TPs. The proposed approach below aims at optimizing this procedure with an optimal distribution of TPs over the corridors for all trains. We aim at maximizing the flexibility for energy-efficient driving by minimizing the number of extra TPs that restrict energy-efficient driving. Arrival time targets from the RTTP are considered as hard constraints. If no solution is possible then the RTTP was not conflict-free and should be adjusted by the TMS, which includes possible relaxation of arrival times, rerouting and reordering.

8.3.2. Initial Train Trajectory Bounds

By definition, a TPE provides a time envelope (or bandwidth) around possible train paths. This envelope may be fixed to a point at a TP where a time target is specified in the RTTP, whereas the train trajectory may be more flexible between such targets. Theoretically, if sufficient running time supplement is available many train trajectories exist over a route with the same planned running time between a given departure and arrival time. The latest such train trajectory corresponds to a postponed departure over the full running time supplement to the next time target, and then running as fast as possible with its minimum running time to the next stopping point. The running time supplement is the extra time above the technical minimum running time in the timetable in order to cope with running time variations and to recover from small delays. Some of the variations during planning may be known during operations at the TMS such as the exact train composition, while others are uncertain such as headwind and driving behaviour. This driving strategy is called the *shifted minimum-time train control* (S-MTTC) strategy. Any other train trajectory will depart earlier and cannot cross this latest train trajectory without the train arriving late at the next stopping point (assuming accurate train characteristics). Similarly, the earliest train trajectory could have the opposite driving behaviour to run as fast as possible to the next stopping point and then wait there for the full running time supplement. However, this approach would imply energy-inefficient train operation, higher capacity occupation at the station platform track, and possible disturbance to other traffic due to early running. Moreover, an early arrival is in fact a deviation from the arrival time target. Therefore, we aim at constructing TPEs based on train trajectories guaranteeing on-time arrivals at stopping points and other passing points with time targets.



Legend: MTTC (red), EETC (green), RMS (magenta), MC (blue), speed limit (black)

Figure 8-1 Illustration of the four basic driving strategies from different perspectives

Since energy-efficient train operation is a preferred goal to utilize the running time supplement (ERTMS/ATO Subset-125, 2023), the TPE should include the *energy-efficient train control* (EETC) strategy consisting of maximal acceleration to an optimal cruising speed, optimal coasting points depending on the gradient and static speed profile, and maximal service braking to standstill (Su, Tian and Goverde, 2024). There may be multiple acceleration, cruising and coasting regimes depending on the gradient and static speed profile. For short stop distances a cruising regime may also be absent, with the train switching directly from acceleration to coasting. Another typical driving strategy is maintaining a timetable cruising speed without using coasting, which is called the *reduced maximum speed* (RMS) strategy (Scheepmaker et al., 2020). This cruising speed is determined to fit exactly the planned running time together with an initial acceleration and final braking regime. In either case, the optimal cruising speed could be affected when speed restrictions apply to part of the route, which are then compensated for by a higher cruising speed elsewhere. The energy-efficient train trajectory is the earliest train trajectory in the time-distance domain compared to the zero-coasting RMS strategy. This is because it accelerates to a higher cruising speed to be able to coast at a later stage, while the speed during coasting may get lower than the no-coasting train. The two trajectories converge at the final braking regime since the time target is the same. Instead of the energy-efficient driving strategy, we may also consider the *maximal coasting* (MC) driving strategy (Scheepmaker et al., 2020), where the cruising speed is predetermined as the maximum speed with corresponding coasting points. These coasting points are earlier than the energy-efficient driving strategy but starting at higher speeds. This maximal coasting train trajectory is earlier than the energy-efficient train trajectory, and might therefore be a more robust choice for bounding the TPE. In this case, the optimal energy-efficient train trajectory computed by the ATO-OB train trajectory algorithm would be slower unless the optimal cruising speed happens to be the maximum speed (or higher but restricted to the maximum speed). This depends on the amount of available running time supplement. Figure 8-1 illustrates the four driving strategies.

The largest drivable flexibility for train trajectory generation over a given route with fixed departure and arrival times is thus given by the area bounded by a shifted minimum-time train control strategy and a maximal coasting strategy. The first represents a departure tolerance for late running while still arriving on time. It includes a late departure up to the full running time supplement, and also represents the largest operational tolerances at any point over the entire corridor. On the other hand, the maximal coasting strategy represents the earliest possible running without unnecessary braking or waiting. The optimal cruising speed for energy-efficient train operation may be lower than the associated maximum speeds, which thus provides additional flexibility to the ATO-OB train trajectory algorithm. Note that the optimal cruising speed is determined by the available running time supplement given by the RTTP.

8.3.3. Blocking Time Overlap Detection and Resolution

If the earliest and latest train trajectories of a train do not conflict with those of the adjacent trains, the time-distance area enclosed by them can be used to optimize the actual train trajectory by the train trajectory generation algorithm. In such cases, no additional constraints have to be set in the TPE, since a train trajectory generation algorithm will not generate a train trajectory outside of these bounds. However, if headways are shorter, the latest trajectory of the preceding train and the earliest trajectory of the following train may get too close and need to be restricted to avoid conflicts. Conflicts can be detected using the blocking time theory (Pachl, 2002). In particular, a variant of the UIC timetable compression method can be used to compute the minimum line headway times between successive train pairs (UIC, 2013). This method has been extended to cover a range of trajectories for a single train between an earliest and latest train trajectory contour (Wang et al., 2024). The choice of the specific driving strategies of these train trajectories determines the width between the contours over distance. These contours may also result from mixed train trajectories, i.e., the minimum and maximum over the considered trajectories.

Blocking times enrich time-distance train paths by including the actual time slots during which successive blocks are blocked for a specific train path to ensure conflict-free train operation. The blocking time theory can be used to compute the actual infrastructure occupation by trains using a microscopic view of the railway operations, particularly focusing on the impact of the signalling system on the required train separation. This infrastructure occupation goes beyond the physical occupation of blocks and makes use of blocking times which indicate the time slot that a block must be allocated exclusively to a specific train for conflict-free operation. The infrastructure occupation of a train path operating under fixed-block signalling takes the form of a blocking time stairway in a time-distance diagram. Conflicts are now easily detected and visualised by overlapping blocking times, which indicate that a train already requests to reserve a block that has not yet been released by the previous train. In addition, by compressing the blocking time stairways over a railway line, the minimum line headway times can be calculated, accounting for the impact of running time differences of successive trains for heterogeneous traffic. The minimum line headway corresponds to critical blocks between the successive train paths where the buffer time between the blocking times is the smallest (and zero in the compressed timetable). If the scheduled train paths respect these minimum headway times at the line level then they are conflict-free. Some buffer time around the (critical) blocking times must be available to preserve conflict-free train operation considering slight train path variations.

A minimum buffer time is required to avoid conflicts due to tracking errors of the train trajectory tracking algorithm. A train trajectory tracking algorithm will never be fully accurate at all times, and, in particular, may deviate from the reference train trajectory during driving regime switches, changes in gradients, or due to parameter variations such as wind speed. Therefore, a tolerance is specified around the reference train trajectory that should be respected by the tracking algorithm. Typically, a *tracking tolerance* is specified. The train trajectories should be robust against such tracking tolerance both before and after.

A train route defines consecutive block sections between stopping (or passing) points, including block sections on the running line and in interlocking areas. A train path is defined by a given train route together with the running time over the route. Hence, a planned route must be provided for each train. This is also needed to identify (partial) conflicting routes of trains. A blocking time consists of six time components as illustrated in Figure 8-2. The *setup time* t^{setup} is the required time to request the route, derive and communicate the movement authority (MA) to the train, and display it on the driver-machine interface (in case of ETCS). The *reaction time* $t^{reaction}$ represents the required time to perceive and respond to a brake indication in case of a restricted MA. The *approach time* $t^{approach}$ models the running time over the braking distance and safety margins to the actual block. The *running time* t^{run} is the time to traverse the block. The *clearing time* t^{clear} is the running time over the train length at the end of the block until the train has left the block. And finally, the *release time* $t^{release}$ is the time to release the route to be used by the next train. In addition, we consider an extended blocking time to account for tracking robustness by adding a tracking tolerance $t^{tolerance}$ to both ends of the blocking time. The approach, running and clearing times depend on the train speed, while the other three time components are often defined as time parameters conditional on the given infrastructure conditions. Note that the blocking time exceeds the physical occupation time of the block due the signalling constraints that require a train to start braking when it would get too close to its predecessor and additional system times required to set up and release the route. Hence, the blocking time represents the minimum headway time between two successive trains at a block.

The setup time in interlocking areas must align with a trigger point to initiate setting up a route ahead. The latest time to receive an MA extension is the brake indication point to the route, which would be optimal from a capacity point of view. In ETCS Level 2, the route request triggering a route setting command to extend a route should therefore be aligned with the setup time consisting of the route request by the ETCS Trackside to the interlocking, the route setting and locking by the interlocking including the time required for operating any points, the MA generation by the ETCS Trackside, the communication of the MA to the ETCS Onboard, the computation by the ETCS Onboard of the supervision limits until the new End of Movement Authority, and displaying the MA information on the Driver Machine Interface (DMI).

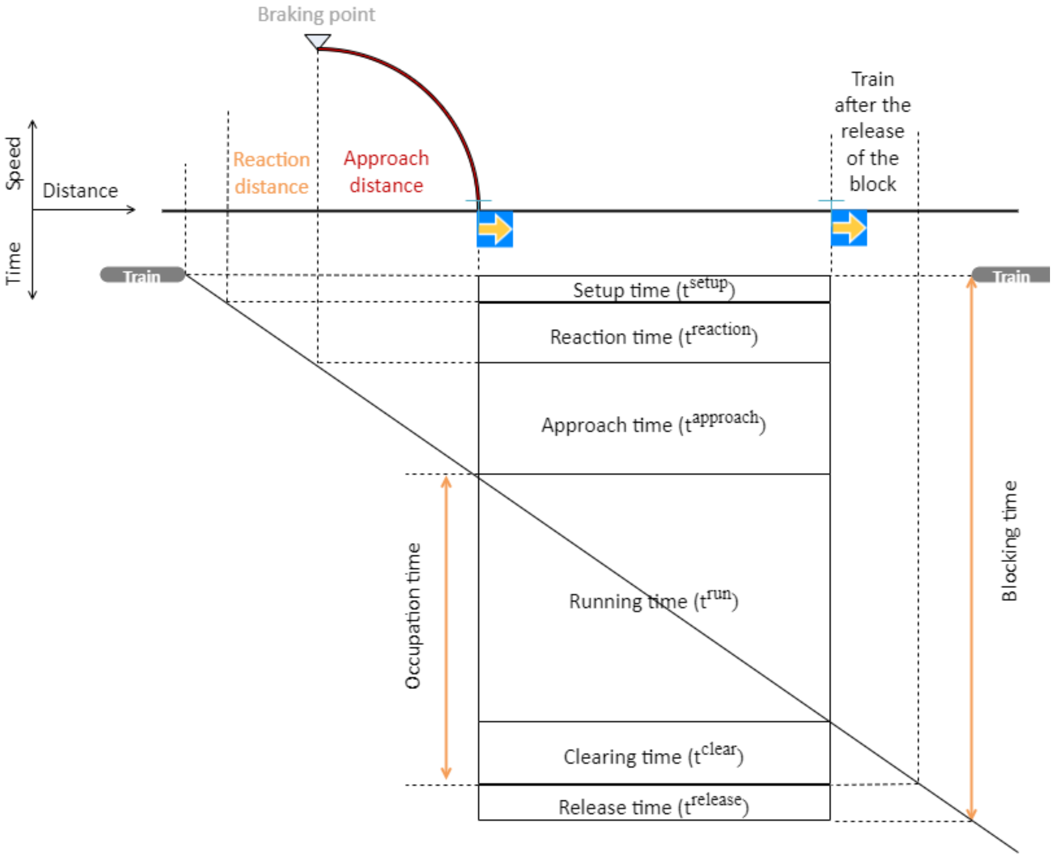


Figure 8-2 Blocking time components in time and distance

The successive blocking times over a train route form a blocking time stairway for that train indicating its infrastructure occupation, see e.g. Figure 8-3. For the computation of the blocking times the running times over the blocks are needed. Hence, the running time over the route in a train path should correspond to an actual speed profile incorporating the application of the running time supplement, i.e., the running time over the successive blocks is based on the subsequent driving regimes such as accelerating, cruising, coasting and braking, and should respect infrastructure and rolling stock characteristics and constraints. These calculations can be done using train trajectory optimization models (Su et al., 2024).

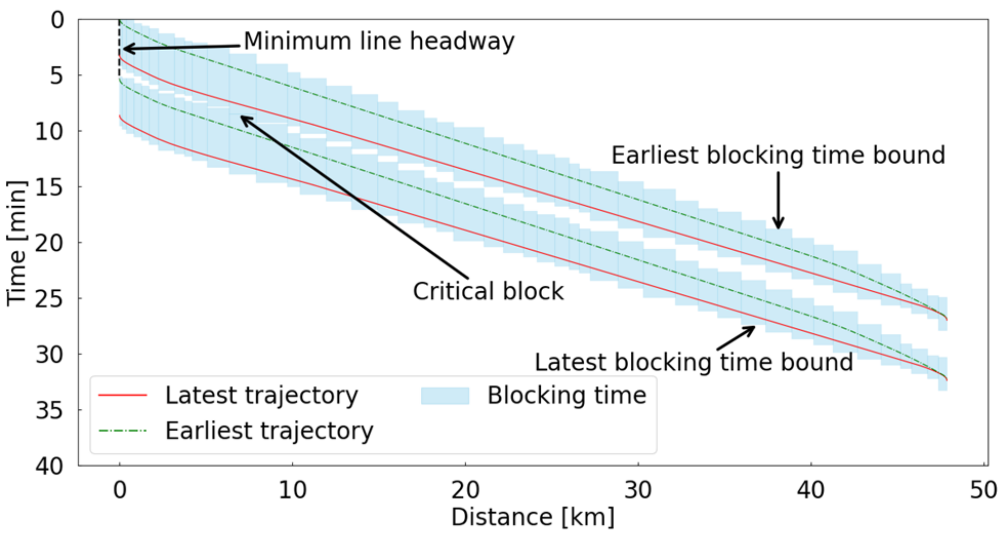


Figure 8-3 Compressed blocking time diagram for multiple driving strategies of two trains

To detect conflicts between the initial train trajectory bounds, we compute the minimum line headway time corresponding to the earliest and latest train trajectories of two successive trains as follows. Consider two consecutive trains p and q, in this order, and denote by $t^L_{p,b}$ the running time to block b by train p according to the latest train trajectory, and by $t^E_{q,b}$ the running time to block b by train q according to the earliest train trajectory. Also denote the corresponding end of the blocking time of block b of train p by

$$\bar{t}^L_{p,b} = t^L_{p,b} + t^{L,run}_{p,b} + t^{L,clear}_{p,b} + t^{L,release}_{p,b} + t^{tolerance},$$

and the beginning of the corresponding blocking time of train q by

$$\underline{t}^E_{q,b} = t^E_{q,b} - t^{E,approach}_{q,b} - t^{E,reaction}_{q,b} - t^{E,setup}_{q,b} - t^{tolerance}.$$

Finally, denote by $B_{p,q}$ the set of block sections over a corridor used by both trains p and q. Then the corresponding minimum line headway between train p and q over this corridor for the given train trajectories is given by the maximum overlap when the successive train paths would be scheduled to` depart at the same time (Wang et al., 2024)

$$h^{L,E}_{p,q} = \max_{b \in B_{p,q}} \left(\bar{t}^L_{p,b} - \underline{t}^E_{q,b} \right).$$

This minimum line headway time is the minimum time separation between two train paths at the beginning of the line that provides conflict-free train runs, see Figure 8-3. The critical block for a train path pair (p, q) where the successive blocking times are closest is the block $b^* = b^*(p, q)$ where the maximum is achieved, i.e.,

$$b^* = \operatorname*{argmax}_{b \in B_{p,q}} \left(\bar{t}^L_{p,b} - \underline{t}^E_{q,b} \right).$$

The critical block does not have to be unique when multiple blocks are at the same shortest time distance. Note that in the compressed timetable all blocks other than the critical block(s) have some extra positive buffer time between the successive trains.

Let $h_{p,q}$ be the actual line headway on the corridor, i.e., the departure time headway at the first station of the corridor. If $h_{p,q} \geq h^{L,E}_{p,q}$ then the two extreme train trajectories are valid bounds for the trains, and there exists an additional nonnegative buffer time between trains p and q of $h_{p,q} - h^{L,E}_{p,q}$. On the other hand, if $h^{L,E}_{p,q} > h_{p,q}$ then the two extreme train trajectories are not conflict-free and have an overlap at the critical block of $h^{L,E}_{p,q} - h_{p,q}$. However, the latest train trajectory of train p corresponds to a shifted departure time over the running time supplement t^{sup}_p to the next stopping point. So, in this case this departure tolerance is too large and we may try to reduce it to resolve the conflict between the two extreme train trajectories. We therefore replace the shifted minimum-time driving style by a shifted reduced maximum speed driving profile. The shifted minimum-time driving strategy can be viewed as a special case of the shifted ‘reduced’ maximum speed strategy with maximal shift of the full running time supplement and zero speed reduction.

The other extreme is the reduced maximum speed (RMS) strategy which has zero shift and maximal speed reduction to cover the scheduled running time without coasting. If this latter RMS train trajectory is conflict-free with the earliest train trajectory of the following train then there exists also a later reduced maximum speed driving strategy starting with a departure tolerance $0 \leq \delta_{p,q} \leq t_p^{sup}$ and running at a higher cruising speed corresponding to the running time supplement $t_p^{sup} - \delta_{p,q} \in [0, t_p^{sup}]$. Another option is a combination of two (reduced) shifted minimum-time driving strategies. One until the critical block and another one starting with a jump assumed at the critical block. In particular, if $t_p^{sup} \geq h_{p,q}^{L,E} - h_{p,q}$ then a shifted minimum-time driving strategy can be used starting at the reduced departure tolerance $t_p^{sup} - (h_{p,q}^{L,E} - h_{p,q})$ until block b^*. Then from block b^* a shifted minimum-time driving strategy can be assumed starting with a jump corresponding to the original overlap time $h_{p,q}^{L,E} - h_{p,q}$ at b^*, which will then model the latest train trajectory arriving on time. Note that this is not a drivable train trajectory due to the discontinuous speed jump but just a latest train trajectory modelling the maximal operational tolerance from the critical block onwards in case the train gets delayed. The different options will have to be evaluated to find the best approach in practice, which will be part of the demonstration phase.

If the overlap between the latest and earliest train trajectories of the two successive trains exceeds the running time supplement, $h_{p,q}^{L,E} > h_{p,q} + t_p^{sup}$, then no feasible solution exists by adjusting the departure tolerance of the preceding train, such that it can still arrive on time at the next stopping point. In this case, we assume an RMS latest train trajectory of the preceding train with no departure tolerance (or multiple SMTTC latest train trajectory bound), and also have to adjust the earliest train trajectory of the following train. In particular, we aim at avoiding that the following train cannot run according to an energy-efficient train trajectory. If the maximal coasting strategy is used as earliest train trajectory, then we may first check if the energy-efficient driving strategy would also generate a conflict. If not, then we can determine a reduced maximal coasting strategy by reducing the cruising speed from the maximum speed to still above the optimal cruising speed for energy-efficient train control.

If the energy-efficient train trajectory of the following train q conflicts with the RMS (or other) train trajectory of the preceding train p, then we have to adjust the energy-efficient driving strategy of train q by slowing it down using an extra TP at the critical block. Note that this critical block has a reduced overlap and may also be located at another block, corresponding to the adjusted latest train trajectory L' of the preceding train p. Denote this updated critical block by b' with overlap $h_{p,q}^{L',E} - h_{p,q}$. The TP at the entry of block b' will get a time window with lower bound (earliest time) equal to $t_{q,b}^{E} - \left(h_{p,q}^{L',E} - h_{p,q}\right) + \Delta t_{q,b}^{E,approach}$, where $\Delta t_{q,b}^{E,approach} = t_{q,b}^{E',approach} - t_{q,b}^{E,approach}$ is the corrected approach time of train q at block b' due to a different train trajectory (speed profile) E' up to TP. Since the train is later at this location than the unconstrained energy-efficient train trajectory, the optimal passage speed may be higher to compensate for the reduced remaining running time from this point.

For the adjusted earliest train trajectory of train q a combination of two driving strategies before and after the TP is proposed. Since the TP generates an earliest passing time that is later than the original earliest train trajectory, the adjusted earliest train trajectory will pass this TP at this lower bound, which will shift part of the used running time supplement to before the TP. However, the optimal speed v_{TP} at this TP still needs to be determined. If the running time supplement of train q exceeds the corrected overlap time, $t_q^{sup} \geq \left(h_{p,q}^{L',E} - h_{p,q}\right) + \Delta t_{q,b}^{E,approach}$, then train q can still arrive on time and the earliest train trajectory after the TP is taken as either an MC or EE train trajectory consuming the remaining running time supplement $t_q^{sup} - \left(h_{p,q}^{L,E} - h_{p,q}\right) - \Delta t_{q,b}^{E,approach}$ from TP with speed v_{TP} to the stopping point. The adjusted earliest train trajectory until TP can also be an EE or MC driving strategy although it might be close to the preceding train, so an alternative is an RMS strategy with cruising speed v_{TP} that needs to be optimized. The best choice will be evaluated in the demonstration phase.

8.3.4. Construction of the TPEs

The TPE is a discrete version of the earliest and latest train trajectories computed in the previous step. Theoretically, each block entry can be defined as a TP with a lower and upper bound generated from the earliest and latest train trajectories at these discrete locations. However, this leads to large JPs (Journey Profiles) and an unnecessary overspecification. Instead, we propose to define minimal TPEs that only provide defining constraints to guide conflict-free train trajectory generation algorithms. In particular, the TPs correspond to the RTTP specified stopping and passing points plus the additional TPs generated at the entries of critical blocks that prevent conflicts. A TPE for train p over a corridor is therefore defined as the discrete ordered list

$$TPE_p = \left\{\left(s, \underline{t}_{p,s}, \overline{t}_{p,s}\right) \middle| s \in S_p\right\},$$

where S_p is the ordered set of TP locations from the RTTP and additional TPs generated by the TPE generation algorithm, $\underline{t}_{p,s} = t_p^E(s)$ and $\overline{t}_{p,s} = t_p^L(s)$, with $t_p^E(s)$ the (final) earliest train trajectory evaluation at location s, and $t_p^L(s)$ the latest train trajectory evaluation at location s. If a TP has a time target then the lower and upper bound are the same, $\underline{t}_{p,s} = \overline{t}_{p,s}$. Note that the TPE may relax the time target of a departure time from the RTTP with a departure tolerance when possible, to provide freedom to the train trajectory generation algorithm. Nevertheless, train trajectory algorithms will always depart as early as possible to reduce energy consumption. The upper bound will function as a flag when the train departs late and violates the upper bound. In such cases, the train may generate conflicts with the next train that cannot be solved by the ATO-TS, and so the TMS should be warned to compute an updated RTTP.

Note that each train may have multiple subsequent corridors. The TPEs computed over each subsequent corridor can be combined into an extended TPE over multiple corridors. The TPEs are included in JPs for the trains with associated SPs (Segment Profiles). Depending on the segments considered in a JP, the embedded TPE may cover part of a corridor or multiple corridors. However, it should end with a time target required by the train trajectory generation algorithm to compute a train trajectory to a well-defined end point.

In summary, the TPE generation algorithm can be given as follows:

- Define corridors and collect all trains running (partially) over the corridor for a given planning horizon.
- For each corridor
  a. Train trajectory computations for multiple driving strategies
     - Latest train trajectories: shifted minimum-time control (SMTTC)
     - Earliest train trajectories: maximal coasting (MC) strategy
     - Optional: reduced maximum speed (RMS) strategy
     - Optional: energy-efficient train control (EETC) strategy.
  b. Detect and resolve blocking time overlaps
     1. Compute blocking times, and resulting lower and upper bounds considering the earliest and latest train trajectories.
     2. Identify blocking time overlaps at critical blocks between latest and earliest train trajectories of successive trains.
     3. Resolve conflicts with preceding trains (if any): maximize departure tolerance within time supplement to next stop.
     4. Resolve conflicts with following trains (if any): add timing point and time window at the critical block.
     5. Recompute the latest and earliest train trajectories for the trains with changed departure tolerance and extra timing points.
     6. Repeat from step 1 for the last resolved conflicting trains to reoptimize the departure tolerances and any remaining conflicts.
  c. Construct TPEs for each train from the generated extra TPs and the RTTP stopping/passing points with departure time windows defined by the departure tolerances.

The TPE generation algorithm will be applied to the initial RTTP, and successively to each RTTP update. In the latter case, only train paths with changed stopping and passing points will have to be considered, including retimed timing points, reordered trains, rerouted trains, and cancelled trains, together with the surrounding trains. The RTTP may also have to be updated at the request of the TPE generation algorithm itself when no feasible TPEs can be found for a subset of trains. In this case, the TPE should provide information to the TMS about the infeasible instances. This information can take the form of a required minimum (line) headway between train pairs or a minimum delay to a target time at a stopping or passing point.

In addition, the TPE generation algorithm can be applied for each train status update from the ATO-OB. First, when an expected train trajectory computed by the ATO-OB cannot satisfy some time window at a (non-RTTP) timing point then the TPE generation algorithm should try to relax the associated time window bound together with that of an adjacent train that may be affected by this. If this is not possible then the RTTP has to be updated by the TMS. Second, an extra TP generated by the TPE generation algorithm may be relaxed or even removed based on the current train positions and speeds. In particular, the impact on latest and earliest train trajectories of two successive trains with a TP controlling a TPE conflict should be monitored and the time window adjusted accordingly. The TPE generation algorithm can also be optimized based on feedback about the train trajectories computed by the ATO-OB of the trains. In first instance, TPEs are generated with the latest and earliest train trajectories to guide the ATO-OB algorithms of the trains. When a train enters the corridor and has computed a feasible train trajectory, this trajectory can be the basis to optimize or remove the time window corresponding to an extra TP set to prevent a conflict. Finally, when an ATO-OB cannot find a feasible train trajectory satisfying all RTTP constraints, such as the arrival time at the next stopping point, and the TPE generation algorithm can also not find a solution then the TMS must be notified to update the RTTP. These feedback control loops will be evaluated in the demonstration phase, see also Section 5.3.

8.3.5. Illustration

We illustrate the TPE generation algorithm based on an example 50 km long corridor between Utrecht Centraal (Ut) and ‘s-Hertogenbosch (Ht) in the Netherlands. The corridor consists of a four-track line from Ut to Houten Castellum (Htnc) and a double-track line from Htnc to Ht with overtaking possibilities at Geldermalsen (Gdm) as shown in Figure 8-4 (note: the open tracks between stations are not to scale). There are seven intermediate local train stations and we assume that ETCS Level 2 has been implemented (with the block layout of the legacy signalling system). The corridor is serviced by twelve alternating Sprinter (SPR, also known as local) and Intercity (IC) trains per hour in each direction (freight trains are not considered here), see Figure 8-5. The trains follow a periodic timetable with a cycle time of 30 minutes repeated throughout the day. The IC trains run non-stop with stopping points at Ut and Ht, whereas the three SPR trains have different destinations, at Houten (Htn), Ht and Gdm, successively, and stop at all stations in between. The third SPR train diverts from the corridor at Gdm and continues to Tiel (Tl) on another line. During a basic period of 30 minutes the successive trains have irregular intervals. The IC trains depart at 03, 14 and 24 every basic half hour, resulting in an 11-10-9 interval pattern. The SPR trains depart at 00, 11 and 22, forming an 11-11-8 pattern. The planned line headway times between the successive trains are 3, 8, 3, 8, 2 and 6 minutes. Note that the first part of the corridor is four-track with the IC and SPR trains running on parallel tracks. Thus, the minimum line headways are determined by critical blocks after Htnc.

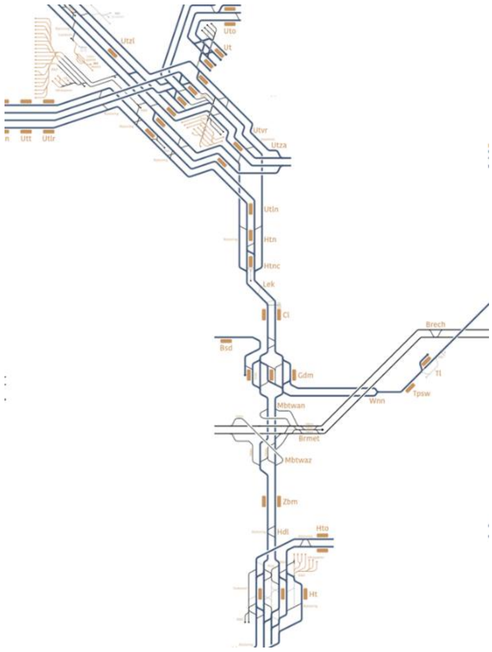
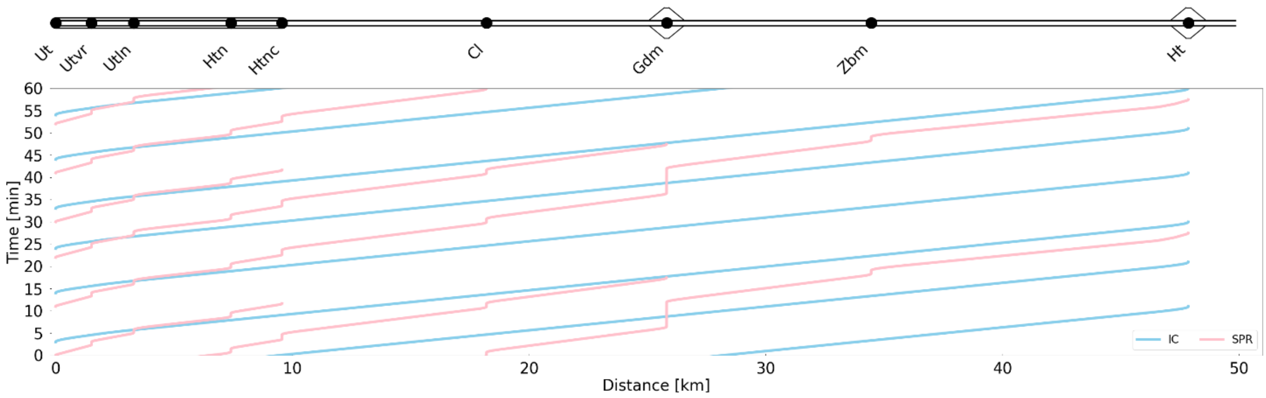


Figure 8-4 Schematic view of the track layout of the corridor Ut-Ht



Legend: IC train (blue) and SPR train (magenta)

Figure 8-5 Time-distance diagram of the basic hour pattern of the corridor Ut-Ht

The case study considers varying gradients and speed limits. The RTTP was computed based on RMS strategies, i.e., the trains apply a cruising speed and no coasting. As an example, Figure 8-6 illustrates the speed profiles for the IC train for the SMTTC, RMS and EETC driving strategies, and the corresponding earliest and latest train paths with the corresponding blocking times in a time-distance diagram. For completeness, the RMS train path is included as well. It can be seen that the EETC train trajectory precedes the RMS trajectory.

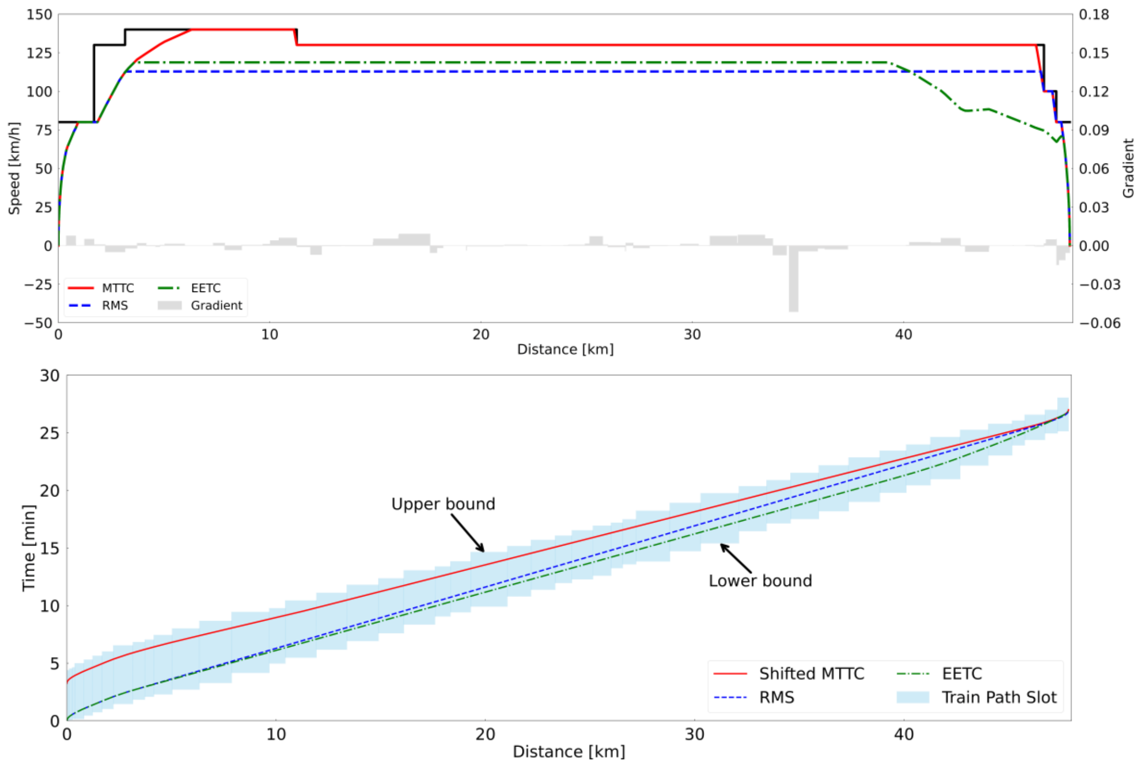
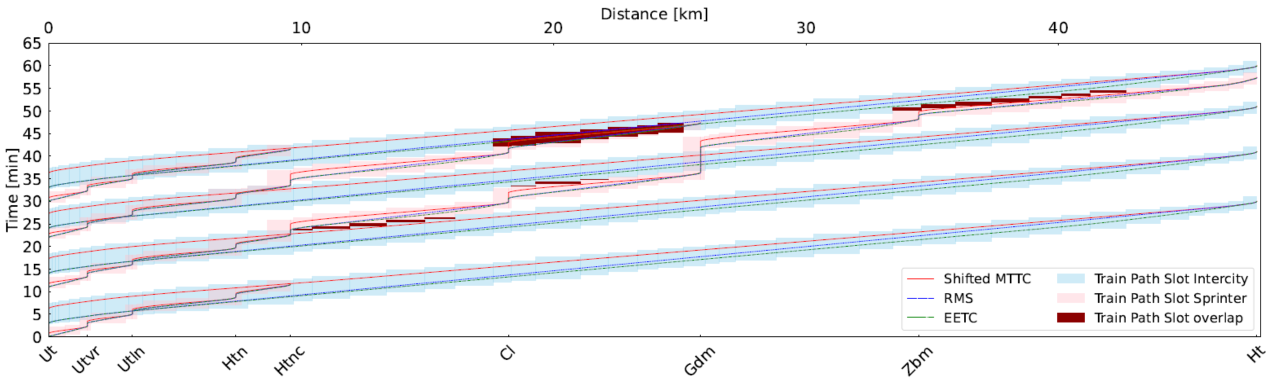
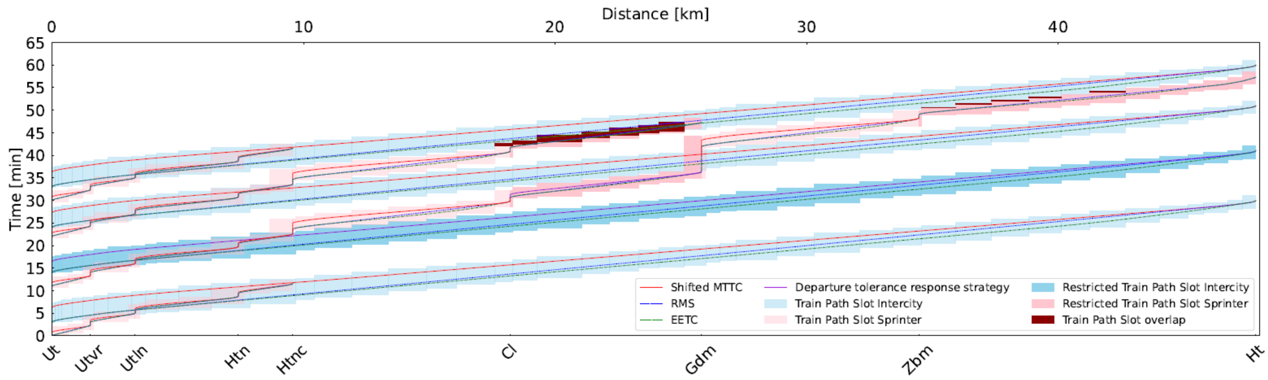


Figure 8-6 IC speed profiles (top) and unconstrained blocking time contours (bottom)

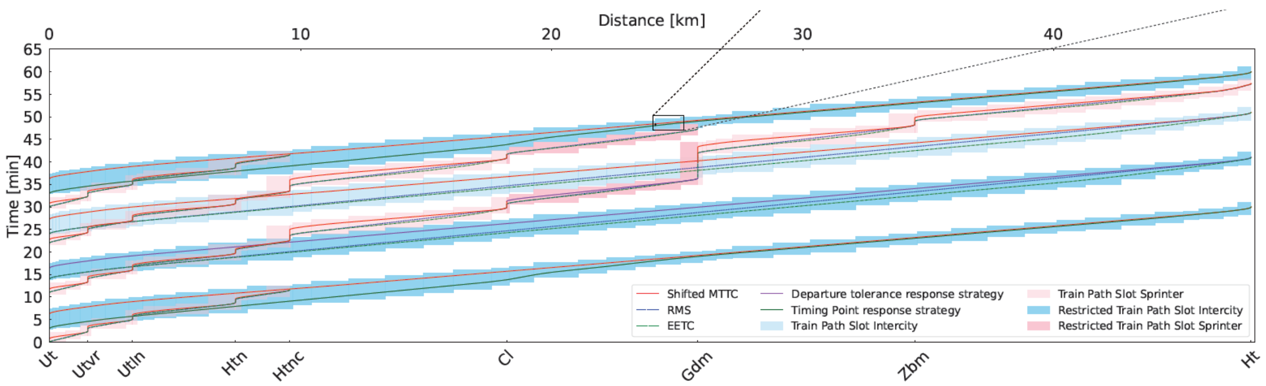
Figure 8-7.a illustrates the blocking time diagram of the trains starting in a 30 minutes period plus a copy of the first SPR and IC trains from the next period, with the initial train trajectory bounds computed by the SMTTC strategy (latest) and the EE strategy (earliest). The train trajectory bounds highlight conflicts in solid red overlaps. In Figure 8-7.b the latest train trajectories are adjusted by reducing the departure tolerances as much as possible using RMS strategies with reduced running time supplements. Note that for the SPR trains only the latest train trajectories require adjustments between consecutive stopping points with conflicts, while the SMTTC strategies can remain on the other legs. Two trains have their departure tolerance reduced: the 2nd IC train from Ut (from 195 s to 145 s), and the 2nd SPR train from Culemborg (Cl) (from 76 s to 39 s). The 2nd and 3rd SPR train get zero departure tolerance at Zaltbommel (Zbm) and Cl, respectively, both due to a conflict with the 4th IC train, i.e., these departure time windows are replaced by the departure time target from the RTTP. The 1st SPR, 3rd IC, and all other departures of the 2nd and 3rd SPR trains keep the full running time supplements as departure tolerances.



a. Initial train trajectory bounds



b. Optimized departure tolerances



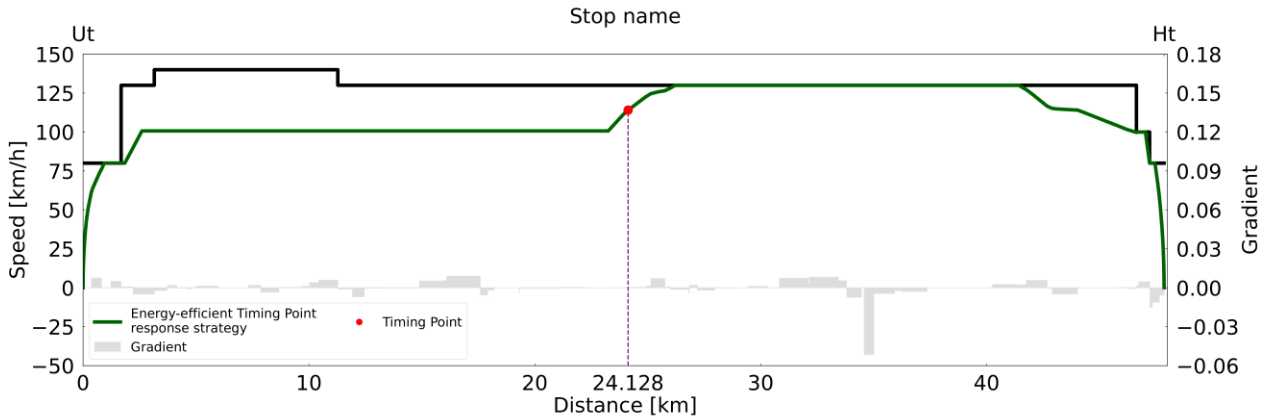
c. Optimal train trajectory bounds with indicated critical block

Figure 8-7 Integrated blocking time diagrams over the successive optimization steps

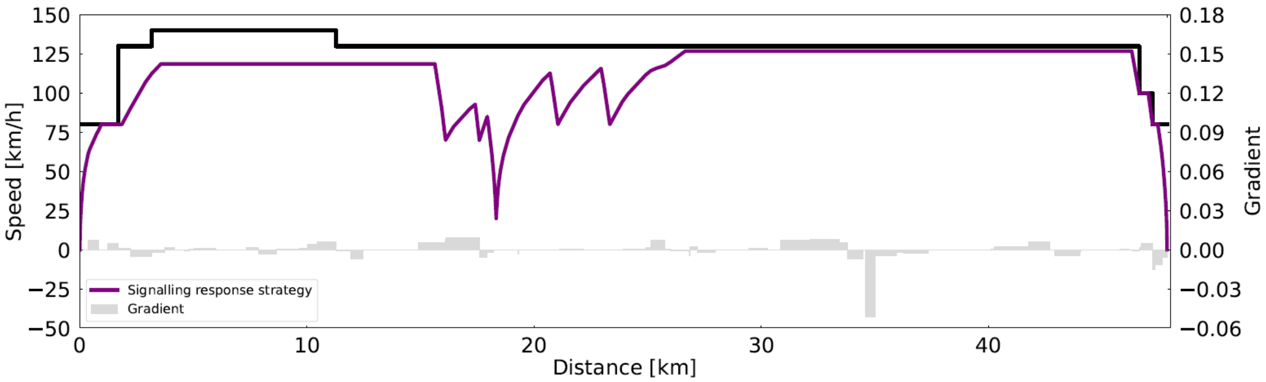
The conflicts between the 2nd and 3rd SPR trains with the 4th IC train (or 1st train in a cycle) must be resolved by adding a TP to the IC train. The critical block between the 3rd SPR train and the IC train is the block before Gdm, see Figure 8-7.c. By adding a TP at the entry of this block at 24.128 km from Ut and using an RMS strategy until this TP, followed by an EETC strategy from this TP, all conflicts are resolved, including those with the 2nd SPR train. After the earliest passage time at the TP still 13 s running time supplement remains, allowing the IC train to arrive on time at the stopping point in Ht including a coasting regime to reduce energy. The departure tolerance from Zbm of the 2nd SPR train can also be restored to the full running time supplement from Zbm to Ht.

Figure 8-8 (top) illustrates the adjusted speed profile for the 4th IC train (compare Figure 8-6 for the energy-efficient speed profile). Figure 8-8 (bottom) illustrates the speed profile without addition of the extra TP, which needs successive braking regimes due to late MA extensions. The extra TP avoids these path conflicts and saves 29.8% energy from 512 kWh to 360 kWh.

In conclusion, this case study illustrated how the TPE generation algorithm can provide conflict-free TPEs to all 12 trains per hour. The TPEs coincide with the stopping points from the RTTPs for all trains with departure tolerances for all but one SPR train departure, and an extra TP added for two IC trains per hour. As a result, the TPEs allow 10 trains to operate by their EETC driving strategies, and 2 trains with an earliest passage time at an extra TP before Gdm to avoid unnecessary braking and reacceleration due to short following of a preceding SPR train before it diverts into another line.



a. Adjusted speed profile as response to the extra TP halfway the corridor



b. Speed profile without extra TP in response to conflicts with preceding SPR train

Figure 8-8 Speed profile IC with extra TP (top) and without (bottom)

8.4. Conclusions

This chapter considered the computation of TPEs to guide ATO-OB train trajectory generation, and specifically focused on flexible TPs, i.e., extra TPs on the route of a train added to the TPE next to the ones specified in the RTTP, depending on operational conditions. The optimal distribution of TP locations and associated time windows is based on the calculation of train trajectory bounds corresponding to various driving strategies, including energy-efficient driving and latest minimum time running. Considering a range of driving strategies may cause conflicts between incompatible driving strategies of adjacent trains on (partially) shared routes with short headways. The developed TPE Generator therefore computes extra TPs at critical blocks between conflicting train pairs together with the earliest passing time that restricts the operational tolerances to avoid conflicting train trajectories. This TPE Generator can be used in combination with any conflict detection and resolution algorithm in the TMS that keeps an up-to-date RTTP. It can be implemented as an extra function in the TMS or in the ATO-TS to optimize the joint TPEs for all trains. The TPE Generator is embedded in the HITL simulation environment discussed in Chapter 11. TRL 4 validation test report of the TPE Generator within the HITL simulation environment is provided in Annex 15.8.

9. ATO-Enhanced TMS

9.1. Introduction

This chapter describes two approaches where ATO/C-DAS is used to improve TMS functionality. Section 9.2 focuses on C-DAS and Section 9.3 on ATO (with GoA2 or higher). The TMS receives from the CMS (Capacity Management System) the capacity plan from which it produces an RTTP. This plan is sent to the ATO-TS or C-DAS TS to generate the TPE for each train, while the ATO-TS or C-DAS TS sends back to the TMS status reports used to update the current RTTP. The status reports can be used by the TMS to improve its performance in updating the RTTP.

The first approach is the 'TMS – C-DAS Enhanced Operation' that focuses on C-DAS for Class B signalling systems (without ETCS), train trajectory calculation by the C-DAS TS and a passive C-DAS OB. The main purpose is to forecast all train paths, detect the level of deviations and to forecast the impact on the planned timetable. Moreover, it updates changes to the RTTP by evaluating all the running time deviations and temporary restrictions.

The second approach is the 'ATO Train Forecast and Operational Plan Update' that interfaces with ATO and which main purpose in addition to improve the forecasting is to detect and resolve conflicts and produce new RTTP as output. This approach is compatible with ATO-over-ETCS as part of the Reference CCS Architecture, where the TMS interacts with the CCS (including ATO) according to the TMS-CCS interface specified by the System Pillar.

9.2. TMS – C-DAS Enhanced Operation

9.2.1. General Description

TMS – C-DAS operation aims to enhance railway operations through communication between TMS and C-DAS. The TMS is able to immediately send the RTTP to the C-DAS TS and thus enables it to guide the drivers with updated TPEs including re-plannings operations and Temporary Speed Restrictions (TSRs). As soon as the RTTP is updated (by manual operation, e.g. solving a conflict) it is sent to the C-DAS TS. In addition, the TMS – C-DAS Enhanced Operation module aims to enhance railway operations by integrating data from the C-DAS TS, enabling more informed decision-making and improved forecast calculations by dispatchers. By receiving status reports from C-DAS TS (based on the Status Reports messages from C-DAS OBs), the TMS can refine forecast calculations and address disturbances, detecting conflicts and optimizing timetable feasibility earlier to ensure smooth train performance.

This approach assumes a legacy signalling system without ETCS, so that the C-DAS can provide accurate train positions to the TMS, as opposed to the train describer systems based on trackside track-clear detection. Also, a passive C-DAS OB is assumed, i.e., the C-DAS TS computes the train trajectory and sends it as a JP to the C-DAS OB using the SFERA protocol.

The main objectives are:

- Avoid or reduce disturbances through immediate dispatching of the RTTP.
- Amend the current RTTP with better forecasts from the C-DAS.
- Detect conflicts more precisely and ensure smooth train performance with C-DAS.
- Analyse the accuracy improvement of the RTTP (difference between the planned and the final audited run with C-DAS operation) using INDRA's simulation environment.

The TMS – C-DAS Enhanced Operation is formed by a TMS, C-DAS TS, C-DAS OBs, and a train/infrastructure simulator belonging to INDRA's simulation environment as is shown in Figure 9-1. The focus is on the communication channel from TMS to C-DAS TS and the use of the train/infrastructure simulator. The trains behave following the traction/brake commands by train drivers based on C-DAS OB speed advice.

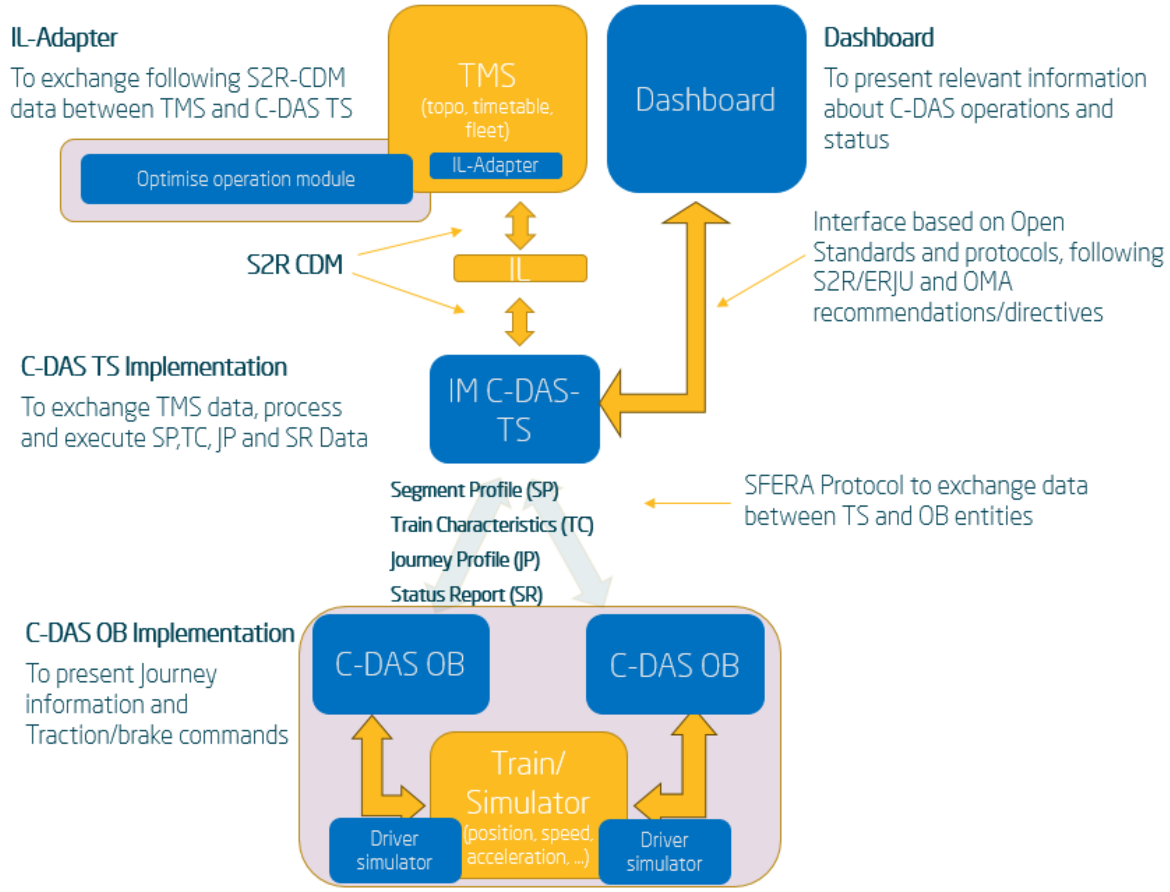


Figure 9-1 TMS – C-DAS enhanced operation.

The input data needed are as follows.

