Ref. Ares(2025)8289296 - 01/10/2025

Deliverable D 8.3
Developed simulation methods and models for capacity evaluation of ETCS and C-DAS/ATO

Project acronym:	MOTIONAL
Starting date:	01/04/2023
Duration (in months):	20
Call (part) identifier:	HORIZON-ER-JU-2022-01
Grant agreement no:	101101973
Due date of deliverable:	Month 24
Actual submission date:	05-12-2024
Code	FP1-WP08-D-PR-001-01
Responsible/Author:	Alwin Pot, PR
Dissemination level:	PU
Status:	Issued

Reviewed: (yes~~/no~~)

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*
1	29-02-2024	50 % version
2	21-10-2024	Internal review version
3	15-11-2024	Final (100%) version
4	05-12-2024	Format check
5	08-05-2025	External review comments processed

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1. Executive Summary

The aim of EU Rail Flagship Project 1, Deliverable 8.3 is to develop simulation methods and models for capacity evaluation of ETCS and C-DAS / ATO. We also include the enhanced TMS-functionality and Next Generation Brakes as DATO (digital and automatic train operation) techniques to be researched. This report describes the developed simulation methods as well as accompanying planned simulation scenarios. For the latter, numerical results and analysis will follow in deliverable 9.2 of the follow-up work package 9.

The report uses the following structure. First, it presents general information on railway traffic simulations to contextualize our simulation method choices later on. Next, the report describes different current simulation tools, all of which will be used to study at least one of the different DATO techniques and scenarios. In total, this report describes 8 simulation packages.

Next, the report describes the developed simulation methods for each DATO-technique. Specifically, for each DATO-technique, the report offers a short description of the technique, an explanation of the developed simulation methods, an outline of how the previously described software packages (may) implement these methods, and a validation of the simulation methods to technical readiness level 4.

The basis for all other methods is ETCS level 2, the signalling system that will replace the current class B systems in the near or further future. Thereafter follows Hybrid Train Detection (formerly HL3), where the report presents a method for simulating the virtual subsections and train integrity monitoring. For NG-Brake, the method consists of altering traction and braking parameter settings compared to the basic ETCS settings. For C-DAS and ATO, the method relies on the implementation of altered driving strategies. The method for TMS includes either an adapted parameter setting for emulation or the configuration of a TMS for a proper simulation of the effect.

Finally, the report describes the scenarios that will be simulated with the developed methods with a brief overview of infrastructure, timetable and rolling stock. In total, the report describes 17 geographical areas across Europe. Each will be used to simulate one or multiple DATO-techniques, using complementary software packages. The methods, scenarios and results are related to several other work packages in FP1-MOTIONAL and FP2-R2DATO.

In sum, this report gathers and presents information about simulation, methods for simulating DATO-techniques, verification of the methods, and scenarios to be calculated. The information gives the possibility of a broad evaluation of methods and results. The follow-up work package 9, deliverable 9.2, will present outcomes of the simulations.

2. Abbreviations and acronyms

Abbreviation / Acronym	Description
ADS	Adhesion Determination System
ATO	Automatic Train Operation
ATP	Automatic Train Protection
BAMS	Brake Adhesion Management System
C-DAS	Connected Driver Advisory System
CO	Coasting
CR	Cruising or speed-holding
CSS	Command and Control System
DATO	Digital automated up to Autonomous Train Operation
DMI	Driver Machine Interface
DMU	Diesel Multiple Unit
EBI	Emergency Brake Intervention
EETC	Energy-efficient train control or energy-optimal driving strategy
EMU	Electric Multiple Unit
ERA	European Agency for Railways
ERTMS	European Railway Traffic Management System
ETCS	European Train Control system
EVC	European Vital Computer
FMB	Full Moving Block
FP	Flagship Project (within Europe's Rail). The official name of FP1 is FP1-MOTIONAL, the official name of FP2 is FP2-R2DATO.
FVB	Fixed Virtual Blocks
GoA2	Grade of Automation level 2
GoA4	Grade of Automation level 4
GSM-R	Global System for Mobile communications for Railways
GUI	Graphical User Interface
HL3	Hybrid Level 3
HTD	Hybrid Train Detection (formerly: HL3)
MA	Maximum acceleration
MB	Maximum braking
MC	Maximal coasting or coasting driving strategy
MTTC	Minimum time train control or minimum running time driving strategy
NG-Brake	New Generation Brakes
OB	Onboard
RBC	Radio Block Centre
RMS	Reduced maximum speed or cruising driving strategy
RTTP	Real Time Traffic Plan
SRS	System Requirements Specifications
TCS	Traffic Control System

TE	Technical enabler
TOC	Train Operating Company
TMS	Traffic Management System
TPE	Train Path Envelope
TS	Trackside
TSI	Technical Specifications for Interoperability
TTD	Trackside Train Detection
VSS	Virtual Sub-Section
WP	Work Package (within Europe's Rail)

3. Background

The present document constitutes the Deliverable D8.3 “Developed simulation methods and models for capacity evaluation of ETCS and C-DAS/ATO” in the framework of the Flagship Project FP1-MOTIONAL as described in the EU-RAIL multi-annual working program.

This is the third deliverable of WP8 *“Development of simulation and operational feedback for improved planning"*, based on input of task 8.4 *"Develop simulation methods and models for capacity evaluation of ETCS and C-DAS/ATO".* The leader of this task is PR and the other beneficiaries are NSR, SNCF, ADIF, INDRA, CAF, CEIT and TRV.[1]

Rail traffic simulation is a powerful tool for analysing and optimising rail transportation systems. It involves the use of software programs that simulate the simultaneous movement of trains and other rail vehicles through a network, considering various factors such as train characteristics, train schedules, track capacities, signalling systems, traffic control and other variables. Simulation models are essential to be able to estimate and evaluate the capacity effects of new technologies such as ETCS, C-DAS and ATO.

There is a need to develop more knowledge about the capacity effects of ETCS Hybrid Train Detection (HTD; previously known as Hybrid Level 3) and C-DAS/ATO implementation because (parts of) these systems are not (fully) implemented in simulation systems and the effects in comparison with the current practice are not fully known or understood. Furthermore, there exist different ways of implementation for some of the individual technologies, for which existing understanding of their relative capacity effects are also not fully clear or fully satisfying.

The Deliverable D8.3 is related to the Technical Enabler 7 “New planning and operational processes using feedback loops from ERTMS, ATO and C-DAS”. In Deliverable 3.1 of FP1-WP3, *“Mapping against scope, specification of technical enablers, high-level use cases, high-level requirements, high-level design for demonstrators in WPs 4-9”*, the following high-level requirements listed for TE7 are relevant to this deliverable:

- *Improved railway traffic simulation models for capacity evaluation of ETCS.*
    - *Simulation methods for capacity evaluation of different development aspects of ETCS, such as ETCS level 2 optimal braking and ETCS Hybrid level 3.*[2]
- *Improved railway traffic simulation models for capacity evaluation of C-DAS/ATO.*
    - *Modelling of C-DAS/ATO in timetables.*
    - *Capacity simulation models including different capacity aspects of C-DAS/ATO such as TMS interaction, NG Brake interaction, driver behaviour and energy efficiency.*

[1] These company name abbreviations are in accordance with those used in the grant agreement.

[2] ETCS Hybrid Level 3 is nowadays called ETCS Hybrid Train Detection, or HTD

4. Objective and Outline

The aim of this document is to describe simulation methods and models we developed for capacity evaluation of ETCS and C-DAS/ATO, fulfilling task 8.4 of the grant agreement. Specifically, we focus on development and validation of simulation methods to test the capacity effects of ETCS and C-DAS/ATO, and then describe how several partners of this working project set up their simulation models to test the capacity effects in practice. In such, this document builds upon D8.1, which described the contemporary state of capacity simulation methodology, outlined current simulation usage at partners of this working project, and identified development needs.

The contribution lies in providing a detailed, highly generalizable account of intended practices for capacity simulation of ETCS and C-DAS/ATO. These insights can be used to improve current and future simulations of ETCS and C-DAS/ATO. We apply our developed simulation methods across multiple software packages and for a wide array of use cases across different geographical and logistical contexts.