- Timetable with different information (e.g., dwell times, train paths with specific tracks)
- Extended and detailed infrastructure data (e.g., speed restrictions, gradients, curvature)
- TMS functionality to support human operators (replanning by retiming, adding extra stops, rerouting, creating TSRs).

The information received by the TMS from the C-DAS TS (Status Reports) allows the following operations:

- Generate improved forecasts of event times at TPs in the TMS.
- The TMS dispatcher manually detects and resolves potential conflicts or directly uses various tools to manually amend the current timetable (so called replanning). He/she can:
    - Modify the scheduled times of train paths (adjustment, technical, commercial stop time, arrival and departure time),
    - Change tracks,
    - Replan the origin or destination.
- Generate and send a new RTTP to the C-DAS-TS.

The main functions of the C-DAS TS are

- Compute train trajectories for each train based on the RTTP and current train positions, and send them to the C-DAS OBs.
- Provide status reports to the TMS.

9.2.2. Internal Concepts

The internal concepts of a TMS relating to TMS-C-DAS enhanced operation involve several interconnected components that optimize railway performance and improve communication between the system and train operators. Figure 9-2 shows the interconnected components within the TMS boundaries and the connections with other systems.

The modules belonging to the TMS that take part in TMS-C-DAS enhanced operation are mainly:

- Updated current timetable
- Forecast calculation
- Forecast optimization.

The updated current timetable generates the RTTP, which is sent to the C-DAS TS, from the updated train routes, the automatic train tracking and timing registry, the agreed plan and the temporary constraints of the infrastructure. The forecast calculation generates the timetable with forecasted/estimated arrival and departure times for the location points of the route from the updated current timetable. The forecast optimization refines the forecast calculation from the updated current timetable and the estimated times to arrival received from the C-DAS TS that allows the conflict detection to act more precisely.

9.2.2.1. Updated Current Timetable

The updated current timetable provides the critical functions to ensure efficient train operations:

- Real-Time Updates: Continuously updates train schedules based on real-time data, including delays, cancellations, and other operational changes.
- Dynamic Rescheduling: Automatically adjusts departure and arrival times in response to unforeseen events, ensuring minimal disruption to service.
- Integration with External Data: Incorporates data from various sources, such as train describers (signalling), agreed plan and infrastructure status (including temporary constrains like temporary speed restrictions, possessions, station closures and isolations) to enhance timetable accuracy.

The updated current timetable works as an input for the Forecasting to anticipate delays and proactively adjust schedules to maintain reliability.

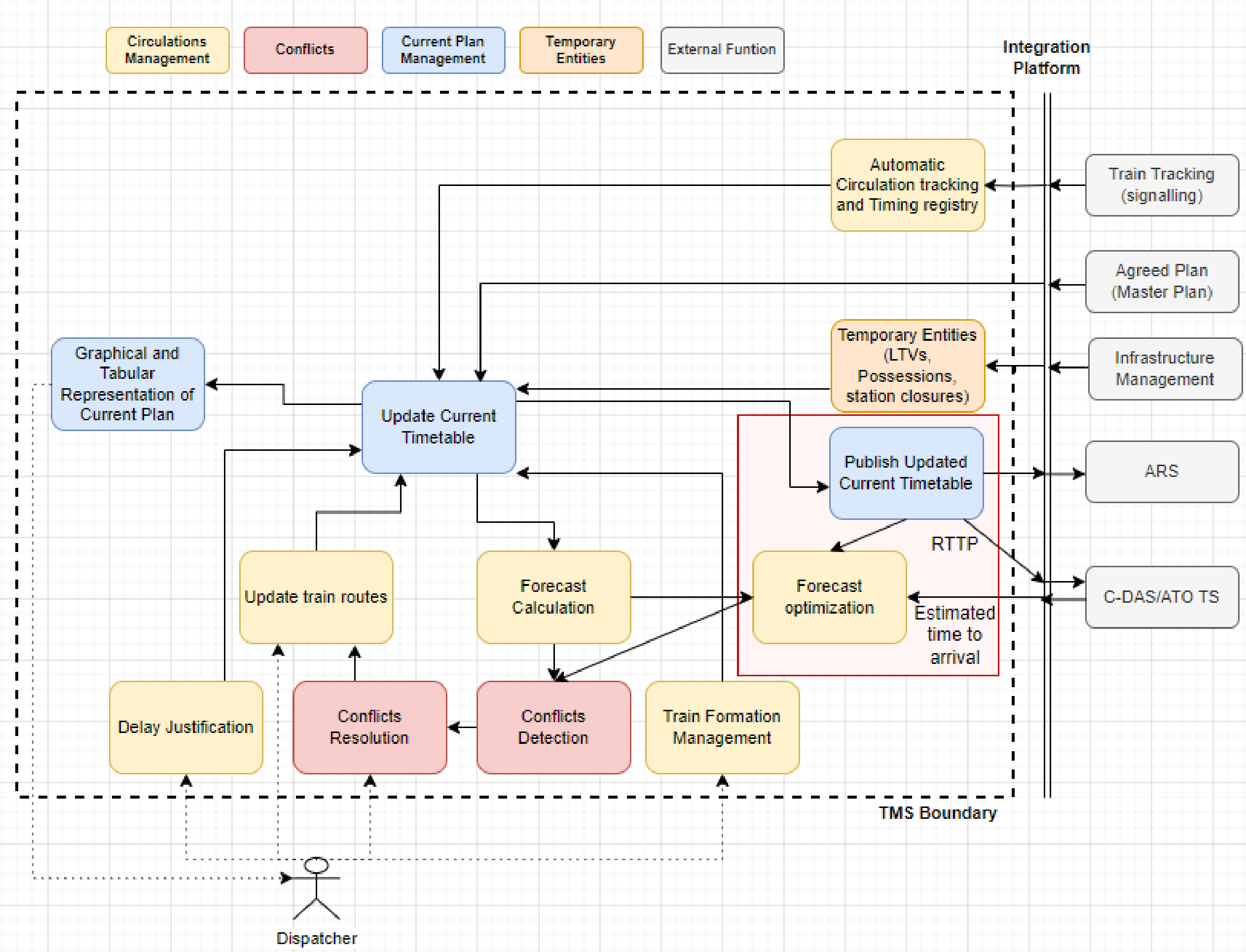


Figure 9-2 Interconnected components of TMS

9.2.2.2. Forecast Calculation

The forecast run is the result of the forecast calculation process. It consists of a timetable with the forecasted arrival and departure times at the location points of the target route. The forecast calculation is triggered by any update of the target timetable, audit (train position from the train describers) or temporary constraints affecting the route. The calculation starts in the last audited movement calculating the forecast in the next movement of the train. Based on this forecast it calculates the forecast for the next movement and does that iteratively until the end of the route.

The calculation of the forecast at each forecasted event is based firstly on a basic calculation without taking into account the temporary speed restrictions (TSRs). After that the calculation with TSRs is applied. Later the calculation with trains' restrictions like links, connections and dependencies, is taken into account. Finally, the fixed hours are contemplated to obtain the final forecast. Figure 9-3 shows the orchestration of the forecast calculation.

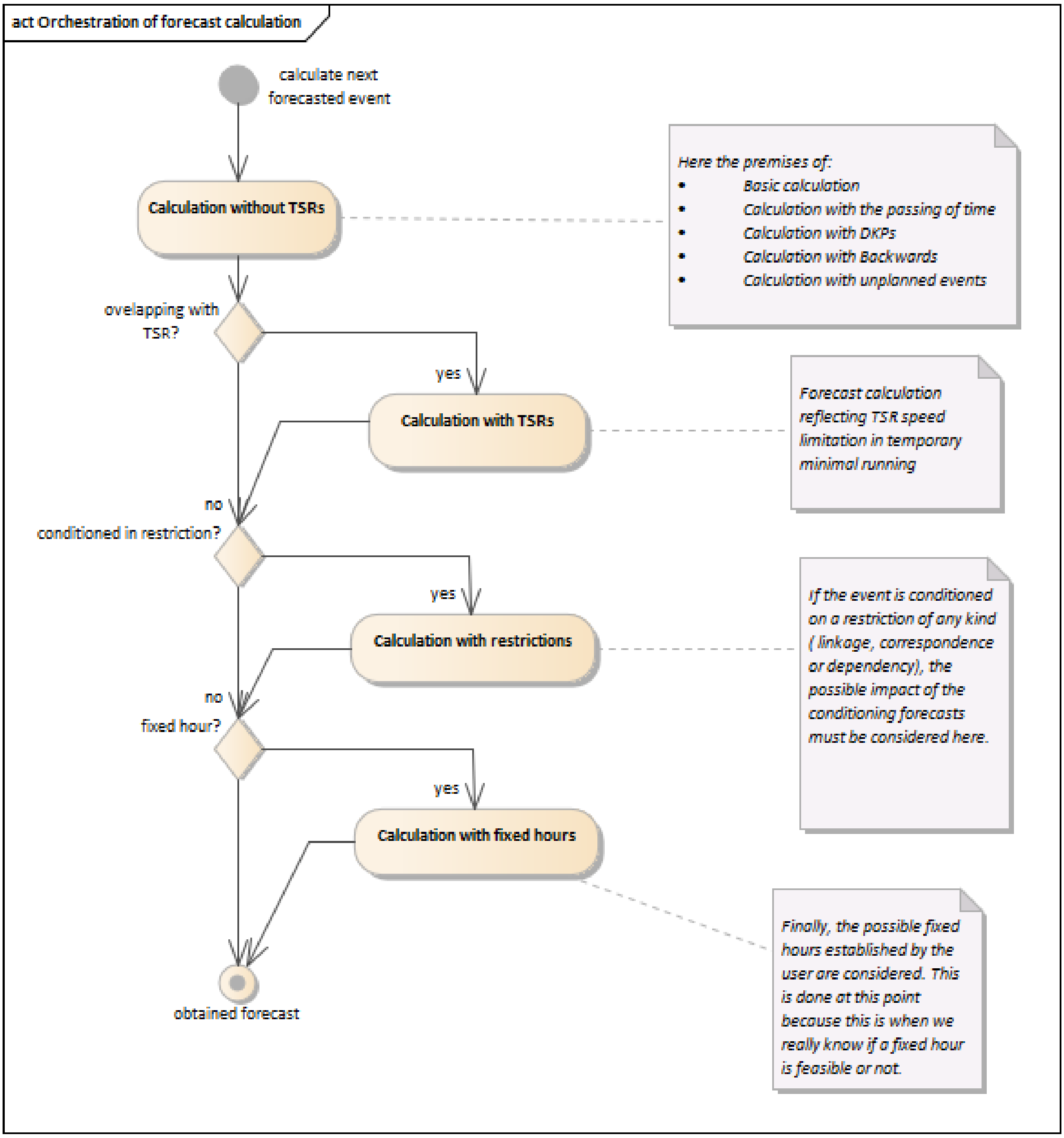


Figure 9-3 Forecast calculation

9.2.2.3. Forecast Optimization

The forecast optimization module in a TMS enhances operational efficiency by predicting train movements and resource needs. Linked with a C-DAS, it leverages real-time data to refine forecasts and improve decision-making in case of delays. The module analyses variables such as train speed, delays, and network conditions, enabling proactive adjustments to schedules and routing. This connection not only optimizes traffic flow but also enhances safety and punctuality by providing drivers with timely information and recommendations, ultimately leading to a more efficient and responsive rail network.

The forecast optimization module calculates a new improved forecast from the current timetable (RTTP) and the estimated time to arrival provided by the train trajectory calculation in the C-DAS

TS. The TMS uses the data received from the C-DAS TS related to the estimated time to arrival and re-calibrates the forecast calculation by means of the optimization module.

9.2.3. Conclusions

Utilization of TMS – C-DAS enhanced operation for Class B signalling systems (without ETCS) can improve the efficiency of the traffic management. The connection between the TMS and C-DAS can provide accurate current train positions and expected time-to-arrivals at TPs. It allows to optimize train schedules and routing to minimize delays and maximize network utilization. It provides accurate real-time adjustments to the forecast based on actual train performance improving the reliability of arrival and departure times. Apart from that, it allows the early detection of potential delays that helps the TMS to implement adjustments minimizing service disturbances. Concerning passenger satisfaction, it can improve the reliability and punctuality leading to a better experience for passengers. Other topics are the integrated communication, data driven insights and the sustainability, promoting energy-efficient driving practises through advisory feedback, reducing overall energy consumption.

9.3. ATO Train Forecast and Operational Plan Update

9.3.1. General Description

The Reference CCS Architecture (RCA), describes the interface between TMS and CCS (Control, Command and Signalling), including ATO, as an exchange of information using a Standard Communication Interface Operational Plan (SCI-OP), which is still under development. The RCA defines the Operational Plan as the result of the planning process performed by the Planning System. It describes either a planned Operational Movement, Operational Restriction, or Operational Warning Measure through a temporal sequence of Operational Events to be implemented by ATO. The TMS provides an operational plan execution request to the CCS. The TMS produces the operational plan starting from the evaluation of forecasts. The plan execution and ATO within the CCS receive the execution request and provide back to the TMS a Status Report (e.g., track occupation and train status). The Status Report is used by the TMS to adjust the forecasts and to provide a new operational plan, closing the loop between TMS and the CCS. The operating state is the logical 'real-time' representation of the actual state of the physical railway system in the controlled area. The knowledge about the operating state enables TMS to keep itself current with the operational situation in the controlled area and to recognise deviations from an operational plan during execution. Further, it allows for identifying upcoming or existing conflicts between operational plans and developing appropriate countermeasures.

Figure 9-4 represents the implemented TMS logic. Simplifying the TMS internal structure the Planner and Deviation Detection block produces an internal Operational Plan (OP) and a related RTTP starting from the capacity plan received from the CMS. This RTTP is shared with the ATO-TS (CCS/ATO block) while the OP is shared internally with the Conflict Detection and Conflict Resolution (CD/CR) module that is also deputed to the forecasting evaluation. The Conflict Detection and Conflict Resolution algorithms are developed in WP17 while the Forecasting algorithm is in the scope of this work package.

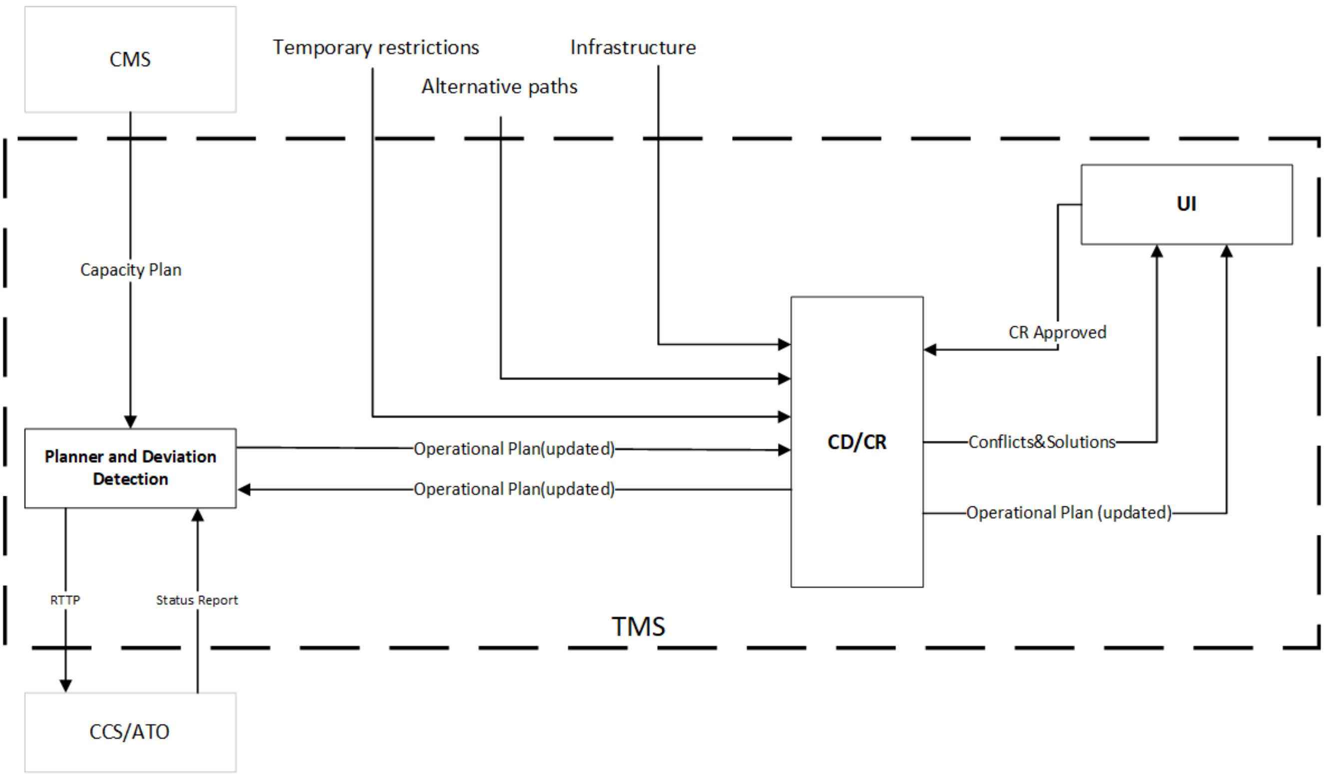


Figure 9-4 TMS - CCS/ATO

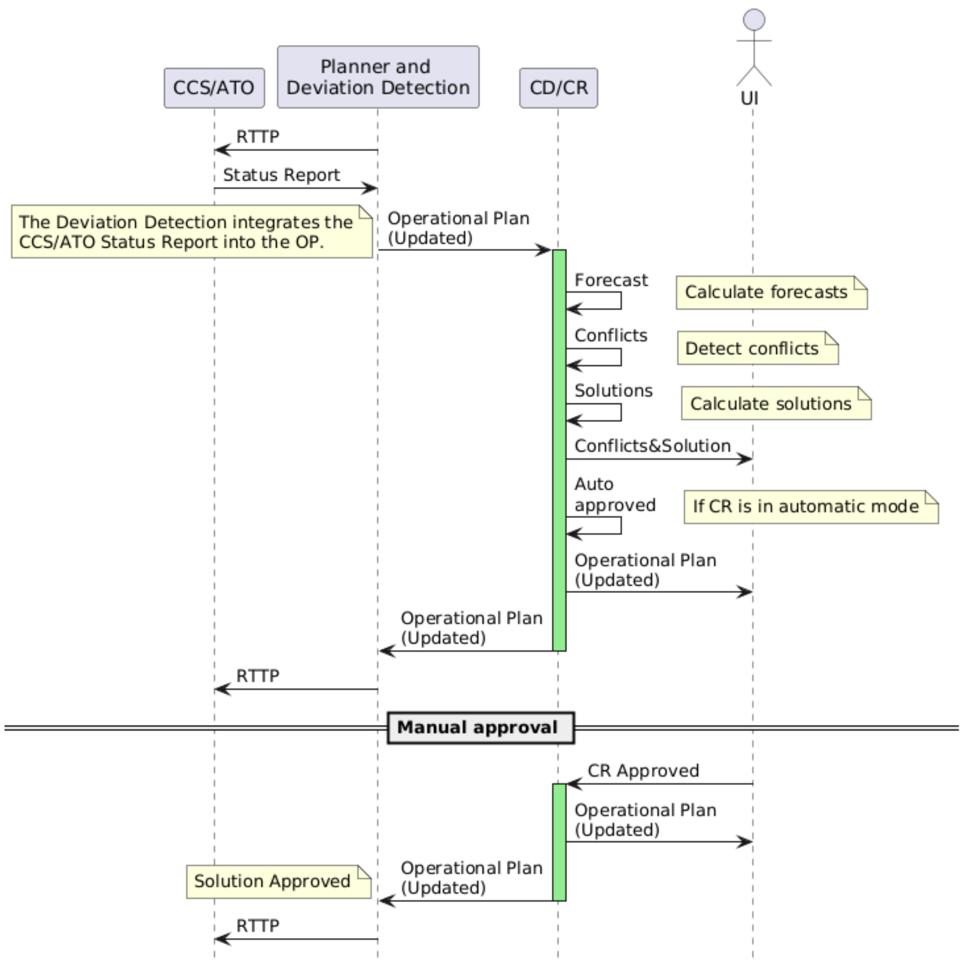


Figure 9-5 Example sequence diagram

When the trains start moving a Status Report is received by the TMS from the ATO-TS, which is used by the planner to produce and update the OP containing train movements to be shared with the CD/CR module that provides a new forecast. Based on this forecast the Planner provides the related updated RTTP to be shared again. At a certain point some conflicts are detected and solved internally, automatically or by user interaction, and an updated OP, and RTTP consequently, are provided accordingly. Figure 9-5 shows an example of a sequence diagram.

9.3.2. Internal Data Concepts

The data domain relevant to the CD, CR and forecasting calculations is made up of two main parts. The first one describes the topological and geometrical structure of the railway network where the traffic takes place. This is imported from the System Pillar infrastructure data model. The second one describes the operational plan, i.e., the (scheduled and/or current) use of the railway network by a given fleet of trains.

The Railway Infrastructure Data Domain is described by following classes:

- Infrastructure
- Operational Point
- Track
- Link
- Speed Profile.

Figure 9-6 shows the class diagram and interaction of the railway infrastructure data domain.

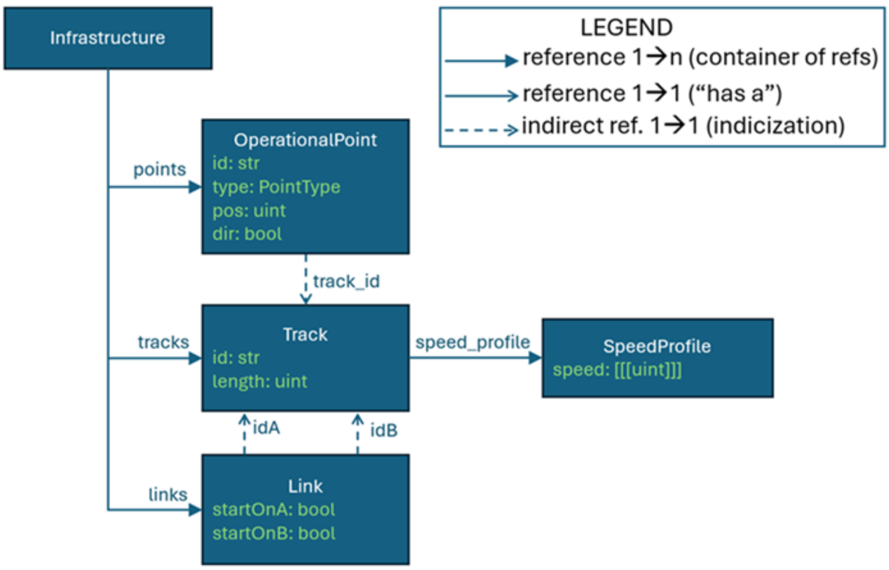


Figure 9-6 Class diagram and interaction Railway Infrastructure Data Domain

The *Infrastructure* class represents the topological structure of (a portion of) the overall railway network at microscopic level. The topology is that of an oriented graph, hence the 'Infrastructure' is made of a collection of 'tracks', a collection of 'links', as described hereafter. It also contains a collection of 'points' relevant to the train operations.

The *Track* class describes an elementary portion of the physical railway network, namely a single railway track, with no bifurcations. At the same time, from an abstract (mathematical) point of view, it represents a single edge of the graph describing the network topology. Each edge is characterized by an intrinsic orientation, namely a privileged running direction. Trains can run through the physical track in both directions, but their actual travelling direction will be registered as 'according to' or 'opposite to' the Track intrinsic orientation. This orientation is coded in the different role of the edge endpoints (start or end), which gives rise to a rule to characterize the position (mileage) of relevant points along the track in terms of distance from the nominal starting point.

The Track is characterized by:

- a unique (string) identifier, 'id', and
- its total length, 'length', in (integer) metres.

The *Link* class represents the permitted practicability of a train from one track to the other. Obviously, a link may exist only between contiguous tracks, but not all physically contiguous tracks can be travelled in both directions. Think, for instance, to a switch linking three rail tracks: typically, the geometry of the tracks, namely the angles they form, make it impossible for a train to travel through all the (three) couples of tracks.

The Link is characterized by two references to (the string identifier of) an instance of Track. These represent the endpoints of the tracks connected by the link. The two references have a different role, encoding the travelling direction associated with the link: the first reference ('idA') points at the track which the train comes from, while the second reference ('idB) points at the track which the train goes towards. Each reference is associated to a Boolean variable as well, specifying the type of endpoint of the referred track which participate to the link: the first variable ('startOfA') is true if the endpoint of track A is the starting point of the origin track ("A"), false if it is the ending point. Analogously, 'startOfB' denotes the role of the endpoint of the destination track (B). See the example below for clarification. An example of a link between two consecutive tracks can be seen in Figure 9-7.

The *OperationalPoint* class represents relevant points of the railway, located on specific tracks, where specific operations take place. OperationalPoint is characterized by:

- a unique (string) identifier, 'id',
- a 'type', specified by a (PointType) enumerator,
- a reference, 'track_id', to (the unique identifier of) a Track, on which the point is located,
- the location of the point on the referred Track, 'pos', expressed as the distance, in (integer), metres, as measured on the Track from its staring point.

The *PointType* enumerator can assume two distinct values:

- *StopLocation* representing a point in a railway station where trains can stop.
- *ETCSMarker* representing a relevant point for the (ETCS) traffic control system.

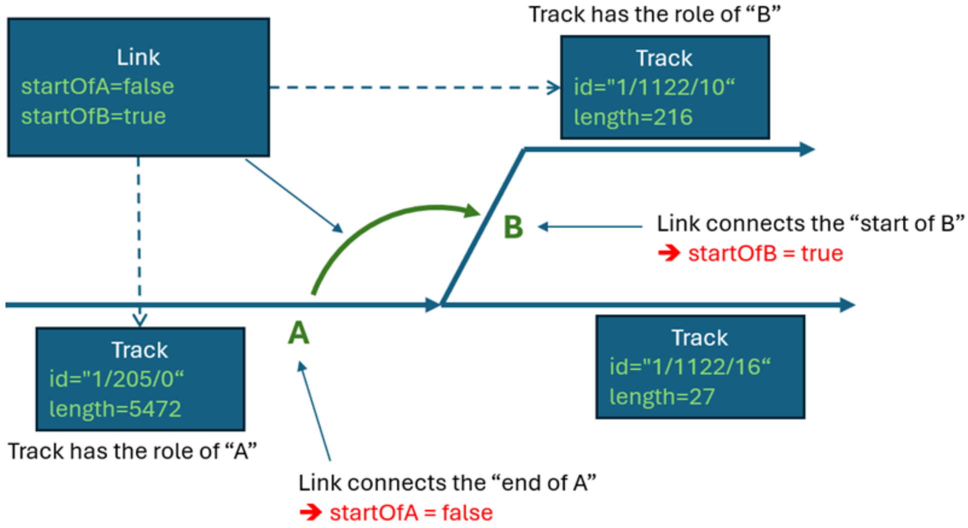


Figure 9-7 Link between two consecutive tracks

The *SpeedProfile* class represents a set of (permanent) speed limitations imposed on the trains running through the corresponding rail track. The set of speed limitations is organized as a three-dimensional tensor of unsigned integers, 'speed', specifying the speed limits in km/h. The three-dimensional entries of the tensor specify respectively:

- The (Boolean) travelling direction of the train to which the speed limit applies, where 'true' means according to the intrinsic orientation of the Track described above.
- The category of the train to which the speed limit applies, expressed in terms of a (Category) enumerator.
- The starting point of the speed limit, expressed in terms of the (integer) distance, in metres, from the Track starting point. It is assumed that the speed limit endures as long as another speed limit is specified.

The actual speed limit applicable to a given train on a given railway track is the minimum value between:

- The maximum speed that the train can achieve, specified by its category,
- The (permanent) speed limit specified by the speed profile for that train category, track portion and travelling direction, and any further temporary speed limit.

The *Category* enumerator specifies the type of train, for the purpose of applying speed limits. In Italy it may assume four values: A, B, C and P.

Figure 9-8 shows an example of speed limits applicable to consecutive portions of a given Track. Each speed limit is specified by the starting point, the travelling direction and the train category (not specified in the diagram).

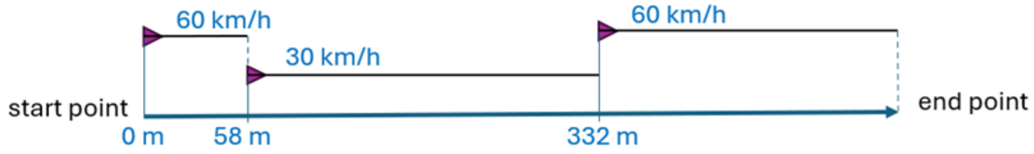


Figure 9-8 Illustration of SpeedProfile

The Operational Plan Data Domain models the train traffic over the previously described railway infrastructure, namely the train fleet characteristics, the scheduling of train runs, eventual setbacks (programmed or unforeseen) that may interfere with the normal scheduling, and the actual traffic state, at a specific instant of time. The domain classes that realize this portion of the model are as follows:

- OperationalPlan,
- TrainRun,
- MovementEvent,
- Path,
- EventTime.

Figure 9-9 shows the class diagram and interaction of the Operational Pan Data Model.

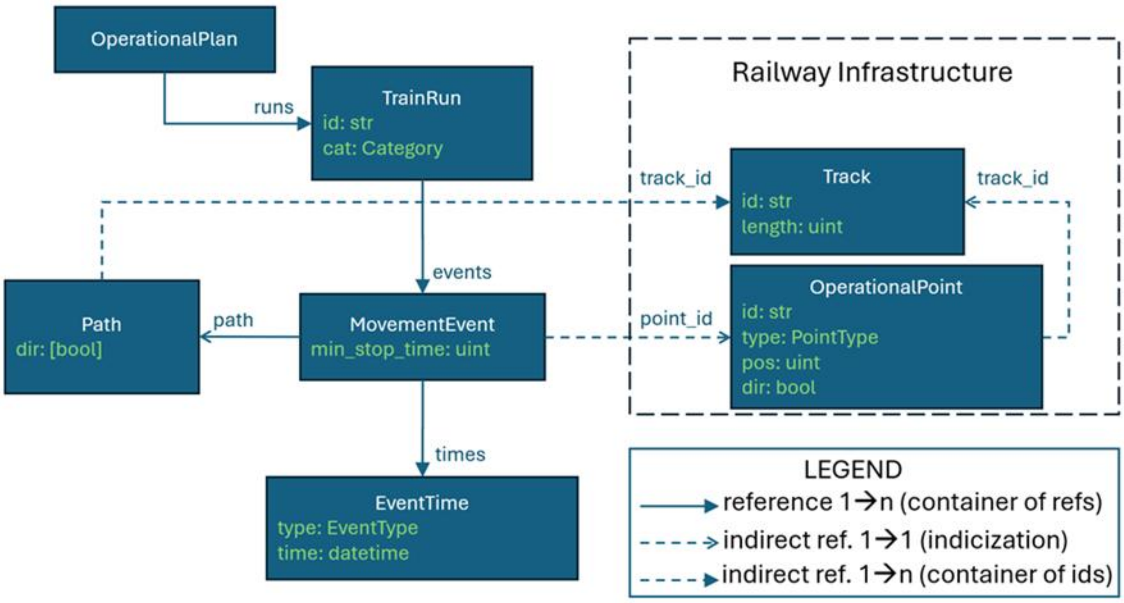


Figure 9-9 Class diagram and interactions Operational Plan Data Model

The *OperationalPlan* class represents the overall planned traffic for the railway infrastructure and actual variants to the scheduling. The operational plan is characterized by a simple list of train runs.

The *TrainRun* class represents the single planned (and/or actual) train run, namely the list of relevant operations of a single train. It is characterized by the following attributes:

- 'id', the unique (string) identifier of the train run
- 'cat', an instance of the Category enumerator specifying the train maximum speed
- 'events', a container (list) of instances of the MovementEvent class.

The *MovementEvent* class represents a relevant piece of information about the motion of a train (planned or actual). It describes the location of the train at specified time instants, coinciding with the transit through, arrival at or departure of the train from a specific operational point of the infrastructure. Its attributes are:

- 'point_id', a reference to (the unique id of) an instance of OperationalPoint describing the event location,
- 'times', a container (list) of instances of the EventTime class describing the event collocation in time. Typically, this list contains a single element in case of transit through an ETCSMarker, and two elements in case of stop and start at a given StopLocation,
- 'path, an instance of the Path class describing the path along the railway infrastructure, that the train will follow to reach the next movement event,
- 'min_stop_time', specifying the minimum duration, in (integer) seconds, of the train stop at the event location.

The *Path* class describes the path of a train along a portion of the railway infrastructure and is characterized by an ordered list of couples ('track_id', 'dir'). The first element of each couple is a reference to (the unique id of) an instance of Track. The second one specifies the train travelling direction and is expressed as a Boolean variable denoting whether the train is travelling according to the implicit track direction (true case) or the opposite one (false case).

The *EventTime* class describes the event time and its type. Its attributes are:

- 'time': the (optional) system date/time at which the event takes place. In case it is specified, it expresses a constraint, such as the intended arrival/departure time of a scheduled event, or the actual time of a real (already happened) event,
- 'type': an EventType enumerator, characterizing the type of event,
- 'movement': a MovementType enumerator, characterizing the type of movement.

The *EventType* enumerator specifies the type of EventTime, whose possible values are:

- 'actual': specifying that the EventTime has already occurred, hence it cannot be altered; it's a matter of fact,
- 'scheduled': specifying that the EventTime is scheduled, hence its date/time is simply the desired one,
- 'foreseen': specifying that the date/time of the EventTime is the result of a forecast computation.

The *MovementType* enumerator specifies the movement type of EventTime, which possible values are:

- 'transit': specifying the transit of the train through –without stopping at– the corresponding operational point,
- 'arrival': specifying the stop of the train at the corresponding operational point,
- 'departure': specifying the start of the train from the corresponding point.

9.3.3. Forecasting Algorithm

The TMS CD/CR module provides three main functions, which require the design and implementation of different algorithms:

- *Forecasting*. This is the ability to predict (namely, compute) the motion (namely, the position in time and the usage of the railway tracks) of a single train, given its scheduled timetable and the actual constraints on the railway infrastructure.
- *Conflict Detection.* This consists in the search for conflicts, once the actual motion of each train has been computed according to the previous function, namely, once the forecasting has been computed for all the scheduled trains.
- *Conflict Resolution*. This consists in the search for possible actions to be taken by the traffic control operators, which alter the operational movements of one or more trains in order to eliminate the occurrence of any conflict and, at the same time, minimize the impact on the train scheduling.

The *Forecasting* function computes the foreseen realization of a given train run. The function input is a single instance of TrainRun whose MovementEvent objects may be in part "actual", namely already occurred hence unmodifiable and in part just "scheduled" or "foreseen" hence adjustable. The output is twofold:

1. An instance of TrainRun with the same events and overall path, but the event times may be properly modified (namely, delayed), while "respecting all the constraints";
2. The track usage of the updated train run, namely a list of instances of the TrackUsage class (see Figure 9-10), containing all the Tracks encountered, and the associated usage time, namely the time interval during which the train occupies each Track.

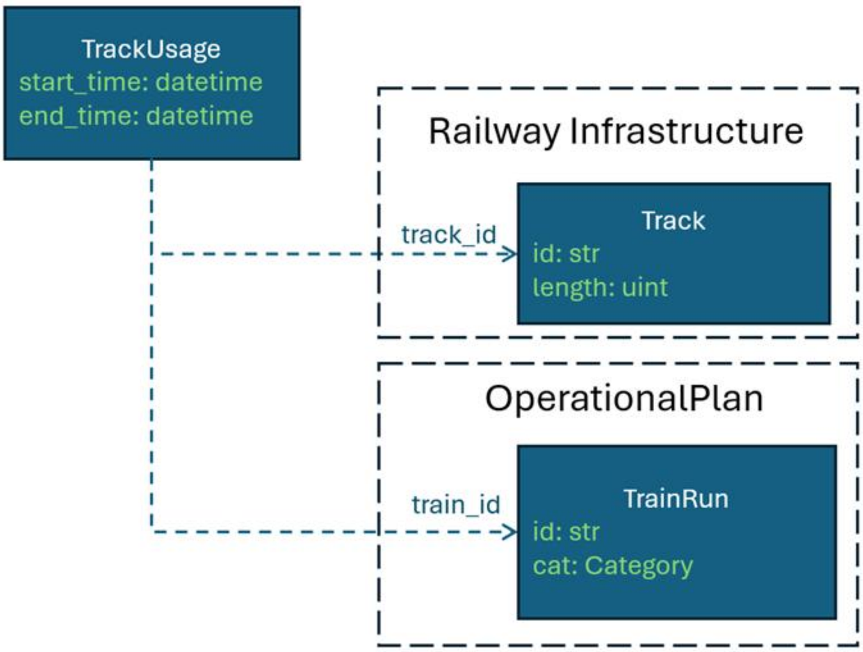


Figure 9-10 TrackUsage class

The list of constraints to be respected by the output train run includes the following:

- The date/time of an EventTime of type ‘actual’ –which is assumed to be specified in the input– shall not be changed by the forecasting algorithm,
- In case it is specified in the input, the date/time of an EventTime of type ‘scheduled’ and movement type ‘departure’ shall not be anticipated: it may only be delayed,
- In case of stop at a given OperationalPoint, namely in case of arrival at and departure from the same MovementEvent point, the duration of the stop shall not be less than the specified min_stop_time,
- The type of an EventTime of type ‘actual’ or ‘foreseen’ shall not be varied,
- The EventTimes of type ‘scheduled’ shall be turned into ‘foreseen’ by the forecasting algorithm,
- The movement type of ‘departure’ or ‘arrival’ EventTimes shall not be varied,
- The travelling speed of the train shall never exceed the intrinsic maximum speed of the train category specified by the input train run,
- The travelling speed of the train shall not exceed the applicable permanent speed limit encountered along the overall path specified in the input train run,
- The travelling speed of the train shall not exceed any applicable temporary speed limit encountered along the overall path specified in the input train run,
- The travelling speed of the train shall not exceed any temporary speed limit due to train problem feedback during its run,
- The acceleration and deceleration of the train cannot exceed the limits specified by the corresponding train category and characteristics,
- In case of temporary limitation of the usage of any track, the foreseen train run shall follow an alternative path, among those allowed by the railway infrastructure.

The basic concepts of the forecasting algorithm are as follows:

1. A copy of the input TrainRun is created, which will be modified according to the constraints above and returned as the algorithm output.
2. The algorithm loops through the whole list of MovementEvent of the TrainRun and changes their properties according to the constraints.
3. For each MovementEvent in the list (the ‘current one’), only the ‘previous’, ‘current’ and ‘next’ events are considered.
    a. At the beginning of each iterative step, the references to the ‘previous’, ‘current’ and ‘next’ MovementEvents are updated.
    b. If all the instances of EventTime of the current MovementEvent are of type ‘actual’, no change is carried out and the algorithm steps up to the next MovementEvent (namely, step 3.a).
    c. If the Path associated with the ‘current’ and ‘next’ MovementEvent (to the successive ones) cannot be travelled –namely, if there are temporary restrictions affecting these Paths– the algorithm looks for an equivalent railway Path in the railway infrastructure

i. If there is no alternative Path, the algorithm returns an invalid result
ii. If there is one, the algorithm updates accordingly the Path of the 'current' and 'next' events; it also updates the 'next' event location.

d. The algorithm computes the time it takes the train to travel the Path associated with the 'previous' MovementEvent, namely the time it takes to travel from the 'previous' OperationalPoint to the 'current' one. This computation considers all the applicable speed and acceleration/deceleration limits, permanent and temporary.
e. The data/time of the EventTimes associated with the 'current' MovementEvent are updated (typically, postponed) according to the constraints.
f. The algorithm computes as well the usage of each Track encountered along the Path.

4. The updated copy of the TrainRun and the overall TrackUsage are returned.

The *Conflict Detection* function implements the calculation of the train conflicts foreseeably arising from a given operational plan, if no action is taken. The definition of a conflict is when two distinct trains need to use the same track at the same time.

The *Conflict Resolution* function computes one or more alternative operational plans presenting ideally no conflict at all. The new operational plans will be chosen (and sorted) to minimize a loss function, given by the cumulative delay (eventually weighed by weights depending on the train categories) of the whole plan, with respect to the original (input) plan. By cumulative delay we mean the sum of the delays at each stop location, for each train in the plan, with respect to the corresponding arrival time in the original plan.

9.4. Conclusions

The chapter proposed two approaches to enhance the TMS functions using ATO/C-DAS feedback. The first approach 'TMS – C-DAS Enhanced Operation' focused on forecasting train paths and train path deviations in a TMS using status reports from C-DAS. This TMS component will be integrated in a manual dispatching system to support traffic managers in keeping an up-to-date RTTP that is shared with the C-DAS TS to update the JPs to the trains. The TRL 4 validation test report of the Forecast Calculation and Optimization algorithm is provided in Annex 15.4.

The second approach is the 'ATO Train Forecast and Operational Plan Update' that focuses on a Forecasting algorithm of the train movements. The Forecasting algorithm will be integrated with Conflict Detection and Conflict Resolution algorithms that are developed in FP1-MOTIONAL WP17 to support rescheduling of the RTTP and updating the Operational Plan in case of disturbances, interactively with the traffic manager. The TRL 4 validation test report of the Forecasting algorithm is provided in Annex 15.5.

10. TMS-ATO Data Models

10.1. Introduction

This chapter focuses on modules for the communication from the TMS to ATO:

- Integration Layer (IL), for the communication between TMS and ATO/C-DAS TS
- Journey Profile Generator, for the translation of the RTTP/Operational Plans into SPs and JPs, that are used in the communication with the on-board using ERTMS/ATO Subset-126.

The communication between TMS and on-board is not completely regulated by standard communication protocols: while ERTMS/ATO Subset-126 defines the protocol and messages between the Trackside and the On-board, there are no Subsets defining the protocol to be used between TMS and ATO/C-DAS TS. For the same reason, since the data arriving to the TS could be in different formats, the Trackside module has to translate them in JP/SP packages.

The IL aims to standardize the communication between different TMS and ATO/C-DAS TS using a common communication protocol (Rest APIs) and a common data model (CDM, Conceptual Data Model). The ATO-TS translates the RTTP (or Operational Plans) received from the TMS into SPs and JPs, including updates from the TPE generation functionality when applicable. This data model should be aligned with the TMS-CCS interface specification from the System Pillar after this is available.

10.2. TMS-ATO Integration Layer

The IL is a distributed data processing platform that manages the communication, data validation, sharing and analysis for railway services (Traffic, Asset and Energy Management Systems, field signalling infrastructure and vehicles) and clients. The main purpose of this solution is interoperability of new software and legacy systems for the creation of an integrated data management and processing solution.

IL data have a standard format, called Conceptual Data Model, to let applications connected to the IL understand the payload (i.e., message content) of the data exchanged. The Conceptual Data Model describes both data and relations among data: relations organize data hierarchically in a tree-based data structure where each tree node is identified with a unique topic. Each tree node has its current status stored in the IL cache with a key value store. This status can be retrieved and deleted through IL functionalities.

Communication is based on a message-style pattern and can be either direct or indirect depending on the IL functionality used: applications can communicate directly sending data and commands to each other using point to point and request-reply patterns, or can use an indirect style of communication through publish-subscribe functionalities.

Data exchanged with the IL are validated against the Conceptual Data Model and can be filtered using payload filtering, topic filtering or a combination of both. If the validation is not successful, data are not published on the IL. The purpose of the IL is to provide all the functionalities and patterns described above in a secure way, implementing access control on tree nodes and state of the art encryption mechanisms.

The IL contains different modules useful for:

1. Validating, analysing, and sharing data in the standard format.
2. Storing and managing of data.

We start with an example that can clarify one of the possible usages of the IL: integrate multiple TMS and ATO/C-DAS TS to each other. It may happen, for example on the border of areas managed by different TMS/ATO (e.g., different countries), that multiple systems have to share data between them. Without the IL, we should connect each system to the others, so, since different application may use heterogeneous communication protocols, we should implement several connectors with a higher configuration and management effort. Moreover, without the IL we should implement a translator for each application to parse data correctly, as data would not be in a standard format. IL usage provides a common language to describe message content to parse it correctly and provides a common access point to exchanged information.

The Conceptual Data Model (CDM) aims at facilitating the integration of collaborating applications by designing an application independent data model. The components may have different data representations internally, but whenever exporting or importing data to/from other components, they must translate this data to the conceptual form. The CDM describes both data and commands. The conceptual data model includes standard description of services and commands exposed by several applications connected to the IL.

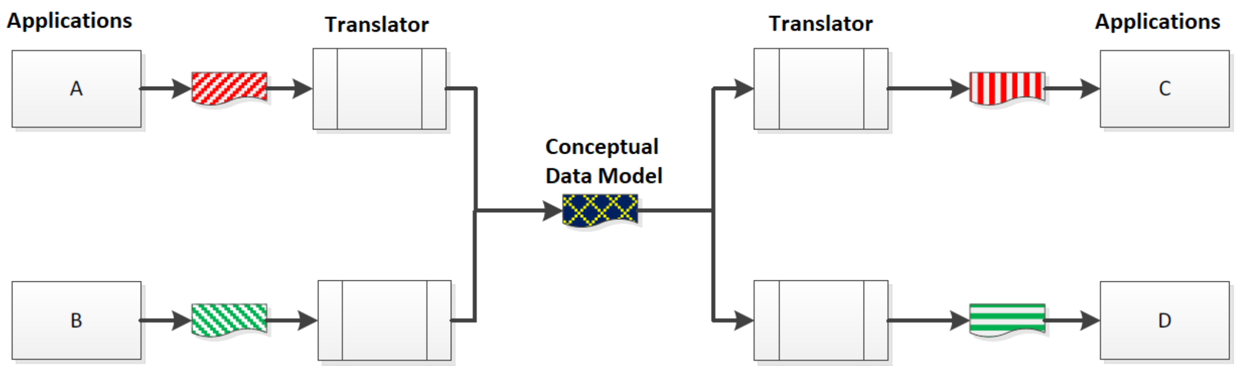


Figure 10-1 Conceptual Data Model Overview

Newly created applications must only provide the transformation between internal data format and the CDM, independently from the number of already existing applications (the internal data format can be the CDM itself avoiding translations), see Figure 10-1. The CDM can be used to enable interoperability between the services of the IL: it represents the contract to be used by software components to share information through IL. Each application has three options to adapt to the CDM:

1. Apply the CDM also internally.

2. Implement a Message Mapper, an internal module converting application domain objects into CDM representation.
3. Implementing a Message Translator, an external adapter to translate from app-specific message format to CDM.

Within the scope of FP1-MOTIONAL WP10, a gap analysis was performed between the CDM used for this demonstrator and the System Pillar CMD. The result of this gap analysis is documented in deliverable FP1- MOTIONAL D10.2 “Definition of Data elements for demonstrators in WPs 11-18".

The IL provides an enhanced publish/subscribe paradigm for processing messages, applying several operations on the content of the published payload itself. Messages to the IL are sent via "topics", the IL allows to subscribe for a given topic passing a callback function. “Topic” is a category of information: business data are categorized into topics. Examples of topics are: position of trains, state of signalling devices, indications from stations, weather information, etc. People refer to topic when they talk about CDM nodes, or information to publish/subscribe to. Information is organized hierarchically in the conceptual data model tree. Topics correspond to nodes in the tree. Wildcarding is used to subscribe to conceptual data model subtrees.

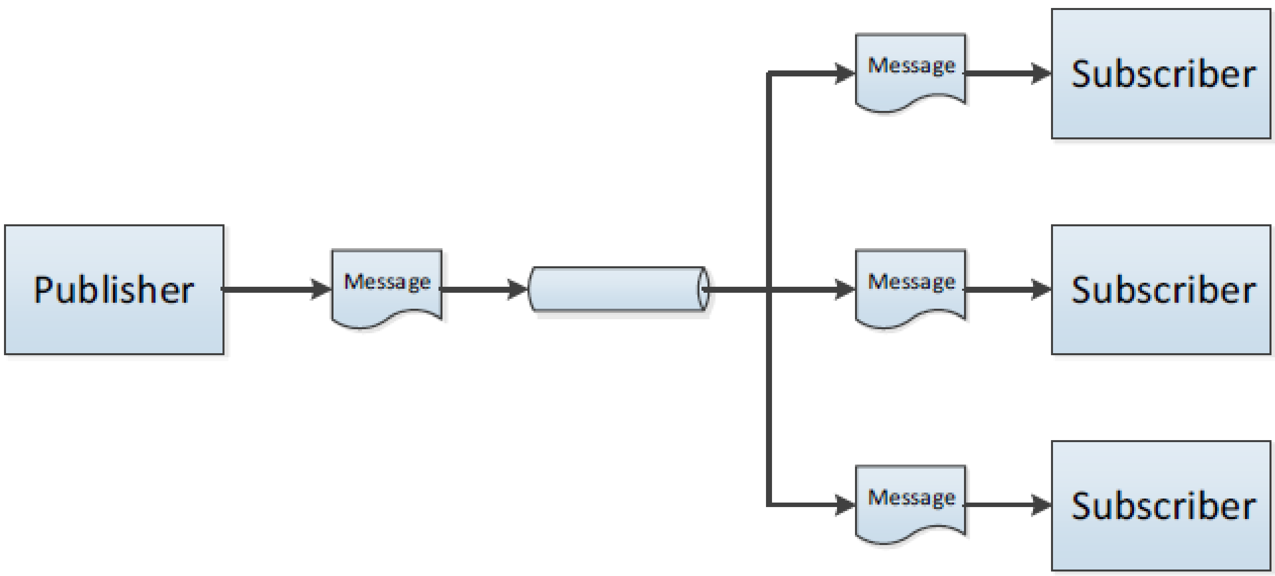


Figure 10-2 Publish Subscribe Architecture

10.3. Journey Profile Generator

ATO/C-DAS requires constant updated information for an improved performance and thus, it needs to be connected to the TMS and receive updated information about times and routes and return current information about train's real position and speed. This section and the corresponding demonstration focus on C-DAS but can also be used for ATO.

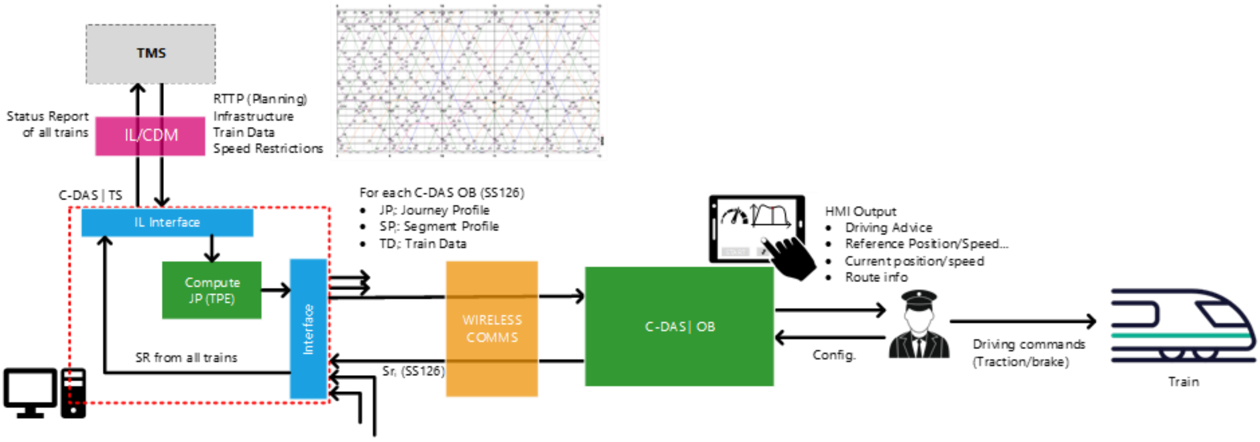


Figure 10-3 Block diagram of C-DAS concept with its main components and data flow

The C-DAS TS system is a module that receives the RTTP from the TMS via the IL (IL) and generates for each connected C-DAS OB the Journey Profile (JP), Segment Profile (SP) and Train Data (TD) and sends this information to every connected device. In return, all the connected C-DAS OB systems send back to the C-DAS TS their Status Report (SR), which the C-DAS TS can send to the TMS via the IL.

The demonstrator covers only the area marked in dashed red in Figure 10-3, including the interface to communicate with the IL, the module to compute the JP and the module to send each information piece to the associated C-DAS OB.

In order to maximize compatibility and interoperability of different systems, the connection between the TMS and the C-DAS TS is made via the IL, which uses a standard data format called Conceptual Data Model (CDM).