Within the context of Europe's Rail, this document especially relates closely to FP1 WP9, where we will describe the results of the capacity simulation models set out in this document. Additionally, the methods and models developed here are especially valuable for FP2 WP32, concerned with establishing a business case methodology for DATO techniques.[3]

The resulting document structure is as follows. In chapter 5, we first shortly introduce general simulation methodology. This contextualizes our choices for specific simulation methods and software tools. Accordingly, in chapter 6, we describe the software tools used. Next, in chapter 7, we describe our developed simulation methods for each DATO concept, describe how the software tools we use implement these methods, and validate these methods up to Technological Readiness Level 4.[4] Subsequently, in chapter 8, we describe the geographical and logistical context of the simulations within FP1 WP9 in which we will apply these developed methods. Chapter 9 constitutes an administrative chapter that explains the links to other work packages and flagship projects. Finally, chapter 10 offers concluding remarks.

[3] DATO techniques here are: ETCS level 2, ETCS HTD, NG-Brake, C-DAS, ATO GoA2, ATO GoA4, and TMS

[4] In accordance with the TRL definitions defined within Europe's Rail for development of methodologies. TRL4:

TRL	General description	Interpretation for method/functionality/algorithm developments	Validation
4	Technology validated in lab	First version of the method/functionality/algorithm validated internally by the development team. Fictive case and data can be used.	Documented in deliverable, documentation of validation with representative problems

5. Introduction

In this section, we describe general simulation theory, mirroring the information presented in deliverable D8.1 of this work package (Köhler et al., 2023). We then contextualize this theory regarding the modelling of DATO techniques specifically and shortly introduce the corresponding software tools we aim to employ to model our developed simulation methods for DATO concepts.

5.1. General simulation theory

Railway simulation is a computational method used to model and analyse various aspects of railway systems. It involves the use of software that simulates the movement of user-defined trains across a user-defined network, optionally including factors such as signalling systems, traffic control, train characteristics, train schedules, driver behaviour and other variables. As a result, railway simulations can be used to model the effect of changes in systems and infrastructure on capacity, timetable punctuality and timetable robustness. Therefore, railway simulations offer operators and planners a powerful tool to improve reliability and efficiency of their current and future networks.

There are different ways to set up and run railway simulations. We shortly discuss them here to contextualize our choices for capacity evaluation of ETCS and C-DAS/ATO. For a more extensive discussion, see deliverable 8.1 of this work package (Köhler et al., 2023).

Broadly, one can divide simulations into two aggregation levels (microscopic and macroscopic), two levels of internal synergy between scheduling process and running operation (synchronous and asynchronous), and two levels of randomisation of train runs and delays (stochastic and deterministic) (Hansen & Pachl, 2014; Botte & D'Acierno, 2018; Pachl, 2024).

The difference between the microscopic and macroscopic level is as follows. At the microscopic level, one models each signal, track and switch, as well as the signalling and train protection systems, at an accuracy level representative of reality. One then simulates exact train paths through the network. By contrast, macroscopic simulation models define infrastructure at a higher aggregation level. They may specify stations as singular points without specifying a precise track plan or signalling system within or between them, and simulate trains solely defined by the state they are in (e.g., waiting to depart, departed, occupying a line between stations). We illustrate the difference between microscopic and macroscopic models in Figure 1 below. While microscopic models more closely represent reality, they require extensive preparation work and are more computationally complex.

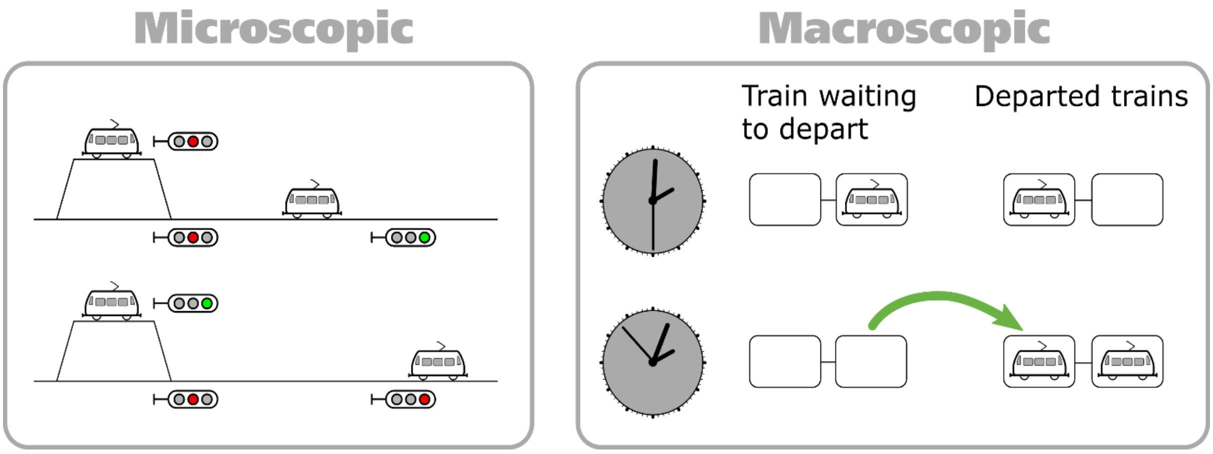


Figure 1. Microscopic and Macroscopic Simulation: Infrastructure and Running Operation Modelling

Synchronous and asynchronous (or event-based) simulations differ as follows (Hansen & Pachl, 2014). In asynchronous simulations, the scheduling process and the train running operation are simulated separately. When scheduled train paths converge, the simulation automatically resolves conflicts based on train priorities and other predefined scheduling principles. This process generates a train running order that prevents any conflicts. Subsequently, the running operation simulation runs the trains in this order. By contrast, a synchronous simulation combines scheduling and running operation in real-time, without a parallel scheduling simulation that resolves conflicts. Trains are run according to their initial schedule, after which conflicts may occur naturally. Hence, synchronous models are vulnerable to deadlocks and asynchronous models are not. However, it also follows that synchronous models are a better approximation of reality.

Capacity simulations can be deterministic or stochastic (Hansen & Pachl, 2014). In deterministic simulations the user specifies exact train paths and initial delays manually. Oppositely, in stochastic simulations, train paths and delays follow some predetermined, often empirically motivated probability distribution. Since the values pulled from this probability distribution are random, one needs to simulate the network multiple times to get a reliable estimate of railway performance. While stochastic simulations approximate reality better, they also require more computational power and are more vulnerable to deadlocks, especially when there is a microscopic aggregation level.

A sizeable number of railway simulation software packages exists nowadays, as outlined in Table 6-1 of D8.1 (Köhler et al., 2023). Each software package has their own strengths and weaknesses, in accordance with the multitude of simulation choices described above. The operator or planner chooses between simulation categories and corresponding software tools based on which of them are most appropriate to answer their research question. Borndörfer et al. (2018) recommend synchronous, microscopic, stochastic simulation to most accurately represent reality. However, following D8.1 Figure 6-1, this may not always be computationally feasible, and certain research questions may still be satisfyingly answered when choosing asynchronous, macroscopic or deterministic simulation methods.

5.2. Resulting generic methods and complementary tools

In this deliverable, we develop simulation methods and models for capacity evaluation of new signalling systems (ETCS) and of alterations to train driving behaviour (C-DAS/ATO). These are very precise changes within a simulation, and to properly evaluate capacity effects of these changes, one needs to model the infrastructure and simulate the running operation to a high level of detail.

Indeed, it requires modelling differences in signal positions, signal behaviour, and exact train paths through the network explicitly. Hence, we require microscopic simulation software tools for capacity evaluation for ETCS and C-DAS/ATO. Additionally, regarding randomisation of travel times, deterministic travel times suffice to accurately study the capacity effects of most DATO concepts. However, we may require some stochastic functionality within the train's speed profile settings to study the effect of exact driving with ATO. Finally, regarding the internal synergy between scheduling and operation, we prefer synchronous simulation. Namely, if a technology causes an uncertain change in capacity, the proper order of causality is to let the change in capacity result from the simulation, and not from predetermined assumptions about how the technology would influence the schedule in real-time.