10.3.1. IL Connection

The IL API defines a series of functions that are used to communicate with the TMS. These requests require connectivity with the TMS, in this case using a VPN, specifically CiscoAnyConnect. This VPN provides access to possible clients to the private network that the TMS participates in. Once there is connectivity to the VPN, the clients can send requests to the TMS CDM.

Using http requests to send and receive information, the IL manages connections between clients and the TMS, that acts as the server. To manage these connections, the IL documentation defines a series of functions to communicate with the TMS, including subscribe, get, publish, delete, among others. These functions are shown in Figure 10-4, showing a python class implementation for an IL client with the relevant methods.

```
You, 3 months ago | 1 author (You)
class IL_Client():
    def __init__(self):
        self.BASE_URL = "localhost:8080/"
        self.clientId = ""
        self.clientSecret = ""
        self.username = "username"
        self.password = "password"
        self.refreshToken = ""

    def access_token(self, grant): ...

    def subscribe(self, endpoint, headers, params): ...

    def get(self, endpoint, headers={}, params={}): ...

    def publish(self, endpoint, data, headers={}, params={}): ...

    def delete(self, endpoint, data, headers, params): ...
```

Figure 10-4 Python class implementation for an integration layer client

Furthermore, based on the documentation provided, the API functions have been implemented considering the body, headers and parameters required in each case. Each method's implementation considers the IL's use of access tokens for authentication.

10.3.2. Data Exchange Definition

The developed functions make use of the different domains defined in the IL to define the required data for the C-DAS TS to be able to generate the messages required by the OB devices. In this section the main data required for exchange is identified. The data is grouped according to the different data domains, see Table 10-1.

Table 10-1 Data domains

Domain	Data exchanged content	Multiplicity	Typical average update rate	In/Out
Topology/ Functional Infrastructure/ Physical Infrastructure	Segment Profile Control Point Platform Balise Balise Group Unprotected LX Stop Powerless section Switch off Area Permitted Braking distance Tunnel Area Static Speed profile Axle Load Speed Profile	1..* 1..* 1..* 1..* 1..* 1..* 0..* 0..* 0..* 0..* 1..* 0..*	1 / 1 year	In
Timetable	Train Service Timetable	1..* 0..*	50 / 1 hour 100 / 1 second	In In/Out
Operation / Authorities (TMS)	Temporary Constraint Train ATO Detail Train Position	0..* 0..* 0..*	1 / 1 hour 1 / 1 second 1 / 1 second	In Out Out

Table 10-2 lists the segment profile data definition. The Timetable contains the minimum timetable data information associated to the arrival and departure at a Control Point. Table 10-3 lists timetable control point data definition. A train service is a complete predicted timetable of a service until the end of the service. A Train Service has associated only one formation during the complete running. The Timetable could be modified during the operation according to the regulation actions and commands. Table 10-4 lists the train service data definition. Finally, Table 10-5 illustrates the Train Data.

Table 10-2 Segment profile data

Attribute	Attribute description for UseCase	Data Type	Admitted values	Multiplicity	Containment
Identifier	Unique identifier	String	-	1	True
Name	Track name	String	-	1	True
Country	Country code the track belongs to	Enumeration	NID_C (Identity number of country or region) values	1	True
Timezone	Local timezone	Number	Timezone [int]	1	True
EoA offset	End of authority offset	Number	Position in centimetre [cm]	1	True
Main direction	Nominal direction of the segment	Enumeration	Enumeration Values: normal, reverse	1	True
Begin	Absolut begin position (Kilometric Point)	Number	Position in metre [m]	1	True
End	Absolut end position (Kilometric Point)	Number	Position in metre [m]	1	True
Length	Track length	Number	Length in centimetre [cm]	1	True
Gradient	Sets value / direction / location for the initial value and changes	Number/ Enumeration / Location at the track	Enumeration Values: Downhill – Uphill Number: value gradient in percentage [%] Location: in millimetre [mm] or centimetre [cm]	1..*	True
Curve	Sets value / curve side / location for the initial value and changes	Number / Enumeration / Location at the track	Number: value radius in metre [m] Enumeration value: Unknown – Right – Left Location: in centimetre [cm]	1..*	True
Power Voltage	Sets value / country identification of the traction system / location for the initial value and changes	Number / Enumeration / Location at the track	Number: Voltage in Volt [V] Enumeration: Country identifiers of traction system Location: in centimetre [cm]	1..*	True
Current Limitation	Pairs value / location for the initial value and changes in	Number / Location at	Number: current value in Ampere [A]	1..*	True

	maximum allowed current consumption	the track	Location: in centimetre [cm]		
Static Speed Profile	Static Speed Profile along the track	List of References	List of Static Speed Profile Data	1	False
Axle Load Speed Profile	Axle Load Speed Profile along the track	List of References	List of Axle Load Profile Data	1	False
Tunnel Areas	List of Tunnel Areas along the track	List of References	List of Tunnel Areas Identifiers	1	False
Powerless Sections	List of Powerless Sections along the track	List of References	List of Powerless Sections Identifiers	1	False
Switch off Areas	List of Switch Off Areas along the track	List of References	List of Switch Off Areas Identifiers	1	False
Permitted Braking Distance Areas	Permitted Braking Distance Area	List of References	List of Permitted Braking Distance Areas Identifiers	1	False
Unprotected Level Crossing Stops	List of Unprotected Level Crossing Stops along the track	List of References	List of Unprotected Level Crossing Stops Identifiers	1	False
Balises Groups	List of Balises Groups with balises placed along the track	List of References	List of Balise Groups Identifiers	1	False
Platforms	List of platforms along the track	List of References	List of Platform Identifiers	1	False

Table 10-3 Timetable control point data

Attribute	Attribute description for UseCase	Data Type	Admitted values	Multiplicity	Containment
Control Point	Point the timetable information refers to	Reference	Operational Control Point Identifiers	1	True
Action	Event of the service	Enumeration	Service Start - Stop - Pass - Service End – Turnback	1	True
Arrival Time	Arrival Time	Date and Time	Timestamp	0..1	True
Minimum Dwell Time	Minimum time in case of stopping	Number	Number: dwell time in second [s]	1	True
Alignment	Train Alignment in Control Point	Enumeration	Enumeration value: Front - Middle – Rear	1	True
Departure Time	Departure Time	Date and Time	Timestamp	0..1	True
Skip Stop	Skip command	Boolean	-	1	True
Hold Train	Hold command	Boolean	-	1	True

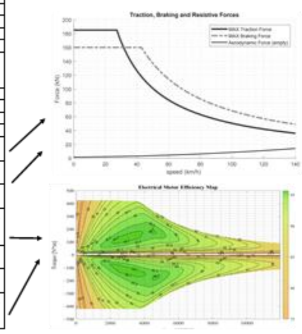
Table 10-4 Train service data

Attribute	Attribute description for UseCase	Data Type	Admitted values	Multiplicity	Containment
Identifier	Unique identifier	String	-	1	True
Name	Service name	String	-	1	True
Train Running Number	Operational Train Number	Number	-	1	True
Formation	Type of formation assigned to the train service	Reference	Formation Identifiers	1	False
Connections at the start	Train Services connected at the start	Reference	Train Service Identifiers	0..*	False
Connections at the end	Train Services connected at the end	Reference	Train Service Identifiers	0..*	False
Timetable Control Points	Ordered list of control points	List of References	-	1 (1..*	True

Table 10-5 Train data

Requirement Details

REQ_ID	Domain	Object	Attribute	Attribute description	Data Type	Static / Dynamic	Admitted values	Multiplicity	Containment	IN/OUT	Comments
REQ_D_XX_1	Rolling Stocks	Train	ID	Train ID	String	Static	-	1	TRUE	IN	Primary Key
REQ_D_XX_2			Manufacturer	Train Manufacturer	String	Static	-	1	TRUE	IN	
REQ_D_XX_3			ConstructionYear	Year of construction	Number	Static	Uint8, [-]	1	TRUE	IN	
REQ_D_XX_4			Series	Vehicle series	String	Static	-	1	TRUE	IN	
REQ_D_XX_5			Operator	Train Owner	String	Static	-	1	TRUE	IN	
REQ_D_XX_6			Gauge	Track gauge	Number	Static	Uint8, [-]	1	TRUE	IN	
REQ_D_XX_7			TrainLength	Total length of the train	Number	Static	Uint16, [mm]	1	TRUE	IN	
REQ_D_XX_8			TrainWidth	Width of the train	Number	Static	Uint16, [mm]	1	TRUE	IN	
REQ_D_XX_9			TrainHeight	Height of the train	Number	Static	Uint16, [mm]	1	TRUE	IN	
REQ_D_XX_10			EmptyMass	Empty mass of the train, tare weight	Number	Static	Uint16, [kg]	1	TRUE	IN	
REQ_D_XX_11			TotalMass	Total weight of the train	Number	Static	Uint16, [kg]	1	TRUE	IN	
REQ_D_XX_12			RotatingMass	Rotating mass	Number	Static	Uint16, [kg]	1	TRUE	IN	
REQ_D_XX_13			WheelDiameter	Diameter of the wheel	Number	Static	Uint16, [mm]	1	TRUE	IN	
REQ_D_XX_14			MaxSpeed	Maximum speed	Number	Static	Uint16, [km/h]	1	TRUE	IN	
REQ_D_XX_15			TransmissionRatio	Ratio of transmission between motor and wheel	Number	Static	Float [-]	1	TRUE	IN	Transmission ratio between motor and wheels (e.g. 103/14) to relate vehicle speed with motor speed
REQ_D_XX_16			TransmissionEfficiency	Efficiency of transmission	Number	Static	Float [%]	1	TRUE	IN	
REQ_D_XX_17			RollResisCoefA	Davis equation parameter A	Number	Static	Float [N]	1	TRUE	IN	Parameters of Rolling Resistance Davis Equation Rr = A + B*v + C*v^2
REQ_D_XX_18			RollResisCoefB	Davis equation parameter B	Number	Static	Float [N/(km/h)]	1	TRUE	IN	
REQ_D_XX_19			RollResisCoefC	Davis equation parameter C	Number	Static	Float [N/(km/h)^2]	1	TRUE	IN	
REQ_D_XX_20			NumTotalAxles	Total number of axles	Number	Static	Uint8, [-]	1	TRUE	IN	
REQ_D_XX_21			NumTractiveAxles	Total number of tractive axles	Number	Static	Uint8, [-]	1	TRUE	IN	
REQ_D_XX_22			MaxAcel	Maximum acceleration	Number	Static	Float [m/s^2]	1	TRUE	IN	
REQ_D_XX_23			MaxDecel	Maximum deceleration	Number	Static	Float [m/s^2]	1	TRUE	IN	
REQ_D_XX_24			PowerInputType	Type of power supply	String / Enumeration	Static	DC, AC, DIESEL	1	TRUE	IN	
REQ_D_XX_25			PowerVoltage	Voltage level	Number	Static	Uint16, [V]	1	TRUE	IN	
REQ_D_XX_26			MaxTractiveEffort	Maximum tractive effort	Number	Static	Uint16, [N]	1	TRUE	IN	
REQ_D_XX_27			MaxBrakingEffort	Max braking effort	Number	Static	Uint16, [N]	1	TRUE	IN	
REQ_D_XX_28			MaxPower	Maximum motor power	Number	Static	Uint16, [W]	1	TRUE	IN	
REQ_D_XX_29			TractionEffortCurve	Curve of tractive effort	Matrix / 2Column array	Static	Uint16 [km/h], Uint16 [km/h]	n	TRUE	IN	Array of traction effort. 2 columns: [Speed (km/h) | Effort (KN)]
REQ_D_XX_30			BrakingEffortCurve	Curve of total braking effort	Matrix / 2Column array	Static	Uint16 [km/h], Uint16 [km/h]	n	TRUE	IN	Array of total braking effort. 2 columns: [Speed (km/h) | Effort (KN)]
REQ_D_XX_31			TractionEfficiencyValue	Value of motor efficiency	Number	Static	Float [%]	1	TRUE	IN	Simplified version of TractiveEfficiencyMap
REQ_D_XX_32			TractionEfficiencyMap	Map of motor efficiency as a function of speed and effort	Matrix / 3Column array	Static	Uint16 [km/h], Uint16 [km/h], Uint16 [km/h]	n	TRUE	IN	Map of motor efficiency as a function of speed and effort
REQ_D_XX_33			BrakingRegenerationEnable	Braking regeneration enabled or possible?	Bool	Static	Bool	1	TRUE	IN	
REQ_D_XX_34			BrakingEfficiencyValue	Value of braking efficiency	Number	Static	Float [%]	1	TRUE	IN	Simplified version of BrakingEfficiencyMap
REQ_D_XX_35			BrakingEfficiencyMap	Map of motor braking efficiency as a function of speed and effort	Matrix / 3Column array	Static	Uint16 [km/h], Uint16 [km/h], Uint16 [km/h]	n	TRUE	IN	Map of motor efficiency as a function of speed and effort



10.3.3. Data Mapping

For the internal mapping and management of the received data, several classes and data structures have been created. Figure 10-5 shows part of these classes, with their respective data elements and methods.

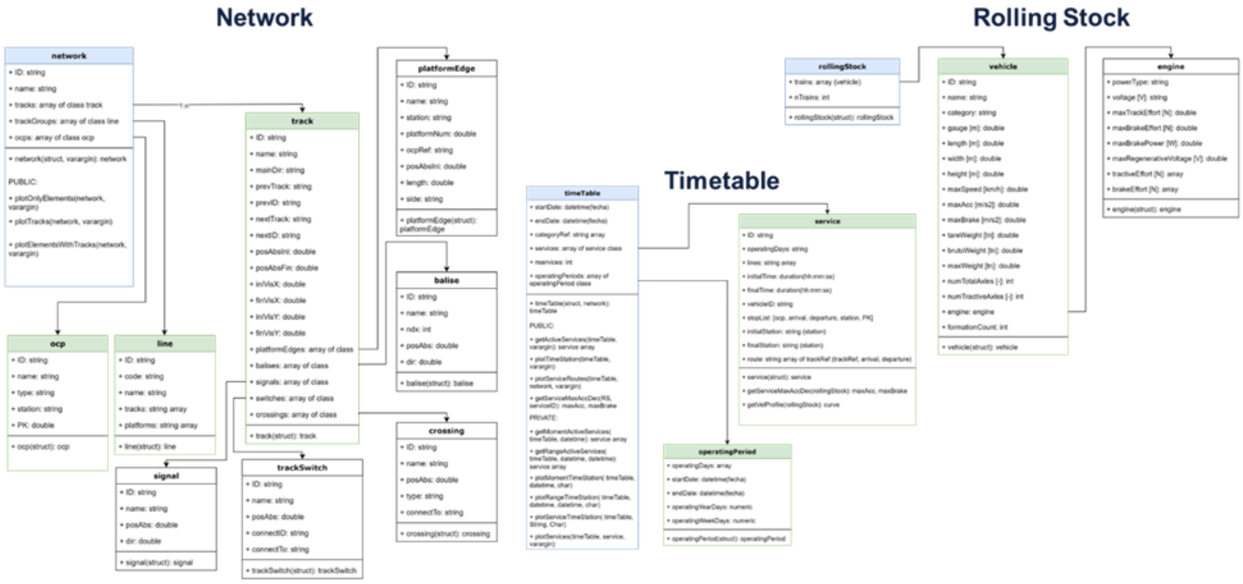


Figure 10-5 Examples of some of the classes defined for internal data management

10.3.4. JP Message Creation

Once the information has been received, the JP Message is created according to the ERTMS/ATO Subset-126, which defines the message information to be exchanged between trackside and onboard devices in ATO.

The JP message mainly covers the following information:

- Status of the JP
- Train route data (list of):
  - SP identifier
  - SP version
  - SP travelling direction
- Operational data (list of):
  - TP identifier
  - Arrival time and tolerance
  - TP alignment
  - Daylight Saving Time information
  - TP type
  - Additional TP information; - End of Journey; - Stopping Point with Relaxed couplers.
  - Departure time
  - Train Hold information
  - Minimum dwell time
  - Doors management information
- Dynamic infrastructure data required to operate (Temporary Constraints) including a list of:
  - Temporary Constraint type (ASR, Low Adhesion, ATO Inhibition Zone, Current Consumption Limitation Zone or DAS Inhibition Zone)
  - Temporary Constraint location

- ASR speed level and a qualifier which indicates if the supervision of the end of the speed restriction relates to the front or the rear end the train
- Low adhesion rate (if applicable).

10.4. Conclusions

This chapter considered the developed data models used for communication between the TMS – ATO subsystems. In particular, the IL, based on The Conceptual Data Model, can be used for exchanging data between the TMS and the ATO-TS. In addition, the Journey Profile Generator translates the Operational Plan received from the IL into SPs and JPs for sending to the ATO/C-DAS OB of all trains. These data models complement the ERTMS/ATO Subset-126 interface specification between the ATO-TS and the ATO-OB, by considering the TMS / ATO-TS interface and the JP generator to derive the JPs from the Operational Plan. The Operational Plan includes the RTTP developed by the TMS, while the JP/SPs contains the TPE from the ATO-TS. The TRL 4 validation test report of the TMS – ATO IL is provided in Annex 15.6, while the TRL 4 test report of the Journey Profile generator is provided in Annex 15.7.

11. Human-In-The-Loop Simulation Environment

11.1. Introduction

This chapter describes a human-in-the-loop (HITL) simulation environment for the Dutch railway system. The simulation environment consists of modules based on a simulation platform. External modules are and will be connected to enable to test the use cases.

One of the modules connected is an emulation of the Human Machine Interface (HMI) for traffic operators on a regional (PRL) and national (VOS) level. By this module scenarios with humans-in-the-loop can be simulated. Also there is a modified traffic optimization module connected that holds ATO trackside functions. For the communication between modules (abstractions of) ERA specifications are followed.

11.2. TMS – ATO Simulation Environment Components

Figure 11-1 illustrates the TMS – ATO joint simulation environment. It consists of a number of components, where some are the digital twins of production applications. The next subsection provides a functional description of the components.

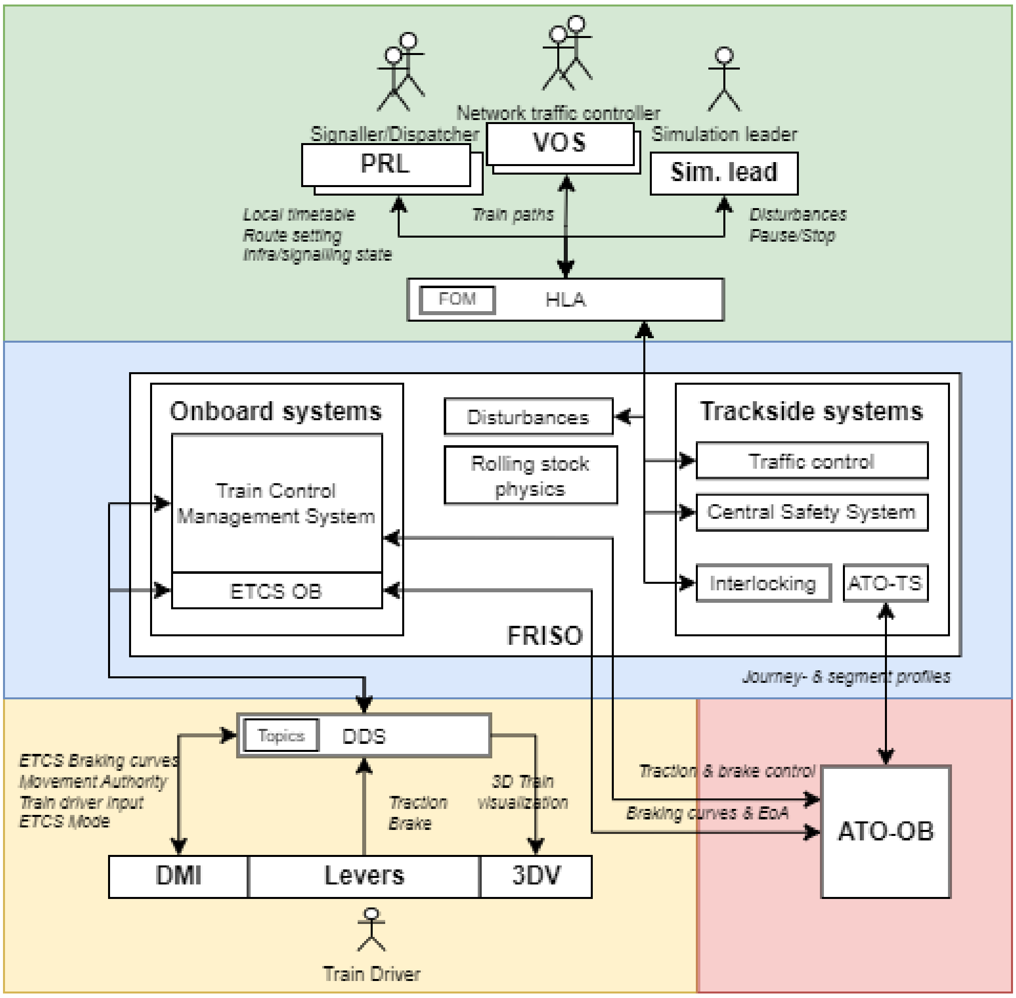


Figure 11-1 TMS - ATO simulation environment

11.2.1. FRISO

FRISO, which stands for 'Flexible Rail Infra Simulation Environment,' is a computer simulation tool developed by ProRail. Its purpose is to facilitate decision-making and enhance insight into railway operations by simulating complex technical and process variables.

FRISO simulates a wide range of technical and process variables relevant to railway infrastructure management. This includes modelling train movements, infrastructure characteristics, signalling systems, scheduling algorithms, and more. By simulating these variables, FRISO can accurately represent real-world railway operations and their complexities.

FRISO enables users to conduct scenario analysis to evaluate the impact of different strategies, policies, or changes to the railway infrastructure. Users can simulate various scenarios, such as changes to train schedules, infrastructure upgrades, or disruptions, to assess their effects on network performance and resilience.

11.2.2. VOS

VOS, which stands for Traffic Control Support System in Dutch, is a digital twin application of a real application used in production. VOS supports the Network controller in monitoring and adjusting train traffic.

The most important components of VOS are:

1. The Time-Distance Diagram (TWD) shows the current plan and the implementation of that plan. This information is displayed graphically as the utilization of the track by trains, plotted over time. The rail infrastructure is divided into predefined track sections. The TWD shows the information for the time period from yesterday to tomorrow. In addition to the current plan and implementation, the TWD also shows infrastructure restrictions and bridge openings. The Network controller can make adjustments to the current plan via the TWD: trains can be scheduled, changed and cancelled. Furthermore, infrastructure restrictions and bridge openings can be added, changed and removed.
2. Train Tracking (VT) shows the current train positions on predefined track sections. For each train it is indicated whether it is delayed compared to the current plan. Significant delays are signalled by VT, so that the Network controller can make timely adjustments to prevent the delay from spreading like an oil slick across the surrounding train traffic.
3. Messages (BR). BR shows information about plan changes that have been requested, plan changes that are being processed, and plan changes that have been finalized.

11.2.3. PRL

The Route Process Management (PRL) system is the digital twin application that supports the train traffic controller in monitoring the route process plan, setting up routes and taking safety measures. With PRL the Train Control Systems and the train describer system TROTS are operated. The most important parts of PRL are: Route Process Plan (PPR), Track Occupancy Graph (SBG) and Automatic Route Setting (ARI).

11.2.4. Train Driver

This component is a standalone train driver simulator. It consists of a visualization part where we can see the outside world, a DMI interface that replicates the ERTMS simulation user interface for train drivers, and a control panel where the driver can manage traction and braking.

11.2.5. Simulation Leader Component

To start, pause, and stop this environment, we use the simulation leader component. This also allows us to configure the workstations and introduce various disruptions during the session.

11.3. TMS – ATO Simulation Environment Feedback Loops

This section describes the mapping of the ATO-TMS feedback loops onto the TMS-ATO Simulation environment. Figure 11-2 shows the ATO-TMS feedback loop with its components assigned to the modules in the simulation environment. The connection between these simulation components is shown in Figure 11-3. The communication between modules follows interface standards, e.g. HLA, DDS, and DLL.

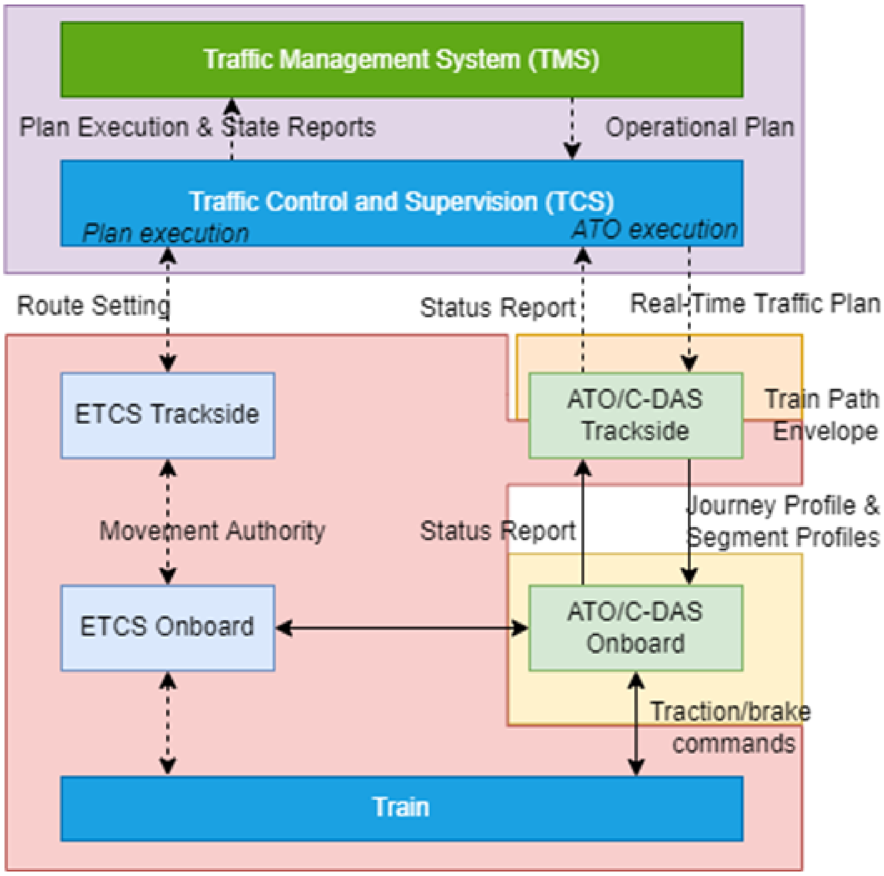


Figure 11-2 ATO-TMS feedback loop with its components

11.3.1. Responsibilities

PRL and VOS are together responsible for the TMS and TCS functionality. Any plan-updates are generated by these systems. PRL uses this plan to automatically initiate route-setting based on the current infra-state and plan state. PRL and VOS are informed about the plan-execution and ATO-execution state.

FRISO is responsible for both the trackside and onboard safety systems. The ETCS-OB safety systems are compliant with ERTMS/ETCS Subset-026, with the Dutch national values. FRISO also models the train driving behaviour. Here perfect reaction on the traction/brake requests is assumed and no brake or traction delays are included. This may lead to slightly over-optimized feedback between the train and ATO-OB.

The ATO-OB function is executed by an ATO-OB of CAF, this ATO-OB is configured to fit the selected rolling stock. The ATO-OB is however limited to controlling C-Type trains, i.e., vehicles with common brake control where separate control of dynamic and air brake is not possible for ATO-OB. This type holds for EMUs and DMUs. It does not apply to locomotive-hauled coaches (so-called S-type train).

The ATO-TS functionality is split between the TPE-generator and FRISO. The TPE-generator is responsible for generating time targets/windows for trains and is described in Section 8.3. FRISO is responsible for the segment-profiles and communication with ATO-OB.

11.3.2. Interfacing

The interfacing between the simulation modules is shown in Figure 11-3. First thing to note is that most models are fed the same static infrastructure information. This information about signal placement, block sections and routing options are not changed during the simulation.

During the simulation, FRISO acts as the central module of the simulation environment. Here the simulation is initialized with a timetable and an initial infrastructure and train state. FRISO communicates with TPE and PRL/VOS via a runtime-infrastructure (RTI) based on the High Level Architecture (HLA) standard for distributed simulation. Here the ETCS-trackside status and train states are published to the TPE and PRL/VOS. PRL/VOS is responsible for initiating route-setting in FRISO and updating train plans. These updates can be automated or controlled by one or more traffic controllers. Using the train states and updated train plans, TPEs are generated for FRISO to enrich and distributed to ATO-OB.

The ATO-OB component implements the TCP/UDP interfaces as defined in the ERA specs for communication of ATO-TS with ATO-OB (ERTMS/ATO Subset-126), ATO-OB with ETCS-OB (ERTMS/ATO Subset-130) and ATO-OB with Rolling Stock (ERTMS/ATO Subset-139). FRISO is responsible for providing this connection to the CAF-OB.

The ATO-OB can optionally be controlled/initiated by a Human-In-The-Loop train driver, as shown in the bottom of the figure. Here the DMI and a 3D-Traincabin view (3DV) are coupled with a train in FRISO. This interface uses Data Distribution Service (DDS), a real-time data exchange middleware often used in simulation. Any train movement is shown in the 3DV and the ATO can be controlled from the DMI.

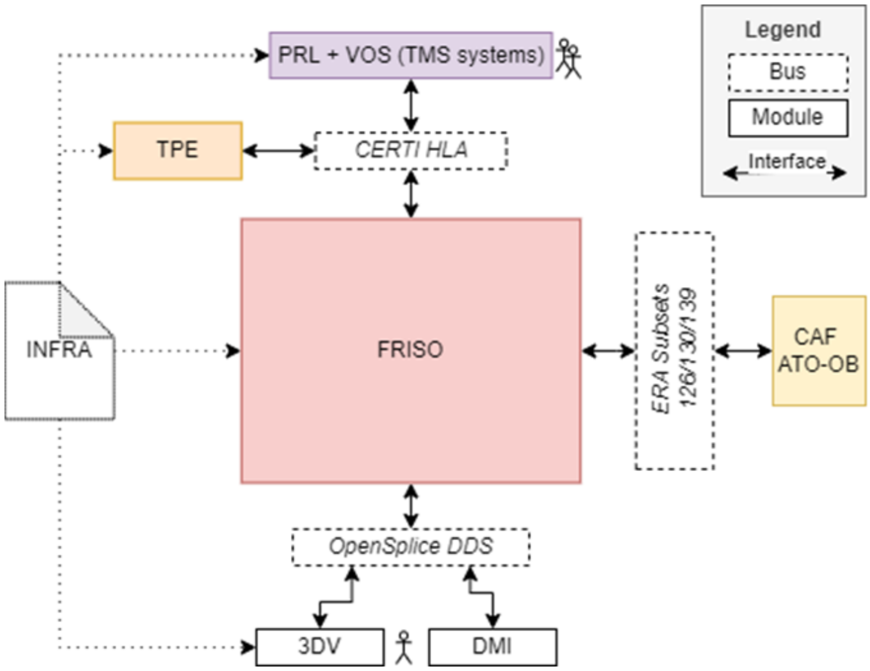


Figure 11-3 Interfaces between simulation components

11.4. Conclusions

This Chapter described the HITL simulation environment that will be used to test and demonstrate the TMS - ATO system in the context of the Dutch railway system architecture. It simulates the Dutch traffic management and traffic control systems, as well as the train drivers' systems, including the interaction with the human operators, and facilitates HF research. Within WP15 this simulation environment has been extended with an ATO-TS including the TPE Generator from Chapter 8. The ATO-OB functionality is also extended with a CAF ATO-OB. The TRL 4 validation test report including the TPE Generator is provided in Annex 15.8.

12. Human Factors

Human factors (also known as applied psychology, cognitive ergonomics, or engineering psychology) as discipline focuses on how operators interact with systems in a safety-critical environment. It involves designing with users (operators) and researching behaviour, cognition, and performance of users for safer, more efficient, and user-friendly systems.

The goal of the human factors activities in WP15 is to learn from previous studies and methods in order to prepare for human factors research on ATO/C-DAS and TMS in the subsequent work package FP1/WP16. The work package focuses on different types of operators, i.e. train drivers as well as traffic controllers.

The following human factors research topics are discussed in this chapter (see also Figure 12-1):

- State-of-the-art on rail human factors for ATO/C-DAS and TMS (12.2): lessons learned on human factors research and developments on automation for both train drivers as traffic controllers are reported, in particular on ATO/C-DAS and TMS.
- Human factors constructs and measurement techniques (12.3): relevant human factors constructs (e.g. mental workload, situation awareness) and measurement techniques in the railway domain are identified.
- Traffic control/management roles (12.4): findings from human factors studies within railway traffic operations are difficult to interpret as operational traffic control/management roles differentiate amongst European countries. Traffic control roles will be described based on a literature review.
- Research requirements (12.5): factors are described that should be considered in the research design of a human factors study. This includes the evaluation or test of a human-machine interface (HMI) design, or the investigation of human and system performance.
- Human Readiness Levels (HRL) (12.6): Human Readiness Levels (HRL) are described in the light of technological developments and Technological Readiness Levels (TRL). HRL can be applied to rate the level of maturity of a technology with respect to its readiness for human use.

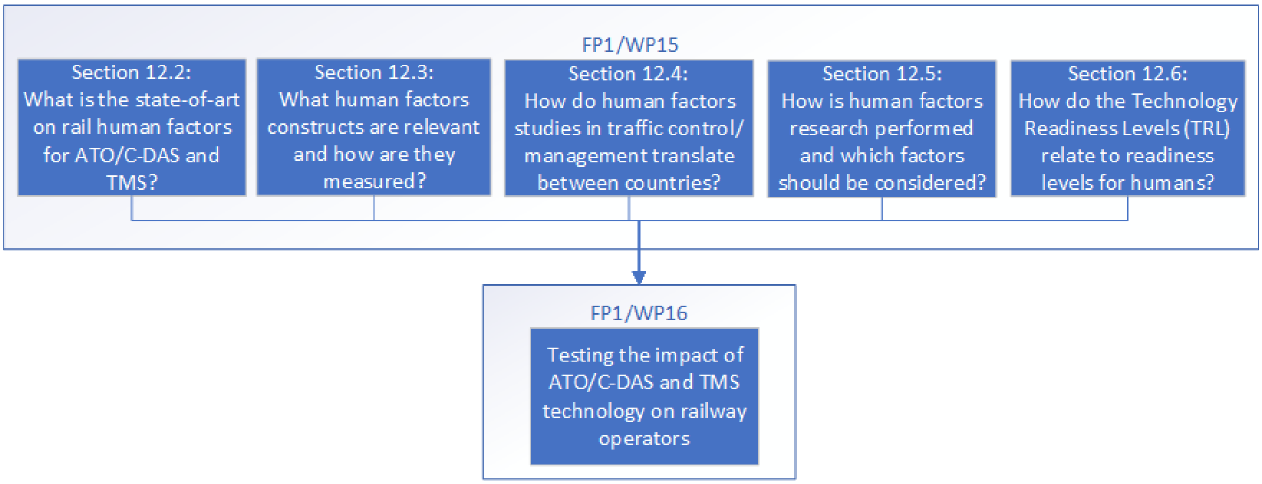


Figure 12-1 Research activities for testing the impact of TMS – ATO/C-DAS technology

The outcomes/guidelines from section 12.4 to 12.6 are widely applicable and can be reused for other technological/system settings. As such, we present a rail human factors toolkit that can help railway practitioners and researchers to guide system development and define and design their own human factors research.

12.1. Systematic Literature Review

This section describes the performed systematic literature review approach that provides the fundament for sections 12.2, 12.3 and 12.4.

The goal of this review is to provide insights into the current literature on human factors in the railway domain with a focus on how it relates to the development of automated systems. The second goal is to map the key human factors measurements in the railway domain, specifically when rail operators are involved as subjects. This includes compiling the methods/tools utilized to empirically measure aspects of human factors, as well as the impact (cognitive, behavioural, etc.) on the experience of train operators (i.e., drivers, controllers, network managers/controllers, dispatchers, signallers etc.) in the context of ATO, particularly at different GoA levels.

As suggested by Munn et al. (2018) to systematically map common practices as well as to identify differences and gaps among practice, methods and domains the most common approach is to perform a Scoping review. Specifically, we adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) approach (Tricco et al., 2018).

The scoping review was performed on articles in the railway domain discussing train operators in the context of train automation. The checklist of the PRISMA-ScR was used to ensure alignment of the review process with the framework.

12.2. State-of-the-Art on Rail Human Factors for ATO/C-DAS and TMS

12.2.1. Research Question and Goal

The main research question in this section is

- What are the key findings and lessons learned about the impact of technological changes (automated systems) in the railway domain from previous studies?

12.2.2. Approach

We searched for articles across six different databases: Web of Science, Scopus, IEEE, ACM, PsycInfo and Business Source. We searched for items that are either a journal article, a conference paper, or book chapter to capture items that are of appropriate scope and length. This also ensures that the article has undergone some level of peer review. We searched only for items available in English to ensure that the contents of the item are available to a wide range of audience. We also limited the articles to those published from the year 2000 and later. In the literature search, two independent reviewers conducted the initial screening, and the results were subsequently cross-checked by two additional reviewers.

Based on our research question, we devised the following inclusion criteria:

- *Item presents literature review and or empirical studies with measurements related to train operators in real and simulated context.* This criterion aims to capture the various types of experimental/observational data and performance measures collected on either train operators or other participants performing train operator duties.
- *Item discusses human factors in railway operations in the context of decision support for driver/traffic controllers.* This criterion helps to capture items that discuss human factors in railways, but specifically in aspects that are relevant to assessing how performance is affected by the availability of tools offered by automated systems.
- *Item discusses the usage and impact of automation related to train operations.* This criterion aims to broadly capture how automation affects the job function of train operators.
- *Item compares grades of automation and/or differences in applications in various countries.* This criterion is added to obtain a wide range of applications of automation in railways and how it functions in different contexts.
- *Item is a journal article, conference paper, or book chapter.* This criterion is to capture items that are of appropriate scope and length. This criterion also ensures that the article has undergone some level of peer review.
- *Item is available in English.* This criterion ensures that the contents of the item is available to a wide range of audience.
- *Item was published from the year 2000*. This criterion is to limit the studies to relatively recent ones.

Exclusion Criteria were formulated to drive the selection of the items as follows:

i) Item or reference of books that do not point to a specific chapter.
ii) Item is only mentioning the context of railways/trains, or it is about innovation, but it is mainly focus on another domain.
iii) Item presents a technical simulation/analysis with very minor behavioural component.
iv) Item presents a very specific aspect of rail operations such as communication systems, door operations, or specific safety features.
v) Item is about innovation or innovative technologies but lack concrete railway application.
vi) Item discusses general railway issues with no particular focus on operators or automation.

12.2.3. Findings

After accounting for duplicated items, initial literature search yielded 287 items. We also solicited articles from human factors reviewers in the railway domain (n=6) to contribute to our list of literature and obtained 26 suggestions. After removing duplicates, the total number of articles was 288. Two Human Factors experts screened the items by title and abstract based on the inclusion and exclusion criteria, which resulted in the removal of 210 items. The full text of the remaining 78 items was screened by the reviewers. After excluding a non-retrievable article, a redundant article (which described the same study as another article already in the selection), and 12 papers that did not meet the exclusion criteria upon further examination, a final list of 65 items was selected. To facilitate the analysis and visualization of the 65 items' characteristics, we organized them into five categories based on the approaches adopted by the authors and the type of studies that were reported. Specifically, the items were initially divided into empirical or analytical studies. Empirical studies generally aim to answer a particular set of research questions and involve some level of data collection. These were further divided into three sub-categories based on the type of study performed by the author i.e., simulations, non-simulation empirical studies, or literature review studies. Concurrently, analytical studies are more theoretical and/or descriptive, for instance, items discussing a technology/system/model that is already in use in the domain, or items that are introducing new technological systems, or models, with or without a validation study.

We further defined the five categories as follows:

1. Empirical Simulations (SIM): items in this category feature studies that involve studies where the participants engage with a simulated environment of train operations. In other words, human-in-the-loop (HITL) simulation studies. The study may be exploratory or experimental.
2. Empirical non-simulation data collection (NSD): items in this category involve collecting data related to relevant rail topics such as surveys, interviews, or other experimental data collection that do not otherwise involve a simulated environment of rail controls. Field studies that observe train operators in their work environment fall into this category.
3. Literature review (LR): items in this category comprise of systematic literature search or literature overview related to various topics that are relevant to the research goals of this study.
4. Analysis of existing technology, systems, or models (ETS): items in this category provide a description or analysis of existing technology or models that are previously or currently utilized in rail systems. This category includes case studies and incident reports.
5. Introduction or proposition of new technology, systems, or models (NTS): items in this category presents either new technology for rail simulations/systems in general or proposes a model of rail operations that incorporate operator behaviour, but in general discusses the human factors aspect involved in the design of the technology and/or model without necessarily having any testing or validation of their proposed technology/model.

Based on our division in the five categories, 32% (n=21) of the items are proposing a SIM study, 25% (n=16) can be categorized as NSD, 8% (n=5) as LR, 31% (n=20) can be categorized as ETS, and 20% (n=13) can be described as NTS analytical studies.

Table 12-1 List of items included in this review divided into one of the five categories

ID	Author	Type of study				
		SIM	NSD	LR	ETS	NTS
1	Fan et al. (2022)			x	x	
2	Papadimitriou et al. (2020)			x		
3	Pacaux-Lemoine, Gadmer & Richard (2020)					x
4	Buksh et al. (2013)		x		x	
5	Brandenburger & Naumann (2018)	x				
6	Niu, Fang & Guo (2018)					x
7	Brandenburger et al. (2017)		x			
8	Brandenburger, Naumann& Jipp (2021)	x				
9	Sebok,et al. (2015)				x	
10	Tschirner, Sandblad & Andersson (2014)		x		x	
11	Richard, Boussif & Paglia (2021)					x
12	Belmonte et al. (2006)					x
13	Scott & Gibson (2012)	x				
14	Naghiyev et al. (2016)	x				
15	Gadmer et al. (2022)					x
16	Metzger & Vorderegger (2012)				x	
17	Wagner, Haramina & Michelberger (2021)		x			x
18	J. Qiu, at al. (2011)		x			
19	Brandenburger & Naumann (2019)	x		x		
20	Makkinga (2004)					x
21	Farrington-Darby et al. (2006)		x			
22	Du, Fang & Niu (2018)		x			
23	Hillege et al. (2020)	x				
24	Kojima et al. (2005)	x				
25	Spring et al. (2012)	x				
26	Young, Stanton & Walker (2006)			x		
27	Tschirner, Andersson & Sandblad (2013)				x	
28	Wackrow & Slamen (2013)				x	
29	Du & Zhi (2022)	x				
30	Smith et al. (2013)				x	
31	Rees et al. (2017)	x				
32	Balfe, Sharples & Wilson (2015)	x				
33	Sharples et al. (2011)		x			
34	Wang et al. (2022)	x				
35	Enjalbert et al. (2021)				x	
36	Lenior et al. (2006)					x
37	Rad et al. (2021)				x	
38	Gadmer, Pacaux-Lemoine & Richard (2021)					x
39	de Egea, Holgado & Suarez (2012)				x	
40	Dobson (2015)				x	
41	Hammerl et al. (2012)				x	

42	Lo et al. (2016)	x				
43	Tabai et al. (2018)		x			
44	Naghiyev et al. (2014)	x				
45	Brandenburger & Jipp (2017)	x				
46	Jun & Choi (2006)					x
47	Collis & Robins (2001)				x	
48	Thompson, Kazi & Scott (2013)				x	
49	Crawford, Toft & Kift (2014)		x			
50	Maag & Schmitz (2012)				x	
51	Verstappen, Pikaar & Zon (2022)	x				
52	Yang, Liden & Leander (2013)				x	
53	Stoop et al. (2009)					x
54	Sandblad et al. (2010)				x	
55	Yin et al. (2017)			x		
56	Lagay & Adell (2018)					x
57	Wikstrom et al. (2004)	x				
58	Albrecht (2013)				x	
59	Brooks et al. (2017)	x				
60	Jansson, Olsson & Fröidh (2023)		x			
61	Jansson, Fröidh & Olsson (2023)		x			
62	Sobrie, Verschelde & Roets (2013)		x			x
63	Golightly et al. (2013)		x			
64	Sandblad, Andersson & Tschirner (2015)				x	
65	Zeilstra, de Bruijn & van der Weide (2012)		x		x	
Total per category		18	14	5	20	13

Legend: Empirical Simulations (SIM); Empirical non-simulation data collection (NSD); Literature review (LR); Analysis of existing technology, systems, or models (ETS); Introduction or proposition of new technology, systems, or models (NTS)

12.2.3.1. Qualitative Synthesis

To draw lessons learned from the body of literature, we conducted a qualitative review of the content of each item. Specifically, four reviewers were involved in data extraction, cross checking and review of each item. The 57% (n=37) of the items discussed aspects mainly related to train drivers, 22% (n=14) discussed aspects mainly related to train traffic controller roles (i.e. traffic controller, signaller, dispatcher, safety controller, etc.), 14% (n=9) discussed aspects related to all stakeholders in railway operations, which may include roles such as infrastructure managers and maintenance operators, while 9% (n=6) did not discuss specific train operator or stakeholder roles in the article. Out of the articles discussing GoA levels, GoA 1 was discussed in 2 articles, GoA 2 was discussed in 4 articles, GoA 3 was discussed in 5 articles, and GoA 4 was discussed in 4 articles (some articles may include more than one GoA level).

12.2.3.1.1. Analysis per Type of Study

12.2.3.1.1.1. Empirical Human-In-the-Loop Simulation Studies (SIM)

A total of 18 studies were included in the SIM category. Of these studies, 72% (n=13) focused on studying train drivers in terms of behavior, cognition and interaction with systems, while only 28% (n=5) of the items were interested in traffic control operators Out of these 18 studies, 83% (n=15) utilized simulations for experiments testing hypotheses or explicitly defined experimental conditions for comparison, 22% (n=4) used it for exploratory purposes, by for instance, investigating how participants adjust or react to a system and do tasks without answering a specific research question, and the other 17% (n=1) utilized simulations for both experimental and exploratory purposes. Table 12-2 presents an overview of the SIM items based on role of operator, type of study and number and characteristics of participants.

Based on the studies in the SIM category outlined in Table 12-2, studies exploring the impact of automation on workload mostly indicate that automation operator workload decreases under automation (Items 5, 19, 51, 32) with the exception of one study (Item 8) that suggests an increase in workload. Overall in terms of working with automated rail operations, literature suggest that the goal of working with automated systems should be to operate under optimal workload that does not lead to under or overload (Item 5).

Various studies attempt to investigate the impact of automation on attention. More studies seem to indicate negative effects for attention under automated systems, such as the decrease of attention over time when driving under automated conditions (Item 29) and vigilance being shown to be lowest in highest level of automation (Item 25). However, there is also evidence that attention is not impacted (Item 51). Another consequence of working with automated systems is that train drivers often employ different monitoring strategies (Item 32), such as shifting their attention from outside the cab to the interface (Items 14, 44). Evidence also points to the fact that operators tend to have higher latency with automatic speed control (Item 45).

Automation also affects situation awareness, with increased automation potentially leading to a loss of awareness (Item 19). Situation awareness also tends to be lower in more experienced operators (Item 42). Skill degradation is another well known consequence of automation where operators feel that relying on automated systems disincentivize them from developing skills associated with their roles (Item 44). Complementary to this literature review, additional insights on skill degradation of train drivers have been obtained by studies from the Dutch railways (NS) (Rypkema et al., 2023), in which they found that skill degradation is both an issue during ATO implementation phases as after ATO is implemented, but from a different perspective. When introducing ATO, it can be the case that train drivers finished their ATO training, but regular ATO shifts are not yet available. Train drivers that mainly drive manually may lose ATO related monitoring and intervention skills. This may also happen when ATO becomes highly reliable and intervention skills are not regularly practiced. This poses a significant risk of overreliance and complacency, where operators may become overly trusting of the automation system and fail to

Table 12-2 Overview of items (ID) that present a Human-in-the-loop simulation study

ID	Operator role	Type of study	Characteristics of Participants
5	Train driver	Experimental	n=20; Sex: all male; Age: M = 39.22 years; SD = 10.86 years; min.: 23; max.: 58); Experience (years): M = 14.5; SD = 11.31.
8	Train driver	Experimental	n=32; sex: all male, Age: 37.13;SD = 11.34); Experience (years): M=12.76;; SD = 11.58.
13	Train driver	Exploratory	n=52
14	Train driver	Exploratory	n=14; sex: all male; Age: M= 44.1; SD= 6.6; min.: 30, max.: 53 years; Experience (years): M=9.1
19	Train driver	Experimental	n/a
23	Train traffic control role	Experimental	n=16; sex: 12 male, 4 female; Experience (years): M = 13.44 years, SD = 10
24	Train driver	Experimental	n=2; sex: all male; experience: trained non train drivers
25	Train driver	Experimental	n=40; sex: 27 males, 13 females; Age: M =22.1; SD=4.31; min.: 18, max.:36; Experience: all novice/not experts n/a
29	Train driver	Experimental	n=42; age: 25–35 years (M=28.47, SD=6.73); experience: university students with more than 40 h of experience in driving simulation training for high-speed trains
31	Train traffic control role	Experimental, exploratory	n=87; sex: 58 females 29 males; age: M=20.57 years, SD = 6.05 years; experience: non experienced university student sample
32	Train traffic control role	Experimental	n=6; sex: all male; experience: at least 5 years as signaller
34	Train driver	Experimental	n=30; sex: all male; age: M = 23.8 years, SD = 1.70 years; experience: university student with no train driving experience
42	Train traffic control role	Experimental	n=11; experience: licensed operator
44	Train driver	Experimental	n=28; (14 ERTMS and 14 conventional drivers); sex: all male; age: ERTMS drivers: 30-53 years (M =44.1 years; SD=6.6 years), conventional drivers: 34-54 years (M =42.2; SD=7.7); experience: ERTMS drivers: 0.25-2 years (M =1.76; SD=0.73), conventional drivers: M=10 years, SD=5.0 years
45	Train driver	Experimental	n=26; sex: all male; age: 21–56 years (M = 36.53, SD=10.92); experience: 1 - 37 years (M = 14.07, SD 10.85)
51	Train driver	Experimental	n=28; sex: 25 male and 3 female; age: 24–61 years (M = 44.56, SD = 11.12); experience: at least 2 years (M = 14.16, SD = 11.43)
57	Train traffic control role	Exploratory	n=8
59	Train driver	Exploratory	n=11; age: M=44.2 years; experience: M=9.9 years as engineer, M=7 years as management

maintain proper vigilance. When train drivers mainly drive with ATO, the original manual tasks will no longer or seldomly be performed. There is a risk that detection skills, decision skills and acting skills may degrade. This may introduce risks such as operators hesitant to take over, longer reaction times, and performance degradation during manual control. It is essential to address this challenge to ensure that train operators maintain the necessary level of proficiency and remain actively engaged in their monitoring role, thus minimizing the potential risks associated with skill degradation and overtrust. Additionally, situation awareness can be supported by automation transparency, which is a design principle that supports humans by making the automation's inner workings observable (van de Merwe et al., 2022). Proposals for solutions that aim to identify the right balance in terms of human operators and technical systems are under exploration. ATO operations with Grade of Automation (GoA) levels above 2 attempts to phase out the need for train drivers. GoA level 3 (driverless with attendant on train, with automated object detection) and 4 (unattended train operation) have been in use for metro systems. Since 2023, GoA3 is used on the Elizabeth Line to speed up the reversing procedure for westbound trains terminating at Paddington Low Level Station (Transport For London, 2023). This capability allows the driver to immediately leave the cab as soon as the train leaves Paddington Low Level (under ATO control), and walk to the other cab while the train is in motion. This reduces the amount of time that the train needs to wait in the sidings for the driver to set up the new cab. For rail systems, a GoA 2.5 concept was introduced in Japan by JR Kyushu. At GoA2.5, a train attendant located at the front of the train is responsible for detecting objects on the guideway instead of a fully-qualified driver (GoA2) or automated system (GoA3). On the Vancouver Skytrain (a GoA4 system without platform screen doors), a train attendant is used to monitor the track for objects during periods with snow, when the automated detection system is unreliable. Additionally, JR East plans to implement unattended train operation in the near future with GoA level 4 planned for shunting operations in Niigata and GoA 3 operations for the Joetsu Shinkansen (high speed rail) (Suzuki, 2024).

Despite some detrimental effects, there is evidence that suggests that overall operator performance can improve in automated modes (Item 32), specifically, with the appropriate allocation of functions, cooperation between drivers and automated train operations (ATO) can enhance both efficiency and safety (Item 57, 59). The usability of interfaces for automation modes is also a point of consideration to the positive or negative impact on operators (Item 8).

12.2.3.1.1.2. Non-Simulation Data Collection (NSD)

Out of 14 studies involving data collection from respondents, 29% (n=4) included input from train drivers, 14% (n=2) from traffic controllers, 21% (n=3) from train dispatchers, 43% (n=6) from general railway operator/staff and 29% (n=4) from domain experts. Out of the more common methods used for data collection, 50% (n=7) of studies conducted interviews with participants, 36% (n=5) utilized survey/questionnaires, and 21% (n=3) were observational studies. The methods used as well as respondents in studies categorized as NSD are outlined in Table 12-3.

The summary of common findings highlights the critical importance of the operator's perspective in adopting automated systems, particularly in identifying their needs and contributing to interface design (Items 7, 10, 17 & 49). Researchers can use ethnographic methods or observation to study how operators interact with technology and identify room for improvement and innovation (Item 21, 26 & 33). Another way of identifying operator duties is through analysis of event logs during train operations (Item 60).

Training and familiarization with these interfaces are crucial components in transitioning to automated systems (Item 4 & 7). Operators expect changes with automation, such as a shift towards more supervisory roles (Items 7, 33 & 49), risk of deskilling (Item 4), and more uniform driving styles for train drivers (Item 4). Additionally, it is expected that there will be a move away from visual perception in inspection of abnormalities/disruptions on train tracks (Item 61).

Table 12-3 List of methods, respondent sample, Items in the NSD category

ID	Method	Respondent sample	Participants
4	Interview	Train driver	n=18; sex=17 males, 1 female; age: 29-59 years (M=42.8); experience: 2-22 years (M=7.38 years)
7	Interview, specifically task analysis	Train driver	Interview n=5; sex: all male; age: M=47 years, SD=5.1 years; experience: M=27 years, SD=5.74 years Survey n=21; sex= 18 male, 3 female; age: M= 42.6; experience: 22.4 years
10	Interview, observation	Train driver, traffic controller	N/A
17	Survey, interview	Experts	N/A
18	Survey/questionnaire, workshop	Railway staff, ergonomics and psychology experts	n=20
21	Ethnography (observation and interviews)	Rail traffic controller	n=24 observations
22	Observation, interview, survey/questionnaire	Railway staff	n=137; sex: all male; age: 21-45 years; experience: over 2 years
33	Ethnography	Traffic controller	
43	Cognitive task	Train driver	n=56; age: 27-63 years (M=39.18, SD=6.921); experience: one group 3-41 years (M=15.62, SD=8.62), other group 5-32 years (M=16.68, SD=6.20)
49	Survey/questionnaire, interview	Managers (technology clients), Designers (technology builders and suppliers), Evaluators (human factors and safety professionals) and end users (railway technology operators)	n total = 315, n managers = 48, n designers = 85, n evaluators = 115, n end users = 68
60	Review of logs	Train dispatchers	n = 7100 log entries
61	Review of logs	Train dispatchers	n= 89 entries
63	Workshop, survey/questionnaire	Railway staff, human factors experts	N/A
65	Rating scale	Train dispatchers	N/A

The role of a train operator demands non-technical skills alongside technical knowledge, including communication, cooperation, problem-solving, decision-making, self-management, and situation awareness (Item 18 &22). The definition of operator roles, especially in traffic control, may vary between countries, necessitating the development of a framework for comparison in research (Item 63). Additionally, additional results from the literature include sustained attention in drivers is identified as a predictor for incidents (Item 43) and operator workload can be estimated based on specified tasks (Item 65).

12.2.3.1.1.3. Empirical Human-In-the-Loop Simulation Studies (SIM) Literature Review (LR)

There are five studies categorized under literature review, which include systematic and non-systematic reviews. The topics of each item in LR are outlined in Table 12-4.

Table 12-4 Items in the LR category

ID	Topic
1	Measurements of workload and fatigue in train drivers
2	Research in human factors issues across transport domains
19	A series of research on the effects of automation on train driver
26	Human factors issues in the application of ERTMS
55	The development and application of automated train systems in urban rail

These literature review articles mostly analyse the body of research concerning human factors issues in rail systems (Items 2, 19, & 26) including methods of measurements used in human factors research (Item 1). Some of the articles connected human factors research from other transport domains such as aviation and road transport (Items 2 & 9). One article provides a description of the role of traffic controllers (Item 55).

12.2.3.1.1.4. Empirical Human-In-the-Loop Simulation Studies (SIM) Analysis of Existing Technology, Systems, or Models (ETS).

Studies categorized under analytical studies attempt to analyse and/or review human factors issues in relation to certain topics in the railway system. For the ETS category, we summarize the system/technology discussed in the item as well as its current implementation in Table 12-5.

In general, the items in the ETS category presents applications of different components of rail technologies from various countries. Items 28 & 47 touched safety issues introduced by automation such as new risks due to overreliance on automated modes and the perceived lesser need for human intervention. Meanwhile, item 9 attempts to apply lessons learned from human factors studies from the aviation domain, particularly challenges with mode complexity and mode transitions, in which operators are unclear whether a system such as automated operations is turned on or not. One article provides a look at human factors issues in rail through analysis of past incidents (Item 37).

Items in ETS also commonly discuss the implementation of specific rail technology such as ERTMS. Articles on ERTMS discuss aspects such as interface design (Items 16, 27, 35 & 48) and how communication systems affect operator performance in ERTMS (Item 30). There is also a series of research articles discussing the implementation of DAS (Items 10, 27, 52, 58, & 64), particularly in the design process of DAS to support drivers in efficient speeding, anticipating issues, coasting and braking as well as integrating the system with traffic planning.

Several studies present aspects related to the utilization of human in the loop simulations (Item 4, 39, & 41) for rail research and human factors measurement such as fatigue (Item 1), workload (Items 1, 40, 52, & 65), and performance (Item 50). In general, studies agree that workload will be likely be impacted as automated systems are introduced and it is important to accommodate it in designs of interfaces and address the needs of operators, in order to aid in their routine tasks so that they can focus on aspects such as problem solving.

Table 12-5 Items in the ETS category

ID	System/technology reviewed	Context/Implementation
1	Technology measuring driver fatigue	HITL simulation to measure driver performance
4	Human factors issues ERTMS/ETCS	UK rail
9	ATP systems meeting Positive Train Control (PTC) standards, and human automation interaction in Aviation	United States rail and aviation system
10	Real-time traffic plan	Swedish train traffic control room operations
16	Development of driver machine interface (DMI) for ERTMS/ETCS systems	ERTMS implementation across Europe
27	Shared Traffic Information between traffic control and driver advisory system (DAS)	Swedish train traffic control room operations
28	Human factors automation design for rail systems	London Underground lines under ATO
30	ERTMS, particularly Global System for Mobile Communications–Railway (GSM-R)	ERTMS implementation across Europe
35	Human-Machine Interface design across transportation simulations	General transportation simulation systems, including rail
37	Safety controls systems in railway, particularly in regard to incidents involving automation	Rail systems in the US, UK, China, Korea, Iran, Singapore, and Australia
39	Rail simulation technology integrating human factors	Rail simulation facility in Spain
40	Human factors issues in transportation control systems	Transportation control in the UK, USA, Canada and Japan
41	Railway simulation to study the human contribution to performance and safety of the railway system	German Aerospace Centre railway laboratory RailSiTe
47	Automatic Train Protection	French and UK systems
48	ERTMS Driver Machine Interface (DMI)	GB Rail
50	Process model (PERMA model) of driver performance assessment	Deutsche Bahn regulations
52	The application of Driver Advisory Systems (DAS) in conjunction with CATO (Computer Aided Train Operation)	Swedish railway system
54	Development and implementation of new principles and systems for train traffic control	Swedish train traffic control room operations
58	Driver Advisory System (DAS)	Diesel hauled regional railway operation in Germany
64	Informational system for train traffic control	Train traffic control centres in Northern Sweden
65	Instrument measuring train dispatcher workload	Dutch train dispatchers

12.2.3.1.1.5. Introduction or Proposition of New Technology, Systems, or Models

Items in the NTS category present the development or ongoing work of rail technologies that touch on human factors aspect of railway systems. A summary of items categorized as NTS is included in Table 12-6.

Table 12-6 Items in the NTS category

ID	System/technology proposed	Potential/planned implementation
3	Human machine cooperation approach to remote driving	French railway system
6	Control centre team task complexity	Railway control room operations
11	Rule-based and managed safety	Autonomous systems in transportation, including rail
12	Railway supervision systems	Railway control rooms, validation through railway control room environment simulator
15	Framework for authority transfer between an autonomous train and a remote driver	French railway system
17	Ergonomic interface for supervision and control of an automated shunting device	Austrian railway system
20	New interface for train traffic control system	Netherlands railway train traffic control room
36	Human factors engineering in designing decision support	Train traffic controller room and autonomous road vehicles
38	Human-machine cooperation model role for the train driving activity and their interactions with technical systems	French railway system
46	Multi train simulator environment	HITL railway simulations
53	Analysis of fully automated train control vs human centred design	ERTMS implementation
56	ATO implementation	French railway system
62	Predictive employee workload analytics	Belgian railway control room

In contrast to items in ETS that presents systems or frameworks that are already in place, items in the NTS category present a proposal of new frameworks and a prescriptive direction towards implementation of rail technology. Many of the articles deal with topics such as how to improve efficiency, punctuality and capacity (Items 3, 36, & 56). There are also discussions on safety, particularly on designing rules and protocols in anticipating hazardous conditions (Items 6, 11 & 12). Interface design also remains to be a common topic, where items 20 & 53 encourage human centred design in interfaces that prioritizes its ability to assist operators in solving problems thus working more efficiently. Another design principle that should be taken into consideration is to minimize potential conflicts due to mode confusion (Item 15). There are also articles that discuss designing systems specifically for train drivers (Item 17 & 38).

Other articles include the presentation of the development of a simulation environment for rail operations (Item 46), while item 62 presents an algorithmic approach to measuring operator workload based on the tasks that operators execute and provides a description of the tasks of Belgian traffic control operators.

12.3. Human Factors Constructs and Measurement Techniques

12.3.1. Research Question and Goal

The goal for this section is to map the key human factors measurements in the railway domain, specifically when rail operators are involved as subjects. This includes compiling the methods/tools utilized to empirically measure aspects of human factors, as well as the impact (cognitive, behavioural, etc.) on the experience of train operators (i.e., drivers, controllers, network managers/controllers, dispatchers and signallers) in the context of ATO, particularly at different GoA levels.

The research question relates to the second question of the literature review:

- What are the most investigated human factors aspects in the context of railway automation and how are they measured to evaluate impact railway operators? (particularly in the context of HITL simulations).

12.3.2. Approach

We built upon the systematic review to identify human factors aspects that were investigated in railway human-in-the-loop studies. Out of items identified in the literature review outlined in Section 12.2, two independent reviewers with expertise in human factors and psychological measurement extracted and compiled a list of a total of 10 human factors related constructs and 36 methods used to measure them. This list of constructs (also referred to as aspects) were then reviewed by two additional senior experts in human factors to further adjust the clarity and accuracy of the content of the toolkit.

In the expert review phase, we distributed a survey asking for evaluation and feedback for aspects listed in our initial toolkit, as well as suggestions for additional aspects or methods to measure them. We utilized a Likert scale for the respondents to evaluate the relevance, usefulness, and sufficiency of information presented in the toolkit. The questions are as follows

- *Relevance:* To what extent do you agree that evaluating [aspect] is relevant in HITL simulations within the railway context? (1: strongly disagree, 2: disagree, 3: somewhat disagree, 4: neither agree nor disagree, 5: somewhat agree, 6: agree, 7: strongly agree)
- *Usefulness:* How would you rate the usefulness of the table and description we provided on [aspect]? (1: not at all useful, 2: somewhat not useful, 3: moderately useful, 4: somewhat useful, 5: very useful)
- *Sufficient:* To what extent do you agree that we have listed all main methods for measuring [aspect]? (1: strongly disagree, 2: disagree, 3: somewhat disagree, 4: neither agree nor disagree, 5: somewhat agree, 6: agree, 7: strongly agree)
- *Terminology:* Do you have any suggestions for alternative or additional terminology or concepts related to [aspect]?

- *Suggestions*
    - Do you have suggestions on other methods that can be used to measure [aspect]? (If yes, please explain below, and please ensure that you provide sufficient details and references for the measurement you are proposing, allowing us to incorporate it into the toolkit)
    - What changes would you like to suggest in order to improve the presentation and/or content of the information we presented on [aspect]?

12.3.3. Findings

12.3.3.1. Human Factors Constructs

We attempted to identify human factors constructs or aspects that were measured as part of simulation studies of train operators. We also derived tools and methods used for measurement related to these constructs. There are two types of measurements that emerged from literature search, objective and subjective measurements. The literature identified aspects are as follows:

1. Task Performance: Performance as a construct generally refers to how well an operator executes a specific task or duty in a simulation. This is connected with the concept of human reliability and safety (Ciani et al, 2022). Measuring performance serves the purpose of identifying the direct impact of certain experimental scenarios and conditions in the simulation. Skill degradation is a specific performance aspect to investigate. The way performance is measured is very dependent on the goals, specifications, and the capability of the simulation, but in general it should be as close as possible to how the performance would be measured in practice.
2. Workload: Workload may be defined as the relationship between the resources required to carry out a task and the resources available to, and hence supplied by, an operator. These resources include, but are not limited to, time, mental and physical resources.
3. Communication: Communication in railways is the ability to clearly and effectively exchange and transmit information between operators and/or passengers. It is often cited by operators to be one of the key non-technical skills that should be possessed by both train drivers and traffic controllers (Brandenburger et al, 2017; Du, Fang & Niu, 2018).
4. Situation Awareness: Situation awareness (SA) is defined as (1) the perception of elements in the environment, (2) the comprehension of these elements, and (3) the projection of these elements in the near future (Lo et al, 2016). SA is one of the most studied human factors construct, including studies concerning human factors in railway contexts. SA is also commonly identified by end users to be a critical aspect to be aware of while performing their duties (Buksh et al, 2013; Brandenburger & Naumann, 2019; Brandenburger et al, 2017; Du, Fang & Niu, 2018).
5. Attention Allocation: Attention allocation refers to the division of an operator's attention during operations. Attention allocation may be used to test the effectiveness and efficiency of information gathering from a new interface.
6. User experience and usability: User Experience and usability is a construct that is oriented towards how operators judge their impressions of the systems they encounter in the

simulation or the field. User Experience functions more as an evaluation towards the system, in contrast to most of the aspects listed in this toolkit that evaluate the operators themselves.

7. Fatigue: Fatigue is a complex state manifested by a lack of mental alertness, reduced physiological functions, and drowsiness (Fan et al, 2022). Researchers generally classify driving fatigue as central nervous fatigue, psychological fatigue, and physical fatigue according to the causes of its generation.
8. Responsiveness: Responsiveness refers to the reaction times of train drivers to critical stimuli either on their Driver Machine Interface (DMI) or inside/outside their train cab (Wang et al, 2022; Brandenburger & Jipp, 2017).
9. Vigilance: Also termed sustained attention or concentration, vigilance is defined as the ability to maintain concentrated attention over prolonged periods (Fan et al, 2022; Spring et al, 2012). During this time, operators attempt to detect critical stimuli in their respective workstations. Mind wandering is considered to be an indicator for a lack of attention (Von Berg & Van Doorn, 2024).
10. Trust in Automation: Trust can be defined as "the attitude that an agent will help achieve an individual's goal in a situation characterized by uncertainty and vulnerability" (Papadimitriou et al, 2020). Trust in automation impacts the extent to which operators utilize the affordances provided by automated systems. Both over and under-reliance on automated systems may lead to safety violations and incidents (Pacaux-Lemoine, Gadmer & Richard 2020; Rad et al, 2021).

12.3.3.1.1. Expert Review Phase

The initial version of the toolkit compiled from the results of the literature search was then distributed to human factors and/or railway experts for further review. Out of 12 experts we contacted for feedback, we received 7 full responses.

For each question, we collected the average value for each response and calculated the percent agreement valuation, which is the percentage of the average value out of max value (7 for Relevance and Sufficiency, 5 for Usefulness). We also included the interquartile range (IQR) for each response, which functions to measure the level of agreement for the responses among experts, i.e. the variation of agreement values between experts. A high interquartile range means that the response values are more spread out between respondents, while a low interquartile range indicates more similar values among respondents. An interquartile range below 2 is considered to represent a high level of agreement.

For Relevance, the average, percent agreement, and IQR for each aspect is displayed in Table 12-7. The responses generally show high evaluation the relevance of the aspects of the toolkit, as indicated by the average values. Performance is noted to be most relevant, and communication and responsiveness are evaluated to be the least relevant, but still mostly judged to be relevant. The low IQR shows a high agreement between experts, i.e. there is not a high variation between their evaluations of relevance

Table 12-7 Relevance

Aspect	Average Relevance Value	Percent Agreement	Interquartile Range (IQR)
Performance	6.9	99%	0
Usability	6	86%	0
Situation Awareness	6.7	96%	0.5
Workload	6.6	94%	1
Fatigue	5.7	81%	1
Responsiveness	5.3	76%	1.5
Attention Allocation	5.7	81%	0.5
Vigilance	5.7	81%	1.5
Communication	5.1	73%	1.5
Trust in Automation	6	86%	1.5

For Usefulness, the average, percent agreement, and IQR for each aspect is displayed in Table 12-8. The responses generally show high evaluation the usefulness of how the aspects are presented on the toolkit, as indicated by the average and median values. The information on fatigue is judged to be most useful and communication to be least useful. The low IQR shows a high agreement between experts. Note that unlike Relevance and Sufficiency, the range of Usefulness is 1-5

Table 12-8 Usefulness

Aspect	Average Usefulness Value	Percent Agreement	Interquartile Range (IQR)
Performance	3.9	78%	1
Usability	4	80%	1
Situation Awareness	3.9	78%	0
Workload	4	80%	1
Fatigue	4.2	84%	0.75
Responsiveness	3.3	66%	1
Attention Allocation	3.7	74%	1
Vigilance	3.7	74%	1
Communication	3	60%	0.5
Trust in Automation	3.6	72%	1

For Sufficiency, the average, percent agreement, and IQR for each aspect is displayed in Table 12-9. The responses indicate that there is more to improve on the sufficiency of the information presented in the toolkit, as the values fall in the 4/5 out of 7 range. There is more variation on the IQR values where some aspects show more disagreement than others. Using a threshold value of 2, we found that there is value agreement in the sufficiency of the measures for usability, responsiveness, attention allocation, communication, and trust in automation, while the measures for performance, situation awareness, workload, fatigue, vigilance have more variation in agreement value (marked with *).

Table 12-9 Sufficiency

Aspect	Average Sufficiency Value	Percent Agreement	Interquartile Range (IQR)
Performance	4.3	61%	3 (*)
Usability	4.6	66%	1
Situation Awareness	4.6	66%	3.5 (*)
Workload	4.4	63%	3 (*)
Fatigue	5.1	73%	2 (*)
Responsiveness	4.9	70%	1.5
Attention Allocation	5.1	73%	1
Vigilance	5	71%	2.5 (*)
Communication	4.4	63%	1
Trust in Automation	4.6	66%	1

Based on the qualitative feedback from experts, we then made several changes to the categories:

- Responsiveness aspect is merged with Performance aspect
- Vigilance and Attention Allocation ware combined into a single Attentional aspect
- Fatigue aspects renamed to Fatigue & Sleepiness aspect

Thus, the final list of human factors aspects in the second version of the toolkit is

1. Task Performance
2. Workload
3. Communication
4. Situation Awareness
5. Attentional aspects (including vigilance and attention allocation)
6. Usability
7. Fatigue & Sleepiness
8. Trust in Automation.

12.3.3.2. Measurement Techniques

Table 12-10 summarizes methods of measure discovered in the literature for each construct.

Table 12-10 Overview of HF measurement techniques for human factors constructs

Construct		Proportion Studies (out of 21)	Methods of measurements	
			Objective	**Subjective**
Task Performance		62% (n=13)	Takeover time, Speed maintenance, Acceleration variability, Braking errors (for train drivers) Response Latency, Punctuality, Arrival/Depart Delay (for traffic controllers), Driver to interface response time, driver to emergency response time	Observational scoring system
Workload		48% (n=10)	Camera-based photoplethysmography (PPG)	Instantaneous Self Assessment (ISA), Rating Scale Mental Effort (RSME), NASA – Task Load Index (NASA-TLX), DLR – Workload Assessment Tool (DLR-WAT), Integrated Workload Scale (IWS)
Communication		29% (n=6)		Observation
Situation awareness		20% (n=4)	Situation Awareness Global Assessment Technique (SAGAT)	Situation Awareness Rating Technique (SART), Low-Event Task Subjective Situation Awareness (LETSSA), Mission Awareness Rating Scale (MARS),
			Expert evaluation and mixed methods	
Attention	Attention allocation	20% (n=4)	Time in areas of interest by eye tracking	Task related time allocation by observation
	Vigilance	10% (n=2)	Psychomotor vigilance task (PVT), Safety Critical Event Detection Task	Mind-Wandering Scale (MWS)
User experience and usability		14% (n=3)		General experience by interviews, user preference by A/B Testing, Questionnaire Measuring Subjective Consequences of Intuitive Use (QUESI), subjective acceptance
Fatigue and Sleepiness		10% (n=2)	Electrocardiogram (ECG), Electroencephalography (EEG)	Karolinska Sleepiness Scale (KSS), Stanford Sleepiness Scale (SSS), Visual analogue scale to evaluate fatigue severity (VAS-F), Observation (physical characteristics)
Trust in automation		10% (n=2)	Reaction time to automated warning	Survey
			Level of monitoring automated system, reaction to conflicting information	

12.4. Comparison of Traffic Control/Management Roles

12.4.1. Research Question and Goal

The main research question in this section is: what similarities and differences exist between the roles of traffic control/management operators at various European infrastructure managers?

12.4.2. Approach

In order to create a benchmark for the operational roles in railway control rooms in Europe, the initial approach started with a systematic literature review surrounding automation in the railway sector. This systematic literature review is outlined in Section 12.1. Articles were examined for any descriptions of the various tasks involving traffic control/management. Findings were aggregated to find similarities and finally consolidated into one coherent overview, see Figure 12-2.

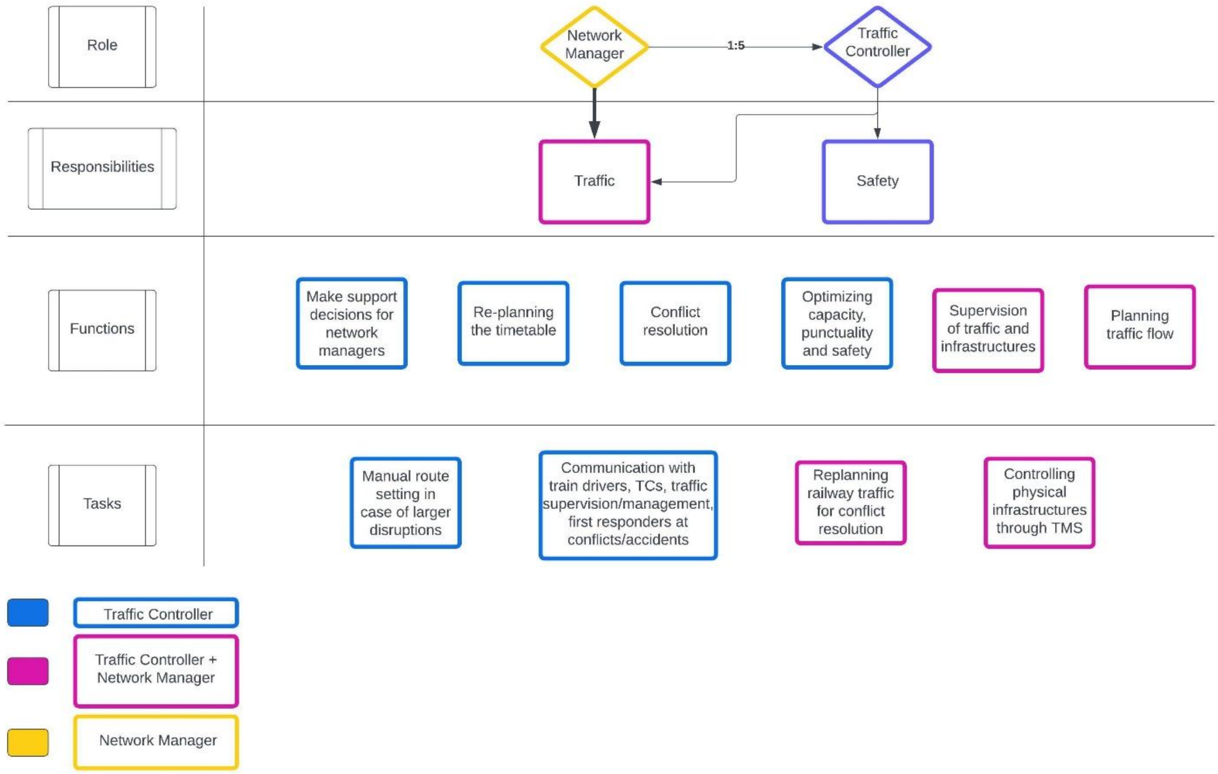


Figure 12-2 Operational roles as found in the systematic literature review

Furthermore, one article in particular provided a more extensive insight into the operations and roles at the Belgian infrastructure manager Infrabel. Findings from this article have been consolidated in Figure 12-3.

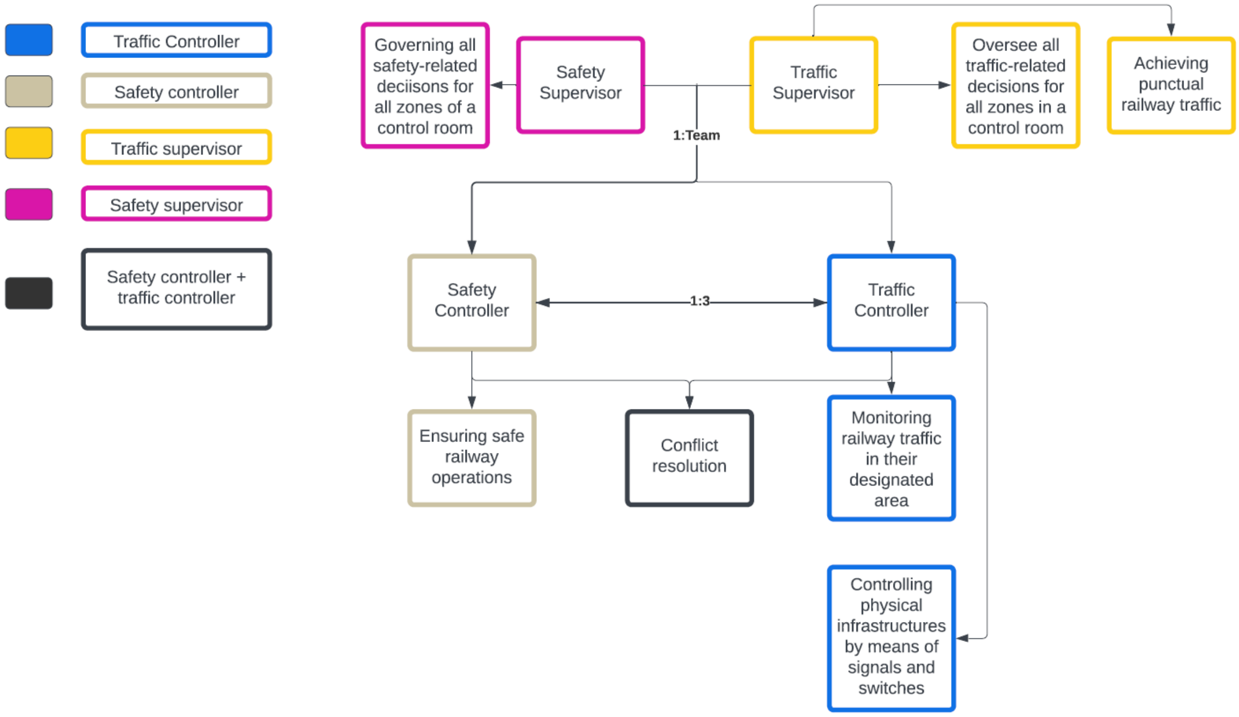


Figure 12-3 Operational roles as described in literature in Belgium

12.4.3. Findings

Common high-level functions, or goals, found in literature include the traffic controller, who operates on a local level, being responsible for short term re-planning of the timetables, conflict detection and resolution, as well as optimizing capacity, punctuality and safety as a whole. Aside from these goals and tasks, traffic controllers also play a supporting role for network managers by providing situational information to keep network managers in the loop when necessary. Network managers, who operate on a regional level, have the main responsibilities of supervision of traffic and infrastructures, as well as planning the traffic flow for a given region.

Conversely, the Belgian infrastructure manager Infrabel, operates their control rooms with 4 types of personnel. Namely, the Safety controller and Traffic controller, who operate on a local level, and the Safety supervisor and Traffic supervisor, who operate on a regional level. Generally speaking, for every 3 Traffic controllers, there is one Safety controller whose sole responsibility it is to maintain safe operations within their given region. The Safety controllers in turn fall under the supervision of a Safety supervisor. These members of personnel govern all safety related decisions for a given control room. Alongside the Safety supervisor is also a Traffic supervisor, whose main tasks are governing all traffic related decisions for a given control room, as well as supervising the flow of traffic and guarantee punctual train operations.

Future steps for the further development of the operational roles benchmark consist of involving (human factors) experts of railway traffic control. These experts will be given a diagram similar to the ones provided in this section and asked to create their own task division and roles representative of the control rooms in their country. Furthermore, they are invited to add any additional roles and/or tasks which may be missing. The end goal is to enable comparability and exchange of lessons learned among European countries by providing a bottom up mapping of control room operations and roles of operators in such countries.

12.5. Research Requirements for Evaluating and Testing

One specific area within the broad Human Factors area is Human–Machine-Interactions (HMI). HMI specify that it is the interaction between an individual and a machine (often a computer system today) that is of special interest. Questions such as usability and user friendliness are frequently raised. This section will highlight some issues of particular importance when conducting evidence-based research within the HF area in general and HMI related research problems in particular. First, this section will use the railway TMS and the development of a decision-support-system (DSS) as an example to illustrate issues the HMI researcher needs to consider. Issues that are rather unique for a general HF approach compared to natural sciences. From a general perspective, control is an important and difficult parameter when humans are involved in the loop of development and experimentation, as they have to be when HMI research is conducted. Secondly, this section will focus on requirements for evaluation and testing new HMI designs when the human is a professional operator. When DSS is developed for users, i.e., novices as well as experts, other issues are more important to consider and it is out of the scope for this section to highlight issues to consider when the user is a novice.

Research requirements for evaluating and testing new Human Machine Interaction designs follow the 'normal' processes for evaluation and testing as most scientific methods with an evidence-based approach. However, the major aspect that needs particular consideration is the involvement of the human and in particular the subject matter expert (SME). HMI designs highlight the interaction between human and machines and the humans vary, i.e., human behaviour is not constant. First, the error that always exist in experimentation is very large in comparison to machines, or technical functions. The human also varies in different ways. A unique person does not perform or act in the same way from time to time (within-participant variation). Humans do neither perform or act as good or as bad as each other (between-participant variation). Secondly, very often a new HMI design is to be used both by expert and novice users. Both expert and novices' users can vary within and between as mentioned, but it is important that the evaluation is performed with the target group in the loop. If a new HMI design is to be used by a unique user group it is important that this user group is studied in the evaluation and testing phase. This section in the deliverable will use the traffic management system within the railway sector as an example throughout the section but can be used in different context and situations. It is important to understand that the examples below is valid for a situation when an evaluation and testing is to be performed with SME's involved in the testing phases.

For instance, the traffic management system (TMS), within the railway sector, is used to optimize efficiency and traffic safety. The TMS is a complex system with different operators, with different expertise and actors who are supported by several decision support systems (DSS). Actors and systems also interact. When a new decision support system (DSS) is developed for a TMS it needs to be evaluated before an implementation, to make sure that the DSS delivers as expected and does not produce unpredicted additional side effects. Research and evaluation are needed! However, what are the research requirements for testing a new DSS with a Human-Machine-Interaction (HMI) approach? What needs to be considered, when 1) different actors with different expertise are involved, and 2) different social and technical decision support systems are used to support the different operators, before a new DSS can be implemented in the TMS for the railway sector? Hence, from a generic approach, the TMS in the railways sector is similar to the pilot and aircraft interaction, the nuclear plant control room, the statistician and the computer program, i.e., expert users vary in their performance when they interact with a (support) system. This variation in expert performance reveals how well the HMI design fulfils the needs requested.

All implemented and 'integrated' systems should take into consideration that the systems and their interfaces (for train drivers and dispatchers in this case) could be used in a 'proper' way (see below), i.e., the DSS should be tested empirically to obtain evidence-based results from a user perspective i.e., it should be proven to work as intended with no, or less important, side effects. The importance of specific requirements could be described in more detail based on the context of implementation - in this case a DSS for a traffic management system within the railway sector. Furthermore, the DSS should support the operator even during disturbed situations. Another DSS might not be needed to fulfil the same criteria as a DSS for the railway sector since, for example, safety could be of less importance. When the librarian is searching for a unique book in the catalogue system (a DSS) no one will get hurt if the information about the book is not perfectly correct. The interaction between humans and the DSS exists in a context with criteria for the requirements. The requirements also depend on the functions that the DSS is supposed to deliver. The context here is operative planning of trains (performed by the dispatcher) and train driving (performed by a train driver). The dispatcher and the train driver use a TMS to communicate the journey plan. The actors are professionals and understand their roles and their tasks (compared to DSS for novices). These two aspects 1) operative planning (context criteria) performed by 2) professionals, are very important prerequisites when research requirements are discussed for all testing of a new HMI design.

The research requirements needed are based on 1) the functions that a DSS will provide, and 2) the aspects that the DSS is supposed to affect. The HMI research approach highlights that it is an interaction between actors (professionals) and, in this example, technical systems in a unique context (operative planning). But the HMI research approach also highlights that the DSS very often will affect the social system – reducing necessary communication between professional operators, for example. This implies that the DSS needs to be studied with that complex context in mind. One important aspect of the railway TMS context is that context demands vary to a great extent: at times, everything is running according to the journey plan, at other times several disturbances need to be considered simultaneously. The demand on operators varies often greatly over time and the DSS should deliver the assumed function in both high and low demanding situations and this variation needs to be evaluated. For example, how will operative planning work when there are trains with and without "new" functionalities when everything is running as normal or when the traffic situation is disturbed?

12.5.1. Factors to Be Considered in the Research Design

The HMI research approach reveals that valid operators, valid tasks (scenarios), and valid technical and social systems should be evaluated in valid contexts before evidence-based conclusions could be drawn about the new DSS. The research requirements needed are therefore an experimental platform that can provide this requested validity. Below is an example of an experimental set-up that would fulfil several of the requirements. Most often, several experiments are needed to fulfil the requirements of systemization and control needed.

12.5.1.1. Maturity Levels

It should be noted that new HMI designs can be evaluated from a research perspective in several ways and the example used below is only one alternative and is used to highlight how research requirements could be considered. It should also be noted that a DSS system probably has been evaluated in less valid platforms before it reaches the simulator platform (tested at lower TRL and possibly at lower HRL (see Section 12.6 for more information about HRL). The DSS for TMS, however, should be implemented in a platform that can simulate its functions in a valid way, i.e., as the DSS would work in an operative setting. One major advantage with simulators is the experimental control provided by the platform. It is not the real world, and the tasks are not performed in "the wild" and safety issues are therefore not a problem for involved operators or systems. This strength (of control) is also its weakness since the actors involved in the tasks to be performed understand that it is a simulation and that will affect them and their behaviour accordingly. Hence, even with a 'perfect' simulator experiment ecological validity is an issue to consider, but it is still the best way ahead if the tasks to be performed in any respect is dangerous for the involved operators or when expensive products or systems might get destroyed.

12.5.1.2. The Simulator Platform

The simulator platform is a platform that has the systems and subsystems used for operative planning. The platform should be capable of (in the context discussed here) presenting a trustworthy scenario with trains following train plans and allow that dispatchers interact in a reality like way. The operator working station (the dispatcher's working station, i.e., one part of the platform) should be designed as the operator working station in reality. If the operator working station in reality is flexible and the dispatcher can design the configuration of the working station based on individual preferences the simulator platform should be able to mimic that.

12.5.1.3. Independent Variables

As mentioned above, in this example, one independent measure is degree of implementation of a new functionality. This independent variable could for example have three levels: all trains have the new functionality, all trains without, and a mixed situation. Another independent variable is level of disturbance, which decides how demanding a scenario is from an operator's perspective. For example, this independent variable could have two levels: one scenario with almost non-existing disturbances, and one scenario with a larger disturbance. For an HMI researcher, these levels or conditions of low to high demand need preparation and subject matter experts (SME) are vital also in that respect. The independent variable for this example is the new DSS functions, i.e., the new DSS compared to the systems used normally (old/no DSS). The second independent variable discussed above was penetration level or a mixed reality. Meaning that one of the three scenarios would be performing operative planning with trains with new DSS and old DSS in the same scenario (condition 1 is all trains with new DSS, the second condition would be all trains with old DSS).

12.5.1.4. Dependent Variables (DV)

The new DSS is assumed to deliver a higher efficiency (punctuality and energy consumption, for instance). It is the operator who is responsible for the operative planning but does not drive the train. Hence, punctuality should be measured and energy consumption too, but the train driver is not a robot and how the new DSS is affecting other operators is vital as well. The DSS might increase punctuality and reduce energy consumption but affect the operators' working conditions in a negative way, i.e., no one wants to work as an operator any longer due to the workload created by the new DSS. Several dependent variables exist such as mental workload (see Section 12.3 for more information about other human factors constructs). Another important DV is how other operators (in a distributed cognitive system) are affected. In this example, train drivers' experiences and performances might be affected even though the new DSS is mainly for supporting another role. If the results from the experiment reveal that punctuality increased and energy consumption was reduced, it will be based on the idea that the train driver will follow the instructions given by the dispatcher (if not a multi actor simulation with human-in-the-loop is carried out). The design of the DSS experiment contains dependent variables and independent variables. The dependent measures discussed when TMS for the railway sector is at hand is often punctuality, energy consumption, and dispatcher's mental workload. The dependent measure is what the researcher wants to achieve or affect with the new DSS.

12.5.1.4.1. Mental Workload

Workload was an aspect that earlier studies showed to be important to evaluate (a dependent variable) when DSS for management is discussed. Several instruments could be used to evaluate mental workload (MWL) and physiological and subjective measures of workload are important for different reasons. The physiological instrument might be valued as the objective from one perspective, but the subjective experience is as important since an experienced increase in MWL might have dynamical effects such as an operator's resistance toward implementation in realty. The physiology is important as well since it will affect health in the long run. Hence, a combination of instruments to study MWL is often the best way ahead. Even if the instruments discussed here measure almost the same concept of interest, they have a uniqueness that provide valuable information.

12.5.1.4.2. Safety

Safety is another important aspect to measure during the experiment when TMS for the railway sector is discussed. The DSS should not create situations that deviate from the safety conditions in any way. The instruments to measure safety aspects are context dependent and directly related to the chosen scenario. The point here is that it is up to the researchers (and existing prerequisites) and the objectives with the experiment to include the necessary dependent variables needed to obtain valid results.

Safety and MWL are only two out of a large amount of possible dependent measures to consider and are only used here to describe possible but very often used dependent measures. For a more extensive discussion see Section 12.3.

12.5.1.5. Design and Conditions

In this example, a simulator study is suggested, phrased as a 3 by 2 factorial design: The first number represents the first independent variable with three levels (Without new DSS, With new DSS, and Mixed). The second number represents the second independent variable (Small disturbance and large disturbances).

The HMI researchers have to decide how the dependent variable should be measured (see Section 12.3) and how the independent measures should be combined. It is out of the scope of this text to define what "punctuality" is and the point here is that how to measure the dependent measures should be thoroughly considered with reliability and validity in mind. The researchers should also consider the combination of the independent variables. If the professional operator (in this case the dispatcher) who takes part in the human-in-the-loop simulator experiment performs in each of all levels for each one of the independent measures, it is very important that we control for order effects (balancing out effects of ordering). If each scenario takes one hour to complete, the dispatcher needs to be engaged for six hours, at least. If one dispatcher only performs one (out of six) condition, only one hour is needed for each dispatcher. Instead, six dispatchers are needed to get the same amount of data as when one dispatcher performed all conditions. The third option is to combine, i.e., to let one independent variable be within (all conditions are performed by the same dispatcher) and the other independent variable to be a between-participants variable (perform only one out of the possible conditions). The configuration of the research design is vital, and all designs have weaknesses. Below are some major issues that the researcher must consider when new DSS are discussed and evaluated.

12.5.1.6. Between versus Within Participant Variables

The strength with between-participant variables is that you as a researcher do not need to consider order effects (often rather large) but the weakness is that more dispatchers are needed. The strength with the within-participant variable is that humans often variate largely, and, in this way, individual variations is controlled for. You do not need as many operators when a within-participants design is used. Availability of operators might not allow for a between participants design. Theoretical as well as pragmatical aspects need to be considered.

12.5.1.7. Knowledge of the New Technology

Furthermore, the operators should be familiar with the new DSS studied. The learning curves of the DSS should not affect the behaviour or performances. The repetition of conditions itself produces a learning effect and the effect of a learning curve should be avoided as much as possible. The training session should therefore not be underestimated, it will reduce the learning curve substantially. Piloting is highly recommended since it will give the researcher an idea of the learning curves.

12.5.1.8. Trust in the New Technology

Another decision the HMI researcher faces is the inclusion of other relevant dependent measures. It might be the case that the operators' "trust" in a DSS is of interest. How should this relevant dependent measure be studied without interfering with the most relevant aspects to measure. Also, as discussed above, studies involving the interacting operators are also needed to obtain evidence-based conclusions. The simulator experiment described here is not a multi-actor simulator study, but a simulator platform that allows a multi-actor scenario will be important for many other specific research questions. One of the experiences from the earlier trials with C-DAS for instance was that communication between dispatchers and train drivers were better. If the communication flow is an important dependent variable to investigate another simulator study (i.e., multi-actor set-up) is needed.

12.5.2. Summary

Research requirements for traffic control roles/actors/operators and a new DSS (as an example) were discussed and highlight that several requirements need to be considered from a research requirement perspective if evidence-based results should be obtained for an HMI design.

- The DSS functionality needs to be described in detail: What is the DSS good for? What do we want to achieve? This will directly present the dependent variables to be investigated.
- What might be negatively affected – this dependent measure should be measured.
- The context needs to be described in some detail: In what technical and organizational situations is the DSS supposed to deliver what we to achieve. This will present that professional operators are needed, and that the platform for investigation, experimentation would need DSS functionality of already implemented technical systems (scenarios etc.).
- The baseline needs to be established (and compared with the new DSS) in order to investigate if the new DSS is delivering as assumed.
- Workload was identified as one possible showstopper for this example and needs to be considered. The identification gave that the DSS needs to be studied under different workload conditions. The DSS should not only work as intended during normal workload situations. It really needs to be an effective support system when MWL demands increases.
- Skills in how to use the new DSS need to be considered since the learning curve will be a confounding variable.
- The sum of especially independent measures needs special care. It might be the case that two (or often three) experiments need to be performed since a reliable and valid result would not be possible to obtain due to pragmatical or theoretical issues.
- Relevant dependent measures such as safety and trust in DSS should be considered (and measured) if deemed necessary.

The DSS should be capable of producing a 'proper' use for the operators to be involved in operative planning within the railway sector. To become "proper", a number of requirements needs to be considered and are summarized above. One very useful way to make sure that the requirements are fulfilled to perform experiments, but the experiments also need to consider several requirements to guarantee, in an evidenced-based way, that the DSS delivers as assumed.

12.6. Human Readiness Levels

Proper attention to human factors aspects during technological development is crucial in ensuring that the intended goals of technical innovations are achieved while minimizing or preventing human error. Human errors account for a significant percentage of accidents and incidents across various systems. Additionally, costs associated with system training, operations, and maintenance can be reduced when human systems issues are addressed early and often throughout design and development. Until recently, however, there was a lack of consensus on what 'often and early' means and when human factors are sufficiently included.

In 2021, the international Human Factors and Ergonomics Society developed the Human Readiness Level (HRL) scale (ANSI/HFES 400-2021). This scale can be used to consistently rate the level of maturity of a technology with respect to its readiness for human use. It focuses on the degree to which human systems evaluation activities and processes have been completed to demonstrate that a technology or system achieves the level of human readiness needed to meet desired mission objectives. This allows management and decision makers to balance time and resource investments necessary to maximize a technology or system's readiness for human use. It is important to note that HRL does not ensure that users are ready to use the technology, but that the technology is properly designed to be used as intended.

The HRL scale provides a simple rating of the level of maturity of a technology with respect to its readiness for human use, ranging from levels 1 to 9. The HRL scale is developed to complement the Technology Readiness Level (TRL) scale. The HRL and TRL scales align directly, and similarly aim to structure the steps required to demonstrate the readiness of a technology for operational use. By aligning activities to achieve a certain TRL level and the associated HRL level, it is ensured that critical choices can be made with knowledge of both technology and human technology interaction. In this way, repair costs later in the project, or problems in the operation, are avoided. Up to HRL 6, human factors research can easily be one level ahead of TRL development and possibly provide early input in choices to be made in the subsequent TRL level. From HRL / TRL 7 onwards it is important to investigate HRL questions with a technique of a similar TRL. When technical developments are ahead of the curve, and therefore move to the next TRL without input from the corresponding HRL level, there is a risk that technology will be adjusted at a later stage. The further TRL is ahead of HRL, the greater the risks and potential recovery costs.

In addition to dividing HF research into nine levels of maturity, the standard determines which exit criteria there are for each level. In its appendix, the standard provides additional guidance and considerations for each of the nine HRL levels. The questions identified at each HRL level in this appendix are meant to serve as triggers to ensure that critical human systems evaluations are not omitted. By reporting the results of activities to answer these questions, it is possible to gain insight into where a development stands within an HRL level. Not every question has to apply to every development, as long as the exit criteria are met.

Table 12-11 Nine Levels of the HRL Scale and related TRL (source: ANSI/HFES 400-2021)

Development Phase	HRL description	TRL description
Basic Research and Development Scientific research, analysis, and preliminary development on paper and in the laboratory occur. This phase culminates in a validated proof of concept that addresses human needs, capabilities, limitations, and characteristics.	**HRL 1:** Basic principles for human characteristics, performance, and behaviour observed and reported	**TRL 1:** Basic principles observed and reported
	HRL 2: Human-centred concepts, applications, and guidelines defined	**TRL 2:** Technology concept and/or application formulated
	HRL 3: Human-centred requirements to support human performance and human technology interactions established	**TRL 3:** Analytical and experimental critical function and/or characteristic proof of concept
Technology Demonstrations The technology is demonstrated at increasing levels of fidelity, first in the laboratory and later in relevant environments. This phase concludes with demonstration of a representative system in a high-fidelity simulation or actual environment, with evaluation of human systems designs provided by representative users.	**HRL 4:** Modelling, part-task testing, and trade studies of human systems design concepts and applications completed	**TRL 4:** Technology validated in lab
	HRL 5: Human-centred evaluation of prototypes in mission-relevant part-task simulations completed to inform design	**TRL 5:** Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
	HRL 6: Human systems design fully matured and demonstrated in a relevant high-fidelity, simulated environment or actual environment	**TRL 6:** Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
Full-Scale Testing, Production, and Deployment Final testing, verification, validation, and qualification occur, with human performance evaluations based on representative users. This phase concludes with operational use of the system and continued systematic monitoring of human-system performance.	**HRL 7:** Human systems design fully tested and verified in operational environment with system hardware and software and representative users	**TRL 7:** System prototype demonstration in an operational environment
	HRL 8: Human systems design fully tested, verified, and approved in mission operations, using completed system hardware and software and representative users	**TRL 8:** Actual system completed and qualified through test and demonstration
	HRL 9: System successfully used in operations across the operational envelope with systematic monitoring of human system performance	**TRL 9:** Actual system proven in operational environment

To illustrate the required activities and related outcomes of HRL based development, Table 12-12 gives an overview of how to apply HRL to develop ATO up to a level of TRL / HRL 6. Additionally, Table 12-12 provides insight in lessons learned that could be implemented in the Control Command and Signalling TSI ETCS baseline 4 (De Bakker and Albers, 2024; European Union, 2023), accepted ATO use cases / business case, and ATO system in the human-in-the-loop simulator for proving HRL/TRL 5. In this example only the train driver and passenger issues are included. For HRL/TRL validation also traffic controller and maintenance issues need to be defined and studied.

Table 12-12 ATO HRL activities and outcomes overview incl. required upcoming activities

HRL	Validation	Outcomes and consequences
HRL 1	Is achieved if basic principles for human characteristics, performance, and behaviour have been observed and reported: • ATO over ERTMS test drives 2020 • Literature review and HF toolkit WP15	**Train driver issues** Vigilance / out-of-loop Skill degradation Situation awareness / transparency **Passenger issues** Safety and comfort perception
HRL 2	Is achieved if human-centred concepts, applications, and guidelines have been defined: • ATO over ERTMS test drives 2020 • Human-in-the-loop simulator research 2022 • Literature review on skill degradation, transparency design principles • Train driver ATO use cases developed • Potential sources of human error and misuse identified • Appropriate metrics for successful human performance identified	**Train driver error and misuse:** Vigilance loss after 10 minutes ATO driving Lack of ATO transparency limits possible ATO parameter settings; no ATO settings possible in which ATO would brake harder/later/tighter than drivers would do manually Transparency design principles identified Vigilance measuring with Mind-Wandering Scale or eye gaze-based Driver Condition Monitoring
HRL 3	Critical characteristics and functions of the initial proof of concept are demonstrated analytically or experimentally: • Control Command and Signalling TSI ETCS baseline 4 (European Union, 2023) has been analysed to allocate human machine function allocations and to identify issues in the situation awareness information flow across human and the automated system components (De Bakker and Albers, 2024)	**Train driver functions and limitations:** ATO parameters evaluated based on HF investigation comfort perception Depending on the level of transparent design and measures for human loss of attention, this means that ATO may or may not be used for longer journeys (> 10 minutes) and harder / later / tighter braking than drivers would do manually Skill degradation prevention implemented in driver training plan Requirements to improve transparency of TSI ATO design defined
HRL 4	Is achieved if human systems design concepts and applications are evaluated in basic laboratory environments or controlled field settings: Human-in-the-loop simulation 2024 ATO test drives 2024 Strategies to mitigate safety implications for human users have been identified and recommended in requirements to improve the TSI ETCS requirements and constraints to be taken into	**Train driver validated components:** Current (TSI) design supports up to 10 minutes of ATO driver, vigilance loss risk in case of > 10 minutes The TSI ATO design is sparse in showing information about the ATO driving strategy and does not always support anticipation from a driver, which consequently leads to higher reaction times and more surprises for drivers than is necessary. With the current TSI ATO design, overspeed situations become less noticeable

	account in the deployment model / use cases for the business case.	compared to a manual situation (due to the loss of colours/auditory signals) and drivers have little insight into the braking behaviour of ATO, which increases their reaction time. In subsequent HRL/TRL levels, it must be investigated what acceptable ATO braking behaviour is with the intended ATO design. As a baseline this cannot be harder / later / tighter braking than drivers would do manually. The ATO system is usable without restrictions within the ETCS system, even if a driver is not eligible for driving with ATO. A risk analysis must be carried out to see whether this is acceptable. The driver has almost no influence on ATO driving behaviour and will be more inclined to take over control. It should be evaluated in next HRL / TRL levels whether this is acceptable. The TSI ATO design provides C-DAS elements when ATO is not engaged, which affects already existing DAS-applications since there is partial overlap, but both can have unique elements. No interface to external DAS-applications or ways to prevent showing these elements are described, potentially leading to double or inconsistent information and differences in driving advice between ATO and C-DAS. Loss of C-DAS gains is possible whenever C-DAS info is (partly) not shown when ATO is introduced. **Passenger validated components:** ATO parameter improvements can support acceptable comfort perception, but different parameters result in differences in comfort perception. This should be evaluated in next HRL / TRL levels.
HRL 5	To validate TRL5 in human-in-the-loop simulation, it is required to validate for which use cases train-driver vigilance is not negatively affected. Only cases for which this is sufficiently validated can be taken into consideration for full-scale testing. With ATO implemented in line with TSI (EU, 2023) the steepness of the braking curve must be limited to a curve that provides the train driver sufficient reaction time + manual braking time after ATO system observably failed to initiate braking.	**Train driver validation topics:** Vigilance loss Reaction times Situation awareness related to braking Situation awareness related to mode confusion Comfort and safety perception **Passenger validation topics:** Comfort and safety perception

HRL 6	HRL 6 requires the system design to be fully matured. It is recommended to further develop the ATO system (and the TSI) according to the recommendations of HRL 4 before proceeding with testing for TRL6 and beyond. If TRL 6 aims to further expand the business case to longer than 10 minutes of driving under ATO or driving with a harder / later / tighter ATO braking strategy, then the effects of these modifications should first be tested in a human-in-the-loop simulation on HF aspects to see whether this is indeed sufficiently mature for TRL/HRL 6 testing.	**Train driver validation topics:** Vigilance loss Reaction times Situation awareness related to braking Situation awareness related to mode confusion Comfort and safety perception related to ATO parameters and DMI design Use restrictions if the driver is not ATO certified Driver influence on ATO behaviour Influence of TSI ATO design C-DAS elements on use and usability of existing DAS-applications **Passenger validation topics:** Comfort and safety perception related to ATO parameters

13. Conclusions

This deliverable D15.2 ‘TMS and ATO/C-DAS timetable test & simulation environment’ is the result of the developments carried out in FP1-MOTIONAL WP15 on ‘Linking TMS to ATO/C-DAS for optimized operations’, in particular the results from Tasks 15.3-15.5. This deliverable fills a gap in the state of the art and practice by considering in detail the interactions between the main system components of TMS – ATO-TS – ATO-OB, including C-DAS TS and OB. The deliverable aligns with the existing standards and complements them with concrete process descriptions, requirements, components and functions for developing and testing TMS-ATO operation. The existing specifications include ERTMS/ATO (ATO-TS/ATO-OB interfaces), SFERA (C-DAS TS/OB interfaces), RCA (CCS, including ATO and SCI-OP), CDM (Conceptual Data Model), and the consolidation activities by the System Pillar based on these specifications, past projects from Shift2Rail and current projects of Europe’s Rail. These specifications mainly relate to ICT system specifications. WP15 focused on the TMS-ATO operations, processes, feedback control loops, algorithms, data interfaces and human factors to improve operations.