Consequently, the software packages we develop our capacity simulation models in complement these methods. We summarize these software packages in Table 1 below. The table shows the corresponding general simulation methods the software employ, the partners that use the software, the DATO techniques tested in the individual softwares, and the corresponding demonstrators within FP1-MOTIONAL.

Specifically, the partners from the Netherlands (PR, NSR), Sweden (TRV / KTH) and France (SNCF) use *RailSys*, which is a commercially available microscopic, synchronous simulation tool. The partners from Spain use microscopic capacity simulation tools they develop in house, titled *TMS_SIM* (INDRA), *CAF-Tool* (CAF) and *railVOS* (CEIT). *CAF-Tool* and *railVOS* use synchronous simulation, while *TMS_SIM* uses asynchronous simulation. In addition, a partner from Sweden (KTH) has one simulation that focuses on a line that is mostly single-track and has mostly freight traffic, which can suffer from long delays. In a microscopic tool, this would lead to a prohibitive risk of deadlocks. Hence, this simulation will use the macroscopic *PROTON*. Chapter 8 below will outline all simulation scenarios in detail.

Table 1. Software used, generic properties, and related FP1 use cases

Software	Micro/ macro	Synchronous/ asynchronous	Deterministic or stochastic	Partner	DATO concepts tested	FP1 use case
RailSys	Micro	Synchronous	Deterministic or Stochastic	PR	ETCS L2, ETCS HTD, NG Brake, C-DAS, ATO, TMS	FP1-DEMO-9.5-UC-1
				KTH	ETCS L2, ETCS HTD, NG Brake, ATO	FP1-DEMO-9.10-UC-1,2,3
				SNCF	ETCS L2, ETCS HTD	FP1-DEMO-9.6-UC-1
VTI TDS*	Micro	Synchronous	Stochastic	VTI	ETCS L2	FP1-DEMO-9.11-UC-1,2,3
HESE*	Micro	Synchronous	Deterministic	KTH	ETCS HTD	FP1-DEMO-9.10-UC-2,3
EPA*	Micro	Synchronous	Stochastic	KTH	ETCS L2	FP1-DEMO-9.10-UC-1
PROTON	Macro	Synchronous	Stochastic	KTH	ATO	FP1-DEMO-9.10-UC-1
TMS_SIM	Micro	Asynchronous	Deterministic	INDRA	C-DAS, TMS	FP1-DEMO-9.7-UC-1
CAF-Tool	Micro	Synchronous	Deterministic	CAF	ATO, TMS	FP1-DEMO-9.8-UC1,2,3,4
railVOS	Micro	Synchronous	Deterministic	CEIT	C-DAS	FP1-DEMO-9.9-UC-1

* Note: these softwares will not be used for capacity analysis (and are not capacity-analysis-oriented software), but they will be used to estimate input data for capacity analysis in RailSys.

Additionally, partners from Sweden will use three Swedish simulation tools that will not focus on capacity evaluation, but rather on empirically motivating and estimating input parameters for later capacity evaluation in RailSys. Since they offer specific inputs for the simulation work developed in this deliverable and are not explained elsewhere in FP1 within that context, this deliverable includes them.

Concretely, Swedish simulations will use estimated driver behaviour settings taken from the *VTI Train Driver Simulator (TDS)*, which simulates the real-time interaction between driver, C-DAS and signalling systems. Second, they will estimate the technical headway resulting from different block section lengths for HTD in *HESE*, which is a microscopic tool specialized in analyzing many different combinations of block length setups quickly. Finally, Swedish simulations will use *EPA* to identify different driver profiles by transforming RBC data from

ETCS trains into speed profiles.

In sum, for accurate simulation of the capacity effects of ETCS and C-DAS/ATO, we require microscopic infrastructure models, with stochastic travel times when necessary, and prefer a synchronous simulation core. In the following chapter, we describe the corresponding software tools in more detail.

6. Description of software tools

In this section, we provide a general overview of the software tools we will use to model the developed simulation methods for ETCS and C-DAS/ATO in FP1-WP9. Through an explanation of the general properties of the software tools, we aim to establish confidence that these tools are suitable to model our studies on capacity effects of ETCS and C-DAS/ATO in. In such, this overview provides context for the description of our developed simulation methods for ETCS and C-DAS/ATO in chapter 7, as well as the geographical and logistical description of the intended models in chapter 8.

6.1. RailSys

RailSys (Radtke & Hauptmann, 2004) is an integrated microscopic simulation and planning tool developed by RMCon. RailSys software comprises three main tools, each with an own executable and set of options: the infrastructure manager, the timetable and simulation manager, and the evaluation manager. The infrastructure manager is where one builds the physical infrastructure, the timetable and simulation manager is where one inputs the timetable, rolling stock and simulation parameters, and the evaluation manager is where one processes results of the simulation.

More specifically, in the infrastructure manager, one builds the physical infrastructure at the microscopic level by defining track links at their exact geographical position with all relevant characteristics, such as maximum speed, gradient and direction of travel. One then adds signals at their exact positions with their respective system specification, and can add signal dependencies if necessary. One then generates block sections between the signals and again indicates which signalling system they operate under. One can then model in station areas by defining station boundaries on the track links, and can define stopping points or timing points within those station boundaries. Finally, one can define specific station routes that trains are allowed to take throughout station areas to reach specific stopping points. The infrastructure manager automatically produces error notifications when one makes a design mistake.

Additionally, in the timetable and simulation manager, one can model rolling stock with their exact physical characteristics as well as exact braking curves and speed profiles. The running time core features native ETCS support and detailed calculations of the ETCS braking curves. While modelling the intended timetable, one gets instant feedback on potential conflicts through a graphical timetable that shows block occupations as well as a rendering of those block occupations in the infrastructure model. Again, one gets error notifications when one makes design mistakes. RailSys operation processes are built on synchronous simulation, so all parts of the network are updated synchronously with each clock tick while simulating.

Finally, in the evaluation manager, a large set of tools is available to process simulation results. For the evaluation of capacity utilisation, RailSys offers a UIC-406 compression tool (UIC, 2013), which compresses sequential timetable train paths for sections under review. RailSys identifies conflicts in the timetable and moves affected trains exactly unhindered behind the conflicting train. After that, RailSys presents the capacity utilisation for the section under review as the percentage of time that remains theoretically available relative to the total time. A second dimension of capacity is how quickly a system can recover from disruptions, such as a departure delay of a single train. Again, the RailSys evaluation manager provides dedicated tools for such systemic robustness analyses.

RailSys is commercially available and is used by over 250 clients worldwide, including many infrastructure managers, operators and industrial companies in Europe (RMCon, 2024), spanning almost all European Union members. Notable users are ÖBB Infra and CFL, the national infrastructure managers of Austria and Luxembourg, as they currently use RailSys for everything from long-term planning to daily operation.

Consequently, the software's core existing functionalities in modelling an infrastructure network, timetabling and simulation are at the highest technological readiness level. Nevertheless, the partners of this project that use RailSys strongly favour developments within the software that improve modelling of a select few technologies, such as energy-efficient driving, which is required for modelling energy benefits of C-DAS/ATO, and TMS. However, implementation of these functionalities is outside of the formal scope of this work package, which the software developer is also external to. The RailSys using partners are currently in ongoing talks with the software developer on implementing these developments, yet cannot guarantee at this moment that all functionality will be available in time for the studies in FP1-WP9 or FP2-WP32. For most functionalities, fallback options exist, whose downsides are that they require a higher user workload or more simplistic simulation setups. Chapter 7 below will describe such baseline modelling setups in case of no new software development as well as what the RailSys using partners aim for.

Altogether, RailSys offers a high level of detail to model ETCS settings and to model braking and driving behaviour. Also, it is relatively user-friendly due to its direct feedback while modelling infrastructure, rolling stock and timetables. This becomes especially advantageous in the context of our work here, where the focus is on studying many new cases with differing infrastructure and train behaviour settings. Finally, RailSys is a widely used tool across Europe with the highest technological readiness level (TRL 9), although some technology-specific developments may be required to more efficiently model them.