Chapter 4 introduces the TMS-ATO operational aspects and provides a list of benefits for the system users, i.e., passengers, railway undertakings, freight carriers, and infrastructure managers. It outlines the general TMS-ATO system components and actors, and describes the TMS-ATO based operation in terms of operational objects. The TMS-ATO system can be viewed as a system revolving around three main objects: the Real-Time Traffic Plan (RTTP), the Train Path Envelope (TPE), and the Train Trajectory (TT). The decision variables, objectives and constraints differ for these three objects with their typical scope on the railway network, railway corridor and single train, respectively. By understanding these differences, the interaction between these objects can be used to optimize operations. This chapter also identifies the various different railway network characteristics that may ask for different solutions, including geographical and operational characteristics, TMS functions, ATO equipped/unequipped trains, and human operators. Finally, it listed these differences in the scope elements over the demonstration use cases that will be considered in WP16, showing a variation in the scope of the use cases considered in the demonstrations following the developments of WP15.

Chapter 5 focuses on the TMS – ATO/C-DAS functions and interactions. It discusses the main TMS functions to keep an up-to-date RTTP: Traffic State Monitoring, Traffic State Prediction, Conflict Detection, Conflict Resolution, and RTTP Updating. A high-level logical architecture visualizes the main functions and interactions of the key system components and actors, including the TMS, ATO-TS, ATO-OB, ETCS-TS, ETCS-OB and TCMS (Train Control and Monitoring System). The relevant interface standards between the various actors/subsystems are also listed. Chapter 5 also proposes four TMS – ATO/C-DAS variants depending on a passive or active role of the ATO-TS and ATO-OB (including C-DAS). The ATO-TS may have a passive role and just forward messages in the right format from the TMS to the ATO-OB and vice versa. Or it can have an active role with a TPE Generator that monitors and optimizes the TPE of each train based on RTTP updates from the TMS and train status reports from the ATO-OBs. Likewise, the ATO-OB can have a passive or active role. A passive role implies that the ATO-OB does not generate a train trajectory itself but receives it from the ATO-TS. This is called a central C-DAS or central ATO in literature. An active ATO-OB has a train trajectory generation algorithm onboard. The ERTMS/ATO Subsets assume an active ATO-OB, while the SFERA protocol also includes a passive C-DAS OB. Depending on the combination of passive/active ATO-TS and ATO-OB different feedback control loops arise between the TMS – ATO-TS – ATO-OB, with the most flexible configuration the active ATO-TS and ATO-OB resulting in a distributed TMS-ATO solution. The developments and demonstrations in WP15/16 all assume an active ATO-OB, according to the ERTMS/ATO specification.

Chapter 6 provides functional requirements to realize efficient and effective TMS-ATO operations, distinguished in requirements for the RTTP, TPE, train trajectories, data communication, and human factors. These requirements are the basis for the developments of the concepts, components and functions in later chapters.

Chapter 7 defines and discusses the concept of the RTTP as main output of a TMS. The RTTP represents the real-time traffic plan that coordinates all operations on the railway network at Timing Points (TPs). It is used by the traffic control and monitoring system (TCS) for both the route plan execution and ATO execution. The RTTP therefore contains the exact routes of the trains, the timings at essential stopping and passing points, and the orders of trains over the (switch) sections. Status reports from both the infrastructure (e.g., track occupation) and the train units (e.g., train positions) are used within the TMS to maintain an up-to-date conflict-free RTTP. The chapter describes two developments that focus on updating the timings at the TPs in the RTTP using feedback from the trains, which optimizes the ATO-OB operations. The first is the RTTP Updater for single-track lines with C-DAS, located in a TMS. Its focus is on optimizing the timings of opposite trains at meeting points to avoid waiting, considering both equipped and unequipped trains. It consists of a short-term runtime estimator for unequipped trains and an RTTP Finetuner. The finetuned TP timings are send via the C-DAS TS to the C-DAS OB that then may recompute its train trajectory based on the updated arrival time targets. The second development is the Traffic Regulator for commuter lines with homogeneous trains with ATO. This centralized Traffic Regulator at the TMS regulates the departure and arrival times of all trains on the line, and therefore the headway times between trains, based on the latest measurements of the departure and arrival times that are communicated from the ATO-OB to the TMS. It is based on a predictive control algorithm that calculates optimal run and dwell control actions, i.e., time corrections to running and dwell times, of all trains within a prediction horizon over a number of stations ahead. This results in updated departure and arrival times that are sent via the ATO-TS to the ATO-OB of the trains. The ATO-OB then generates train trajectories accordingly. The result is a more stable train traffic that quickly recovers from disturbances. The RTTP Updater and the Train Regulator are examples of a passive ATO-TS, where the optimization is done to the RTTP in the TMS.

Chapter 8 defines and discusses the concept of the TPE. The TPE is the sequence of TPs with time targets or time windows that the ATO-TS sends to the ATO-OB (or C-DAS OB) within a journey profile, which is used as timing constraints in a train trajectory generation algorithm. In the simplest case, the TPE contains just the information from the RTTP for a specific train, but the TPE may also contain extra TPs to guide the train trajectory generation. This is particularly useful on mainline railways. The chapter describes the developed TPE Generator that computes a TPE for each train by considering multiple driving strategies including energy-efficient driving. It computes the corresponding train trajectories and infrastructure occupation, and resolves any conflicting blocking times by adding TPs at critical blocks with a time window that prevents the conflicts by essentially reducing energy-efficient driving. In addition, it maximizes the operational tolerances within the TPE considering the conflict-free use of available running time supplement. This approach maximizes the possibilities for conflict-free energy-efficient driving but leaves as much freedom as possible to the train trajectory algorithm. It can be applied independently from the RTTP computation in the TMS, and therefore can also be seen as a drivability and feasibility check on the RTTP before each train computes a detailed train trajectory. Additionally, the TPE Generator can relax or strengthen time windows in the TPEs based on the current train positions received from the ATO-OBs. The TPE Generator can be situated either in the TMS or in the ATO-TS, resulting in a passive or active ATO-TS, respectively. The demonstrations in WP16 will be focused on an implementation in the ATO-TS.

Chapter 9 focuses on two developments that enhance the train forecasting functionality in a TMS for improved conflict detection and resolution by using status reports from the ATO-OB via the ATO-TS. The first is the TMS-C-DAS Enhanced Operation focusing on C-DAS without ETCS and a passive C-DAS OB, where the C-DAS TS calculates the train trajectories. This module aims at generating improved train forecasts from the ATO-TS, that can be used by TMS operators to detect and resolve potential conflicts, leading to an improved RTTP. The second module is the ATO Train Forecast and Operational Update that is based on the CDM and automated algorithms for Forecasting, Conflict Detection and Conflict Resolution. The focus in WP15 is on the Forecasting Algorithm, while the CD/CR algorithms are developed in FP1 MOTIONAL WP17/18.

Chapter 10 is concerned with TMS-ATO data models. This chapter describes the developed Integration Layer (IL) that can be used to share data between TMS and the ATO-TS. The IL is a distributed data processing platform based on a standard data format, the Conceptual Data Model. The CDM describes both data and relations among data. The IL provides an enhanced publish/subscribe paradigm for processing messages between the TMS and ATO-TS. In addition, this chapter describes the Journey Profile Generator located at the ATO-TS that receives an RTTP from the TMS via the IL and generates Journey Profiles and Segment Profiles to be sent to the ATO-OB.

Chapter 11 describes the Human-In-The-Loop (HITL) simulation environment from ProRail that is extended with the TPE Generator. This simulation environment consists of the FRISO simulation platform that simulates microscopic railway operations including the safety layers (interlocking and ETCS), and several connected components including digital twins of traffic management, traffic control, ATO-OB and a driver cabin, including HMIs for simulating human interaction. The TPE Generator has been embedded in a new ATO-TS component and also a new ATO-OB has been implemented. This simulation environment will be used in WP16 for testing the full TMS/ATO-TS/ATO-OB operation, including feedback loops and human factors.

Chapter 12 considers Human Factors (HF) which focuses on how operators interact with systems in a safety-critical environment. It involves designing with users (operators) and researching behaviour, cognition, and performance of users for safer, more efficient, and user-friendly systems. Both train drivers and traffic controllers/managers are considered within a TMS and ATO/C-DAS environment. The chapter includes a state-of-the-art review of HF for TMS and ATO/C-DAS and compares the roles of traffic control/management operators at various European IMs. It identifies HF constructs and measurement techniques and developed a rail HF toolkit with the following HF aspects: Task Performance, Workload, Communication, Situation Awareness, Attentional aspects (including vigilance and attention allocation), Usability, Fatigue & Sleepiness, and Trust in Automation. The chapter also provides research requirements for a HF study, and finally describes Human Readiness Levels (HRLs) as a complement to TRLs to assess the level of maturity of technology to its readiness for human use. The findings will be applied in WP16 in a HF study based on the HITL simulation environment.

The annex is contained in Chapter 15 and contains the TRL 4 results for technology validation in a lab environment of the key components developed within WP15: RTTP Updater for single-track lines, Traffic Regulator for urban railway lines, TMS – C-DAS Enhanced Operation, ATO Train Forecast and Operational Plan Update, TMS-ATO Integration Layer, Journey Profile Generator, and the Human-In-The-Loop Simulation Environment including the TPE Generator for mainline railways. These components will be further developed and demonstrated in WP16 to reach TRL 5 about technology validation in a relevant environment.

WP15 has developed a range of components and functions to optimize operations by linking TMS and ATO/C-DAS. These include improved functions in the TMS based on ATO/C-DAS information (traffic state monitoring, traffic state prediction, conflict detection, conflict resolution) and proposed new functions of TPE generation at either the TMS or ATO/C-DAS TS based on information from the TMS and ATO-OB. The Integration Layer is proposed as communication platform between the TMS and ATO/C-DAS. Simulation environments and Human factors methods have been developed for testing TMS – ATO/C-DAS operations and the feedback control loops between the three components TMS – ATO/C-DAS TS and ATO/C-DAS OB with the key objects of the RTTP, TPE and Train Trajectories. The next step is to validate these functions and components in relevant environments, and learn from these tests to provide recommendations for different railway conditions (e.g., urban railways, single-track lines, mainline railways), which will be done in WP16.

14. References

Albrecht, T., 2013. Human factor challenges in the development of a driver advisory system for regional passenger trains. *Rail human factors: supporting reliability, safety and cost reduction*, pp. 129-138.

ANSI/HFES 400-2021, 2021. *Human Readiness Level Scale in the System Development Process*. Human Factors and Ergonomics Society.

Balfe, N., Sharples, S., Wilson, J. R., 2015. Impact of automation: Measurement of performance, workload and behaviour in a complex control environment. *Applied Ergonomics,* 47, 52-64.

Belmonte, F., Boulanger, J. L., Schön, W., Berkani, K., 2006. Role of supervision systems in railway safety. *WIT Transactions on The Built Environment*, 88, 129-138.

Brandenburger, N., Hörmann, H. J., Stelling, D., Naumann, A. *Tasks, 2017.* Skills, and competencies of future high-speed train drivers. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 231(10), 1115-1122.

Brandenburger, N., Jipp, M, 2021. Effects of expertise for automatic train operations. *Cognition, Technology & Work*, 19, 699–709.

Brandenburger, N., Naumann, A., 2018. Towards remote supervision and recovery of automated railway systems: The staff's changing contribution to system resilience. *International Conference on Intelligent Rail Transportation (ICIRT)*, IEEE.

Brandenburger, N., Naumann, A., 2019. On track: a series of research about the effects of increasing railway automation on the train driver. *IFAC-PapersOnLine*, 52(19), 288-293.

Brandenburger, N., Naumann, A., Jipp, M., 2021. Task-induced fatigue when implementing high grades of railway automation. *Cognition, Technology & Work*, 23, 273–283.

Brooks, J. D., Subrahmaniyan, N., Miller, B. W., Liu, A. M., Groshong, H., Oman, C., Houpt, P., 2017. Human-Centered Automation Design: An Application to In-Cab Rail Technology. *TRB 96th Annual Meeting Compendium of Papers*.

Buksh, A., Sharples, S., Wilson, J. R., Morrisroe, G., Ryan, B., 2013. Train Automation and Control Technology-ERTMS from User's Perspectives. *Proceedings of the international conference on Ergonomics & Human Factors*, Cambridge, UK, 15-18 April 2013, Taylor & Francis.

Cacchiani, V., Huisman, D., Kidd, M., Kroon, L., Toth, P., Veelenturf, L., Wagenaar, J., 2014. An overview of recovery models and algorithms for real-time railway rescheduling. *Transportation Research Part B: Methodological*, 63, 15–37.

Ciani, L., Guidi, G., Patrizi, G., 2022. Human reliability in railway engineering: Literature review and bibliometric analysis of the last two decades. *Safety Science*, 151, 105755.

Collis, L., Robins, P., 2001. Developing appropriate automation for signalling and train control on high speed railways. *People in Control: The Second International Conference on Human Interfaces in Control Rooms, Cockpits and Command Centres.*

Crawford, E. G., Toft, Y., Kift, R. L., 2011. Attending to technology adoption in railway control rooms to increase functional resilience. *Engineering Psychology and Cognitive Ergonomics: 11th International Conference*, Springer, 11, 447–457.

D'Ariano, A., Corman, F., Pacciarelli, D., 2014. Rescheduling. In: Hansen, I.A., Pachl, J. (eds.), *Railway Timetabling & Operations*, 2nd Edition, EurailPress, pp. 253-273.

De Bakker, D., Albers S., 2024. *ATO-TSI Implications Report.* NS Reizigers, ATO_TSI/00001

de Egea, B. G., Holgado, P. C., Suárez, C. G., 2011. Human factors integration in rail simulators. *Rail Human Factors around the World: Impacts on and of People for Successful Rail Operations*.

Dobson, K., 2015. Human Factors and Ergonomics in transportation control systems. *Procedia Manufacturing*, 3, 2913-2920.

Du, Y., Fang, W., Niu, K., 2018. A Method for Evaluation System of Railway Driver Non-Technical Skills Construction. *International Conference on Intelligent Rail Transportation (ICIRT)*, IEEE.

Du, Y., Zhi, J. Y., 2022. Impacts of attention level on manual take-over performance in automatic driving on high-speed railways*. International Journal of Human–Computer Interaction*, 40(3), 603-612.

Enjalbert, S., Gandini, L. M., Pereda Baños, A., Ricci, S., Vanderhaegen, F., 2021. Human-Machine Interface in Transport Systems: An Industrial Overview for More Extended Rail Applications. *Machines*, 9(2), 36.

ERA, 2023a. *ERTMS/ATO: System Requirements Specification*. ERTMS/ATO Subset-125, issue 1.0.0.

ERA, 2023b. *ERTMA/ATO: ATO-OB / ATO-TS FFFIS Application Layer*. ERTMS/ATO Subset-126, issue 1.0.0.

European Union, 2023. *Commission Implementing Regulation (EU) 2023/1695, Control Command and Signalling TSI ETCS baseline 4*, 10 august 2023.

Fan, C., Huang, S., Lin, S., Xu, D., Peng, Y., Yi, S., 2022. Types, risk factors, consequences, and detection methods of train driver fatigue and distraction. *Computational Intelligence and Neuroscience*, 8328077.

Farrington-Darby, T., Wilson, J. R., Norris, B. J., Clarke, T., 2006. A naturalistic study of railway controllers. *Ergonomics*, 49(12-13), 1370-1394.

FR8RAIL II, 2020. *Requirements & concept of C-DAS functions*. Deliverable 4.2.

Gadmer, Q., Pacaux-Lemoine, M. P., Richard, P., 2021. Human-Automation-Railway remote control: how to define shared information and functions? *IFAC-PapersOnLine*, 54(2), 173-178.

Gadmer, Q., Richard, P., Popieul, J. C., Sentouh, C., 2022. Railway Automation: A framework for authority transfers in a remote environment. *IFAC-PapersOnLine*, 55(29), 85-90.

Golightly, D., Sandblad, B., Dadashi, N., Andersson, A., Tschirner, S., Sharples, S., 2013. A sociotechnical comparison of automated train traffic control between GB and Sweden. *Rail human factors: Supporting reliability, safety and cost reduction*.

Goverde, R.M.P., 2010. A delay propagation algorithm for large-scale railway traffic networks. *Transportation Research Part C: Emerging Technologies*, 18(3), 269-287.

Goverde, R.M.P., Kecman, P., 2014. Train delay prediction. In: Hansen, I.A., Pachl, J. (eds.), *Railway Timetabling & Operations*, 2nd Edition, EurailPress, pp. 237-252.

Hammerl, M., De Filippis, M., Steinhäuser, I., Torens, C., Gantz, O., zu Hörste, M. M., Lemmer, K., 2009. From a testing laboratory for railway technical components to a human factors simulation environment*. Rail human factors around the world: impacts on and of people for successful rail* *operations*.

Hillege, R. H., Lo, J. C., Janssen, C. P., Romeijn, N., 2020. The mental machine: classifying mental workload state from unobtrusive heart rate-measures using machine learning. *Adaptive Instructional Systems: Second International Conference*, AIS 2020, Held as Part of the 22nd HCI International Conference, HCII 2020, Copenhagen, Springer.

HFES 400 Committee, 2021. *Human Readiness Level Scale in the System Development Process* ANSI/HFES 400-2021

Jansson, E., Fröidh, O., Olsson, N.O., 2023. The use of human senses by train drivers to detect abnormalities. *Transportation Research Procedia*, 72, 3650-3655.

Jansson, E., Olsson, N.O., Fröidh, O., 2023. Challenges of replacing train drivers in driverless and unattended railway mainline systems—A Swedish case study on delay logs descriptions. *Transportation Research Interdisciplinary Perspectives*, 21, 100875.

Jun, H. K., Choi, S. K., 2006. Development of a multi-train operation simulator with interactive human computer interfaces. *International Conference on Hybrid Information Technology*, Vol. 1.

Kojima, T., Tsunashima, H., Shiozawa, T., Takada, H., & Sakai, T., 2005. Measurement of train driver's brain activity by functional near-infrared spectroscopy (fNIRS). *Optical and Quantum Electronics*, 37, 1319-1338.

Lagay, R., Adell, G. M., 2018. The Autonomous Train: a game changer for the railways industry. *16th international conference on intelligent transportation systems telecommunications (ITST)*, IEEE.

Lenior, D., Janssen, W., Neerincx, M., Schreibers, K., 2006. Human-factors engineering for smart transport: Decision support for car drivers and train traffic controllers. *Applied ergonomics*, 37, 4, 479-490.

Lidén, T., 2013. Optimal adjustments of scheduling times in railway real time traffic planning. Presented at Svenska Operationsanalyskonferensen and the 6th Nordic Optimization Symposium, Gothenburg, October 2013.

Lidén, T., Rydberg, S., 2014. Optimal Adjustment of Scheduling Times in Real Time Traffic Planning. Report, project ON-TIME, 2014.

Lim, B., Arık, S.Ö., Loeff, N. and Pfister, T., 2021. Temporal fusion transformers for interpretable multi-horizon time series forecasting. *International Journal of Forecasting*, 37(4), 1748-1764.

Lo, J. C., Sehic, E., Brookhuis, K. A., Meijer, S. A., 2016. Explicit or implicit situation awareness? Measuring the situation awareness of train traffic controllers. *Transportation Research Part F: Traffic Psychology and Behaviour*, 43, 325-338.

Maag, C., Schmitz, M., 2012. Assessment of train drivers' performance in a driving simulator. *Rail human factors around the world: impacts on and of people for successful rail operations*, 136.

Makkinga, F., 2004. A new user interface for the train traffic control system. *WIT Transactions on The Built Environment*, 74, 725-732.

Metzger, U., Vorderegger, J., 2012. *Railroad*. In: M. Stein, P. Sandl (eds.), *Information ergonomics: a theoretical approach and practical experience in transportation*. Springer, pp. 227-239.

MOTIONAL, 2024. *Requirements for the deployment of TMS linked with ATO/C-DAS*. Deliverable

D15.1, Europe’s Rail, 2024.

Munn, Z., Peters, M. D., Stern, C., Tufanaru, C., McArthur, A., Aromataris, E., 2018. Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC Medical Research Methodology*, 18, 143.

Naghiyev, A., Sharples, S., Carey, M., Coplestone, A., Ryan, B., 2014. ERTMS train driving-in cab vs. outside: an explorative eye-tracking field study. *Contemporary Ergonomics and Human Factors 2014: Proceedings of the International Conference on Ergonomics & Human Factors*, CRC Press.

Naghiyev, A., Sharples, S., Ryan, B., Coplestone, A., Carey, M., 2016. Real world verbal protocol data analysis of European Rail Traffic Management System train driving and conventional train driving. *IEEE International Conference on Intelligent Rail Transportation (ICIRT)*, IEEE.

Niu, K., Fang, W., Guo, B., 2018. Team task complexity of traffic dispatchers in operating control center: A network-based concept. *International Conference on Intelligent Rail Transportation (ICIRT)*, IEEE.

Pacaux-Lemoine, M. P., Gadmer, Q., Richard, P., 2020. Train remote driving: A Human-Machine Cooperation point of view. *IEEE International Conference on Human-Machine Systems (ICHMS)*, IEEE.

Pachl, J., 2002. *Railway Operation and Control*. VTD Rail Publishing.

Papadimitriou, E., Schneider, C., Tello, J. A., Damen, W., Vrouenraets, M. L., Ten Broeke, A., 2020. Transport safety and human factors in the era of automation: What can transport modes learn from each other? *Accident Analysis & Prevention*, 144, 105656.

Parasuraman, R., Sheridan, T.B., Wickens, C.D., 2000. A model of types and levels of human interaction with automation. *IEEE Transactions on Systems, Man and Cybernetics*, 30, 286–297.

Pichardo Vicencio, J. C. (2024). Machine Learning-Based Prediction Model for Enhancing Passenger and Freight Train Arrival Time Forecasting In Railway Systems. MSc thesis, Mälardalen University.

Qiu, J., Helbig, R., Rabenstein, H., Williams, M., 2011. A preliminary study of work problems on train drivers. *International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering*, IEEE.

Quaglietta, E., Pellegrini, P., Goverde, R.M.P., Albrecht, T., Jaekel, B., Marlière, G., Rodriguez, J., Dollevoet. T., Ambrogio, B., Carcasole. D., Giaroli, M., Nicholson, G., 2016. The ON-TIME real-time railway traffic management framework: A proof-of-concept using a scalable standardised data communication architecture. *Transportation Research Part C: Emerging Technologies*, 63, 23-50.

Rad, M. A., Lefsrud, L. M., Hendry, M., Blais, D., 2021. *Human-Factors and Automation-Related Accidents in the Railway Industry*. *Hazards 31 Conference*.

Rees, A., Wiggins, M. W., Helton, W. S., Loveday, T., O'Hare, D., 2017. The impact of breaks on sustained attention in a simulated, semi-automated train control task. *Applied Cognitive Psychology*, 31(3), 351-359.

Richard, P., Boussif, A., Paglia, C., 2021. Rule-based and managed safety: a challenge for railway autonomous driving systems. *31th European Safety and Reliability Conference*.

Rypekema, J., van Doorn, E.C., Albers, S., 2023. Skill degradation in using ATO. *NS Techniek*.

Sandblad, B., Andersson, A. W., Kauppi, A., Isaksson-Lutteman, G., 2010. Development and implementation of new principles and systems for train traffic control in Sweden. *Computers in Railways,* XII, 441-450.

Sandblad, B., Andersson, A. W., Tschirner, S., 2015. Information systems for cooperation in operational train traffic control. *Procedia Manufacturing*, 3, 2882-2888.

Scheepmaker, G.M., Willeboordse, H.Y., Hoogenraad, J.H., Luijt, R.S., Goverde, R.M.P., 2020. Comparing train driving strategies on multiple key performance indicators. *Journal of Rail Transport Planning & Management*, 13, 100163.

Scott, A., & Gibson, H., 2012. Red means stop, doesn't it? A human factors trial of a UK train safety system driver-machine interface. *Rail Human Factors Around the World*.

Sebok, A., Wickens, C., Laux, L., Jones, M., 2015. Supporting human-automation interaction in the rail industry by applying lessons from aviation*. Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 59, 1.

Sharples, S., Millen, L., Golightly, D., Balfe, N., 2011. The impact of automation in rail signalling operations*. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 225(2), 179-191.

Smith, P., Kyriakidis, M., Majumdar, A.,Ochieng, W.Y., 2013. Impact of European railway traffic management system on human performance in railway operations: European findings. *Transportation Research Record*, 2374, 83-92.

Sobrie, L., Verschelde, M., Roets, B., 2023. Explainable real-time predictive analytics on employee workload in digital railway control rooms. *European Journal of Operational Research*, 317(2), 437-448.

Spring, P., McIntosh, A., Caponecchia, C., Baysari, M., 2009. Level of automation: effects on train driver vigilance. *Proceedings of Third International Conference on Rail Human Factors.*

Stoop, J., Baggen, J., Vrancken, J., Vleugel, J., Beukenkamp, W., 2009. A diabolic dilemma: towards fully automated train control or a human centred design? *IFAC Proceedings*, 42(15), 251-256.

Su, S., Tian, Z., Goverde, R.M.P., 2023. *Energy-Efficient Train Operation: A System Approach for Railway Networks*. Springer.

Tabai, B.H., Bagheri, M., Sadeghi-Firoozabadi, V., Sze, N.N., 2018. Evaluating the impact of train drivers' cognitive and demographic characteristics on railway accidents. *Safety Science*, 110, 162-167.

Thompson, E., Kazi, T., Scott, A., 2017. Bridging the gap between technology and adoption: a case study. *Rail Human Factors: Supporting reliability, safety and cost reduction*, 183.

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., ..., Straus, S. E., 2018. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. *Annals of Internal Medicine,* 169(7), 467-473.

Tschirner, S., Andersson, A. W., Sandblad, B., 2013. Improved railway service by shared traffic information. *IEEE International Conference on Intelligent Rail Transportation Proceedings*, IEEE.

Tschirner, S., Sandblad, B., Andersson, A. W., 2014. Solutions to the problem of inconsistent plans in railway traffic operation. *Journal of Rail Transport Planning & Management*, 4(4), 87-97.

UIC, 2013. *UIC Code 406: Capacity*, 2nd edition.

Vaswani, A., Shazeer, N., Parmar, N., Uszkoreit, J., Jones, L., Gomez, A.N., Kaiser, Ł. and Polosukhin, I., 2017. Attention is all you need. *Advances in neural information processing systems*, 30.

Verstappen, V.J., Pikaar, E.N., Zon, R.G., 2022. Assessing the impact of driver advisory systems on train driver workload, attention allocation and safety performance. *Applied Ergonomics*, 100, 103645.

Von Berg, J.A.M., Van Doorn, E.C., 2024. Post-Trip Mind-Wandering Assessment: A Scale and Protocol for Evaluating Train Driver Focus Across Multiple Journey Phases. In: *ASPIRE 2024: Proceedings of the Human Factors and Ergonomics Society Annual Meeting.*

Wackrow, J., Slamen, A., 2013. The implications of automation on human intervention at London underground. *Rail Human Factors: Supporting reliability, safety and cost reduction*, Taylor and Francis.

Wagner, A., Haramina, H., Michelberger, F., 2021. Proposal of an Ergonomic Interface for Supervision and Control of an Automated Shunting Device. *Proceedings of the 8th International Ergonomics Conference*, Springer.

Wang, A., Guo, B., Du, H., Bao, H., 2022. Impact of Automation at Different Cognitive Stages on High-Speed Train Driving Performance. *IEEE Transactions on Intelligent Transportation Systems*, 23(12), 24599 - 24608.

Wang, Z, Quaglietta, E., Bartholomeus, M.G.P., Cunillera, A., Goverde, R.M.P., 2024. Optimising timing points for effective automatic train operation. Under review.

Wikström, J., Kauppi, A., Hellström, P., Andersson, A.W., Sandblad, B., 2004. Train traffic control by re-planning in real-time. *WIT Transactions on The Built Environment*, 74, 733-742.

Yang, L., Lidén, T., Leander, P., 2013. Achieving energy-efficiency and on-time performance with driver advisory systems. *IEEE International Conference on Intelligent Rail Transportation proceedings*, IEEE.

Yin, J., Tang, T., Yang, L., Xun, J., Huang, Y., Gao, Z., 2017. Research and development of automatic train operation for railway transportation systems: A survey. *Transportation Research Part C: Emerging Technologies*, 85, 548-572.

Young, M. S., Stanton, N. A., Walker, G. H., 2006. In loco intellegentia: human factors for the future European train driver. *International Journal of Industrial and Systems Engineering*, 1(4), 485-501.

Zeilstra, M., de Bruijn, D. W., van der Weide, R., 2012. Development and implementation of a predictive tool for optimizing workload of train dispatchers. *Rail Human Factors around the World: Impacts on and of People for Successful Rail Operations*.

Zhu, Y., Goverde, R.M.P., 2019. Railway timetable rescheduling with flexible stopping and flexible short-turning during disruptions. *Transportation Research Part B: Methodological*, 123, 149-181.

Zhu, Y., Goverde, R.M.P., 2020. Dynamic and robust timetable rescheduling for uncertain railway disruptions. *Journal of Rail Transport Planning & Management*, 15, 100196.

15. Annex: Validation Results

15.1. Testing Methodology

WP15 developed several components/functions for TMS-ATO operations. Prototypes of these functions were validated at Technology Readiness Level 4 (TRL 4), i.e., technology validated in lab. In WP16 these functions will be further validated in the demonstrations at TRL 5, technology validated in relevant environment.

The developed component/functions were described in this deliverable as follows:

1. RTTP Updater for single-track lines (Section 7.2)
2. Traffic Regulator for urban railway lines (Section 7.3)
3. TPE Generator for mainline railways (Section 8.3)
4. TMS – C-DAS Enhanced Operation (Section 9.2)
5. ATO Train Forecast and Operational Plan Update (Section 9.3)
6. TMS-ATO Integration Layer (Section 10.2)
7. Journey Profile Generator (Section 10.3)
8. Human-In-The-Loop Simulation Environment (Chapter 11).

The TRL 4 validation reports are provided in this annex. For each developed function/component test scenarios were defined, which were then executed in a lab environment. The TPE Generator (number 3) was developed to be demonstrated within the Human-In-The-Loop simulation environment (number 8). Therefore, the TRL 4 validation of the TPE Generator has been integrated with the TRL 4 validation of the Human-In-The-Loop simulation environment.

Each of the validation results is reported in three parts: first the test report(s) are given with a summary of the test description and test execution, then details are given in separate sections on the test description and test execution.

15.2. RTTP Updater

The test of the RTTP Updater is divided into three parts. The first test corresponds to testing the module Runtime estimator, the second corresponds to the module RTTP Finetuner, and the third and final part is testing the communication from Trafikverket TMS (Digital graf test environment) to the RTTP Updater module at RISE.

15.2.1. Module Runtime Estimator

15.2.1.1. Test Report

Table 15-1 Test report for RTTP Updater: module Runtime estimator

Test description	**Name**	**Runtime Estimator**
	ID	1
	(Short) description	The Temporal Fusion Transformer (TFT) model is utilized to predict train runtimes and delays for the next 1 to 5 stations along selected routes in the Swedish railway system. It generates delay forecasts based on historical train data and weather conditions, providing predictions for upcoming station stops.
	Test case responsibles	Zohreh Ranjbar and Martin Joborn, RISE
	Pre-conditions	A transformer model is trained on both passenger and freight trains, focusing on the southern region of Sweden.
	TRL	4
	Input data description	Train timetable data: Train types, departure/arrival stations, delays, trip IDs, disturbance data Weather data: Temperature readings sourced from the Swedish Meteorological and Hydrological Institute (SMHI) See 15.2.1.2
	Expected result	The TFT model predict train delays with a high accuracy
	Sequence	1. Test data loading: The unseen test set, including train schedules, delays, and weather data, is loaded for model evaluation. 2. Prediction: The TFT model generates delay predictions on the unseen test set. 3. Prediction evaluation: The model's predicted delays are compared to actual delays using MAE and Threshold Percentage Closeness 4. Model comparison: The results of the TFT model are compared with those from the baseline and LSTM models to assess relative performance. 5. Results analysis: The analysis confirms that the TFT model outperforms the baseline and LSTM models, providing accurate delay predictions and meeting the requirements for TRL 4 validation.
Test Execution	Testing environment	The TFT model was trained using PyTorch with GPU acceleration managed by PyTorch Lightning. A Tesla V100-SXM2-32GB GPU

		was used, supported by 30 processing cores and 100 GB of local disk storage. The experiments were run in a Jupyter Lab instance connected to a Python environment on the supercomputer.
	Components and versions	Python version 3.10 JupyterLab version 4.0 optuna version 3.4.0 torch version 2.1.0
	Input data used	Historical train timetable data, including planned and actual time train trip data (2023) SMHI weather data Historical data on train trips for 2023.
	Test time stamp	27/09/2024 15:25
	Testers	Juan Carlos Pichardo Vicencio (within his master thesis), RISE; Zohreh Ranjbar, RISE
	Test result	See Section 15.2.1.3
	Test status	PASSED
	Notes	Even though the model is trained on only one year's data, the model successfully predicted train delays with acceptable accuracy for short term predictions.

15.2.1.2. Test Description

The test focuses on validating the Temporal Fusion Transformer (TFT) model for predicting train delays using historical train operation data and weather temperature. The TFT model is specifically designed for time-series forecasting and is tested to assess its ability to handle various types of input data, including both continuous variables like train delay times and categorical data such as station names, train types and delay cause. The dataset used for this test consists of historical executed train schedule data collected from the Swedish railway system over the period of 2023 with a granularity of 1 minute. However, the long-term goal is to use train execution data with a granularity in seconds and also to utilize RTTP data, allowing for more precise predictions and enhanced model performance in future iterations. The data includes both passenger and freight trains, covering different routes and trip lengths, as well as external factors such as temperature data obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The test aims to assess how well the model can predict train delays at specific points along the routes, considering planned departure and arrival times, historical delays, and the impact of environmental conditions. The test is further described in (Pichardo Vicencio, 2024).

The data engineering process, which is a crucial step in the development of the machine learning model, includes data cleaning and encoding, feature selection and feature engineering. During data cleaning, the raw dataset, containing historical execute train schedules and delays from 2023, was analysed for completeness and irrelevant variables were removed. In the feature engineering stage, existing variables were transformed and additional sources, such as weather data from SMHI, was integrated. The data encoding phase involved applying robust scaling for removing outlier from variables like time deviation and for normalization. We conducted the test for two different cases: predicting delays 3 stops ahead and 5 stops ahead. These cases were designed to evaluate the model's ability to forecast short-term and medium-term delays, allowing us to examine how well the model handles different prediction horizons.

The dataset is divided into three parts: training set, validation set, and test set. The training set is used to build the model by teaching it to recognize patterns and relationships between the different input features and delay times. During training, the TFT learns from multiple trips, identifying patterns that can predict delays based on various influencing factors. The validation set is used during training to monitor performance and prevent overfitting, while the test set, consisting of unseen data, is reserved for the final evaluation of the model's performance. Key metrics used for evaluation include Mean Absolute Error (MAE) and Threshold Percentage Closeness. Mean Absolute Error calculates the average magnitude of the errors between the predicted and actual delay times, providing an indication of the model's overall accuracy. Threshold Percentage Closeness is a custom metric that measures the percentage of predictions that fall within a predefined acceptable range of the actual delay times, offering insight to the reliability of the model's predictions.

Additionally, the TFT model's performance is compared against a baseline model, a model that uses the last known target value to make a prediction and repeats the prediction in all the future steps, and a Long-short-term memory (LSTM) which is one of the most used models for the solution of time series forecasting. Both are used to evaluate the TFT model's relative accuracy and robustness. This comparison helps to demonstrate the advantages of the TFT model to have a better accuracy for delays prediction.

The validation of the Runtime Estimator at TRL4 focuses on demonstrating the system's performance using historical data. The evaluation relied on metrics, including Mean Absolute Error (MAE), Threshold Percentage Closeness, to evaluate the predictions precisions. Also compare the predictions accuracy of the TFT model using these metrics compare to the baseline and LSTM model.

15.2.1.3. Test Execution

The objective of the test is to evaluate the trained TFT model using the test set of unseen historical train data. The test begins by loading the test dataset, which includes train schedules, delays, and temperature data. Once the test data is loaded, the TFT model generates predictions for train delays at specific points along the routes. These predictions are based on the input features provided, including historical delay patterns, weather data, and station details. The model predicts delays for both within 3 stations stop and across 5 station stops.

The training and evaluation of the (TFT) model were carried out using the PyTorch library. The environment was set up on a system with GPU acceleration, using PyTorch Lightning to handle the training process. The computational power for the training was provided by a GPU, which allowed for faster processing and efficient handling of large datasets. The TensorFlow environment provided the necessary resources to process and analyse large datasets. Due to the size of the training data to execute this experiment, the computational resources allocated include 30 processing cores and 100 GB of local disk storage. A Jupyter lab instance was created for this supercomputer, focused on developing the experiments using a GPU Tesla V100-SXM2-32GB. This

instance also connected to a Python environment each time it was created and initiated within the supercomputer system.
The predictions generated by the model are compared to the actual delay times recorded in the test data. The performance of the TFT model is evaluated using the following metrics: Mean Absolute Error (MAE) which measures the accuracy of predictions, and Threshold Percentage Closeness, which evaluates the percentage of predictions falling within a predefined threshold of actual delay times.

The results from the TFT model are compared to predictions from both a simple baseline model and an LSTM model. The LSTM model is a recurrent neural network commonly used for time-series data. The comparison highlights the TFT model's advantages, especially in terms of its ability to handle complex, multi-step time-series predictions and its integration of categorical and continuous data.

The results are analysed to determine the strengths and weaknesses of the TFT model. The model's performance, as measured by MAE and Threshold Percentage Closeness. The TFT model consistently outperforms both the baseline and LSTM models, demonstrating its suitability for this application where delay predictions with high accuracy are crucial for optimizing train operations.

Overall, the tests validated the effectiveness of the TFT model in forecasting train delays, especially for short to medium-length trips, making it a promising tool for utilization in the forthcoming demonstrations and for real-time railway operations.

Table 15-2 Metric evaluation of TFT model and comparison

	TFT model (1-step)	TFT model (3-steps)	TFT model (5-steps)	Baseline (1-step)	LSTM model (1-step)
MAE (minute)	0.53	0.57	0.7	1.9	1
Threshold percentage closeness	88%	86%	82%	22%	65%

Table 15-2 compares the performance of the TFT model for 1-step, 3-steps and 5-steps predictions against a baseline model and an LSTM model. For the Mean Absolute Error (MAE), the TFT model demonstrates superior accuracy, with an MAE of 0.53 minutes for 1-step predictions, 0.57 minutes for 3-steps and 0.7 minutes for 5-steps predictions, indicating that the average prediction error is less than a minute. In contrast, the baseline model has a much higher MAE of about 2 minutes, and the LSTM model, while better than the baseline, still shows a higher MAE of 1 minute. In terms of Threshold Percentage Closeness, which measures the percentage of predictions that are closer to the actual delays than a certain threshold, the TFT model performs well with 88%, 86% and 82% closeness for 1-step, 3-steps and 5-steps predictions, respectively, by far outperforming the baseline model's 22% and even the LSTM model's 65% for 1-step prediction. This demonstrates the TFT model's overall superior performance in predicting train delays. The model achieved a high percentage of closeness for 1-step (above 88%), but as the distance increased for 5-steps, the percentage dropped slightly to around 82%, indicating that while the predictions were still reliable, there was more uncertainty over longer distances.

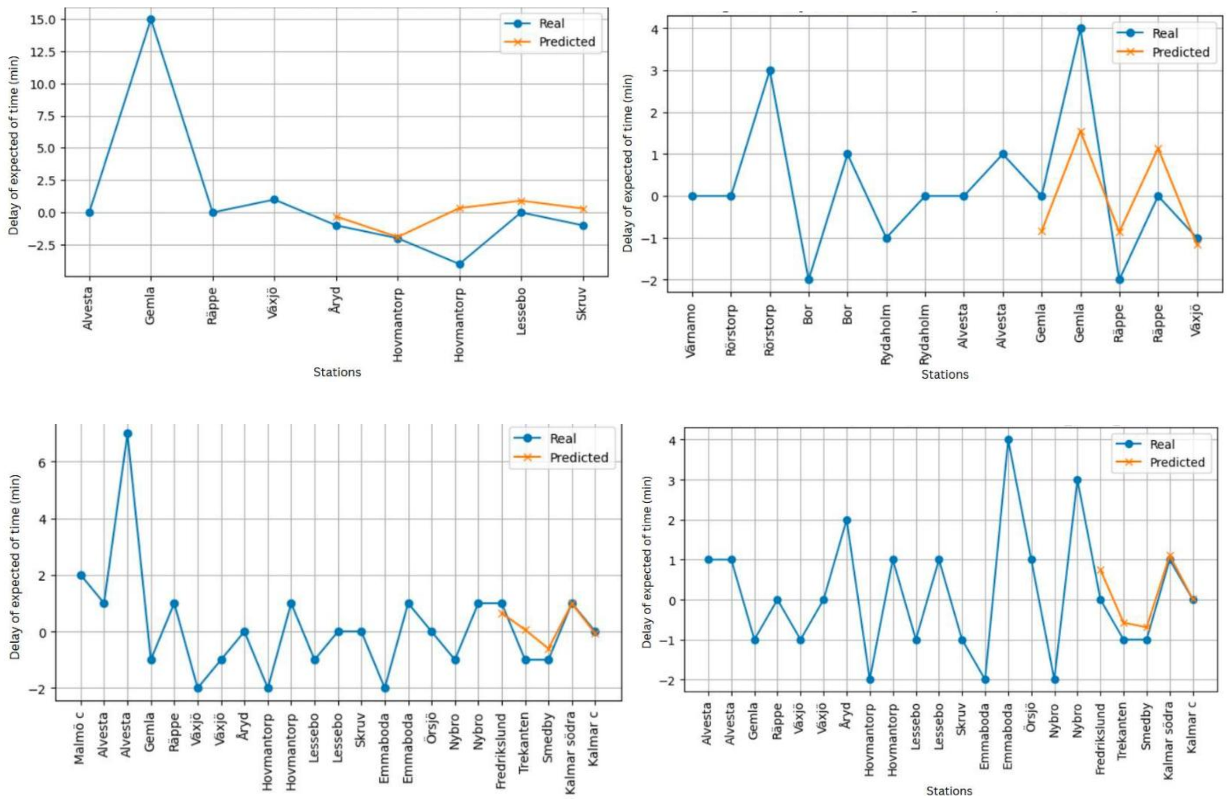


Figure 15-1 Prediction vs. actual delays across various train stations along selected routes

The four plots in Figure 15-1 illustrate the predicted vs. actual delays across various train stations along selected routes. In each plot, the blue line represents the real delay recorded at each station, while the orange line represents the predicted delay generated by the Temporal Fusion Transformer (TFT) model. A positive value means a delay relative to the scheduled time, while a negative value signifies that the train took fewer minutes than estimated. The graphs illustrate the prediction results for different long trips. The upper graphs represent shorter trips with fewer stops, while the lower graphs depict prediction results for longer trips, providing the model with more historical data to consider.

Top-left Plot: This plot shows closer alignment between the actual and predicted delays. The model performs reasonably well in capturing the overall delay patterns, with minimal deviations between the two lines, particularly for stations towards the end of the route. Top-right Plot: In this plot, there are clear discrepancies between actual and predicted delays at the second predicted step since the real delay is 3 minutes. This delay may depend on a new unseen disturbance which is difficult to predict. The model captures the overall pattern. However, as the route progresses, the predictions become closer to the actual delays. Bottom-left Plot: This plot shows the closest alignment between predicted and actual delays. The model can track the general trend across the stations with minimal error. Bottom-right Plot: Here, in the beginning of prediction the actual delay is significant. Which make a gap between actual and predicted delays. However, at stations where delays remain steady or consistent, the model provides reasonable predictions.

Overall, the TFT model demonstrates a strong ability to predict train delays across various stations, capturing the general trends and providing reasonably accurate forecasts. However, in some instances, the model struggles with extreme delays or outliers, which may be due to unforeseen events in the input data. The consistency in predicting smaller delays shows the model's robustness in capturing regular patterns, but further improvement may be needed for handling larger deviations. The test execution confirms that the TFT model meets the requirements for TRL 4 validation, showing that it can predict train delays with high accuracy in a simulated lab environment. This provides a solid foundation for further development and demonstration.

The tests also highlight areas for improvement. For example, data for executed train timetable should be with higher granularity (seconds), and the RTTP should be considered to include effects changed stopping pattern between STP and RTTP.

15.2.2. RTTP Finetuner

15.2.2.1. Test Report

Table 15-3 Test report for RTTP Updater: module RTTP Finetuner

Test description	**Name**	**RTTP Finetuner**
	ID	2
	(Short) description	RTTP Finetuner is updated with forecasted train positions (departure and/or arrival times) of some trains and the RTTP Finetuner calculates an p-RTTP. Test shall verify that the calculated adjustment to in p-RTTP are relevant. In the tests the forecasted train positions are varied and the adjustments in the p-RTTP are evaluated.
	Test case responsibles	Martin Joborn, RISE
	Pre-conditions	RTTP Finetuner is a separate module, reading input data from files. RTTP Finetuner includes an MIP-solver (IBM ILOG CPLEX).
	TRL	4
	Input data description	Swedish rail infrastructure between Värnamo and Kalmar. RTTP and STP for Trains 1056 and 1097 with a scheduled meeting in Åryd. Emulated data for energy-runtime correlation. Emulated forecasted train positions. Four different scenarios are tested, representing different forecasted deviations from the RTTP, see Section 15.2.2.2
	Expected result	p-RTTP includes relevant adjustments that resolve conflicts and allow optimized the driving profiles.
	Sequence	Step 1: Set up input data Step 2: Run RTTP Finetuner Step 3: Evaluate results
Test Execution	Testing environment	Standalone PC. Test performed i IBM ILOG CPLEX Optimization Studio.
	Components Versions	IBM ILOG CPLEX Optimization Studio 22.1.1
	Input data used	Relevant extract from STP/RTTP for trains 1056 and 1097 complemented with simulated departure and arrival time forecast for the trains.
	Test time stamp	
	Testers	Martin Joborn, RISE
	Test result	See Section 15.2.2.3
	Test status	PASSED
	Notes	

15.2.2.2. Test Description

The scope of the test is to show that RTTP Finetuner makes expected types of adjustments to the

RTTP. The infrastructure used in the test represent the single-track line from Värnamo to Kalmar (see Figure 7-4). The tests include the meeting between train 1056 and 1097, travelling Malmö-Alvesta-Kalmar and vice versa. We assume that train 1097 is equipped with C-DAS and 1056 is not. The two trains are scheduled to meet in station Åryd.

The traffic situation is a meeting of a C-DAS-train and a non-C-DAS-train on a single-track line. The arrival time of the non-C-DAS-train to the meeting station is given input data, representing an emulated arrival time estimation from the *Runtime estimator*. The estimated arrival time represent different deviations from the RTTP. Four scenarios are evaluated. Two aspects are varied in the different scenarios: a) which train is stopping and which is passing, b) if the non-C-DAS-train is early or late to the meeting station. Table 15-4 summarize principal differences in the scenarios. The four scenarios represent the most important basic cases for the RTTP Finetuner to be able to handle. Naturally, a real traffic situation will include more complex situations, but for illustration of the RTTP Finetuner functionality, we consider these four cases to be the core of functionality.

Table 15-4 Test scenarios RTTP Finetuner with C-DAS Train 1097 train and 1056 unequipped

Scenario	Stopping train in RTTP	Deviation	Other aspects included
1	1056	1056 is late	
2	1056	1056 is early	
3	1097	1056 is late	RTTP after STP
4	1097	1056 is early	Other stopping pattern of trains

When calculating p-RTTP, the RTTP Finetuner not only consider deviation from RTTP, but also robustness and energy consumption. However, in the tests summarized here, the focus is on handling deviations and restoring the RTTP. Therefore, the four evaluated scenarios focus on stopping pattern and delay situation. The input data also include emulated energy-runtime-correlations (see Figure 7-3) and robustness parameters. In most cases, the STP is not considered in the calculation of p-RTTP, but scenario 3 illustrates a case when the STP plays a role.

15.2.2.3. Test Execution

Tests are executed on a standalone standard laptop (Lenovo ThinkPad T14s) using Windows 11 operating system. The computer includes a standard installation of IBM ILOG CPLEX Optimization Studio 21.1.1. RTTP Finetuner is (this far) developed directly in the Optimization Studio in the modelling language OPL. For future demonstrations in WP16, the RTTP Finetuner will most likely be implemented outside the Optimization Studio, which will increase the computational performance and simplify integration and communication. However, for initial development and evaluation, it has been beneficial to use the integrated optimization development environment.

The execution of the test and its scenarios is straightforward:

1. Set up test data for chosen scenario. The major difference in the data between the scenarios are the RTTP and the departure/arrival estimation.
2. Run *RTTP Finetuner* by executing the calculations in IBM ILOG CPLEX Optimization Studio

3. Evaluate the results, e.g., by drawing very simple graphical timetables in Excel, illustrating the modifications to the RTTP.

The scheduled timetables (STP) of the involved trains are shown in Table 15.x. The STP plays an active role in Scenario 3, while in the other scenarios the role of STP is indirect as it is the basis for the RTTP.

Scenario 1

In scenario 1, we evaluate that RTTP Finetuner calculates appropriate changes to RTTP when a non-C-DAS-train is deviating from its RTTP (delayed). The deviation from RTTP causes the RTTP to be an inefficient base for journey profile since there is a risk that the C-DAS-train has to make an unplanned, unnecessary stop if it drives according to the RTTP. The timetable data characterizing the scenario is summarized in Table 15-5. Here, times are written in the format hh:mm and in minutes in parentheses. Arrival times at Vx and Hvp are considered as delivery commitments, i.e., we should try to avoid delays at these stations, while times at Ard are "technical" in the sense that they are important for coordinating the traffic, but since there is no passenger exchange at Ard, the operated times, i.e., the RTTP, at Ard can be changed with no consequences as long as the times at the delivery commitments are kept.

Table 15-5 Input summary for scenario 1

	Train 1056		Train 1097		
Timetable event	**STP**	**RTTP**	**STP**	**RTTP**	**Scenario**
Vx dep/arr	13:51 (831)	13:51 (831)	14:07 (847)	14:07 (847)	
Ard arr/dep	13:58 (838)	13:59 (839)	13:59 (839)	14:00 (840)	Train 1056 late: 14:01 (841)
Ard dep/arr	14:00 (840)	14:01 (841)	13:59 (839)	14:00 (840)	
Hvp arr/dep	14:10 (850)	14:10 (850)	13:50 (830)	13:51 (831)	

The resulting p-RTTP is summarized in Table 15-6. The results are also illustrated in Figure 15-2.

Table 15-6 The resulting p-RTTP from scenario 1

	Train 1056		Train 1097	
Timetable event	**RTTP**	**p-RTTP**	**RTTP**	**p-RTTP**
Vx dep/arr	13:51 (831)	13:51 (831)	14:07 (847)	14:07 (847)
Ard arr/dep	13:59 (839)	14:01 (841)	14:00 (840)	14:02 (842)
Ard dep/arr	14:01 (841)	14:02:30 (842.5)	14:00 (840)	14:02 (842)
Hvp arr/dep	14:10 (850)	14:10 (850)	13:51 (831)	13:51 (831)

Figure 15-2 shows a graphical timetable of the results from scenario 1. Time scale on the y-axis is in minutes from midnight (840 represents 14:00). The dashed lines are the RTTP for 1056 and 1097, respectively, and the dashed lines represent the p-RTTP, i.e., the result from *RTTP Finetuner*. The horizontal solid line represents the time om the arrival time estimate to Ård for the non-C-DAS-train 1056. The robustness aspect considered can been seen as the time margins between the arrival and departure events at the meeting station. Another robustness aspect considered (not possible to see in the figure) is that travel time on each leg has a margin to the minimum runtime. Also, the p-RTTP includes consideration to the energy-runtime correlation (see Figure 7-3) and balance the total energy consumption towards robustness and timetable aspects. However, this is hard to see in the figure.

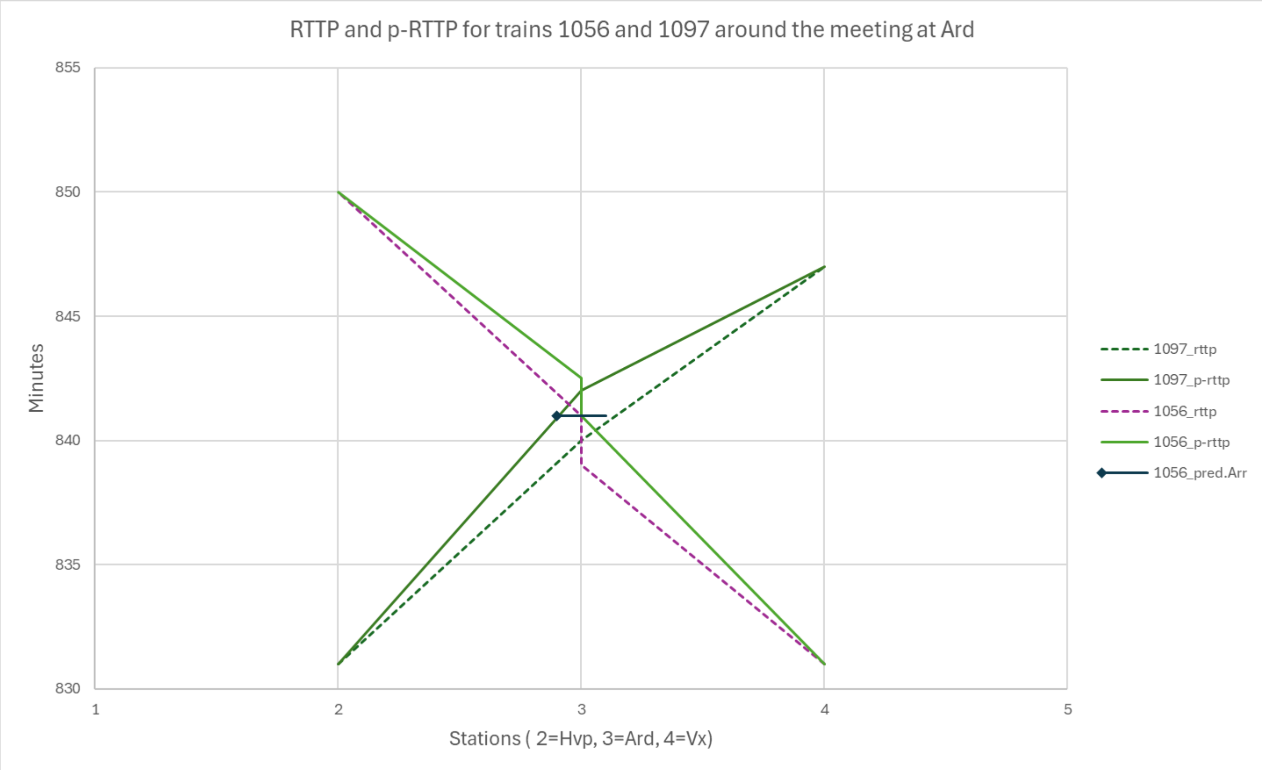


Figure 15-2 Graphical timetable of results from scenario 1

Figure 15-3 shows a screenshot from the IBM ILOG CPLEX Optimization Studio solving scenario 1. The calculation time for CPLEX for solving the optimization problem is 0.03 seconds; in addition there is model compilation and loading time taking about 5 seconds. However, when evaluating the performance of the module, the loading and compilation time can be neglected since in the 'real' demonstration setting, the loading and compilation will be made in advance. Note that even the scenario is small, it is of relevant size of a full-scale problem. Hence, the RTTP Finetuner can be expected to very efficiently perform its task.

The results from scenario 1 show that *RTTP Finetuner* can handle delayed non-C-DAS-trains and can very efficiently calculate an p-RTTP, considering both delays, energy efficiency and robustness.

Scenario 2

In Scenario 2, the non-C-DAS-train 1056 is estimated to be early, before the RTTP, otherwise scenario 2 is similar to scenario 1. Figure 15-4 illustrate the result from scenario 2. The explanation to the figure is the same as to Figure 15-2. The figure illustrates that the p-RTTP includes the expected type of modifications of the RTTP, since the p-RTTP is conflict free and includes relevant buffers. There is very little modifications to r-RTTP for train 1097, but some minor changes are made to optimize energy consumption. Solution time for CPLEX is 0.03 seconds.

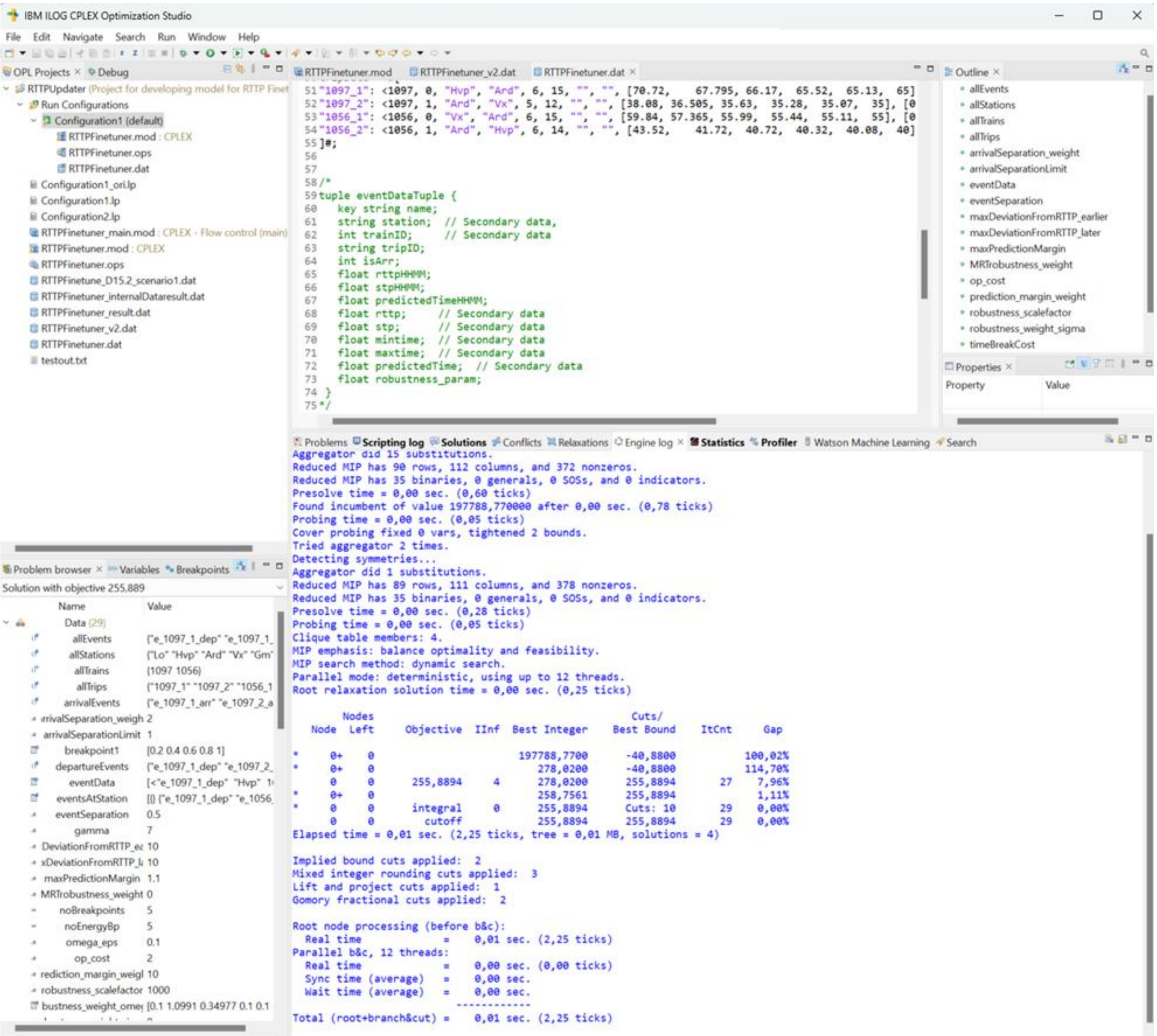


Figure 15-3 Screenshot from IBM ILOG CPLEX Optimization Studio solving scenario 1

Scenario 3

In scenario 3, the C-DAS-train is stopping, while the non-C-DAS-train is passing and late. Furthermore, the arrival time according to RTTP at Vx for train 1097 is after the STP. In this case, the *RTTP Finetuner* is expected to create a p-RTTP that minimizes the delays, still considering minimal runtimes between the stations. The test result is summarized in Figure 15-5. In addition to the previous figures, the dotted lines represent the STP for each train. The figure illustrates the results and that the p-RTTP is that also in scenario 3, the p-RTTP is created in the expected way. The p-RTTP includes a reduction of the delay at Vx for train 1097 by planning for utilizing minimum runtime from Ard to Vx; however, the delay in Vx cannot be fully eliminated. CPLEX solution time is 0.03 seconds.

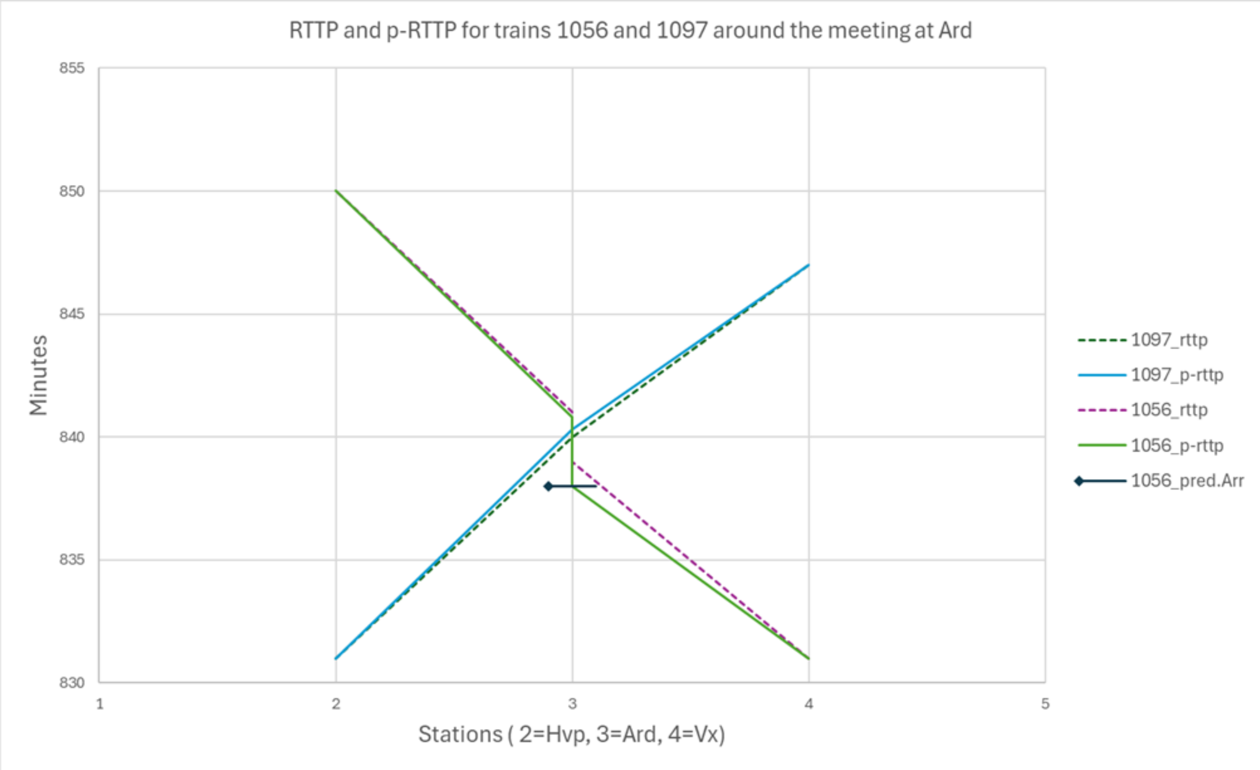


Figure 15-4 Graphical timetable representing results from scenario 2

Figure 15-5 Graphical timetable representing the results from scenario 3

Scenario 4

Scenario 4 includes the following variation of the settings:

- The considered legs in RTTP for train 1056 is Gm-Ard-Hvp.
- The considered legs in RTTP för train 1097 is Lo-Ard-Vx.
- Meeting between 1056 and 1097 is planned at Ard.
- The C-DAS-train 1097 is stopping.
- The non-C-DAS-train 1056 is passing.
- Estimated arrival time of train 1056 to Ard is before RTTP.

The results are illustrated in Figure 15-6. Also in this case, the created p-RTTP includes the expected type of modifications to the RTTP. The scenario also shows that RTTP Finetuner is able to handle asymmetric train legs of the considered trains. CPLEX solution time is 0.01 seconds.

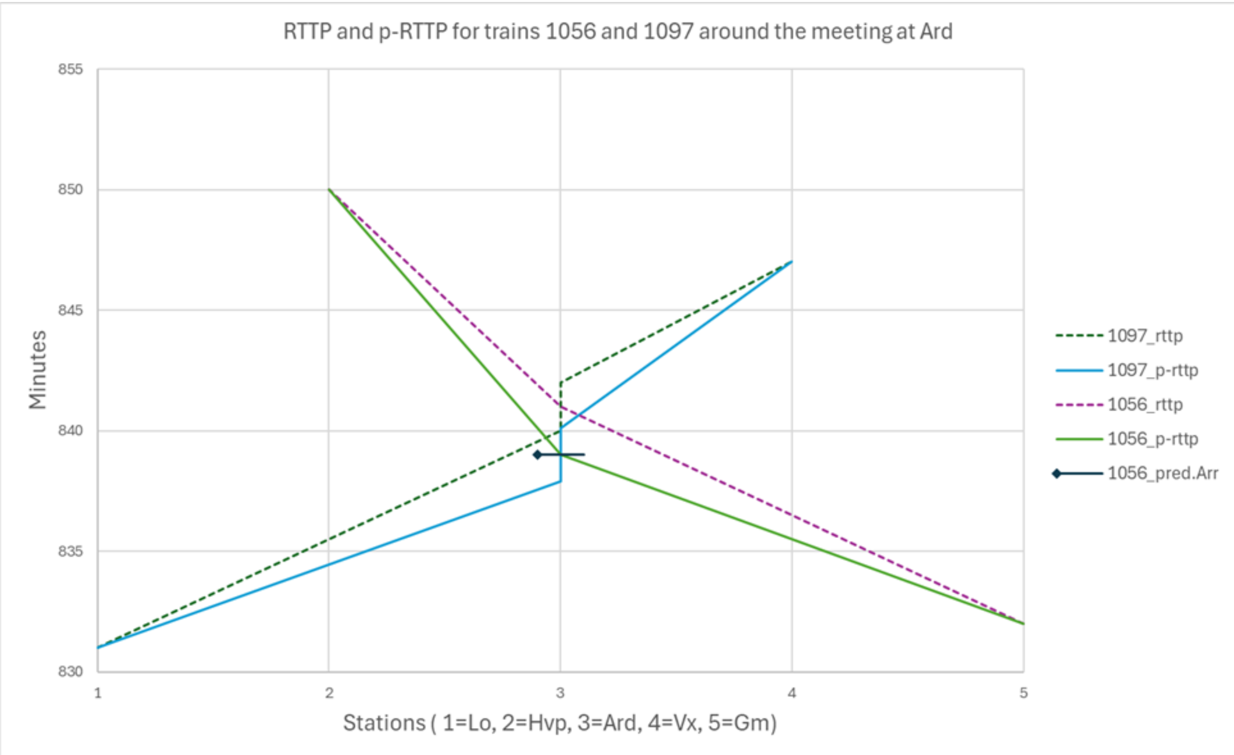


Figure 15-6 Graphical timetable representing scenario 4

Concluding remarks

The executed tests represent the cornerstones of the modifications that RTTP Finetuner should be able to make and the tests verify that it very efficiently can create an modified RTTP (p-RTTP) that both solves the conflicts arise from the deviating non-C-DAS-train, and take both delay, energy consumption and robustness into consideration. In the continuation, the RTTP Finetuner will be integrated with the other parts of RTTP Updater and further tests and demonstrations will also involve real users.

15.2.3. Data Communication

15.2.3.1. Test Report

Table 15-7 Test report for RTTP Updater: Data Communication with Digital graf

Test description	**Name**	**RTTP Updater Data Communication with Digital graf**
	ID	3
	(Short) description	The component, digital graf-topic-to-motional-topic-component, filters out specific train messages from Trafikverket's TMS subsystem Digital Graf system, that will be used in RTTP Finetuner, and stores them in an Apache Kafka topic.
	Test case responsibles	Henrik Teinelund, RISE
	Pre-conditions	An integration to Trafikverket's TMS subsystem Digital Graf is in place and a storage location is created where all messages from Digital Graf is put. We use Apache Kafka and a topic where all messages from Digital Graf are stored. We also need a topic, motional.raw, where filtered messages will be stored.
	TRL	4
	Input data Description	RTTP in the form of JSON messages from Digital Graf, see Section 15.2.3.2.
	Expected result	The specified messages sent from Digital graf is stored in the Apache Kafka topic motional.raw.
	Sequence	Step 1: Start the digitalgraf-topic-to-motional-topic-component
Test Execution	Testing environment	The application Offset Explorer, that is able to visualize data in an Apache Kafka topic.
	Components and versions	Apache Kafka 3.6 digitalgraf-topic-to-motional-topic-component 1.0.3 Offset Explorer 2.3.2
	Input data used	The JSON messages from Digital Graf.
	Test time stamp	2024-10-18 10:10:00
	Tester	Henrik Teinelund
	Test result	Correct RTTP-messages are stored, see Section 15.2.3.3.
	Test status	PASSED
	Notes	

15.2.3.2. Test Description

RTTP Updater uses messages from Trafikverket's TMS subsystem Digital Graf as a base for its calculations. Messages represent RTTP for different trains. Relevant messages are stored. In particular, we are filtering out messages representing the trains 1056 and 1097, trains that are also used in other tests of RTTP Updater.

Message handling is accomplished using RISE integration platform for research projects, denoted

Deplide. It consists of Apache Kafka as core component and has components that integrates to RISE customer API's, and it stores messages from these API's on different topics. Each integration uses its unique topic. There is one topic that stores messages from Trafikverket's TMS subsystem Digital graf. In this project we have created one component, digitalgraf-topic-to-motional-topic-component, that filters out messages regarding trains 1056 and 1097, and stores these in the topic motional.raw.

15.2.3.3. Test Execution

The test starts when the component, digitalgraf-topic-to-motional-topic-component, is started. It listens to the topic with Digital graf messages, and as new messages are published, it fetches them and analyses them. If the message has a value of 1056 or 1097 in a specific field, it stores the message in the topic motional.raw.

Offset Explorer is a program that visualizes an instance of Apache Kafka. Among its features it can display the number of messages in a specific topic. As of the data 2024-10-18 10:10 Swedish time), the topic motional.raw contains 737 messages, see Figure 15-7. It is also possible to display a (small) list of messages, and view messages, one at a time, see Figure 15-8. It also displays the content of the last message. Note the value in the filed Core, which represents the train number: 1097.

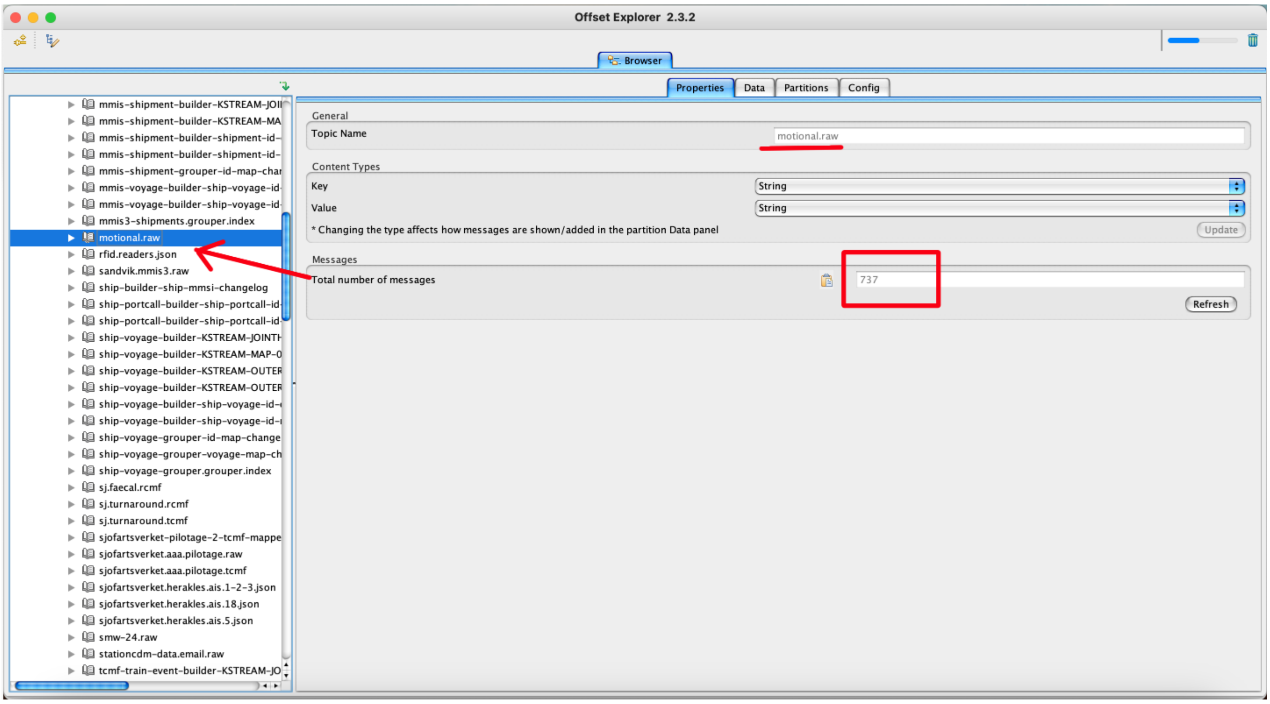


Figure 15-7 Offset Explorer displays number of messages in topic motional.raw

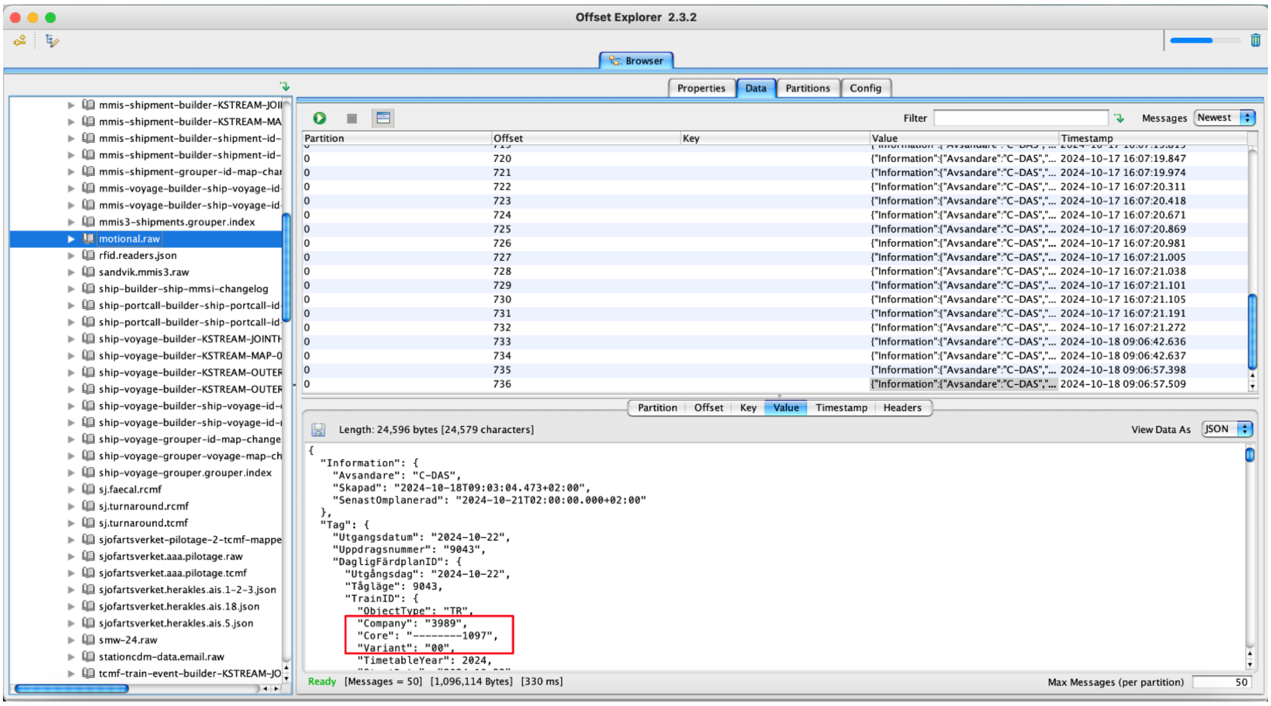


Figure 15-8 Offset Explorer displays the 50 latest messages as a list in the topic motional.raw

15.3. Traffic Regulator

15.3.1. Test Reports

This section describes the Train Regulator TRL 4 validation results obtained after designing the predictive control algorithm and its subsequent implementation in a traffic regulator for a two-track line with two terminal stations, where the operational constraints specific to a railway line have been considered. Two test scenarios were selected to validate the Traffic Regulator at TRL 4, which each containing two cases. The first test scenario considers an open-loop simulation for two sets of control weights, while the second test scenario considers a closed-loop simulation for two sets of delay scenarios.

Table 15-8 Test report for Traffic Regulator open-loop simulation

Test Description	**Name**	**Traffic Regulator open-loop simulation**
	ID	1
	(Short) description	The results of the predictive control algorithm before its implementation in the traffic simulator. To this end, a specific 90-second delay is imposed on a train to study the transient evolution of the recovery from that delay
	Test case responsibles	Paloma Cucala, IIT, Antonio Fernandez, IIT
	Pre-conditions	This situation is tested in two different cases: when the objective function of the model does not distinguish between positive and negative control actions, and when different values for the weights are applied for positive and negative control actions
	TRL	4
	Input data description	See Section 15.3.2
	Expected result	See Section 15.3.2
	Sequence	15.3.2
Test Execution	Testing environment	Isolated situation before include the algorithm inside the regulator
	Components and versions	Regulation algorithm v1.0
	Input data used	See Section 15.3.3.1
	Test time stamp	13/09/2024 10:00
	Testers	Isabel Meseguer, CAF Adrián Fernandez, IIT
	Test Results	See Section 15.3.3.1
	Test status	PASSED
	Notes	-

Table 15-9 Test report for Traffic Regulator closed-loop simulation

Test Description	Name	Traffic Regulator closed-loop simulation
	ID	2
	(Short) description	A simple simulator of a commuter line is designed, into which both the mathematical control algorithm and the CAFS speed profile generator are implemented to enable a closed-loop simulation.
	Test case responsibles	Paloma Cucala and Antonio Fernandez, IIT
	Pre-conditions	There will be two case studies: first, a 90-second delay will be imposed on a train in the fleet to study the transient evolution of delays; second, the transient evolution of delays will be analysed when random disturbances at stops, due to passenger get on and off of the train, are considered.
	TRL	4
	Input data Description	See Section 15.3.2
	Expected result	See Section 15.3.2
	Sequence	See Section 15.3.2
Test Execution	Testing environment	Isolated situation before include the algorithm inside the regulator using the CAFS speed profile generator.
	Components Versions	Regulation algorithm v1.0; CAFS speed profile generator v1.28
	Input data used	See Section 15.3.3.2
	Test time stamp	13/09/2024 12:00
	Testers	Isabel Meseguer, CAF, Adrián Fernandez, IIT
	Test results	See Section 15.3.3.2
	Test status	PASSED
	Notes	-

15.3.2. Test Description

Considered is a commuter loop line where terminal stations are modeled as turnback platforms as presented in Figure 15-9. Trains travel in both directions along a closed circuit, stopping along their journey at stations with one platform in each direction. Traffic is modeled as a set of trains ($i = 1, \dots, 15$) circulating along 60 platforms ($k = 1, \dots, 60$), where each train i follows train $i - 1$ and stops at every platform k for passengers to get on and off.

Each interstation segment of the line has a nominal running time of 100 seconds, which can be modified by the run control actions increasing it by 30 seconds or decreasing it by 10 seconds. In the same way, the nominal dwell time at the platforms is 20 seconds but, through dwell control actions, it can be increased by 20 seconds or decreased by 5 seconds.

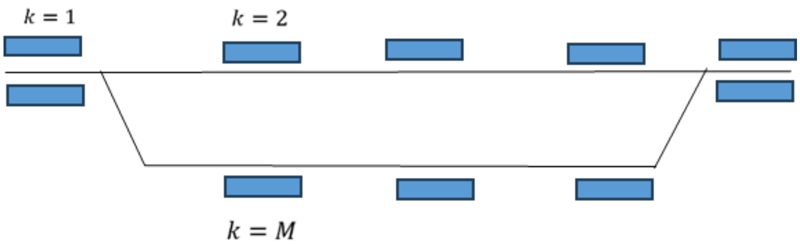


Figure 15-9 Loop line with terminal stations

Two test scenarios are selected to validate the Traffic Regulator at TRL 4, which each two cases.

1. Open-loop simulation for two sets of control weights.
2. Closed-loop simulation for two sets of delay scenarios.

In the first scenario, an open-loop simulation is considered, that is, the results of the predictive control algorithm before its implementation in the traffic simulator. To this end, a specific 90-second delay is imposed on a train to study the transient evolution of the recovery from that delay. This situation is tested in two different cases: when the objective function of the model does not distinguish between positive and negative control actions, and when different values for the weights are applied for positive and negative control actions.

In the second scenario, a simple simulator of a commuter line is designed, into which both the mathematical control algorithm and the CAF Signalling speed profile generator is implemented to enable a closed-loop simulation. In this scenario, there will be two case studies: first, a 90-second delay will be imposed on a train in the fleet to study the transient evolution of delays; second, the transient evolution of delays will be analysed when random disturbances at stops, due to passenger get on and off of the train, are considered.

15.3.3. Test Execution

15.3.3.1. Scenario 1: Open-Loop Simulation

The objective of this section is to present and describe the most relevant results provided by the predictive mathematical algorithm in response to different types of inputs, which are detailed in each subsection. As was mentioned in the test description, the traffic is modeled as a set of 15 trains circulating along 31 platforms per track, so the prediction horizon has been set to $L = 30$ stations.

In the case of applying a 90-second delay to a single train, the run and dwell control actions can be managed with either a distinction between positive and negative control actions or no distinction.

No distinction between positive and negative control actions

These results correspond to the first version of the control algorithm where the positive and negative control action are weighted equally in the cost function. In this case, the weights for each term of the cost function are those listed in Table 15-10. In view of these weights, it can be deduced that the regulation strategy implemented in response to a delay, prioritizes maintaining the nominal headway between trains, at the expense of deviating from the nominal schedule. On the other hand, the weights for the run and dwell control actions have the same value, meaning that in this case there is no prioritization of the type of control action in the regulation strategy.

Table 15-10 Weights in cost function with equal control weights

Definition	Value
Deviation from nominal schedule	0.25
Deviation from nominal headway	1
Run control action	0.1
Dwell control action	0.1

Figure 15-10 presents the evolution of the delays of each train of the convoy when a punctual delay of 90 s is applied on a specific train. It can be observed how an intentional delay is introduced in the rest of the trains of the convoy to find the right balance between adhering to the nominal headway and adhering to the nominal schedule. This specific balance is determined by the weights in the cost function. It is worth noting that, after some stations, the delays of all the trains are taken to zero.

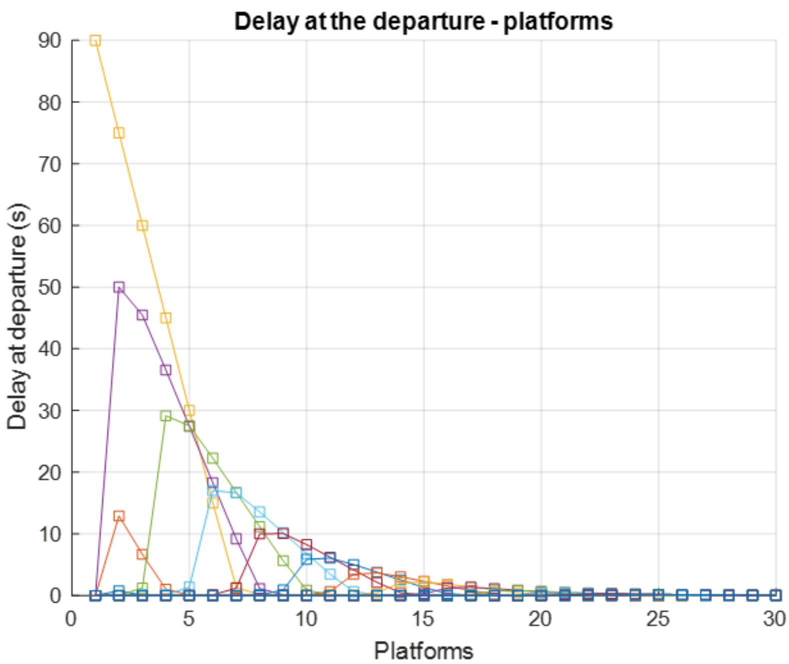


Figure 15-10 Transient evolution of each train in scenario 1 with equal control weights

For a better comprehension of the results, Figure 15-11 illustrates the transient evolution of the delays at the departure of the platforms of the delayed train, the previous one and the posterior one are presented. These trains have been chosen because of their relevance since they are the adjacent trains to the delayed one. Complementary to Figure 15-10, Figure 15-11 describes the delay at the departure (black curve) and the run (red curve) and dwell (blue curve) control actions that these trains take at each platform to take the delays to zero.

Figure 15-12 illustrates how the delay of a train at the departure from a platform is the result of the delay it had at the departure from the previous platform $k-1$, plus the run control action applied at that same previous platform $k-1$, and the dwell control action applied at the current one k.

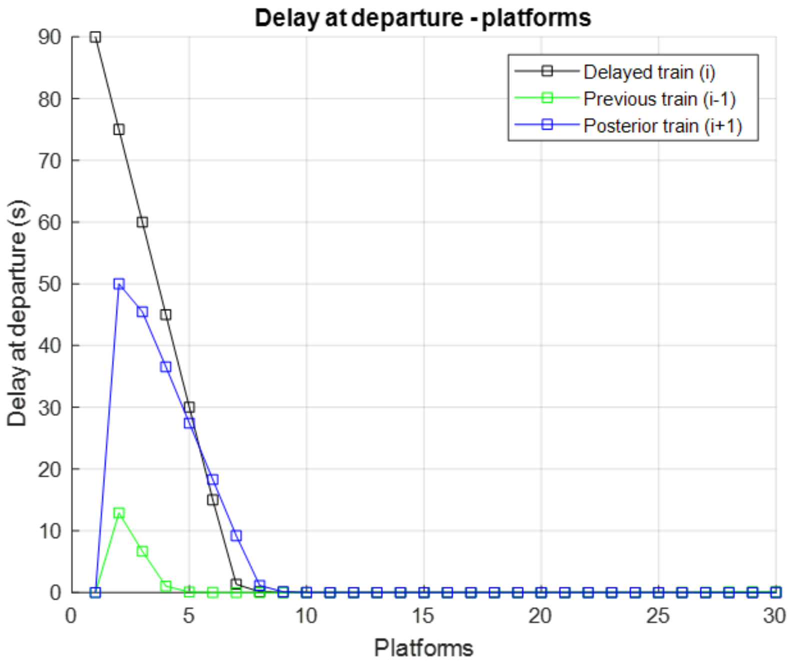


Figure 15-11 Transient evolution of trains in scenario 1 with equal control weights

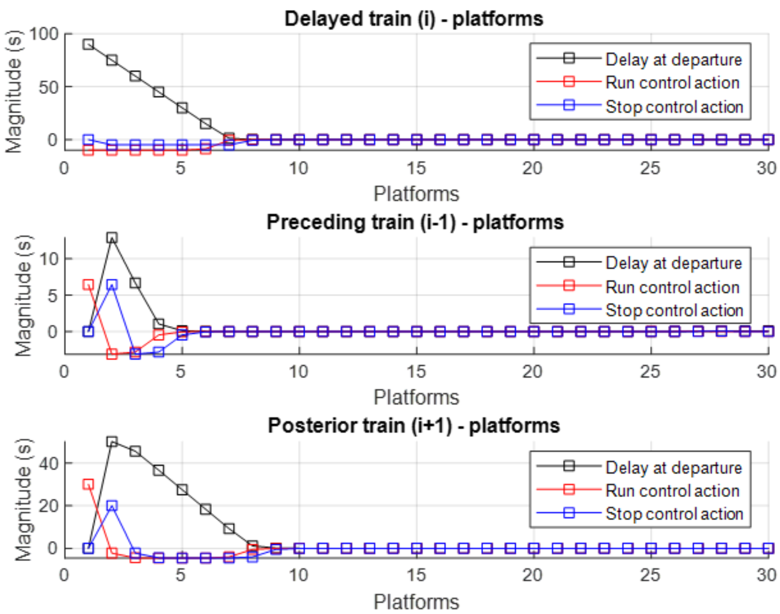


Figure 15-12 Control actions in scenario 1 with equal control weights

Distinction between positive and negative control actions

In this scenario, the goal is to describe how the transient of the delays changes if the cost function is able to assign different weights to positive and negative control actions. The differentiation between positive and negative control actions allows for the application of some eco-driving techniques, thereby increasing energy efficiency. The ability to assign greater weight to negative run control actions and positive dwell control actions in the cost function helps to reduce the speed of the trains (lower energy consumption) and shorten stop times at platforms (the longer a train is stopped at a platform, the more it will need to accelerate upon departure).

To appreciate the distinction of the traffic regulation when the control actions are separated in positive and negative terms, two comparisons (case 1 and case 2) with the previous baseline case of no distinction between positive and negative control actions are presented. In these two new cases, the regulation strategy is based on weighting more heavily the negative run control actions and positive dwell control actions than positive run control actions and negative dwell control actions. The weights of each part of the cost function for each study case are shown in Table 15-11.

Table 15-11 Weights in cost function in scenario 1 cases 1 and 2 for different control weights

	Baseline case	Case 1	Case 2
Deviation from nominal schedule	0.25	0.25	0.25
Deviation from nominal headway	1	1	1
Positive run control action	0.1	0.1	0.1
Negative run control action	0.1	1	3
Positive dwell control action	0.1	1	3
Negative dwell control action	0.1	0.1	0.1

For each case, two figures are presented: Figure 15-13 and Figure 15-15 show the transient evolution of the most significant trains in the fleet, while Figure 15-14 and Figure 15-16 provide a detailed comparison between the baseline case and each study case of the delays at platform departures (black curve) and the run (red curve) and dwell (blue curve) control actions for the most significant trains (delayed, preceding, and posterior).

From the results of these two cases, it can be observed that, as determined by the regulation strategy, the imposition of delays on the trains to avoid deviating too much from the nominal headway in Case 1 and Case 2 is governed by the run control actions, while the recovery of these delays is governed by the dwell control actions at the platforms.

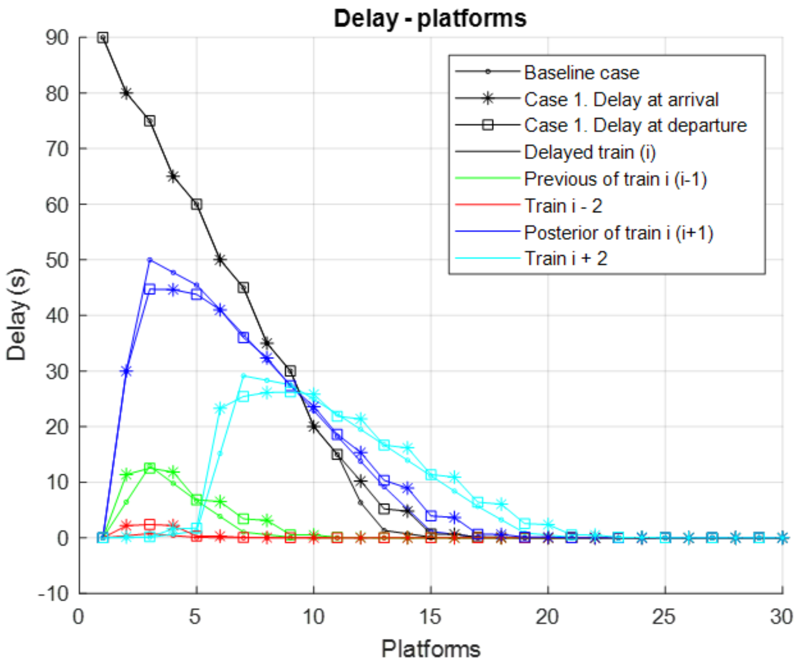


Figure 15-13 Baseline and Case 1 representative trains

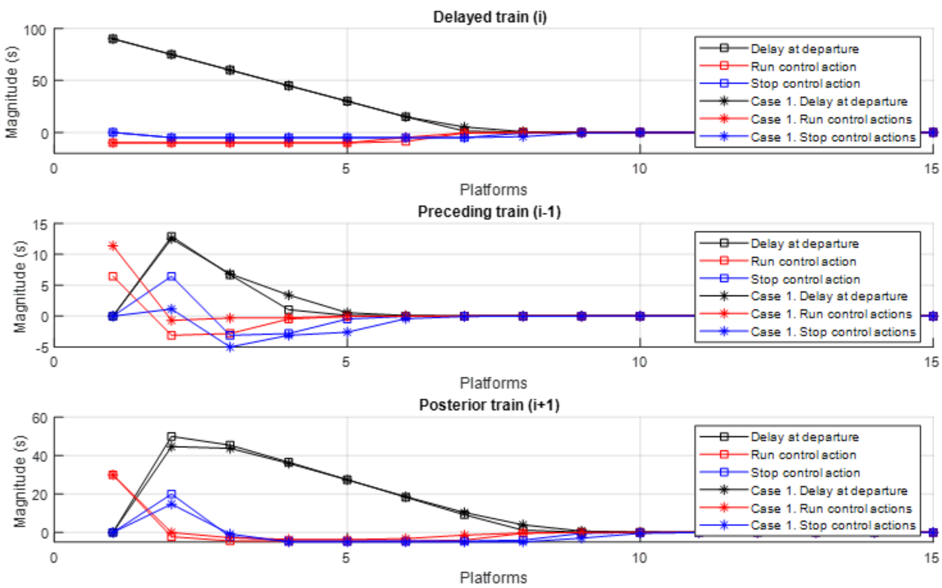


Figure 15-14 Case 1 detailed comparison

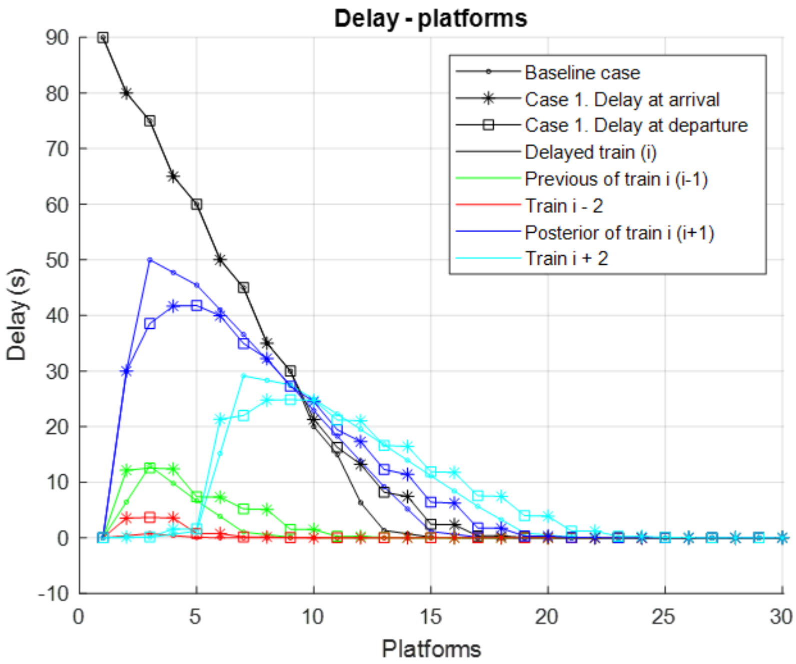


Figure 15-15 Baseline and Case 2 representative trains

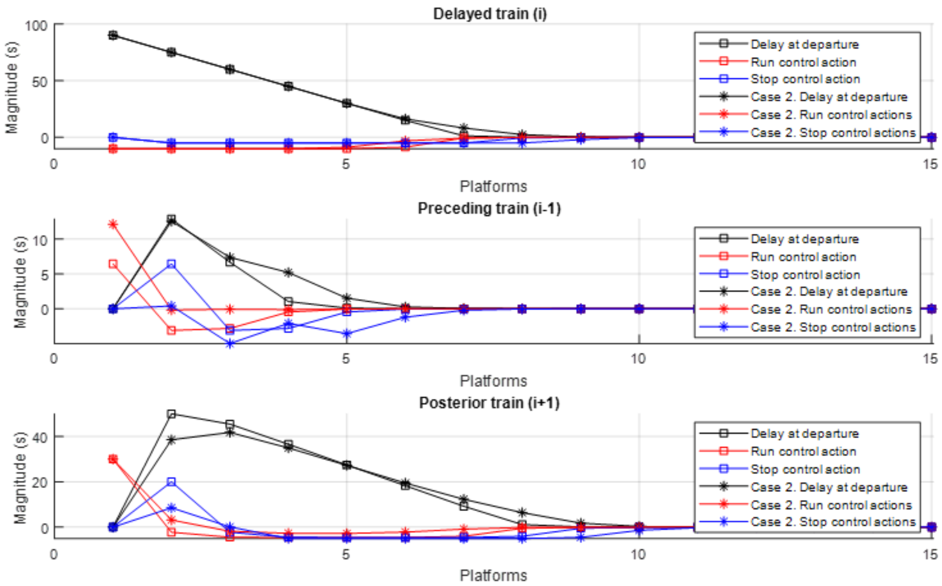


Figure 15-16 Case 2 detailed comparison

As a summary and final comparison, Figure 15-17 presents the delay at the departure from stations, as well as the run and dwell control actions for the posterior train, as it is the most representative one, in each of the three previously explained cases. As can be observed, the larger the weight of the negative run control actions and positive dwell control actions, the smaller their absolute value, thus aligning with the regulation strategy established in each case.

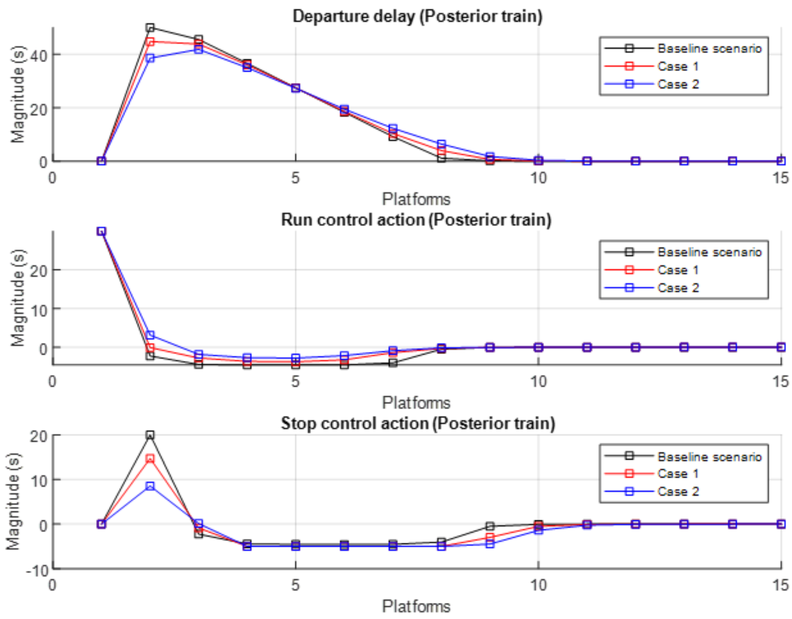


Figure 15-17 Summary comparison for the posterior train

15.3.3.2. Scenario 2: Closed-Loop Simulation

The goal of this second scenario is to validate the dispatching of commands generated by the mathematical control algorithm to the different trains running on a track. To do so, a simulator of a railway commuter line has been developed. In this section, first the characteristics and operating of the simulator are described. Then the results are presented for two case studies: the system's response to a 90-second delay of a single train, and the system's response to random delays at station stops caused by passenger getting on and off the train, respectively.

Description of the simulator

Considered is a commuter loop line where terminal stations are modeled as turnback platforms and trains travel in both directions along a closed circuit, stopping along their journey at stations with one platform in each direction. Additionally, traffic is modeled as a set of trains ($i = 1, \dots, 15$) circulating along 60 platforms ($k = 1, \dots, 60$), where each train i follows train $i - 1$ and stops at every platform k for passengers to get on and off.

For this first approximation to reality, it has been considered that the track speed limit is 80 km/h and that the track slope is zero. Additionally, all interstation distances are 1 km, with a nominal running time of 100 seconds. This nominal running time can be modified by the run control actions increasing it by 30 seconds or decreasing it by 10 seconds. Consequently, the fastest interstation running time will be 90 seconds and the slowest one will be 130 seconds. Likewise, the nominal dwell time at the platforms is 20 seconds but, through dwell control actions, it can be increased by 20 seconds or decreased by 5 seconds.

The speed profile that the train must follow during the interstation run will be generated by the CAFS generator speed profile module. By inputting the interstation data into the speed profile generator module and starting the train from zero speed, the speed and time for the fastest, nominal and slowest speed profiles are shown in Figure 15-18.