6.2. PROTON

PROTON is a simulation software originally developed within Shift2Rail by DB Analytics (Zinser, 2019). They intended to create a macroscopic simulation tool which could simulate large networks in short computation times. PROTON is macroscopic. It does not model the trains and the track layout within the nodes, but does model overtaking and train meetings. The lines between the nodes contain attributes such as their total length, average block length, and number of tracks. The software detects conflicts using the minimum headway times. DB Analytics have continued developing the tool after Shift2Rail ended, and extended it to handle microscopic modelling of infrastructure and train movements. Development is still ongoing. However, within FP1, the Swedish partner that uses PROTON for one simulation will use a macroscopic model.

Swedish partners used PROTON for capacity simulations within Shift2Rail projects PLASA-2 and FR8RAIL II/III. They connect infrastructure, timetable and simulation parameter data with PROTON by running multiple scripts to convert data from other sources and create valid input data for PROTON. This means that the tool becomes a program library of sorts, with paths to input data locations and simulation parameter settings. The Swedish use of PROTON is further described in Deliverable 8.2 of this work package.

6.3. CAF-Tool

The CAF Tool project provides advanced tools for the characterisation and dimensioning of high-capacity railway lines, always in a microscopic way.

The current protection (ETCS Level 2) and communications systems allow for a significant improvement in the transport capacity of the lines through an operation with shorter headways, always respecting their safety. The combination of these systems with the introduction of automatic driving systems (ATO) also facilitates the possibilities of centralised traffic control and optimisation, together with considerable energy savings by enabling the application of globally coordinated strategies.

In view of these operating scenarios, it is considered necessary to have new models for calculating transport capacity and line design that enable results to be obtained that are adapted and appropriate to each new possible operating situation. These models must be useful for both railway managers and suppliers, as they allow obtaining capacity and dimensioning results in an agile and simple way for very different operation scenarios, combining factors such as the signalling system, the driving mode, the characteristics of the rolling stock and the operation patterns.

The capacity analysis by infrastructure element present on the line (track section, head-end, intermediate head-end, track bed or bifurcation) makes it possible to identify the limiting sections or nodes on each line in order to analyse them in detail and look for alternative designs, if necessary, while the dimensioning analysis makes it possible to obtain an optimised cantonment design to the real operating needs of the manager. During the simulation, the chase of two trains can be simulated.

Today, within the framework of the EU-Rail FP1-MOTIONAL project, the functionalities of this tool are being extended to allow capacity analysis using an ETCS HTD protection level. Figure 2 below presents a screenshot of the graphical user interface of the current version of the software.

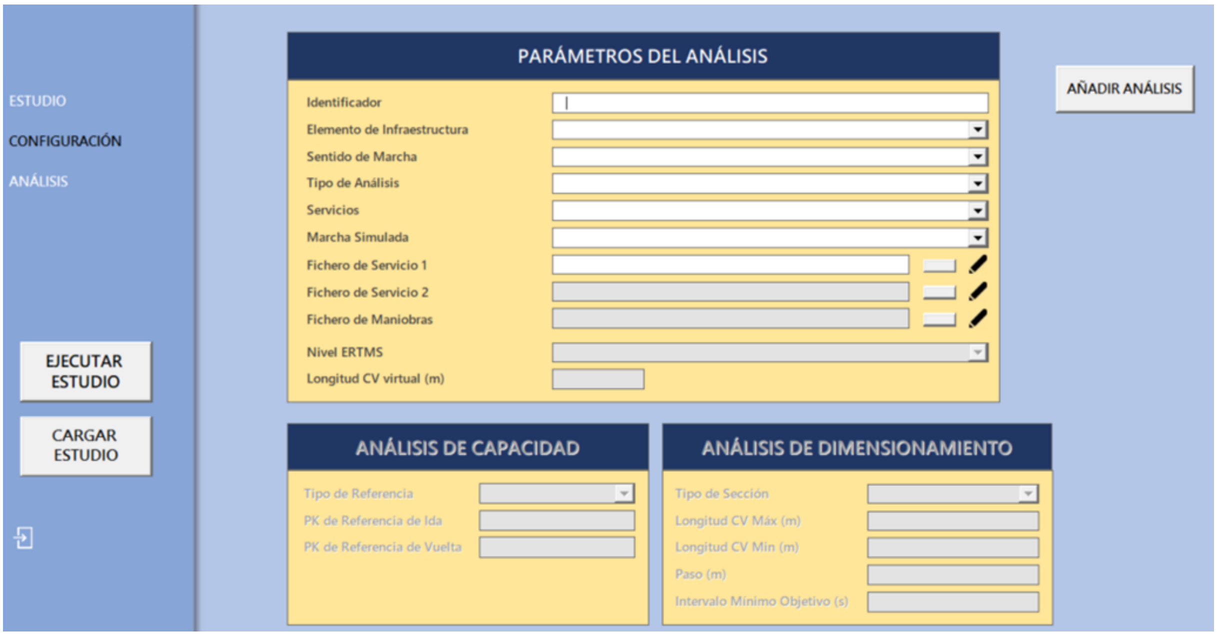


Figure 2. CAF Tool GUI for entering Simulation Settings

6.4. RailVOS

RailVOS, previously named OPTICON, was created as an energy optimization tool developed under the Spanish national research program *Retos Colaboración*. This software tool is designed to assist decision-making in optimizing energy consumption in railway systems in a holistic way, making it highly valuable for railway and infrastructure operators looking to minimize energy usage in their systems (see Figure 3 below). The tool focused on generating energy-efficient driving profiles, as well as simulating the movement of the different trains in a line and evaluating overall energy demand.

During this project, the tool is being updated with more capabilities within different WPs in FP1 and in other EU-Rail projects, expanding it towards capacity studies, C-DAS and ATO simulation, as well as power supply infrastructure design and optimization, among others. This new version of the tool is named railVOS.

As the tool was conceived as an energy evaluation tool with specific focus on generating energy efficient speed profiles, it required microscopic modelling of the track topology in terms of gradients and curves, but not related to traffic. Therefore, for capacity studies, the new microscopic tool has been added the same level of detail in terms of track information, switches, signals, et cetera.

RailVOS is designed as a synchronous simulation tool, simulating the movement of the different trains through the line at the same time and with deterministic scenarios, although some levels of stochastic parameters are intended to be introduced at certain points of the software to allow more reliable simulation results, especially regarding the behaviour of the driver.

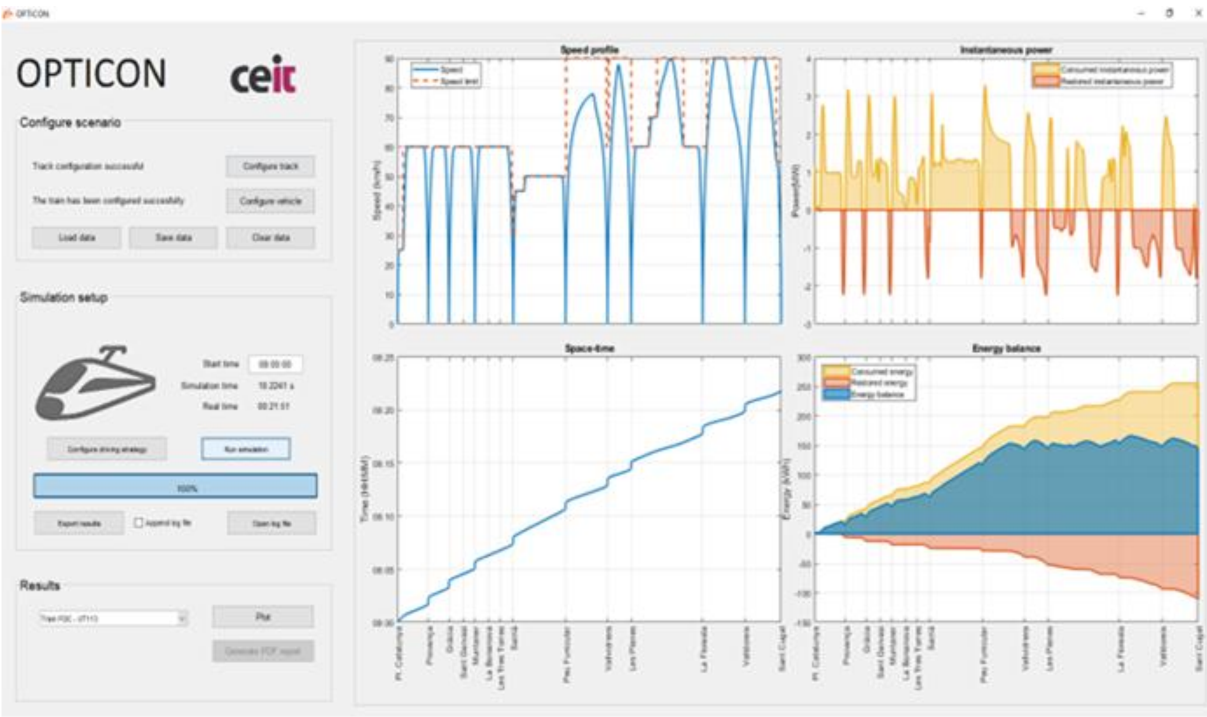


Figure 3. Screenshots of the existing OPTICON Tool

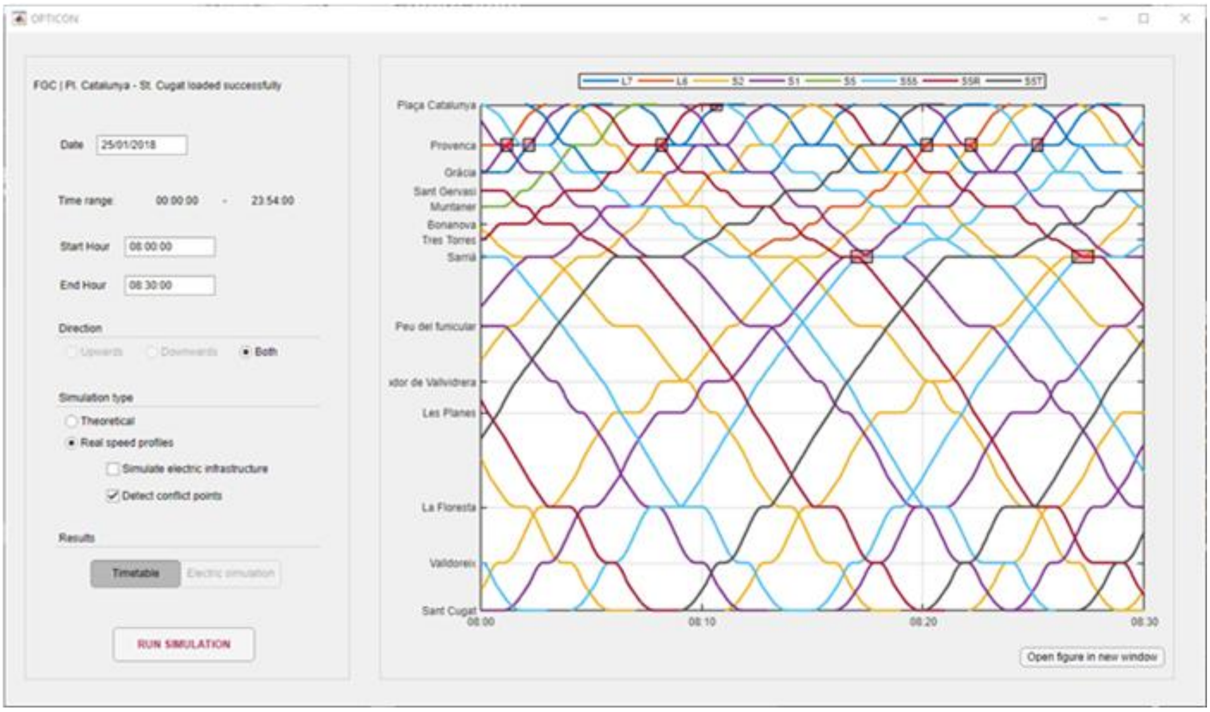


Figure 4. Screenshot of the existing OPTICON Tool

6.5. TMS_SIM

TMS_SIM is designed for the capacity evaluation of railway networks, using microscopic, deterministic, and asynchronous simulation methods to analyse timetables across various network topologies. The tool performs detailed capacity analysis to track train movements, interactions, and block times within the network. Specifically, the tool simulates train movements and registers the time trains occupy specific block sections. It also signals conflicts automatically.

TMS_SIM supports multiple ATP systems, extending functionality with ETCS Level 1 and ETCS Level 2. This support allows for accurate modelling of these systems' behaviours in simulation and signalling procedures. Figures 4-6 below present some screenshots of the software.

In the TMS_SIM User Interface in figure 4 below, we can see how the system models the rolling stock, allowing users to interact with and configure the simulation and visual representation of the infrastructure, displaying how the tracks, signals, and other elements are integrated into the simulation model.

Figure 5 below shows how the infrastructure model is visualised within the software. Finally, figure 6 below shows the output of the simulation, in the form of speed-distance diagrams.

Two panels are displayed. The first shows a speed-time diagram using class B signalling, while the second displays a speed-time diagram using ETCS Level 2. This allows us to visualize and compare the results between the two signalling systems.