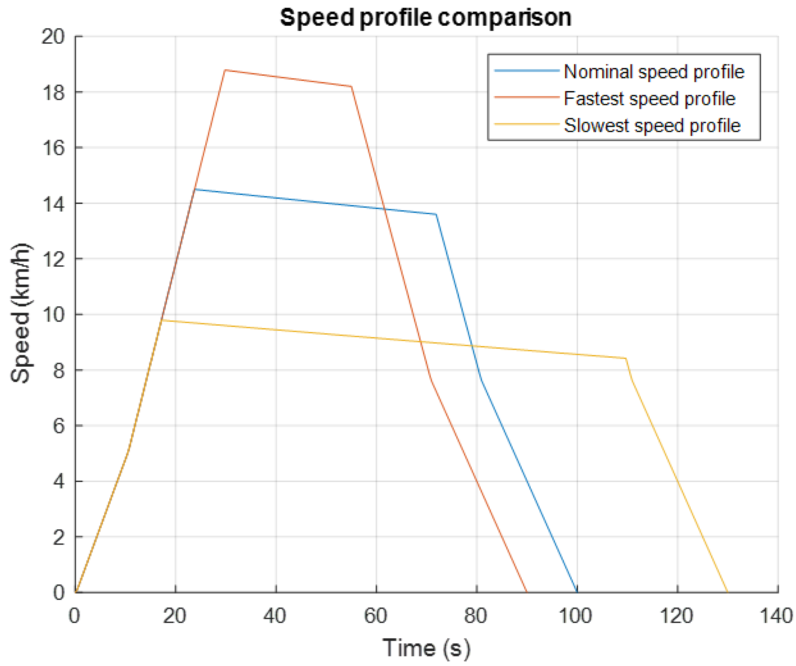


Figure 15-18 Speed profile comparison scenario 2

To ensure a prompt response of the train fleet to train delays and incidents, the delay experienced by each train is continuously measured both during station stops and while running between stations. If a train is in transit, the delay for that interstation segment is calculated as the difference between the actual time recorded by the train at its current position and the time it should have recorded at the same position if it had followed the nominal schedule.

Simulation of 90-second delay to a single train

To impose a 90-second delay on a train, the running time for one interstation segment is set to 190 seconds, which is the nominal travel time plus an additional 90 seconds. This delay is imposed on a single train in the first interstation it traverses. Additionally, following the criteria explained in Section 15.3.3.1**,** the positive run control actions and negative dwell control action weights have a value of 0.1 while negative run control actions and positive dwell control actions weights have a value of 1.5. Finally, the regulation strategy has been defined in such a way that deviating from the nominal schedule has a weight in the cost function of 0.25 and deviating from the nominal headway has a weight of 1.5.

For this scenario, a total of 5000 seconds was simulated, with a regulation cycle of 5 seconds. This means that every 5 seconds, the control actions for the train are recalculated, leading to adjustments in the speed profile that the train must follow. As the main result, Figure 15-19 shows the transient evolution of delays when arriving and departing from platforms for the most significant trains (delayed train, following train, and preceding train). It can be observed that, similar to the open-loop case, the mathematical control algorithm finds a delay for the adjacent trains in the fleet to find the optimal balance between adherence to the nominal schedule and maintaining the nominal interval between trains.

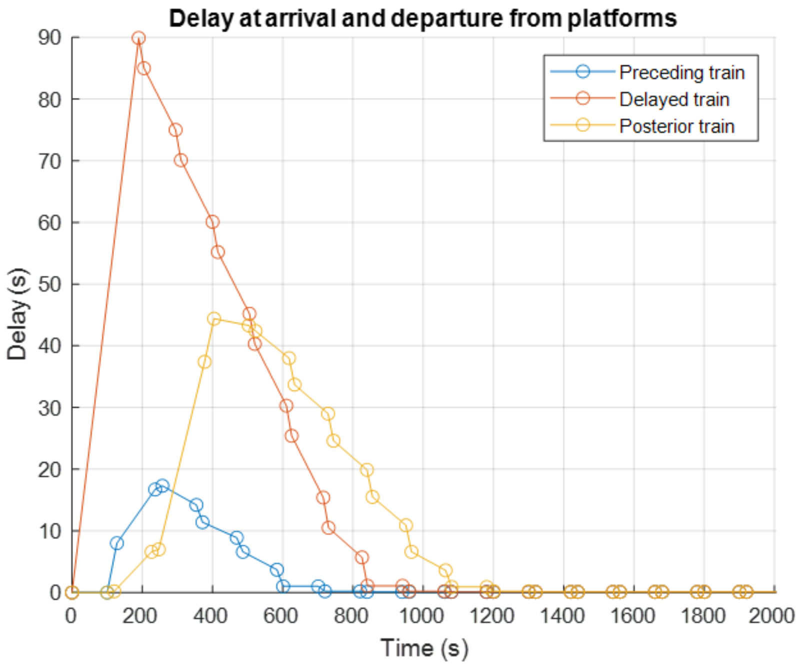


Figure 15-19 Delay at arrival and departure from platforms scenario 2

Additionally, Figure 15-20 presents the continuous delay of all the trains running on the track. The same logic applies to all trains: they first experience delays observing the headway, and later, the delays are brought back to zero. Finally, Figure 15-21 presents the average of continuous delays of the trains.

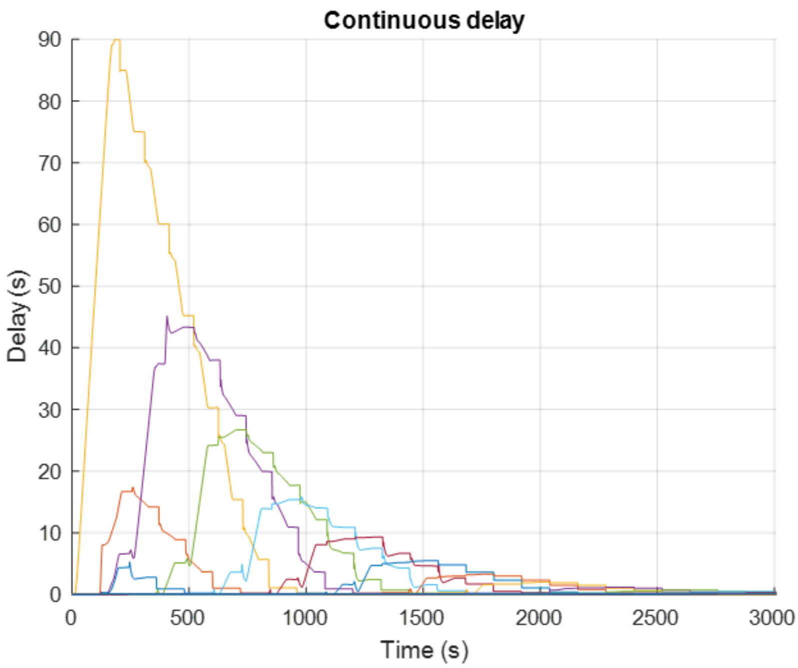


Figure 15-20 Continuous delay scenario 2

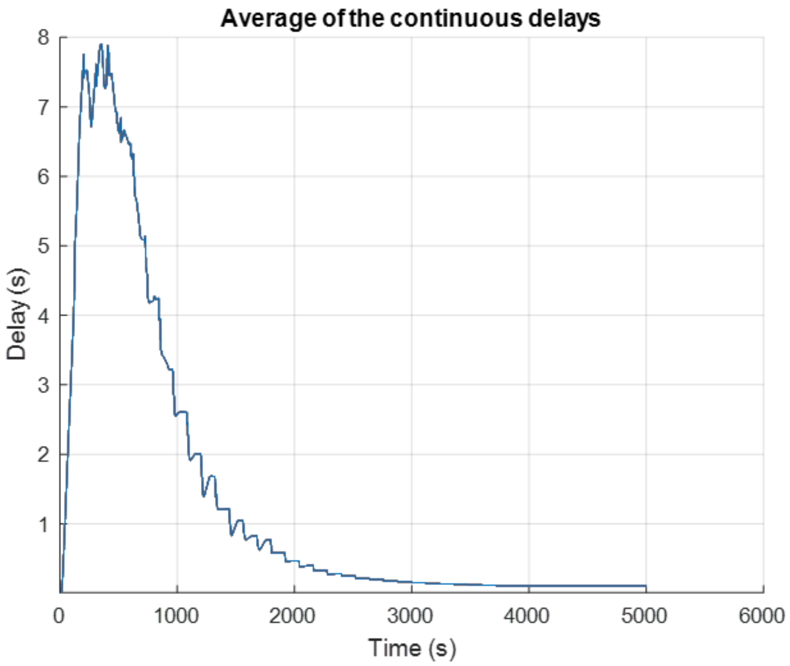


Figure 15-21 Average of continuous delays scenario 2

Simulation of perturbances produced by passengers

In this scenario, the simulation addresses the impact of random disturbances caused by passengers getting on and off at stations. These perturbations introduce variability in the stop times, which can affect the overall schedule and delay management of the train system. The simulation aims to assess how well the control algorithm handles these random disturbances and maintains schedule and headway adherence despite the added variability.

The train waiting time at stations due to passenger flow has been simulated by adding a random extra stop time to the nominal stop time at stations. This random stop time has been simulated using a lognormal distribution, from which values are randomly drawn, with a mean of 0.5 seconds and a standard deviation of 1.2 seconds. The use of a lognormal distribution is justified by its proven accuracy in simulating such events. Additionally, the extra stop time produced by this disturbance has been limited to 200 s.

The simulation time for this scenario is 5,500 seconds, with a regulation cycle of 5 seconds. Additionally, the weights of all control actions in the cost function have been set to the same value and equal to 0.1. Finally, the weight in the cost function of deviating from the nominal schedule is lower than the weight of deviating from the nominal headway (0.25 against 1).

Figure 15-22 shows the continuous delay of all trains to illustrate how they indeed experience delays at each stop and how these delays are periodically corrected. It is observed that at the beginning of the simulation, three trains experience significant delays, with the most critical reaching nearly 120 seconds. The regulator's effectiveness is demonstrated by how, despite delays being injected at each station stop, these delays are gradually reduced over time to values close to zero.

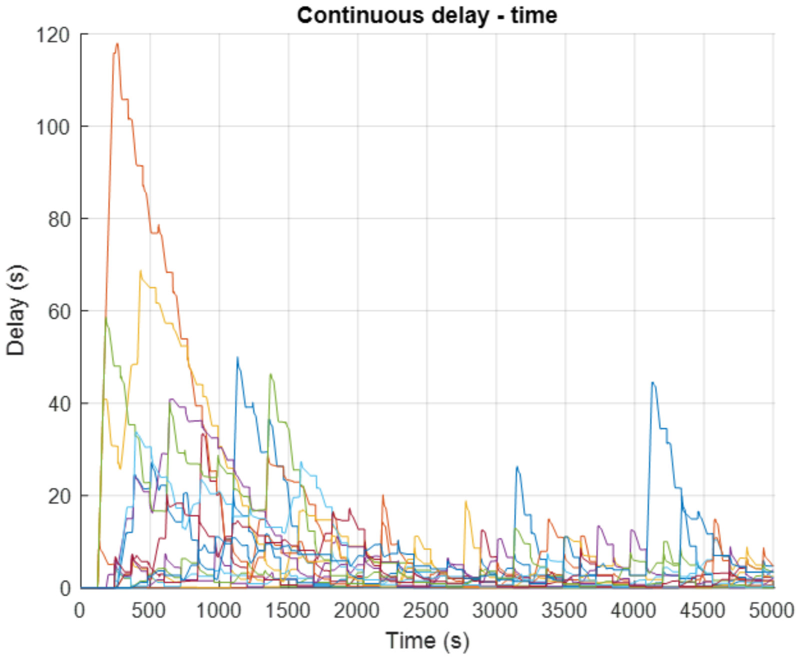


Figure 15-22 Continuous delay of each train scenario 2 case 2

Finally, the evolution of the average of the continuous delays is shown in Figure 15-23. In this figure, the delays — particularly the most critical ones — that the trains experience over time are reflected. It demonstrates that, despite continuous disturbances on the line, the average of the continuous delay eventually stabilizes between 1 and 4 seconds. For a convoy of 15 trains, this indicates that the trains are operating practically on schedule.

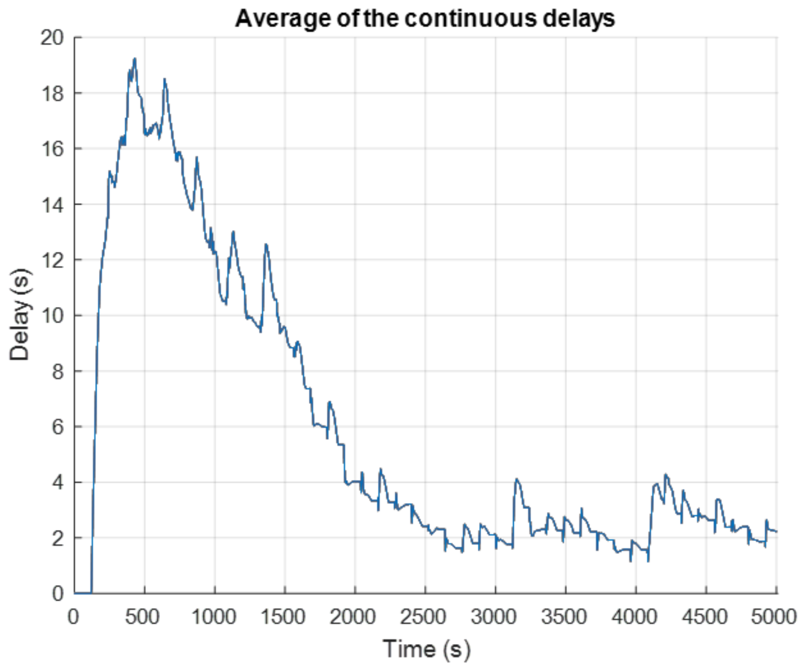


Figure 15-23 Average of the continuous delays scenario 2 case 2

15.4. TMS – C-DAS Enhanced Operation

15.4.1. Test Reports

This section describes the TRL 4 validation results obtained for TMS-C-DAS enhanced operation. Two tests were done, one test for improved forecast calculation by using information provided by C-DAS and another test for the RTTP using C-DAS TS data. Both tests were tested separately.

Table 15-12 Test report Forecast calculation using information provided by C-DAS

Test description	**Name**	**Forecast calculation using information provided by C-DAS**
	ID	1
	(Short) description	This test case checks that the forecast calculation using C-DAS TS data by TMS for a train is more accurate than using only data from TMS.
	Test case responsible	Enrique Gómez, INDRA
	Pre-condition(s)	Access to TMS. There shall be a planned train in the TMS. For instance, the train route is scheduled along five stations. There shall be an established communication between TMS and C-DAS TS through an integration layer. There shall be an established communication between C-DAS TS and C-DAS OB. There shall be a simulator of trains and infrastructure.
	TRL	4
	Input data description	The route (order of the stations) and timetable (target times at each station) of the train. The run times calculation. The topology or infrastructure modelled by which the train is going to go through. The rolling stock characteristics that make up the train. See Section 15.4.2/15.4.2.1.
	Expected result	The forecast calculation from sent C-DAS TS data is more adjusted to the audited times (recorded times in stations based on track-circuit occupancy) than the forecast calculation only with TMS data.
	Sequence	1. Operator plans a train with route and schedule established (RTTP). 2. The TMS launches the forecast calculation for this train and at the same time sends the RTTP to C-DAS TS. 3. The TMS saves the forecast calculation results. 4. The C-DAS TS generates the train trajectories, sends them to the C-DAS OBs, receives the status reports from the C-DAS OBs, and send information to TMS. 5. The TMS launches the forecast calculation considering the information received from C-DAS TS (forecast optimization) and saves the result. 6. The TMS compares both forecasts with the audited times and the user checks the forecast optimization is adjusted better to the real audit than the initial forecast calculation.
Test Execution	Testing environment	Simulation environment
	Components	TMS 3.2.2

	and versions	
	Input data used	Realistic layout data, realistic train path
	Test timestamp	23/10/2024
	Tester	Enrique Gómez, INDRA
	Test result	See Section 15.4.3.1
	Test status	PASSED
	Notes	

Table 15-13 Test report RTTP using C-DAS TS data

Test description	**Name**	**RTTP using C-DAS TS data**
	ID	2
	(Short) description	This test case checks that the TMS can send a new RTTP based on forecast update from data received from C-DAS TS.
	Test case responsible	Enrique Gómez, INDRA
	Pre-condition(s)	Access to TMS. There shall be a planned train in the TMS. For instance, the train route is scheduled along five stations. There shall be an established communication between TMS and C-DAS TS through an integration layer. There shall be an established communication between C-DAS TS and C-DAS OB. There shall be a simulator of trains and infrastructure.
	TRL	4
	Input data description	The route (order of the stations) and timetable (target times at each station) of the train. The run times calculation. The topology or infrastructure modelled by which the train is going to go through. The rolling stock characteristics that make up the train. See Section 15.4.2/15.4.2.2
	Expected result	The TMS can send a RTTP based on forecast update calculated from data received from C-DAS TS.
	Sequence	1.The operator plans a train in the TMS with route and schedule established (RTTP). 2.The TMS calculates the forecast with its internal data. 3.The TMS sends the RTTP to C-DAS TS. 4. The C-DAS TS generates the train trajectories, sends them to the C-DAS OBs, receives the status reports from the C-DAS OBs, and send information to TMS. 5.The TMS updates the forecast with the data received from C-DAS TS. 6.The operator re-plans manually based on forecast update. 7.The TMS sends the new RTTP to C-DAS TS. 8. The TMS compares both RTTPs with the audited times and the user checks the re-scheduled RTTP is adjusted better to the recorded times than the initial RTTP.
Test Execution	Testing environment	Simulation environment
	Components and versions	TMS 3.2.2
	Input data used	Realistic layout data, realistic train path

	Test timestamp	24/10/2024
	Tester	Enrique Gómez, INDRA
	Test result	See Section 15.4.3.2
	Test status	PASSED
	Notes	

15.4.2. Test Description

These tests describe the particular case in which the class B signalling system (that do not have accurate ETCS train position reports) is used, a passive C-DAS on-board is used and a C-DAS TS calculates the train trajectories based on the RTTP received from TMS. The validation is about the benefits of a C-DAS for class B signalling systems, where the rough train positions based on the track occupation data is complemented with the C-DAS train positions/speeds and the computed train trajectories by the C-DAS TS.

Realistic data has been used for this validation. Figure 15-24 shows the schematic view of the route used that goes from Station 1 to Station 5, going through stations Station 2, Station 3 and Station 4. Both tests have been done over this route.

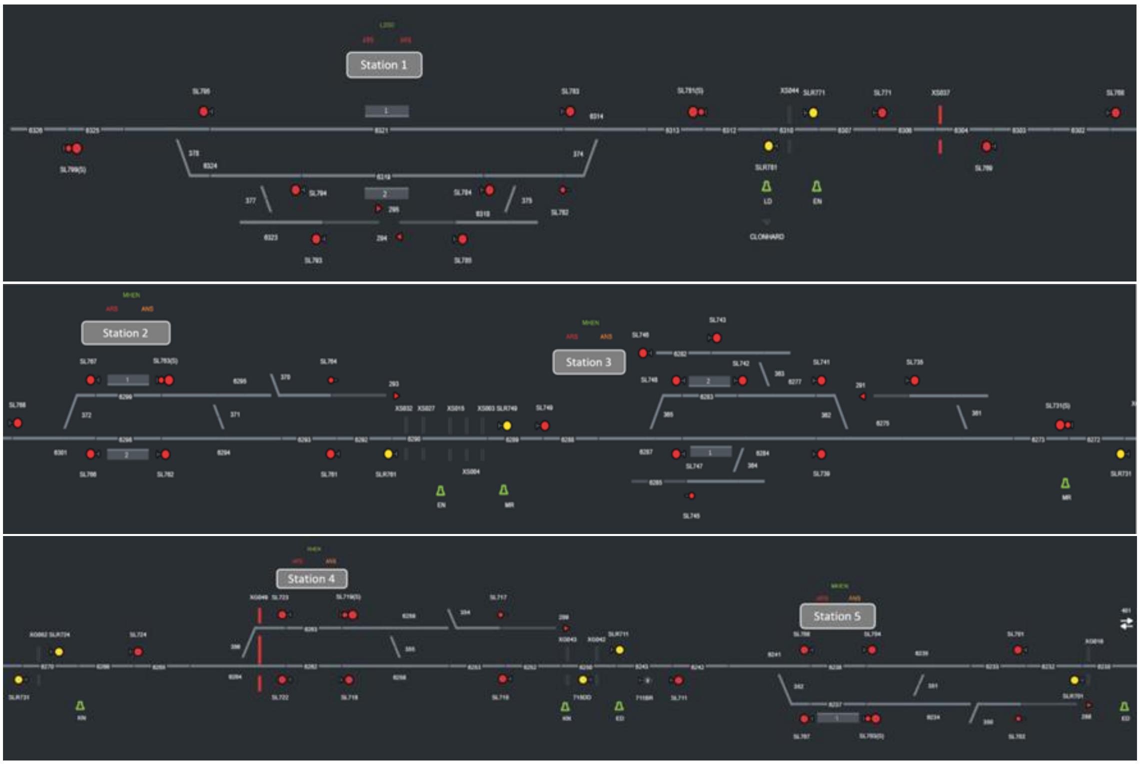


Figure 15-24 Schematic view of the route Station 1 - Station 5

15.4.2.1. Test Scenario 1: Forecast Calculation using C-DAS Information

This test starts having a train with a route and a scheduled timetable. The train path is identified as "S002" within the TMS. The train has scheduled the route and the timetable for 23/10/2024. The route is composed of five stations, Station 1, Station 2, Station 3, Station 4 and Station 5. The origin of the train path is Station 1 and the destination is Station 5. The train has forecasted stops in Station 2 and Station 3 and does not have a forecasted stop in Station 4. Initially, the scheduled timetable and the forecasted timetable is the same. Table 15-14 shows the scheduled and initial forecasted timetable for this train path.

Table 15-14 Scheduled and initial forecasted timetable for "S002"

Route	Scheduled and initial forecasted timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	10:30:00	10:31:00	00:01:00
Station 2	10:43:00	10:44:30	00:01:30
Station 3	11:03:20	11:04:50	00:01:30
Station 4	11:14:20	11:14:20	00:00:00
Station 5	11:28:50	11:30:20	00:01:30

The train "S002" will run from the origin to the destination in the simulation tool that simulates the train movements and applies a delay between the stations. The C-DAS will provide estimated times for the successive stations of the route. These estimation points' data will be treated by the TMS for re-calculation of the forecast. The train movement have been audited in the different stations of the route.

15.4.2.2. Test Scenario 2: RTTP using C-DAS-TS Data

This test starts having a train with a route and a scheduled timetable. The train path is identified as "S001" within the TMS. The train has scheduled the route and the timetable for 24/10/2024. The route is composed of five stations, Station 1, Station 2, Station 3, Station 4 and Station 5. The origin of the train path is Station 1 and the destination is Station 5. The train has forecasted stops in Station 2 and Station 3 and does not have forecasted stop in Station 4. Initially, the scheduled timetable and the forecasted timetable is the same. Table 15-15 shows the scheduled and initial forecasted timetable for this train path.

Table 15-15 Scheduled and initial forecasted timetable for "S001"

Route	Scheduled and initial forecasted timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	09:30:00	09:31:00	00:01:00
Station 2	09:42:30	09:43:30	00:01:00
Station 3	10:02:00	10:03:30	00:01:30
Station 4	10:13:00	10:13:00	00:00:00
Station 5	10:27:30	10:29:00	00:01:30

The target timetable of this train is initially equal to the planning timetable. This timetable contains all re-planning times according to re-planning actions. In the same way the train will run from the origin to the destination through the simulation tool that simulates the train movement. Along the route, when the train goes between two stations the C-DAS will provide estimated times for the following stations of the route. These estimation points' data will be treated by the TMS for re-calculation of the forecast. The user will re-plan the train timetable according to the forecast recalculated. The train movement will produce the audit (recorded times in stations based on track-circuit occupancy) in the different stations of the route.

15.4.3. Test Execution

15.4.3.1. Scenario 1: Improved Forecast Calculation using C-DAS Information

First, the departure of the train at origin (Station 1) is audited at the same time as the planned departure. Table 15-16 shows the forecast/audit timetable for this train path. The colour green within forecast/audit timetable means that the event (arrival, departure) was audited. The colour white within forecast/audit timetable means the event is forecasted. The rest of the event of the train path were not audited yet, so the events are forecasted or belongs to the forecast.

Table 15-16 Audit of "S002" at location Station 1

Route	Forecast/Audit timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	10:30:00	10:31:00	00:01:00
Station 2	10:43:00	10:44:30	00:01:30
Station 3	11:03:20	11:04:50	00:01:30
Station 4	11:14:20	11:14:20	00:00:00
Station 5	11:28:50	11:30:20	00:01:30

The next step consists of the simulation of the train movement and providing data to the TMS. First, the simulator generates the movement of the train based on a driving strategy slower than the one recommended by C-DAS OB. This implies that a delay is being generated. Meanwhile, the C-DAS OB sends regularly the Status Report to the C-DAS TS. The C-DAS TS uses the information to generate new speed profiles that fulfil the RTTP. When a threshold is reached, the C-DAS TS sends the Status Report to the TMS. This process involves detecting whether the estimated arrival at Station 2 exceeds a configurable threshold (2 minutes in this case) compared to the scheduled timetable. The TMS receives the train status report information when the train runs between the stations 1 and 2. The estimated times generated by the C-DAS TS serve as input for the forecast optimization within the TMS, which are then used to re-calculate the forecast. Finally, the TMS provides a new forecast calculation. The steps are summarized as follows:

1. Train arrives at origin (station 1) at 10:30:00.
2. The departure from the origin is audited at 10:31:00. The behaviour of the driver is simulated according to a driving strategy slower than recommended by the C-DAS OB.
3. The C-DAS OB sends regularly the Status Report information to the C-DAS TS.
4. The C-DAS TS sends new trajectories regularly to the C-DAS OB.
5. The C-DAS TS sends the Status Report to TMS when the threshold is reached, which occurs at 10:40:00.
6. The TMS receives the estimated time-to-arrival to station 2 and uses this information to update the forecast.

Table 15-17 shows the optimized forecast/audit timetable for this train path. The colour blue indicates the optimized forecast. The forecast has been updated from Station 2 to the end of the route. It means that the changes affect all next locations. The forecasted arrival and departure times were updated. Both of them were delayed 2 minutes at each location.

Table 15-17 Optimized forecast/audit timetable for "S002" at location Station 1

Route	Forecast/Audit timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	10:30:00	10:31:00	00:01:00
Station 2	10:45:00	10:46:30	00:01:30
Station 3	11:05:20	11:06:50	00:01:30
Station 4	11:16:20	11:16:20	00:00:00
Station 5	11:30:50	11:32:20	00:01:30

The next step consists of the simulation of the train movement to arrive at Station 2 and audit the arrival and departure at this location. Table 15-18 shows the audit at location Station 2. The audit times vary 30 seconds with respect to the optimized forecast. The audit was done 30 seconds after the optimized forecast at station 2. This implies a new forecast calculation by TMS in which the forecasted times were delayed the same time. The audit varies 2 minutes and 30 seconds with respect to the initial forecast (without C-DAS data).

Table 15-18 Audit of "S002" at location Station 2

Route	Forecast/Audit timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	10:30:00	10:31:00	00:01:00
Station 2	10:45:30	10:47:00	00:01:30
Station 3	11:05:50	11:06:50	00:01:30
Station 4	11:16:20	11:16:20	00:00:00
Station 5	11:30:50	11:32:20	00:01:30

All these steps are done along all the stations obtaining the following results. Table 15-19 shows the complete audit of train path S002. Figure 15-25 Audit of "S002" at Station 5 in the graphical timetable shows the results of the audit in the graphical timetable. The horizontal axis shows the time and the vertical axis shows location. This graphical timetable is a graphical view within the TMS.

Table 15-19 Audit of "S002" at location Station 5

Route	Audit timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	10:30:00	10:31:00	00:01:00
Station 2	10:45:30	10:47:00	00:01:30
Station 3	11:06:40	11:07:40	00:01:30

Station 4	11:17:35	11:17:35	00:00:00
Station 5	11:32:00	11:33:35	00:01:30

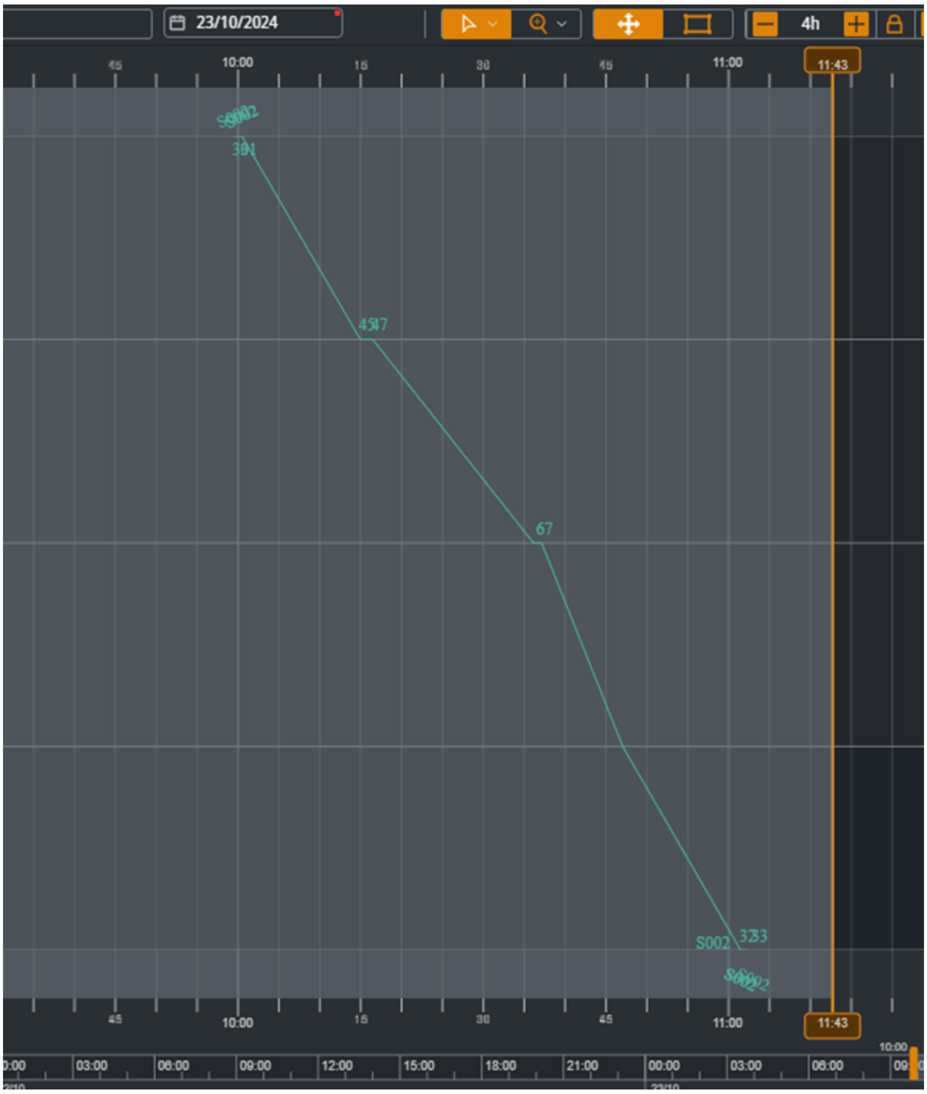


Figure 15-25 Audit of “S002” at Station 5 in the graphical timetable

Table 15-20 shows the variations of audit with respect to the forecasts. The results in the table indicate that the optimized forecast calculation using the data provided by the C-DAS adjusts better to the final audit of the train than the initial forecast calculation by TMS.

Table 15-20 Variations of audit with respect to the forecasts of “S002”

Audit location	Forecast calculation	Forecast optimization
Station 1	Audit equal to forecast	Audit equal to forecast
Station 2	Audit 150 seconds after forecast	Audit 30 seconds after forecast
Station 3	Audit 50 seconds after forecast	Audit 40 seconds after forecast
Station 4	Audit 25 seconds after forecast	Audit 10 seconds before forecast
Station 5	Audit 5 seconds before forecast	Audit 5 seconds before forecast

15.4.3.2. Scenario 2: RTTP using C-DAS-TS data

First, the departure of the train at origin (Station 1) is audited at the same time as the planned departure. Table 15-21 shows the forecast/audit timetable for this train path. As before the colour green within forecast/audit timetable means that the event (arrival, departure) was audited and the colour white within forecast/audit timetable means the event is forecasted. The rest of the events of the train path were not audited yet, so the events are forecasted or belongs to the forecast. The target timetable remains equal. The audit does not affect the target timetable. Table 15-22 shows the initial target timetable.

Table 15-21 Audit of "S001" at location Station 1

Route	Forecast/Audit timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	09:30:00	09:31:00	00:01:00
Station 2	09:42:30	09:43:30	00:01:00
Station 3	10:02:00	10:03:30	00:01:30
Station 4	10:13:00	10:13:00	00:00:00
Station 5	10:27:30	10:29:00	00:01:30

Table 15-22 Initial target timetable of "S001"

Route	Target timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	09:30:00	09:31:00	00:01:00
Station 2	09:42:30	09:43:30	00:01:00
Station 3	10:02:00	10:03:30	00:01:30
Station 4	10:13:00	10:13:00	00:00:00
Station 5	10:27:30	10:29:00	00:01:30

The next step consists of the simulation of the train movement and providing data to TMS. First, the simulator generates the movement of the train based on a driving strategy slower than the recommended one by C-DAS OB, which implies a delay is being generated. Meanwhile, the C-DAS OB sends regularly the Status Report to C-DAS TS. The C-DAS TS uses the information to generate new speed profiles that fulfil the RTTP. The C-DAS TS sends the status Report to the TMS when a threshold is reached. The threshold consists of the detection of the estimated arrival to station 2 larger than a configurable threshold (1 minute in this case) comparing to scheduled timetable. The TMS receives the train status report information when the train is running between stations 1 and 2. The estimated times generated by C-DAS TS are inputs for the forecast optimization within the TMS, which are used to re-calculate the forecast. Finally, the TMS provides a new forecast calculation. The steps could be summarized as follows:

1. Train arrives at origin (station 1) at 09:30:00.
2. The departure from origin is audited at 09:31:00. The behaviour of the driver is simulated according to a driving strategy slower than recommended by the C-DAS OB.
3. The C-DAS OB sends regularly the status report information to C-DAS TS.
4. The C-DAS TS sends new trajectories regularly to C-DAS OB.

5. The C-DAS TS sends the Status Report to the TMS when the threshold is reached, which occurs at 09:40:00.
6. The TMS receives the estimated times to arrival to station 2 and uses this information to update the forecast.

Table 15-23 shows the optimized forecast/audit timetable for this train path. As before the colour blue indicates the optimized forecast. The forecast has been updated from Station 2 to the end of the route. This means that the changes affect all next locations. The forecasted arrival and departure times were updated. Both of them were delayed 1 minute at each location.

Table 15-23 Optimized forecast/audit timetable for "S001" at location Station 1

Route	Forecast/Audit timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	09:30:00	09:31:00	00:01:00
Station 2	09:43:30	09:44:30	00:01:00
Station 3	10:03:00	10:04:30	00:01:30
Station 4	10:14:00	10:14:00	00:00:00
Station 5	10:28:30	10:30:00	00:01:30

The user re-plans the timetable (modify the target timetable) of arrival and departure of the Station 2 according to the optimized forecast. Table 15-24 shows the modification of the target timetable. The colour dark yellow indicates the re-scheduled time by the user. The target timetable modification makes the RTTP (target timetable) using C-DAS data move away from the values of initial RTTP (without C-DAS data). The target timetable has been delayed 1 minute for the arrival and departure at Station 2. Consequently, the target timetable for the subsequent events has been delayed the same time.

Table 15-24 Re-scheduled target timetable of "S001" at Station 2

Route	Target timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	09:30:00	09:31:00	00:01:00
Station 2	09:43:30	09:44:30	00:01:00
Station 3	10:03:00	10:04:30	00:01:30
Station 4	10:14:00	10:14:00	00:00:00
Station 5	10:28:30	10:30:00	00:01:30

The next step consists of the simulation of the train movement to arrive the Station 2 and audit the arrival and departure at this location. Table 15-25 shows the audit at location Station 2. The audit times vary 15 seconds with respect to the optimized forecast. The audit was done 15 seconds after. This implies a new forecast calculation by TMS in which the forecasted times were delayed the same time. The audit varies 1 minutes and 15 seconds with respect to the initial forecast (without C-DAS data). Figure 15-26 shows the results of the audit in the graphical timetable.

Table 15-25 Audit of "S001" at location Station 2

Route	Forecast/Audit timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	09:30:00	09:31:00	00:01:00
Station 2	09:43:45	09:44:45	00:01:00
Station 3	10:03:15	10:04:45	00:01:30
Station 4	10:14:15	10:14:15	00:00:00
Station 5	10:28:45	10:30:15	00:01:30

Figure 15-26 Audit of "S001" at Station 2 in the graphical timetable

The initial RTTP (without using C-DAS data) deviates 1 minute and 15 seconds with respect to the audit. However, the RTTP using C-DAS data deviates 15 seconds with respect to the audit. Therefore, the audit fits more to the new RTTP than the initial RTTP.

All these steps are done along all the stations obtaining the following results. Table 15-26 shows the complete audit of train path "S001". Figure 15-27 shows the results of the audit in the graphical timetable.

Table 15-26 Audit of "S001" at location Station 5

Route	Audit timetable		
Station	**Arrival**	**Departure**	**Minimum stop**
Station 1	09:30:00	09:31:00	00:01:00
Station 2	09:43:45	09:44:45	00:01:30
Station 3	10:03:00	10:04:30	00:01:30
Station 4	10:14:10	10:14:10	00:00:00
Station 5	10:28:40	10:33:15	00:01:30

Figure 15-27 Audit of "S001" at Station 5 in the graphical timetable

Table 15-27 gathers the data of audit and RTTPs and Table 15-28 shows the variations of audit with respect to the RTTPs. The table shows that the re-scheduled RTTP with data provided by C-DAS fits better to the final audit of the train than the initial RTTP by the TMS.

Table 15-27 Audit and RTTP results for "S001"

Location	Audit	Initial RTTP	Re-scheduled RTTP
Station 1	9:30:00 – 9:31:00	9:30:00 – 9:31:00	9:30:00 – 9:31:00
Station 2	9:43:45 – 9:44:45	9:42:30 – 9:43:30	9:43:30 – 9:44:30
Station 3	10:03:00 – 10:04:30	10:02:00 – 10:03:30	10:02:50 – 10:04:30
Station 4	10:14:10 – 10:14:10	10:13:00 – 10:13:00	10:14:15 – 10:14:15
Station 5	10:28:40 – 10:30:15	10:27:30 – 10:29:00	10:28:45 – 10:30:15

Table 15-28 Variations of audit with respect to the RTTPs of "S001"

Audit location	Initial RTTP	re-scheduled RTTP
Station 1	Audit equal to RTTP	Audit equal to RTTP
Station 2	Audit 75 seconds after RTTP	Audit 15 seconds after RTTP
Station 3	Audit 60 seconds after RTTP	Audit 10 seconds after RTTP arrival, Audit equal to RTTP departure
Station 4	Audit 70 seconds after RTTP	Audit 5 seconds before RTTP
Station 5	Arrival audit 70 seconds after RTTP, Departure audit 75 seconds after RTTP	Audit 5 seconds before RTTP arrival, Audit equal to RTTP departure.

15.5. TMS–ATO Train Forecast and Operational Plan Update

15.5.1. Test Report

Table 15-29 Test report Forecast

Test description	**Name**	**Forecast**
	ID	1
	(Short) description	The algorithm calculates the time trajectory of different train types between two given operational points, along specified paths, considering all the constraints about the train kinematics, such as the maximum allowed acceleration/deceleration profile, track speed limits, initial and final speed.
	Test case responsibles	Angelo Naselli and Mirko Ghersi, MERMEC
	Pre-conditions	The setup consists of a pc hosting the CDR module and the input data files. A Python script executes all the tests by calling the Forecast function of the CDR module passing it the data folder path/names.
	TRL	4
	Input data description	The single-track section between Albacina and Civitanova of the Italian railway in the Marche region, see Section 15.5.2. The input data, for each test case, is made of the following files: • an XML file describing the static railway infrastructure (tracks, links, operational points and speed limit profile for each track) • an XML file defining an appropriate timetable containing different train runs. Three cases are considered: 1. Base scenario 2. Temporary speed restriction Morrovalle and Corridonia 3. Train delay at San Severino
	Expected result	The output of the algorithm is made of the time trajectory of each train, namely a list of events along the run, each one characterized by: • the position of the train along the current track • the transit time at the given position.
	Sequence	The following sequence is repeated for each test case: Step1: Load input data. Step2: Compute the time trajectory of each train in the operational plan, consistently with the railway infrastructure speed limitations and the train characteristics acceleration and deceleration profiles. Step 3: Save the output time trajectories Step 4: Plot the time diagrams.
Test Execution	Testing environment	Controlled (simulation) environment with operational data
	Components and versions	CDR module v.1.0

	Input data used	For case 2 a TSR between Morrovalle and Corridonia For case 3 a train delay of 5 minutes at San Severino
	Test time stamp	17/10/2024 11:45
	Testers	D. Castagni Fabbri and F. Martinelli, MERMEC
	Test result	The algorithm generates the time trajectories of each train in the operational plan of the test case in all three scenarios, see Section 15.5.3.
	Test status	PASSED
	Notes	-

15.5.2. Test Description

To test and validate the forecast algorithm implemented into the CDR module, we considered a portion of the Italian railway infrastructure between stations Albacina and Civitanova, see Figure 15-28. The line was modelled using data structures as described in Section 9.2.2. This route consists of a single-track railway with two terminals and nine intermediate stations (Figure 15-29).

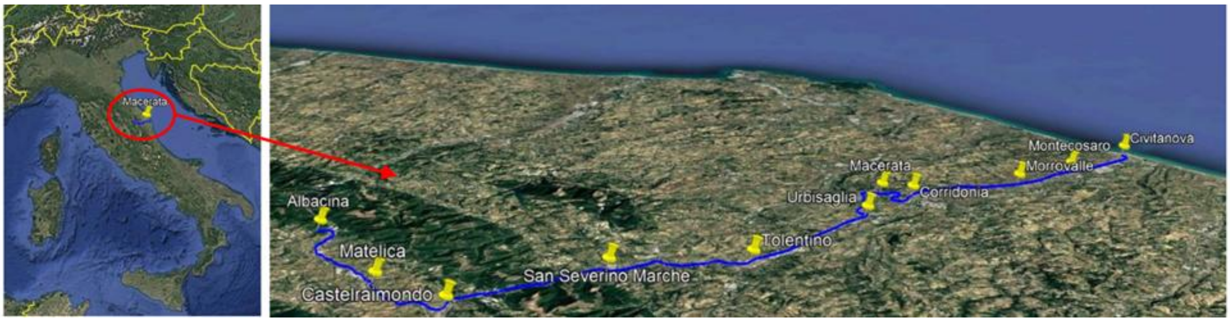


Figure 15-28 The Albacina-Civitanova line, in the Marche, a region of central Italy

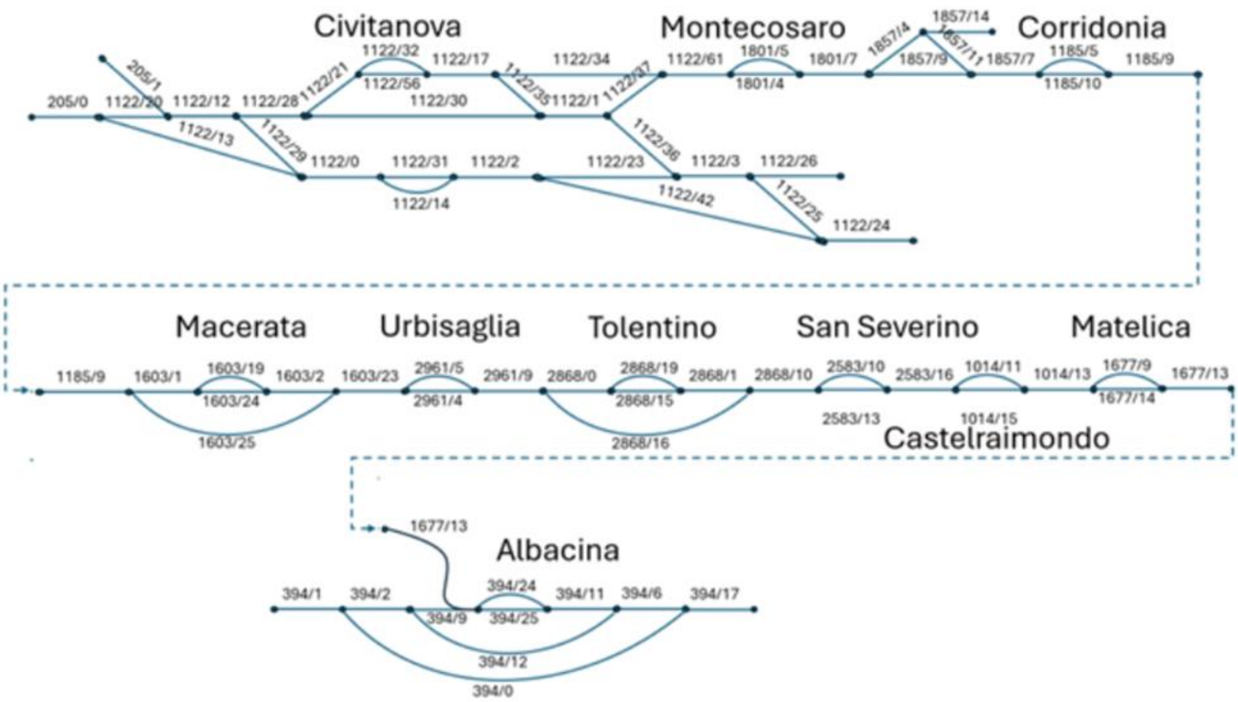


Figure 15-29 Topology of the chosen railway line

The tests of the forecast algorithm make use of the timetable published by RFI, the Italian railway operator, and consist of simulating the propagation of regional trains departing from the terminal stations (Civitanova and Albacina) at the scheduled times and verifying any possible timetable deviations.

Three test scenarios were applied:

1. Base case
2. Temporary speed restriction between Morrovalle and Corridonia
3. Train delay of 5 minutes at San Severino.

The system environment setup consists of a Workstation hosting the CDR module and the input data files. A Python script executes all the tests by calling the Forecast function of the CDR module passing it the data input data. In this work package we used data files as input because the aim is to test the developed forecast algorithm, the final demo (WP16) will interface an ATO-TS simulator to provide data so that the algorithm can use the Status Report as input and show the different behaviours when the ATO is used or not.

15.5.3. Test Execution

This section presents the output data obtained by executing the tests described into the previous one. The tests were executed against the timetable currently published by RFI for the 2024 autumn season.

Figure 15-30 shows the output of the first test with a forecast without deviations and restrictions.

Stazione	Data Arr	Ora Arr	Scost	Res.Da Giu.	Data Par	Ora Par	Scost	Res.Da Giu.	MP	Bin.	Ser.In	Ser.Out
CIVITANOVA					17/10/2024	11:45:00	0	0	NO			SI
Montecosaro	17/10/2024	11:52:00	0	0	17/10/2024	11:53:00	0	0	NO	I	SI	SI
Morrovalle MSG	17/10/2024	11:58:00	0	0	17/10/2024	11:59:00	0	0	NO	I	SI	SI
S.Claudio	17/10/2024	12:03:00	0	0	17/10/2024	12:03:00	0	0	NO		SI	SI
Corridonia M.	17/10/2024	12:08:00	0	0	17/10/2024	12:13:00	0	0	NO	I	SI	SI
Macerata Univers	17/10/2024	12:19:00	0	0	17/10/2024	12:20:00	0	0	NO		SI	SI
Macerata	17/10/2024	12:25:00	0	0					NO	I	SI	

Figure 15-30 Operational plan without deviation and restrictions

The second test shows that train 23845 gets delayed due to a speed restriction at S. Claudio and Corridonia and it goes back on time after Corridonia thanks to its speed curve, see the operational plan in Figure 15-31 and the train graph in Figure 15-32.

Stazione	Data Arr	Ora Arr	Scost	Res.Da Giu.	Data Par	Ora Par	Scost	Res.Da Giu.	MP	Bin.	Ser.In	Ser.Out
CIVITANOVA					17/10/2024	11:45:00	0	0	NO			SI
Montecosaro	17/10/2024	11:52:00	0	0	17/10/2024	11:53:00	0	0	NO	I	SI	SI
Morrovalle MSG	17/10/2024	11:58:00	0	0	17/10/2024	11:59:00	0	0	NO	I	SI	SI
S.Claudio	17/10/2024	12:05:00	2	2	17/10/2024	12:05:00	2	0	NO		SI	SI
Corridonia M.	17/10/2024	12:12:00	4	2	17/10/2024	12:13:00	0	0	NO	I	SI	SI
Macerata Univers	17/10/2024	12:19:00	0	0	17/10/2024	12:20:00	0	0	NO		SI	SI
Macerata	17/10/2024	12:25:00	0	0					NO	I	SI	

Figure 15-31 Operational plan for speed restriction between S. Claudio and Corridonia

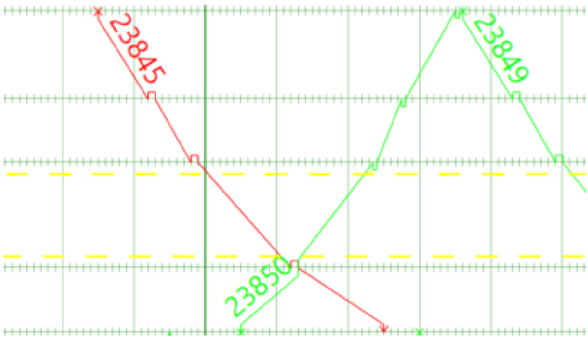


Figure 15-32 Train graph with temporary speed restriction

The output of the third test shows how a train (23848) that is five minutes delayed at S. Severino can go back on scheduled time after that station, arriving at the stopping station 1 minute delayed, see Figure 15-33 for the resulting operational plan and Figure 15-34 for the train graph.

Stazione	Data Arr	Ora Arr	Scost	Res.Da Giu.	Data Par	Ora Par	Scost	Res.Da Giu.	MP	Bin.	Ser.In	Ser.Out
ALBACINA					17/10/2024	10:43:00	0	0	NO			SI
Cerreto d'Esi	17/10/2024	10:48:00	0	0	17/10/2024	10:49:00	0	0	NO		SI	SI
Matelica	17/10/2024	10:58:00	0	0	17/10/2024	10:59:00	0	0	NO		SI	SI
Castelraimondo	17/10/2024	11:07:00	0	0	17/10/2024	11:08:00	0	0	NO		SI	SI
Gagliole	17/10/2024	11:11:00	0	0	17/10/2024	11:11:00	0	0	NO		SI	SI
S.Severino M.	17/10/2024	11:24:00	5	5	17/10/2024	11:24:30	4.5	0	NO		SI	SI
Tolentino	17/10/2024	11:34:30	4.5	0	17/10/2024	11:35:00	4	0	NO		SI	SI
Pollenza	17/10/2024	11:39:30	3.5	0	17/10/2024	11:40:00	3	0	NO		SI	SI
Urbisaglia S.	17/10/2024	11:44:00	3	0	17/10/2024	11:44:30	2.5	0	NO		SI	SI
Macerata Fontesc	17/10/2024	11:51:30	2.5	0	17/10/2024	11:52:00	2	0	NO		SI	SI
Macerata	17/10/2024	11:56:00	1	0					NO		SI	

Figure 15-33 Operational plan for a train with 5 minutes delay

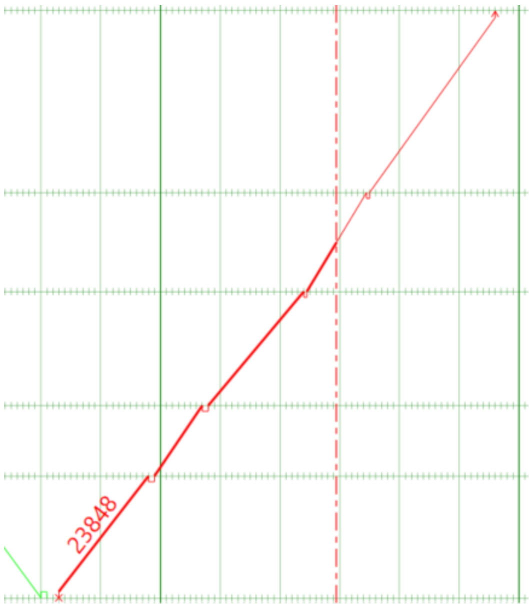


Figure 15-34 Train graph of Train 23848

15.6. ATO – TMS Integration Layer

15.6.1. Test Report

Table 15-30 Test report Integration Layer timetable generation and update

Test description	Name	Integration Layer Timetable generation and update
	ID	1
	(Short) description	A timetable is generated, and then updated by the TMS, and the ATO-TS receives both of them
	Test case responsible	Roberto Divano, STS
	Pre-conditions	Both TMS and ATO-TS are connected to the IL and subscribed to the Timetables domain
	TRL	4
	Input data description	See 15.6.2
	Expected result	Timetable and ATO State from the ATO-TS to the TMS
	Sequence	1. ATO-TS subscribes on IL to the Timetables domain 2. TMS publishes on IL the first timetable 3. ATO-TS gets the timetable 4. A timetable is updated at the TMS side 5. TMS publishes on IL the updated timetable 6. ATO-TS gets the updated timetable
Test Execution	Testing environment	Lab environment of TMS, TMS-ATO Integration Layer, ATO-TS
	Components and versions	IL 2.16.1, ATO-TS 0.1.6, TMS 10.4.7, C-DAS OB 1.2.4.0
	Input data used	See Section 15.6.2.1
	Test time stamp	23/09/2024 05:00:45
	Testers	Roberto Divano, STS
	Test result	TMS publishes the two timetables on the IL, see Section 15.6.3.1
	Test status	PASSED
	Notes	-

Table 15-31 Test report Integration Layer status report feedback

Test description	Name	Integration Layer Status report feedback
	ID	2
	(Short) description	After C-DAS Onboard computation, a Status Report is fed back to the TMS
	Test case responsible	Roberto Divano, STS
	Pre-conditions	Both TMS and ATO-TS are connected to the IL and subscribed to the Timetables and ATO State domains
	TRL	4
	Input data description	Status Report from C-DAS OB, see 15.6.2

	Expected result	Timetable and ATO State from the ATO-TS to the TMS
	Sequence	1. C-DAS OB calculates the train trajectory and produces the status report (SR) 2. C-DAS O sends the SR to the ATO-TS 3. ATO-TS publishes the updated timetable and ATO state on the IL 4. TMS receives the updated timetable and ATO state.
Test Execution	Testing environment	Lab environment of TMS, TMS-ATO Integration Layer, ATO-TS, C-DAS OB
	Components and versions	IL 2.16.1, ATO-TS 0.1.6, TMS 10.4.7, C-DAS OB 1.2.4.0
	Input data used	See Section 15.6.2.2
	Test time stamp	23/09/2024 13:06:07
	Testers	Roberto Divano, STS
	Test result	TMS correctly receives the SR published by the ATO-TS, see Section 15.6.3.2
	Test status	PASSED
	Notes	-

15.6.2. Test Description

The TMS-ATO Integration Layer demonstrator is validated at TRL 4 using two selected test scenarios:

1. Timetable generation and update: TMS sends a first RTTP to the ATO-TS (publishing it on the Timetable domain of the IL) and then updates it with a new one.
2. Status report feedback: ATO-TS publishes a status report (SR) received from the on-board on the Integration Layer for the TMS.