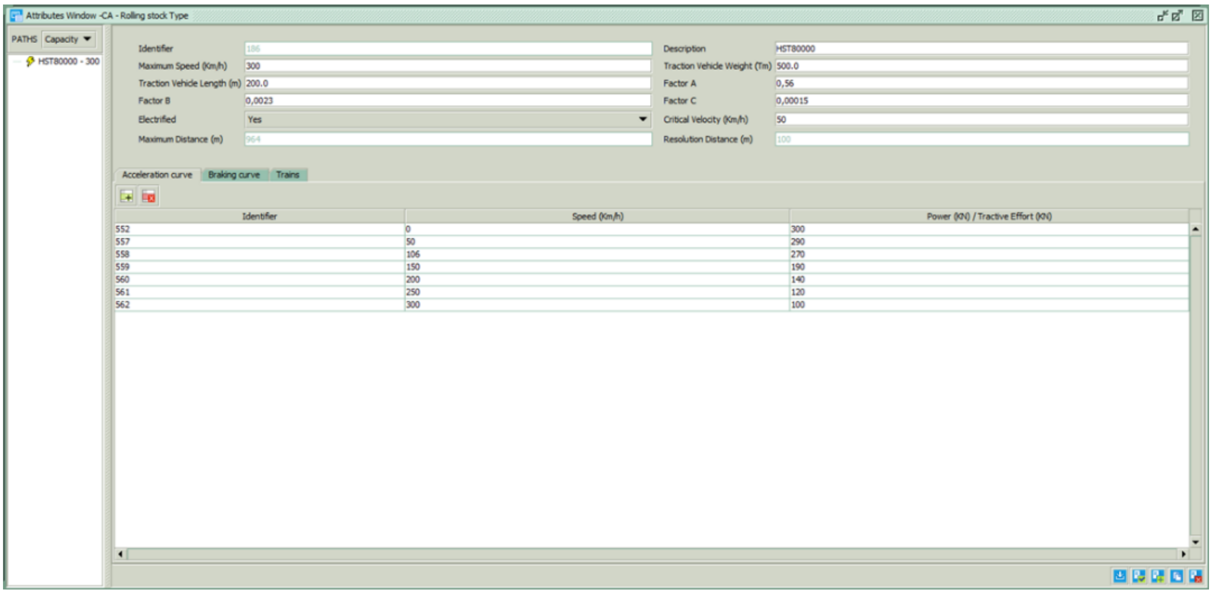


Figure 5. TMS_SIM GUI

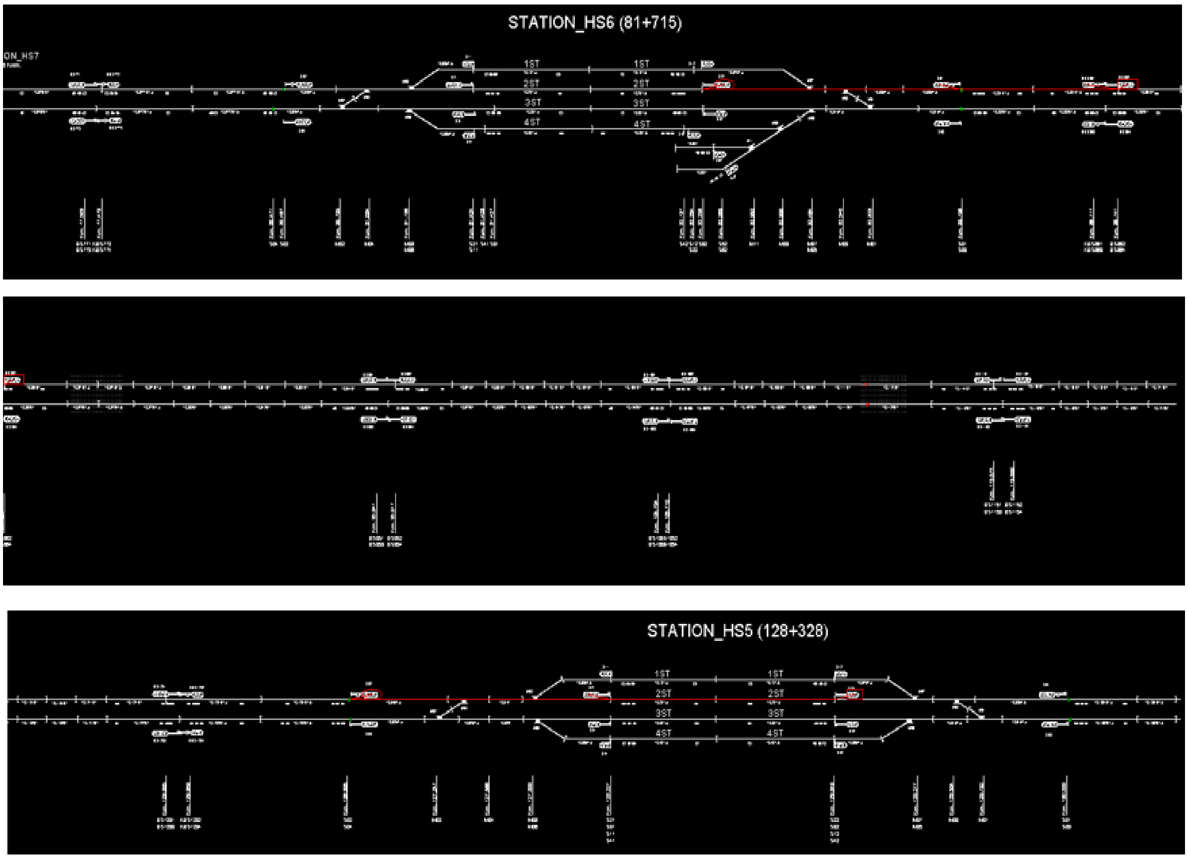


Figure 6. TMS_SIM Infrastructure Model Visualisation

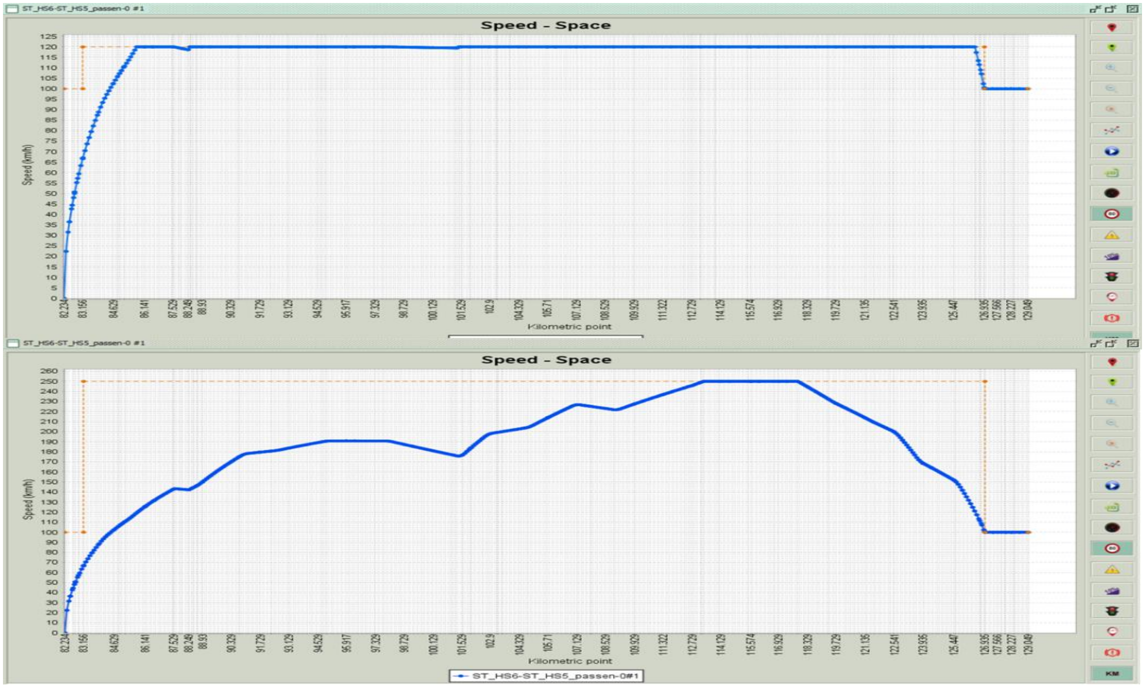


Figure 7. TMS_SIM Output Speed-Distance Diagrams, for class B signalling and ETCS L2

Note: Top panel presents speed-distance diagram for class B signalling, bottom panel presents speed-distance diagram for ETCS L2.

Overall, TMS_SIM facilitates informed decision-making for optimizing railway operations by incorporating advanced simulation capabilities and adhering to international ATP standards. In terms of simulation methodology, the tool employs an event-based approach, which identifies conflicts precisely. The simulations are conducted in medium-complexity stations on a double-track layout, using real data adapted from two model stations. This setup does not connect to a real TMS but provides a realistic environment for testing.

6.6. VTI train driving simulator

The VTI train driving simulator is a microscopic train driving simulation tool available in more than 60 copies in Sweden, distributed among 14 TOCs, and is developed by VTI. Different versions of hardware meet different needs for users. Some prefer portable desktop simulators (flexible use) while others have simulators that reflect a specific train model. The train in Figure 7 below is a replica of a well-known EMU in Sweden, called Regina. The software is the same for all hardware and is validated by experts from the TOCs. This makes the software updated according to the actual train-driving reality. The simulator replicates real tracks in Sweden and the functional fidelity is high. It is mainly used by the TOCs for training and examinations, and at VTI for research on train driver behaviour. VTI has studied run-time, braking behaviour and visual behaviour of driving under ETCS level 2 using this simulator. These performance indicators will be used as inputs for Swedish capacity simulations in RailSys. The data outcome is stochastic.

Figure 8. VTI TDS – Human Machine Interface

6.7. EPA

The EPA-tool is train dynamics measurement tool developed by VTI. The tool uses train and track information sent between RBC and ETCS onboard equipment, enabling studies on train routes over time in a cost-efficient and time-efficient manner. Namely, it collects ETCS data remotely and independently of the railway operator. The main research objectives with this tool have been to study train driving behaviour under different levels of ETCS when compared to standardized ERA braking curves, as well as the impact of train driving behaviour under different levels of ETCS on different rail planning strategies.

Specifically, the input to the tool is time-based GSM-R ETCS radio logs for the trains of interest, provided by the GSM-R radio-net owner. The tool then processes this data and can output distance-based or time-based recordings of several train movement variables, such as speed and movement authorities. One can export these recordings to Excel sheets, but also visualize them in the GUI, as exemplified in Figure 8 below. EPA currently supports up to ETCS level 2 SRS v3.4.0. The output of this tool will be used as input for the train driving behaviour in some Swedish RailSys capacity simulations.