Three actors are involved in these scenarios:

- TMS: updates the timetable data and receives SR.
- ATO-TS: uses the timetable data to generate the JP to be used on-board and send to TMS the SR received by on-board.
- C-DAS OB: uses the JP/SP to calculate the driving directives and produces the SR to be feedbacked to the TMS.
- IL, the demonstrator: the communication module in the simulation environment.

15.6.2.1. Test Scenario 1: Timetable Generation and Update

Figure 15-35 summarizes the integration layer application to timetable generation and update. At the beginning of this scenario, both the TMS and the ATO-TS connect to the IL: ATO-TS subscribes to the Timetables domain to get data related to the timetable, while the TMS publishes the timetable updates. After that, the TMS publishes the first timetable, and the ATO-TS gets it and uses it to calculate the JP to be sent on board. Then, a timetable is updated on the TMS side, so the TMS publishes it again on the IL: the ATO-TS, since it is subscribed to that domain, retrieves the new data and can use it for the calculation of a new JP.

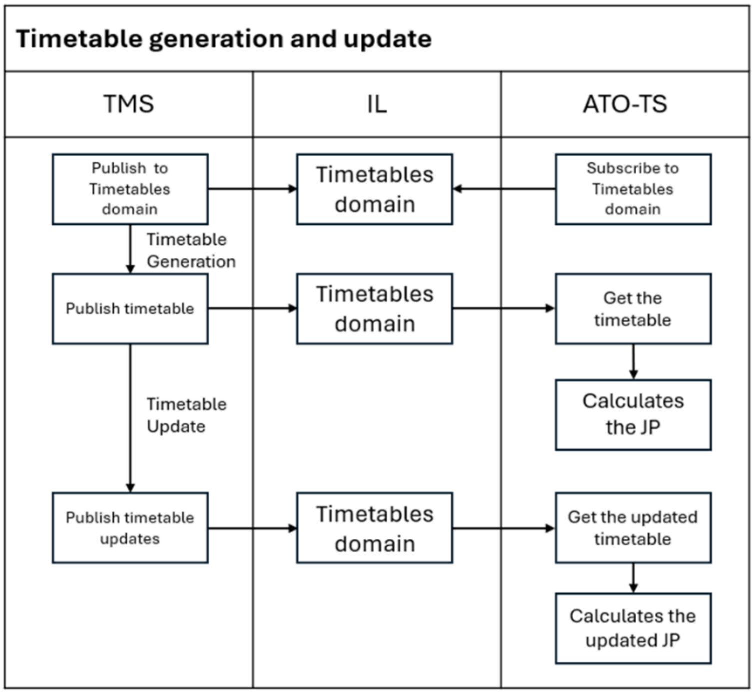


Figure 15-35 Timetable generation and update

15.6.2.2. Test Scenario 2: Status Report Feedback

Figure 15-36 summarizes the integration layer application to status report feedback from the C-DAS OB to the TMS. At the beginning of this scenario, both the TMS and the ATO-TS connect to the IL to subscribe to Timetables domain to both publish and retrieve timetables. After that, the TMS publishes the first timetable, and the ATO-TS gets it and uses it to calculate the JP to be sent on board. The C-DAS OB receives the JP and uses it to calculate the SR to be sent back to the TMS. So, the C-DAS OB sends the SR to the ATO-TS, which publishes it on the IL. The TMS, since it is subscribed to the Timetables domain, retrieves the new data.

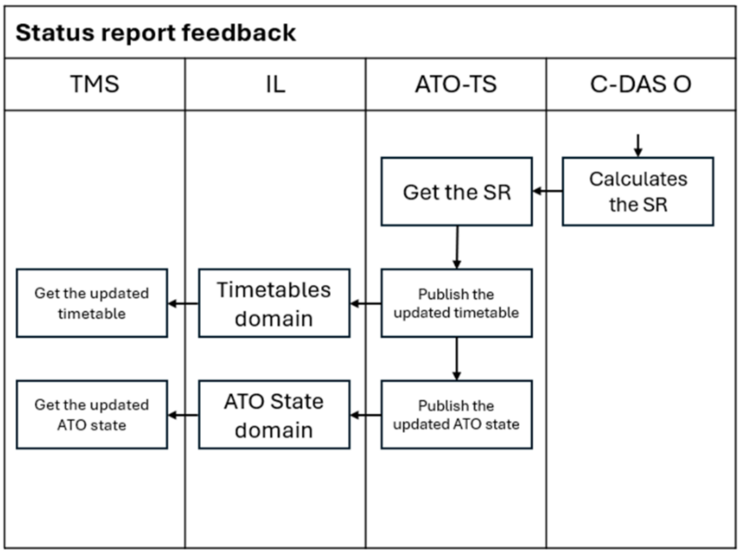


Figure 15-36 Status report feedback

15.6.3. Test Execution

15.6.3.1. Test Scenario 1: Timetable Generation and Update

Both the timetables published by the TMS are received by the ATO-TS and were manually checked on correctness, see Figure 15-37. The arrival and departure times of train 3 and 4 were changed.

```
23/09/2024_05:00:45 - TRAINPART
  id                   tpa_1X11_1
  name                 -
  trainNumber          1X11
  nidOperational       01070101
  nidEngine            NIDENGINE
  code                 65
  processStatus        planned
  categoryRef          -
    OCPTT:
      sequence               1
      incomingSectionTT      path_DUP_2_-_-_-_BGR_2_-_-_-
      ocpRef                 sta_BGR
      ocpType                STOP
      platformRef            plf_BoggoRoadPlatform2
      arrival                23/09/2024 05:02:00(1727060520)
      scopeArrival           calculated
      departure              23/09/2024 05:03:00(1727060580)
      scopeDeparture         calculated
      outgoingSectionTT      -
      sectionTT              -
      hold                   false
    OCPTT:
      sequence               2
      incomingSectionTT      path_BGR_2_-_-_-_WGB_2_-_-_-
      ocpRef                 sta_WGB
      ocpType                STOP
      platformRef            plf_WoolloongabbaPlatform2
      arrival                23/09/2024 05:05:00(1727060700)
      scopeArrival           calculated
      departure              23/09/2024 05:06:00(1727060760)
      scopeDeparture         calculated
      outgoingSectionTT      -
      sectionTT              -
      hold                   false
    OCPTT:
      sequence               3
      incomingSectionTT      path_WGB_2_-_-_-_ALB_2_-_-_-
      ocpRef                 sta_ALB
      ocpType                STOP
      platformRef            plf_AlbertStreetPlatform2
      arrival                23/09/2024 05:08:00(1727061000)
      scopeArrival           calculated
      departure              23/09/2024 05:09:00(1727061060)
      scopeDeparture         calculated
      outgoingSectionTT      -
      sectionTT              -
      hold                   false
    OCPTT:
      sequence               4
      incomingSectionTT      path_ALB_2_-_-_-_RSU_2_-_-_-
      ocpRef                 sta_RSU
      ocpType                STOP
      platformRef            plf_RomaStreetUndergroundPlatform2
      arrival                23/09/2024 05:11:00(1727061060)
      scopeArrival           calculated
      departure              23/09/2024 05:12:00(1727061120)
      scopeDeparture         calculated
      outgoingSectionTT      -
      sectionTT              -
      hold                   false
```

```
23/09/2024_05:06:37 - TRAINPART
  id                   tpa_1X11_1
  name                 -
  trainNumber          1X11
  nidOperational       01070101
  nidEngine            NIDENGINE
  code                 65
  processStatus        planned
  categoryRef          -
    OCPTT:
      sequence               1
      incomingSectionTT      path_DUP_2_-_-_-_BGR_2_-_-_-
      ocpRef                 sta_BGR
      ocpType                STOP
      platformRef            plf_BoggoRoadPlatform2
      arrival                23/09/2024 05:02:00(1727060520)
      scopeArrival           calculated
      departure              23/09/2024 05:03:00(1727060580)
      scopeDeparture         calculated
      outgoingSectionTT      -
      sectionTT              -
      hold                   false
    OCPTT:
      sequence               2
      incomingSectionTT      path_BGR_2_-_-_-_WGB_2_-_-_-
      ocpRef                 sta_WGB
      ocpType                STOP
      platformRef            plf_WoolloongabbaPlatform2
      arrival                23/09/2024 05:05:00(1727060700)
      scopeArrival           calculated
      departure              23/09/2024 05:06:00(1727060760)
      scopeDeparture         calculated
      outgoingSectionTT      -
      sectionTT              -
      hold                   false
    OCPTT:
      sequence               3
      incomingSectionTT      path_WGB_2_-_-_-_ALB_2_-_-_-
      ocpRef                 sta_ALB
      ocpType                STOP
      platformRef            plf_AlbertStreetPlatform2
      arrival                23/09/2024 05:10:00(1727061000)
      scopeArrival           calculated
      departure              23/09/2024 05:11:00(1727061060)
      scopeDeparture         calculated
      outgoingSectionTT      -
      sectionTT              -
      hold                   false
    OCPTT:
      sequence               4
      incomingSectionTT      path_ALB_2_-_-_-_RSU_2_-_-_-
      ocpRef                 sta_RSU
      ocpType                STOP
      platformRef            plf_RomaStreetUndergroundPlatform2
      arrival                23/09/2024 05:13:00(1727061180)
      scopeArrival           calculated
      departure              23/09/2024 05:14:00(1727061240)
      scopeDeparture         calculated
      outgoingSectionTT      -
      sectionTT              -
      hold                   false
```

Figure 15-37 Received two timetables by the TMS from the ATO-TS via the IL

15.6.3.2. Test Scenario 2: Status Report Feedback

The train status report is received by the TMS and was manually checked, see Figure 15-38.

```
23/09/2024_13:06:07 - STATUS_REPORT
  trainNumber                         1X11
  trackingId                          65
  nidOperational                      01070101
  nidEngine                           -
  m_ato_state                         1
  consistencyError                    false
  routingError                        false
  skipNextSP                          false
  lowAdhesion                         false
  operationalConditionsFulfilment     false
  trainIsMoving                       true
  unableStopNextSP                    false
  slipSlide                           false
  v_train_ato                         45
  l_train                             190
  driver_id                           DRIVER_245
  nid_c_sp                            548
  nid_sp                              1
  d_sending_position                  25900
  previous_nid_c_tp                   0
  previous_nid_tp                     0
  q_pass_stop_depart                  0
  q_accurate_stopping                 0
    TIMING_POINT_ESTIMATION
      nid_c             548
      nid_tp            1402
      t_arrival_date    5379
      t_arrival_seconds 10920
    TIMING_POINT_ESTIMATION
      nid_c             548
      nid_tp            1602
      t_arrival_date    5379
      t_arrival_seconds 11097
    TIMING_POINT_ESTIMATION
      nid_c             548
      nid_tp            1302
      t_arrival_date    5379
      t_arrival_seconds 11337
    TIMING_POINT_ESTIMATION
      nid_c             548
      nid_tp            1502
      t_arrival_date    5379
      t_arrival_seconds 11510
```

Figure 15-38 Received train status report by the TMS from the ATO-TS via the IL

15.7. Journey Profile Generator

15.7.1. Test Report

Table 15-32 Test report JP and SP message structure generation

Test description	**Name**	**JP and SP message structure generation**
	ID	1
	(Short) description	This function generates message information for a train with all the necessary information based on the data structure defined in the ERTMS/ATO Subset-126 for information exchange between trackside and onboard ATO.
	Test case responsibles	Pablo Ciaurriz and Unai Diez de Ulzurrun, CEIT
	Pre-conditions	Synthetic data is used in this first stage to test the module.
	TRL	4
	Input data description	Synthetic input data has been used at this stage just for validation of the functionality. Real data will be later used in a second stage with full integration with the Integration Layer (IL), which will be the origin of the data to be then transmitted to the OB systems in the JP and SP formats. See Section 15.7.2.
	Expected result	The output should be the message with the required data needed by the OB device and in the correct message structure defined in ERTMS/ATO Subset-126
	Sequence	Step 1: Synthetic data is inserted in the internal data structure Step 2: Using this data, the JP and SP messages are generated Step 3: Messages are converted to xml format for validation
Test Execution	Testing environment	Controlled laboratory environment with synthetic data
	Components and versions	railVOS TS v0
	Input data used	Infrastructure data, Timetable data, Train data
	Test time stamp	20/09/2024 14:00
	Testers	Unai Diez de Ulzurrun, CEIT
	Test result	See Section 15.7.3
	Test status	PASSED
	Notes	-

15.7.2. Test Case Description

This TRL 4 validation study showcases the generation with synthetic data of the JP (Journey Profile) packet defined by ERTMS/ATO Subset-126 with all the required fields to be sent to the C-DAS OB system. Additionally, this JP message includes the fields defined in the SP (Segment Profile).

15.7.3. Test Execution

This section shows screenshots of the results obtained from the module with the synthetic data. The following figures shows sections of two xml files with all the required fields for the JP and SP respectively, where a manual inspection has been done to check that all the necessary fields are included and in the correct format. Figure 15-39 shows the JP data file and Figure 15-40 the SP data file.


```xml
▼<JP>
  <Header NID_ENGINE="654321" NID_OPERATIONAL="3927" NID_PACKET_ATO="4" N_Packet_Counter="1" T_Timestamp_Date="2024-06-13T12:23:18Z"
  T_Timestamp_Seconds="2024-06-13T12:23:18Z"/>
 ▼<JourneyProfileDetails Q_JP_Status="Valid">
  ▼<SegmentProfileReferences N_ITER_SP="7">
   ▼<SegmentProfileReference M_SP_Version="2.3" NID_C="429" NID_SP="4174528" Q_SP_DIR="Nominal">
    ▼<TimingPoints N_ITER="1">
     ▼<TimingPointConstraints NID_TP="380" Q_Day_Light_Saving="Saving hour" Q_Stop_Skip_Pass="Stopping Point" Q_TP_Alignment="Front"
      Q_TP_Information="No specific information" T_Arrival_Window="PT0H0M0S" T_Latest_Arrival_Date="2024-06-13T05:08:00Z"
      T_Latest_Arrival_Seconds="2024-06-13T05:08:00Z">
        <StoppingPointInformation Q_Centralised_Opening="Opening by passengers" Q_Opening_Door_Side="None" Q_Relaxed_Coupler="No request
        for coupler relaxation"/>
        <StoppingPointDeparture Q_Automatic_Closing="ATO-OB does not manage train doors closing" Q_Train_Hold="Do not hold Train"
        T_Departure_Date="2024-06-13T05:09:00Z" T_Departure_Seconds="2024-06-13T05:09:00Z" T_Minimum_Dwell_Time="PT0H0M0S"/>
      </TimingPointConstraints>
    </TimingPoints>
   </SegmentProfileReference>
   ▼<SegmentProfileReference M_SP_Version="2.3" NID_C="429" NID_SP="4172831" Q_SP_DIR="Nominal">
    ▼<TimingPoints N_ITER="1">
      <TimingPointConstraints NID_TP="457" Q_Day_Light_Saving="Saving hour" Q_Stop_Skip_Pass="Passing Point" Q_TP_Alignment="Front"
      Q_TP_Information="No specific information" T_Arrival_Window="PT0H0M0S" T_Latest_Arrival_Date="2024-06-13T05:09:00Z"
      T_Latest_Arrival_Seconds="2024-06-13T05:09:00Z"/>
    </TimingPoints>
   </SegmentProfileReference>
   ▼<SegmentProfileReference M_SP_Version="2.3" NID_C="429" NID_SP="4172574" Q_SP_DIR="Nominal">
    ▼<TimingPoints N_ITER="1">
      <TimingPointConstraints NID_TP="484" Q_Day_Light_Saving="Saving hour" Q_Stop_Skip_Pass="Passing Point" Q_TP_Alignment="Front"
      Q_TP_Information="No specific information" T_Arrival_Window="PT0H0M0S" T_Latest_Arrival_Date="2024-06-13T05:11:00Z"
      T_Latest_Arrival_Seconds="2024-06-13T05:11:00Z"/>
    </TimingPoints>
   </SegmentProfileReference>
   ▼<SegmentProfileReference M_SP_Version="2.3" NID_C="429" NID_SP="4173092" Q_SP_DIR="Nominal">
    ▼<TimingPoints N_ITER="1">
     ▼<TimingPointConstraints NID_TP="319" Q_Day_Light_Saving="Saving hour" Q_Stop_Skip_Pass="Stopping Point" Q_TP_Alignment="Front"
      Q_TP_Information="No specific information" T_Arrival_Window="PT0H0M0S" T_Latest_Arrival_Date="2024-06-13T05:12:42Z"
      T_Latest_Arrival_Seconds="2024-06-13T05:12:42Z">
        <StoppingPointInformation Q_Centralised_Opening="Opening by passengers" Q_Opening_Door_Side="None" Q_Relaxed_Coupler="No request
        for coupler relaxation"/>
        <StoppingPointDeparture Q_Automatic_Closing="ATO-OB does not manage train doors closing" Q_Train_Hold="Do not hold Train"
        T_Departure_Date="2024-06-13T05:13:36Z" T_Departure_Seconds="2024-06-13T05:13:36Z" T_Minimum_Dwell_Time="PT0H0M0S"/>
      </TimingPointConstraints>
    </TimingPoints>
   </SegmentProfileReference>
   ▼<SegmentProfileReference M_SP_Version="2.3" NID_C="429" NID_SP="4166374" Q_SP_DIR="Nominal">
    ▼<TimingPoints N_ITER="1">
     ▼<TimingPointConstraints NID_TP="155" Q_Day_Light_Saving="Saving hour" Q_Stop_Skip_Pass="Stopping Point" Q_TP_Alignment="Front"
      Q_TP_Information="No specific information" T_Arrival_Window="PT0H0M0S" T_Latest_Arrival_Date="2024-06-13T05:16:00Z"
      T_Latest_Arrival_Seconds="2024-06-13T05:16:00Z">
        <StoppingPointInformation Q_Centralised_Opening="Opening by passengers" Q_Opening_Door_Side="None" Q_Relaxed_Coupler="No request
        for coupler relaxation"/>
        <StoppingPointDeparture Q_Automatic_Closing="ATO-OB does not manage train doors closing" Q_Train_Hold="Do not hold Train"
        T_Departure_Date="2024-06-13T05:17:00Z" T_Departure_Seconds="2024-06-13T05:17:00Z" T_Minimum_Dwell_Time="PT0H0M0S"/>
      </TimingPointConstraints>
    </TimingPoints>
   </SegmentProfileReference>
```


Figure 15-39 Part of the xml file result with the information of the Journey Profile

```xml
▼<SegmentProfile>
  <Header NID_ENGINE="654321" NID_OPERATIONAL="3927" NID_PACKET_ATO="7" N_Packet_Counter="1" T_Timestamp_Date="2024-06-13T12:23:18Z"
  T_Timestamp_Seconds="2024-06-13T12:23:18Z"/>
 ▼<SegmentProfilesStatus N_ITER="2">
  ▼<SegmentProfile NID_C="429" NID_SP="4174528" Q_SP_Status="Valid">
    <SegmentProfileDetails D_EoA_Offset="25" L_SP="4174528" M_SP_Altitude="2.795" M_SP_Version="1.1" Q_ATOTS_Contact_Info_Dir="No Contact
    info follows" Q_UTC_Offset="60"/>
   ▼<SP_Profile>
    ▼<StaticSpeedProfile N_ITER_SSPC="1" N_ITER_SSSP="1">
      <StaticSpeedProfileStart Q_FRONT="No train length delay on validity end point of profile element" V_STATIC="0"/>
      <SpecificStaticSpeedProfile NC_CDDIFF="Specific SSP applicable to Cant Deficiency 80 mm" Q_DIFF="Cant Deficiency specific category"/>
     ▼<StaticSpeedProfileChange D_Location="10" N_ITER_SSSPC="1" Q_FRONT="No train length delay on validity end point of profile element"
      V_STATIC="0">
       <SpecificStaticSpeedProfileChange NC_CDDIFF="Specific SSP applicable to Cant Deficiency 80 mm" Q_DIFF="Cant Deficiency specific
       category"/>
      </StaticSpeedProfileChange>
    </StaticSpeedProfile>
    ▼<Gradient N_ITER_GC="1">
      <GradientStart G_New_Gradient="0" Q_GDIR="Uphill"/>
      <GradientChange D_Location="40" G_New_Gradient="5" Q_GDIR="Uphill"/>
    </Gradient>
    ▼<Curve N_ITER_CC="1">
      <CurveStart Q_Radius_Category="R>7000m"/>
      <CurveChange D_Location="350" Q_Radius_Category="4500m≥R>2800m"/>
    </Curve>
    ▼<PowerVoltage N_ITER_PVC="0">
      <PowerVoltageStart M_VOLTAGE="Line not fitted with any traction system"/>
    </PowerVoltage>
    ▼<CurrentLimit N_ITER_CLC="0">
      <CurrentLimitStart M_CURRENT="0"/>
    </CurrentLimit>
   </SP_Profile>
   ▼<SP_Position>
    ▼<BaliseGroups N_ITER="1">
     ▼<BaliseGroup NID_BG="3421" N_ITER_BG="1" Q_NEWNID_C="Use NID_C of SP">
       <Balises D_Location="1208" N_PIG="1"/>
      </BaliseGroup>
    </BaliseGroups>
    ▼<TimingPoints N_ITER="1">
     ▼<TimingPoint D_Location="1856" NID_TP="367" Q_STP_Reached="20cm" Q_Stop_Location_Tolerance="50cm">
       <TimingPointName L_TEXT="7" X_TEXT="uyctduj"/>
      </TimingPoint>
    </TimingPoints>
    ▼<UnprotectedLevelCrossingStops N_ITER="1">
      <UnprotectedLevelCrossingStop D_UnprotectedLx_Stop_Nominal="10324" D_UnprotectedLx_Stop_Reverse="23667"/>
    </UnprotectedLevelCrossingStops>
   </SP_Position>
   ▼<SP_Area>
    ▼<PlatformAreas N_ITER="1">
      <PlatformArea D_End_Location="1886" D_Star_Location="1816" Q_Range="StartsEnds"/>
    </PlatformAreas>
    ▼<Tunnels N_ITER="1">
      <Tunnel D_End_Location="2886" D_Star_Location="2416" Q_Range="StartsEnds" Q_Tunnel_Category="Double track tunnel"/>
    </Tunnels>
    ▼<PermittedBrakingDistances N_ITER="1">
```


Figure 15-40 Part of the xml result file with the Segment Profile information

15.8. Human-In-The-Loop Simulation Environment

15.8.1. Test Report

This section reports the results of the TRL 4 validation tests for the TPE Generator and its coupling within the FRISO simulator. The validation process was twofold: first, to verify the correct coupling of these two components, and second, to ensure that their combined execution meets the expectations for improved performance. Prior to testing, the specifications and design were validated.

Table 15-33 Test report TPE calculation in simulation environment

Test description	**Name**	**Train Path Envelope calculation in simulation enviroment**
	ID	1
	(Short) description	The FRISO simulator sends an RTTP to the ATO-TS, where the TPE Generator calculates the TPEs for all trains. These are sent in JPs/SPs to the ATO-OB (FRISO simulator).
	Test case responsibles	Rob Goverde, TU Delft (TPE); Emdzad Sehic, ProRail (FRISO simulator).
	Pre-conditions	Friso and TPE were coupled. All trains in simulation have ATO OB, ATO is enabled, safety system is ETCS level 2.
	TRL	4
	Input data description	To perform these tests, we utilized a section of the Dutch rail infrastructure, specifically the ERTMS line from Lelystad to Zwolle. We created a timetable for executing the test scenarios, see Section 15.8.1.
	Expected result	Based on an RTTP received from the FRISO simulator, the TPE generator computes the TPEs for all connected trains, possibly including additional timing points to ensure conflict-free traffic. The TPEs are then sent to the ATO-OBs of the connected trains. The simulated train runs then show conflict-free ATO operations.
	Sequence	Test case step 1: FRISO sends RTTP to ATO-TS Test case step 2: TPE Generator in ATO-TS calculates TPE Test case step 3: ATO-TS sends JPs/SPs to FRISO ATO-OB Test case step 4: FRISO ATO-OB simulates train runs.
Test Execution	Testing environment	Controlled (simulation) environment with operational data
	Components and versions	FRISO v6.02.beta with FRISO ATO-OB; TPEG v0.1
	Input data used	Infra data, Timetable data, Train data, Scenarios
	Test time stamp	27/09/2024 15:25
	Testers	Ziyulong Wang, TU Delft (TPE); Gerben Aalvanger, Incontrol (FRISO simulator)
	Test result	See Section 15.8.3
	Test status	PASSED
	Notes	-

Table 15-33 provides the test report with a summary of the Test description and the Test execution. Section 15.8.1 provides the details of the test description and 15.8.3 describes the results of the test execution in more detail.

15.8.2. Test Description

To perform the validation test, we created a simulation model. For this model, we used part of the Dutch railway infrastructure, specifically the ERTMS Level 2 route from Lelystad (Lls) to Zwolle (Zl) known as the Hanzelijn, as illustrated in Figure 15-41. This is a double-track section with two local train stations in between: Dronten (Dron) and Kampen Zuid (Kpnz). Two train types use this corridor: a local train serving all four stops called a Sprinter (SP), and an intercity (IC) train that does not stop at the two intermediate stations.

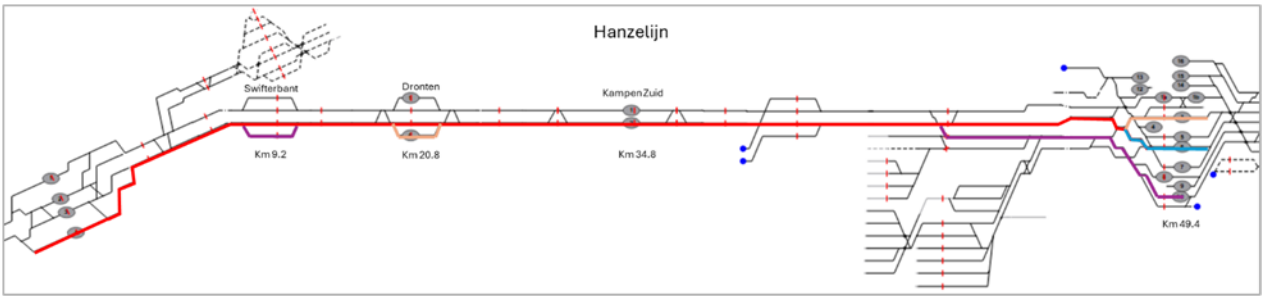


Figure 15-41 Hanzelijn infrastructure for the test case

Subsequently, a series of test scenarios was developed:

- Scenario 1: Overtaking Sprinter by Intercity in Dron. SPA1 (Sprinter A1) has sufficient dwell time. ICA1 can achieve the plan with less energy consumption.
- Scenario 2: Overtaking Sprinter by Intercity in Dron. SPA2 has less dwell time, and ICA2 must pass in time to avoid delaying SPA2.
- Scenario 3: Arrival at Zwolle. The ICA3 does not overtake the SPA3 and approaches the SPA3 at the end of the route.

These test scenarios were integrated in one timetable with sufficient buffer time in between, see Figure 15-42. Figure 15-43 also shows the static speed profile of the IC train.

In the construction of the scenarios, first the minimum running times were computed with FRISO. Then, a 7% running time supplement was added, and new running times were simulated while tuning the cruising speeds to reach the final station approximately on time for each train. Based on these running times, the planned departure and arrival times were derived, which made the final RTTP. This RTTP was conflict-free based on these speed profiles, but the train driving strategies to make this timetable are different from the algorithms in the FRISO ATO-OB module. Also, the TPE Generator has its own train trajectory calculations. In this validation, the internal FRISO ATO-OB module was used, which generates a train trajectory under the constraints of the TPE, and then simulates the train movements by computing traction/braking commands to track the speed profile.

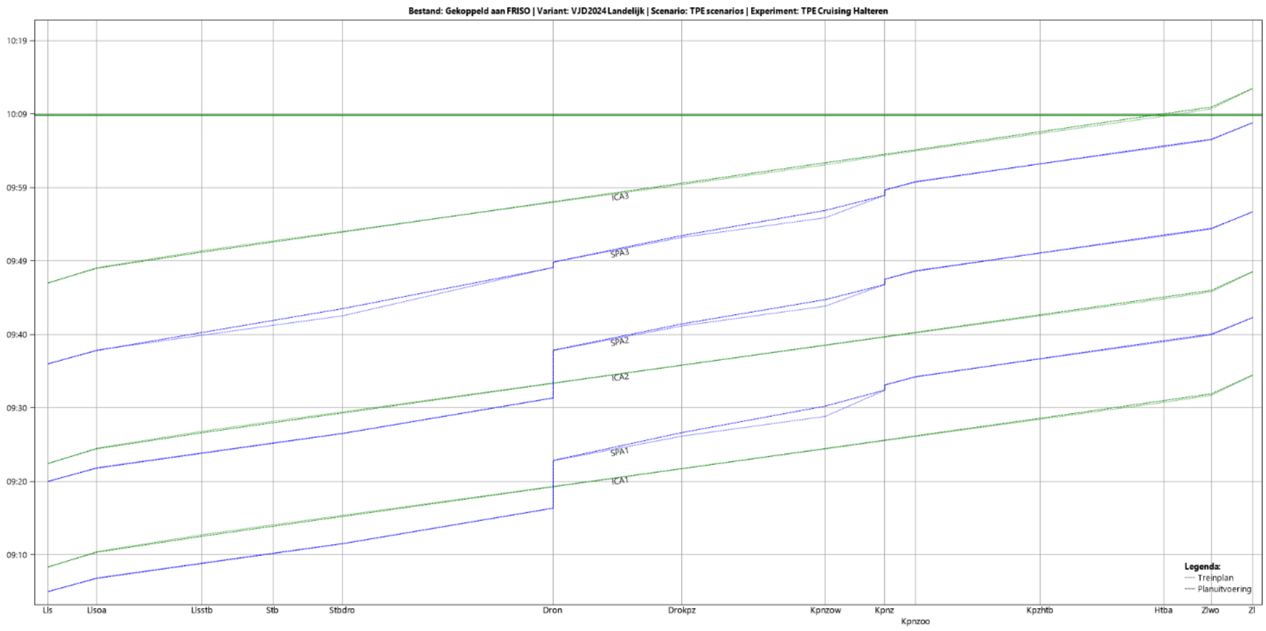


Figure 15-42 Time-distance diagram of the test scenarios

Figure 15-43 Static Speed profile of Intercity train

15.8.3. Test Execution

In step 1, the RTTP was successfully sent to the ATO-TS, containing the three test scenarios, which were imported to the TPE Generator. Only the departure and arrival times at the stopping points were included, excluding through times of the IC at the local stops and the yard. In this validation study, it is the task of the TPE Generator to check if any additional TPs are needed.

In step 2, the TPE Generator generated the TPEs for all trains. Figure 15-44 illustrates the integrated blocking time diagram for the RMS (latest) and EETC (earliest) driving strategies for each train. The TPE Generator identified blocking time overlaps in scenario 2, where a series of overlaps occurs between the SPA2 and the ICA2 before station Dron, as the slower SPR train path interferes with the train path of the faster IC train. The largest overlap is approximately 14 seconds at 15.686 km due to a tightly scheduled headway. Note that the IC does not stop at these locations and did not have passing points defined in the RTTP. So, although the original RTTP did not show any blocking time overlaps, these can occur when considering a range of different driving strategies, in particular for short line headways. In this validation study, the range of train trajectories for the IC considered in the TPE Generator includes the lower scheduled cruising speed according to the RMS driving strategy and the optimal cruising speed for EETC that is higher in the first part of the train run due to the coasting regime at the end. All driving strategies used for the TPE generation assume punctual departure and arrival times. As a result, extra TPs are needed to the IC in scenario 2 to avoid the blocking time conflicts.

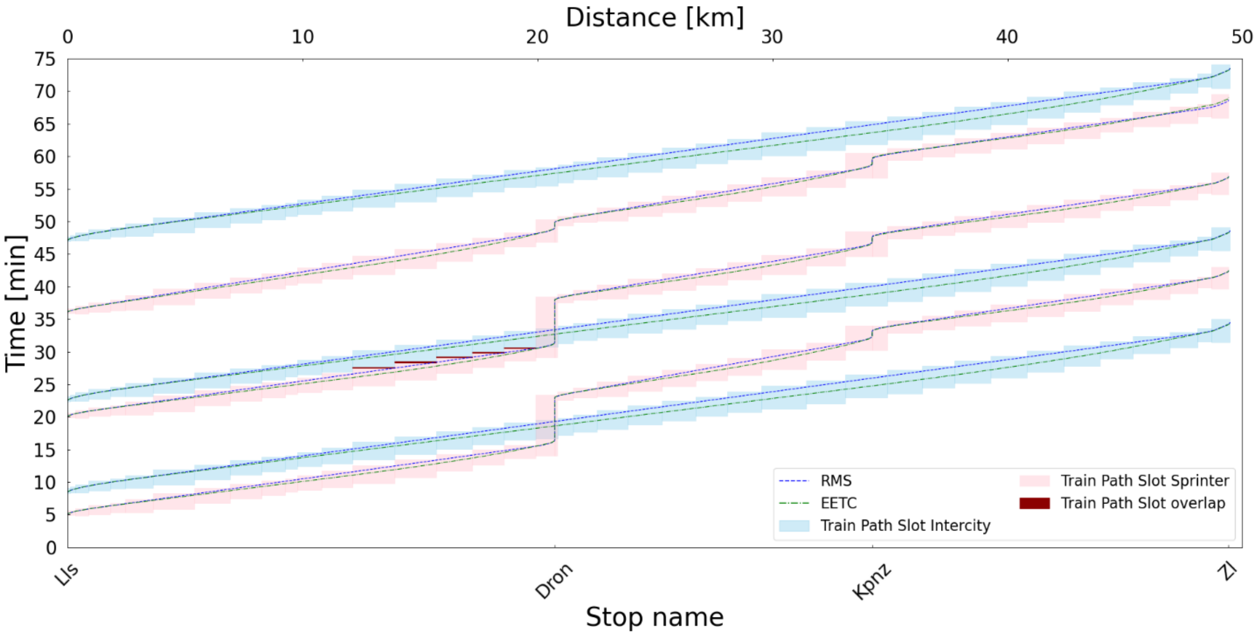


Figure 15-44 Blocking time diagram based on RMS and EETC driving strategies

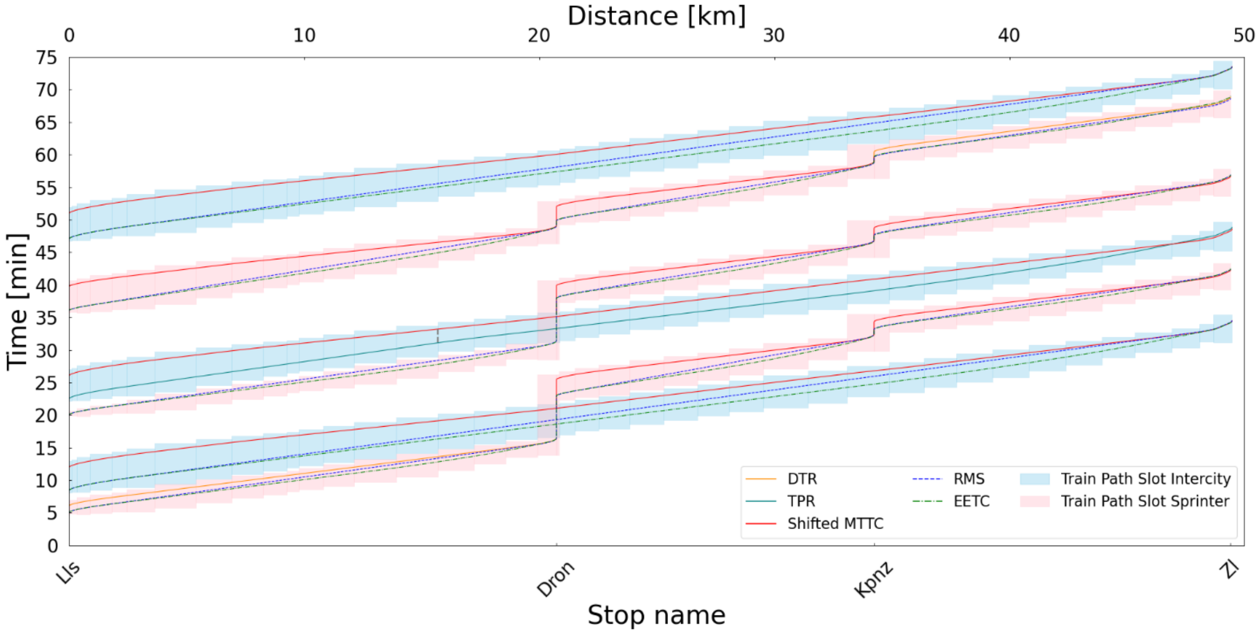


Figure 15-45 Optimized blocking time diagram with extra TP and departure tolerances

The TPE Generator computed an extra TP to resolve the blocking time conflicts in scenario 2. The optimized integrated blocking time diagram is illustrated in Figure 15-45. A TP is added to ICA2 at 15.686 km. The resulting energy-efficient timing point response driving strategy is shown in Figure 15-46. This speed profile shows how the addition of a TP could affect the speed profile for the IC, in particular up to Dron (the speed restriction at around 20 km). In this case, the time window is 151 seconds, representing the difference between the passing times under shifted minimum-time driving and timing point response driving.

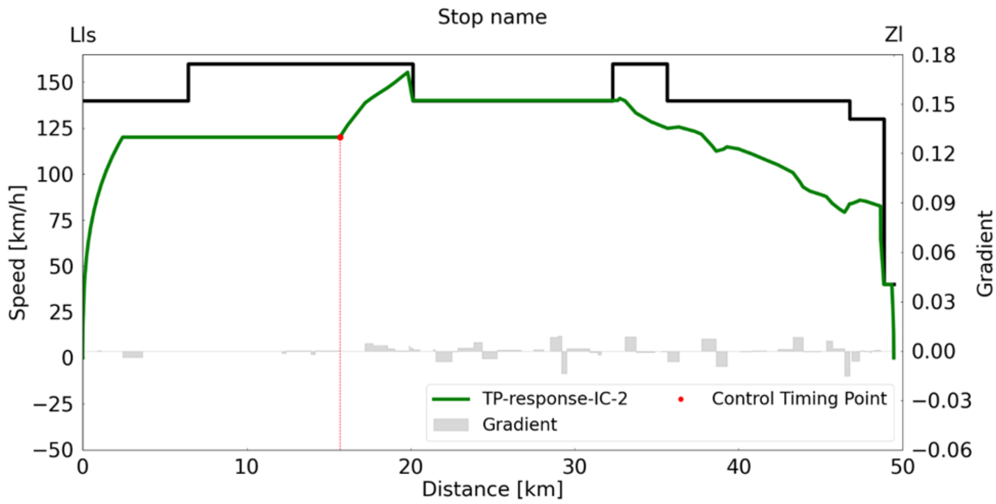


Figure 15-46 Energy-efficient timing point response driving strategy for ICA2

Finally, the TPE Generator fine-tuned the departure tolerances to enhance the timetable robustness. First, a tracking tolerance (buffer time) of 20 seconds was added to the upper bound and 10 seconds to the lower bound of all blocking times. The departure tolerances were then computed as follows. The departure tolerance for SPA1 at station Lls was reduced from 115 seconds to 75 seconds, while no departure tolerance could be assigned to SPA2 at station Lls. The departure tolerance of SPA3 at station Kpnz is reduced from 68 seconds to 60 seconds. For the remaining trains, the departure tolerances at their respective stations could be set to the full running time supplement for the journey leg to the next stop. These trains include ICA1 and ICA3 at Lls, SPA1 and SPA2 at Dron and Kpnz, as well as SPA3 at stations Lls and Dron.

In step 3, the TPEs were wrapped in the JP and sent to the FRISO ATO-OB. In step 4, the FRISO ATO-OB generated train trajectories for each train and tracked the train movements accordingly. Figure 15-47 illustrates the FRISO simulation results in a time-distance diagram. Details about the simulated train paths and the tracking deviations from the computed reference train trajectories by FRISO ATO-OB over a sequence of locations are given in Figure 15-48. All trains depart 5 s late from Lls, and thus all trains respect the earliest departure time. All SPR trains arrive between -2 s and +5 s at the intermediate stations, and all trains arrive between -12 s and +1 s in Zwolle. In between the TPs, the deviations from the originally planned train paths are larger, with the maximal deviations achieved in Scenario 1 of 64 s lateness for the passage of the SPA1 through Kpnzow (where the planned train path shows less smooth behaviour) and 65 s earliness for the passages of the ICA1 through Kpnz and Kpnzoo. This illustrate the relatively large deviations between planned and actual train paths between timing points, which however does not have to be a problem when there is sufficient buffer time between the trains, while it may benefit energy efficiency. The extra TP for ICA2 (having the same scheduled running time as ICA1), reduced the deviation between the originally planned and actual train paths to 30 s earliness for the passage through Kpzhtb. No conflicts were reported, indicating that FRISO was able to simulate all trains conflict-free based on the computed TPEs.

In conclusion, the combination TMS – ATO-TS – ATO-OB was successful in all three scenarios with no conflicts occurring during the simulation, punctual departures and arrivals (with a few seconds deviations), and the trains allowed to run energy-efficient although this was not planned as such in the RTTP construction.

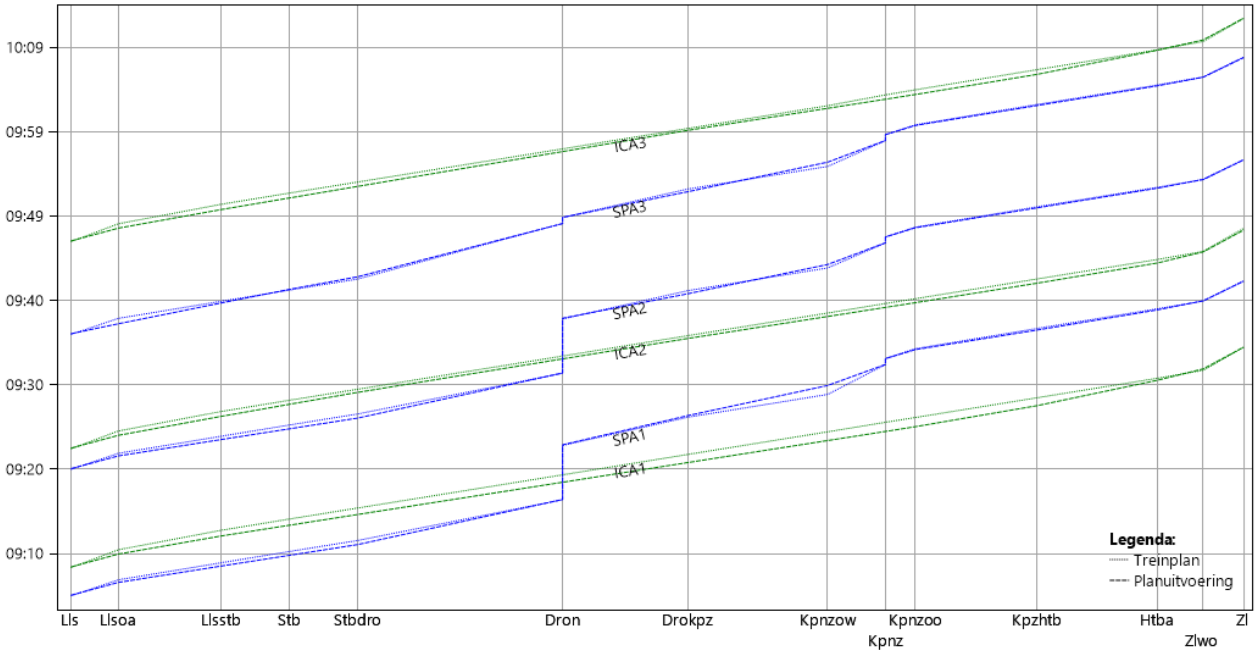


Figure 15-47 FRISO simulation results in time-distance diagram

Dienstregeling:
Trein: SPA1-H-1 (Lls-Zl) 1e uur (repl. 1) (exp. Onverstoord)

Drgl. pt	Act.	Plantijd	Realisatietijd	Vertraging
Lls	V	09:05:00	09:05:05	5
Llsoa	D	09:06:54	09:06:35	-18
Llsstb	D	09:08:55	09:08:31	-23
Stb	D	09:10:16	09:09:48	-27
Stbdro	D	09:11:34	09:11:04	-29
Dron	A	09:16:24	09:16:25	2
Dron	V	09:22:50	09:22:54	5
Drokpz	D	09:26:11	09:26:22	11
Kpnzow	D	09:28:53	09:29:56	64
Kpnz	K_A	09:32:26	09:32:26	0
Kpnz	K_V	09:33:08	09:33:08	0
Kpnzoo	D	09:34:18	09:34:12	-6
Kpzhtb	D	09:36:42	09:36:30	-11
Htba	D	09:39:02	09:38:54	-7
Zlwo	D	09:39:58	09:39:58	1
Zl	A	09:42:21	09:42:18	-2

Dienstregeling:
Trein: SPA2-H-1 (Lls-Zl) 1e uur (repl. 1) (exp. Onverstoord)

Drgl. pt	Act.	Plantijd	Realisatietijd	Vertraging
Lls	V	09:20:00	09:20:05	5
Llsoa	D	09:21:54	09:21:35	-18
Llsstb	D	09:23:55	09:23:31	-23
Stb	D	09:25:16	09:24:48	-27
Stbdro	D	09:26:34	09:26:04	-29
Dron	A	09:31:24	09:31:25	2
Dron	V	09:37:50	09:37:54	5
Drokpz	D	09:41:11	09:40:49	-22
Kpnzow	D	09:43:53	09:44:17	24
Kpnz	K_A	09:46:51	09:46:51	1
Kpnz	K_V	09:47:33	09:47:33	1
Kpnzoo	D	09:48:43	09:48:38	-4
Kpzhtb	D	09:51:07	09:51:00	-7
Htba	D	09:53:26	09:53:20	-6
Zlwo	D	09:54:23	09:54:21	-1
Zl	A	09:56:45	09:56:41	-3

Dienstregeling:
Trein: SPA3-H-1 (Lls-Zl) 1e uur (repl. 1) (exp. Onverstoord)

Drgl. pt	Act.	Plantijd	Realisatietijd	Vertraging
Lls	V	09:36:00	09:36:05	5
Llsoa	D	09:37:54	09:37:15	-38
Llsstb	D	09:39:55	09:39:43	-12
Stb	D	09:41:16	09:41:20	5
Stbdro	D	09:42:34	09:42:50	16
Dron	K_A	09:49:10	09:49:08	-2
Dron	K_V	09:49:52	09:49:52	0
Drokpz	D	09:53:14	09:52:55	-19
Kpnzow	D	09:55:55	09:56:25	30
Kpnz	K_A	09:58:59	09:58:59	0
Kpnz	K_V	09:59:41	09:59:41	0
Kpnzoo	D	10:00:51	10:00:46	-4
Kpzhtb	D	10:03:15	10:03:08	-7
Htba	D	10:05:34	10:05:28	-6
Zlwo	D	10:06:31	10:06:29	-1
Zl	A	10:08:53	10:08:49	-3

Dienstregeling:
Trein: ICA1-H-1 (Lls-Zl) 1e uur (repl. 1) (exp. Onverstoord)

Drgl. pt	Act.	Plantijd	Realisatietijd	Vertraging
Lls	V	09:08:21	09:08:26	5
Llsoa	D	09:10:28	09:09:57	-31
Llsstb	D	09:12:46	09:12:05	-40
Stb	D	09:14:07	09:13:22	-44
Stbdro	D	09:15:25	09:14:38	-46
Dron	D	09:19:21	09:18:28	-53
Drokpz	D	09:21:46	09:20:48	-58
Kpnzow	D	09:24:27	09:23:24	-62
Kpnz	D	09:25:35	09:24:29	-65
Kpnzoo	D	09:26:09	09:25:03	-65
Kpzhtb	D	09:28:29	09:27:32	-56
Htba	D	09:30:48	09:30:33	-14
Zlwo	D	09:31:45	09:31:54	10
Zl	A	09:34:29	09:34:29	1

Dienstregeling:
Trein: ICA2-H-1 (Lls-Zl) 1e uur (repl. 1) (exp. Onverstoord)

Drgl. pt	Act.	Plantijd	Realisatietijd	Vertraging
Lls	V	09:22:26	09:22:30	5
Llsoa	D	09:24:33	09:24:02	-31
Llsstb	D	09:26:51	09:26:16	-35
Stb	D	09:28:12	09:27:43	-29
Stbdro	D	09:29:30	09:29:07	-22
Dron	D	09:33:26	09:33:05	-20
Drokpz	D	09:35:51	09:35:30	-20
Kpnzow	D	09:38:32	09:38:07	-24
Kpnz	D	09:39:40	09:39:12	-28
Kpnzoo	D	09:40:14	09:39:45	-28
Kpzhtb	D	09:42:34	09:42:04	-30
Htba	D	09:44:53	09:44:28	-25
Zlwo	D	09:45:50	09:45:47	-3
Zl	A	09:48:34	09:48:22	-12

Dienstregeling:
Trein: ICA3-H-1 (Lls-Zl) 1e uur (repl. 1) (exp. Onverstoord)

Drgl. pt	Act.	Plantijd	Realisatietijd	Vertraging
Lls	V	09:47:00	09:47:05	5
Llsoa	D	09:49:07	09:48:36	-31
Llsstb	D	09:51:25	09:50:47	-37
Stb	D	09:52:46	09:52:11	-35
Stbdro	D	09:54:04	09:53:33	-31
Dron	D	09:58:00	09:57:40	-19
Drokpz	D	10:00:25	10:00:11	-13
Kpnzow	D	10:03:07	10:02:48	-19
Kpnz	D	10:04:24	10:03:53	-31
Kpnzoo	D	10:05:00	10:04:26	-33
Kpzhtb	D	10:07:23	10:06:49	-34
Htba	D	10:09:44	10:09:42	-2
Zlwo	D	10:10:44	10:10:54	11
Zl	A	10:13:30	10:13:28	-1

Scenario 1 | Scenario 2 | Scenario 3

Figure 15-48 Detailed FRISO train paths of the three scenarios for the Sprinter (top) and Intercity trains (bottom)