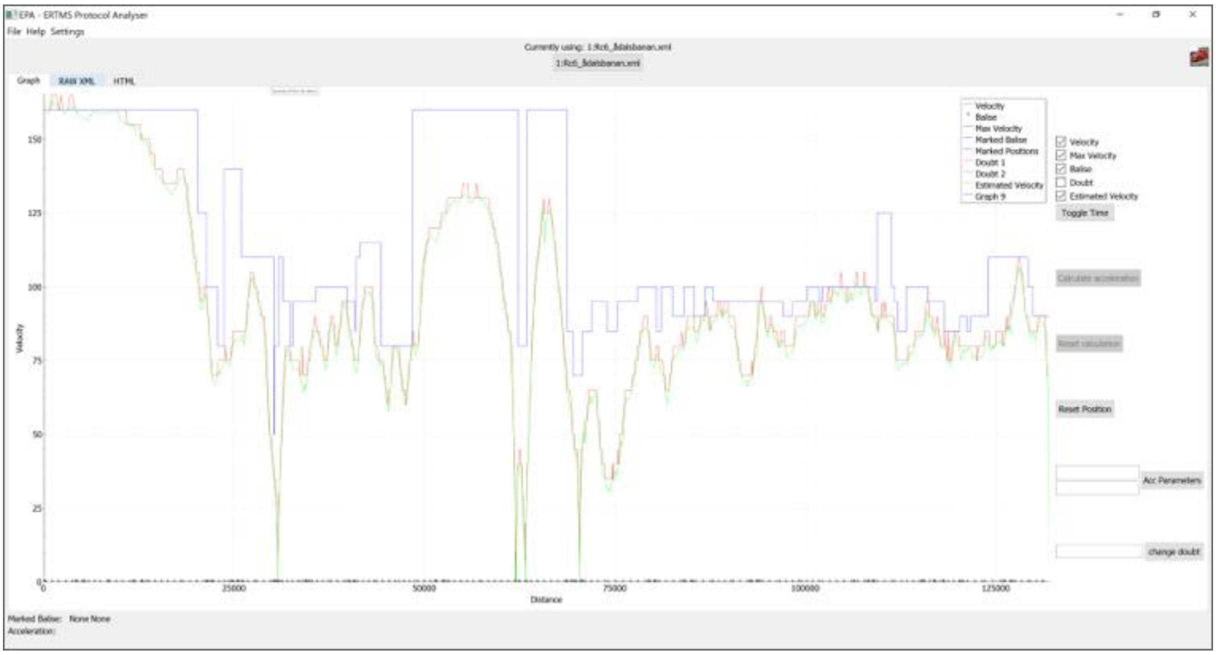


Figure 9. VTI EPA tool – GUI and example of output of a Speed-Distance Diagram

6.8. HESE

HESE is a tool designed for calculating technical headways in ETCS L2 setups, developed within a research project at KTH. It allows for a relatively easy variation of track, signal (marker board), and other input data, as well as ETCS parameters. The tool calculates braking, intervention, and warning curves according to ETCS SRS 3.6.0 and has been verified against the ERA Braking Curves Simulation Tool. Calculations of dynamic speed profiles (i.e., train runs) have been verified against RailSys in various setups, as well as technical headways.

Infrastructure input is provided via Excel sheets, including line speed profiles, gradients, marker board and position balise locations. Train stopping locations, e.g. a station stop, can be modelled. Multiple sets of these inputs can be compared visually. ETCS national values and system parameters are also imported from Excel sheets, while train data is imported and converted from RailSys train model files. The technical headway outputs will be used as inputs for Swedish capacity simulation scenarios in RailSys.

HESE lacks a graphical interface and relies on scripts in which relevant file paths are set together with additional running instructions. However, the primary output is graphical. Figure 9 below shows an example. It handles scenarios where two trains run on the same track, or a second train overtakes another one where the first train typically needs to reduce speed for navigating a diverging turnout and brake down to a stop on a side track.

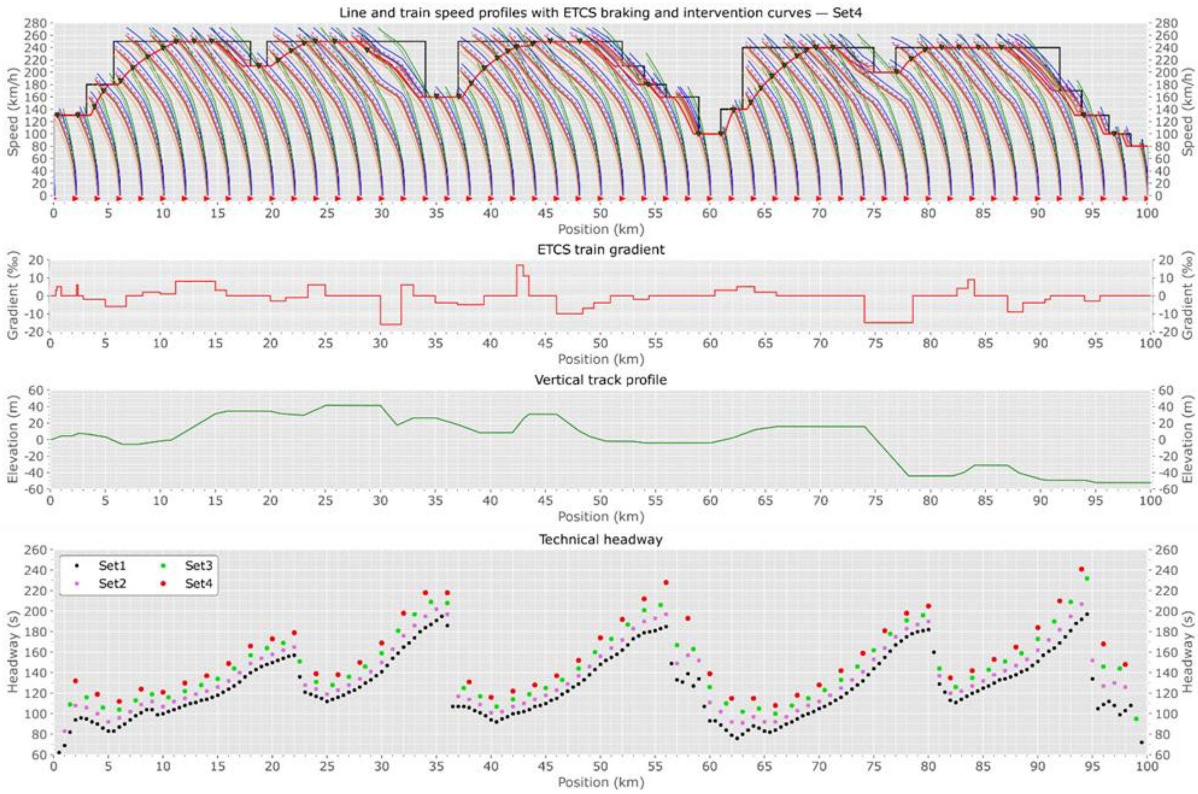


Figure 10. HESE Tool – Example of Primary Output

Note: from top to bottom: line and train speed profiles, train gradients, vertical track profile and technical headway. This example shows headway values for four different block section distances.

7. Developed simulation methods for DATO techniques, application and validation

This chapter describes the developed simulation methods for DATO techniques, their application and validation. ETCS Level 2 forms the basis for all following techniques and will be described first. Thereafter follow ETCS HTD, NG Brake, C-DAS, ATO and TMS respectively.

Moreover, for each technique, we divide the description of developed simulation methods, application and validation in 4 subchapters:

- (7.x.1) Explanation of the DATO technique
- (7.x.2) Explanation of the developed simulation method(s)
- (7.x.3) Implementation of the simulation method into one or more of the software packages outlined in chapter 6 above
- (7.x.4) Validation of the method towards TRL4, as required for this Work Package.

For all aforementioned DATO techniques (ETCS L2, ETCS HTD, NG Brake, C-DAS, ATO and TMS), the developed methods relate to the demonstrator FP1-DEMO-9.5-UC-1 (PR). Other than that, methods developed for ETCS L2 also relate to the demonstrator FP1-DEMO-9.11-UC-1,2,3 (VTI). They also form the benchmark case for demonstrators related to the developed methods for ETCS HTD, which also include FP1-DEMO-9.6-UC-1 (SNCF) and FP1-DEMO-9.10-UC-2 (KTH). In addition, methods developed for NG Brake also relate to the demonstrator FP1-DEMO-9.10-UC-3 (KTH), and methods developed for C-DAS also relate to the demonstrators FP1-DEMO-9.7-UC-1 (INDRA) and FP1-DEMO-9.9-UC-1 (CEIT). Finally, methods developed for ATO also relate to the demonstrators FP1-DEMO-9.8-UC1,2,3,4 (CAF) and FP1-DEMO-9.10-UC-1 (KTH).

7.1. ETCS Level 2

7.1.1. Description of concept

ETCS level 2 is a signalling system that does not require trackside signals. However, it retains ground-based presence detection. Signalling information is transmitted by GSM-R. The RBC (Radio Block Centre) is the computer in direct contact with an interlocking, providing it with the state of the track and the rolling stock on-board subsystem EVC (European Vital Computer).

The RBC gives a movement authorization consistent with the state of the track to the trains. The EVC calculates deceleration curves based on the movement authorizations received from the RBC. It also communicates with the RBC to inform it of its location and requests for movement authorizations.

In the driver's cab, the driver observes and obeys the in-cab signalling, which provides him with the real time information he needs to keep the train moving, including target distances. In ETCS, braking indications are displayed on the DMI (driver HMI) on the basis of (1) the guaranteed safety braking curve, which is directed towards the danger point; (2) the service braking curve, which brakes harder and targets a point located ahead of the danger point; and (3) the marker board (more precisely the end of the movement authorisation issued to the train). These curves are shifted by the time required to apply the brakes and by the time required for driving ergonomics, and are then displayed to the driver in the form of an indication to brake or a speed overrun warning.

The deceleration curves in the on-board subsystem take into account (1) the execution point and the associated target speed, (2) the instantaneous speed of the train, (3) the characteristics, such as gradients, of the infrastructure, and (4) the technical characteristics of the rolling stock, including gamma or lambda coefficients.

Gamma trains are trains with a fixed or predefined composition, which means deceleration profiles and brake build up times can be preconfigured in the ETCS on-board equipment. By contrast, a lambda train has a variable composition, making it impossible to preconfigure braking curves based on train characteristics. Instead, the driver or train preparer enters variables such as braked weight and total train weight into the ETCS on-board equipment ahead of the trip, which then computes and stores deceleration curves for that specific trip.

ETCS provides continuous cab signalling and associated speed control. It monitors both the position and speed of the train to ensure that it constantly remains within the authorised speed and distance limits and, if necessary, commands an intervention of the train's braking system. The minimum interval allowed between two trains is therefore guaranteed continuously in real time.

7.1.2. Developed simulation methods

As ETCS level 2 is a signalling system that involves both trackside and on-board functions, one needs to accurately model the way it works both in infrastructure and in rolling stock to simulate its capacity effect.

First, in modelling the infrastructure, one should define each ETCS block section on the lines of interest. This includes axle counters or ETCS marker boards. Depending on the type of signal box and technology used in ETCS L2, interlocking times may vary, as do infrastructure capacity and train spacing. Figure 10 below illustrates the different components of information transfer in ETCS level 2. As an example, total interlocking time is generally around 19 seconds near train stations or switches, while it is generally around 8 seconds on a bare stretch of line. Hence, to model ETCS L2 accurately, one needs to be able to model interlocking time as well.

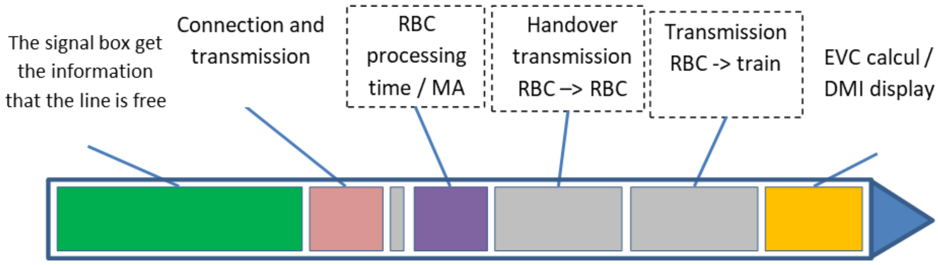


Figure 11. Information Transfer in ETCS L2 – Components of Interlocking Time

Second, in modelling the rolling stock, one of the main features of the ETCS system is that the minimum interval between two trains is defined according to the braking capacity of the rolling stock and the characteristics of the infrastructure. Line performance is therefore intrinsically linked to train braking performance. Therefore, one should accurately model and parameterise the braking rates.

In practice, one should accurately set a train as having gamma or lambda braking parameters, depending on whether it is a gamma or lambda train. EMU/DMU type rolling stock usually requires gamma braking parameters, while locomotive hauled trains usually require lambda braking parameters. The coefficients validated and parameterised in the on-board subsystem must be transmitted by the train operators such that they can be integrated into the timetable production tool and the simulation tool.

For the gamma-method, the following parameters must be specified for each rolling stock in order to calculate braking curves.

- $A_{brake_{service}}(v)$: Deceleration rate for service braking
- $A_{brake_{emergency}}(v)$: Deceleration rate for emergency braking
- T_{bs}: Service braking set-up time
- T_{be}: Emergency braking set-up time
- $K_{dry_{rst}}(v)$: Braking degradation coefficient
- $K_{wet_{rst}}(v)$: Braking degradation coefficient (in low-adhesion conditions).
- Maximum speed of rolling stock.

For the lambda-method, the following parameters must be specified:

- The braked weight percentage of the unique train formation
- Braking settings
- Train length

- Maximum speed of rolling stock

Alongside these parameters, one requires an accurate list of (often national) generic parameters that concern assumptions on driver response times, adhesion weighting factors, and permitted release speeds.

7.1.3. Implementation in software

RailSys
In RailSys, in the infrastructure manager, recall that one adds signals of the intended signalling system type at their exact positions on microscopic line segments, and then generates block sections between the signals and again indicates which signalling system they operate under. For ETCS L2, this means adding ETCS marker board (or similar) type signals, and then generating block sections of ETCS L2 type. These functionalities already exist in the current software.

To model the on-board ETCS functions correctly, RailSys contains a menu with ETCS national values, in which one can define system-wide parameters for the calculation of the ETCS run curve. The default parameters are those supplied by the ERA, and the range of values one can enter is constrained by the range of values the ERA permits. Table 2 below specifies this list of national values.

Table 2. ETCS National Values – Inputs in RailSys

Description of parameter	Default value	Value used by RailSys-using partners in this WP
Release speed	40 km/h	30 km/h (SNCF), 40 km/h (PR, KTH)
Permission to use service brake in target speed monitoring	Yes	Yes
Permission to inhibit the compensation of the speed measurement inaccuracy	No	No (SNCF, PR), Yes (KTH)
Weighting factor for available wheel/rail adhesion	0	0
Train length dependent integrated correction factor $\boldsymbol{Kr_{int}}$	0.9	0.9 (SNCF, PR), 1.0 (KTH)
Speed dependent integrated correction factor $\boldsymbol{Kt_{int}}$	0.7	0.7 (SNCF, PR), 1.0 (KTH)
Integrated correction factor for brake buildup time $\boldsymbol{Kt_{int}}$	1.1	1.1 (SNCF, PR), 1.0 (KTH)
Maximum deceleration value under reduced adhesion conditions (1)	1.0 m/(s^2)	1.0 m/(s^2)

Maximum deceleration value under reduced adhesion conditions (2)	0.7 m/(s^2)	0.7 m/(s^2)
Maximum value under reduced adhesion conditions (3)	0.7 m/(s^2)	0.7 m/(s^2)

Note: SNCF and PR themselves define their national values; TRV supplies the input parameters to KTH.

In addition, in the Timetable and Simulation Manager, RailSys offers the possibility to input certain Fixed Values, which determine time intervals and brake curve restrictions based on ERA Subset 026-3-340. Table 3 below specifies these fixed values.

Table 3. ETCS Fixed Values – Inputs in RailSys

Description of parameter	Default value (= value used by Railsys using partners in this WP)
Speed difference between Permitted speed and Emergency Brake Intervention supervision limits, minimum and maximum value	7.5 km/h - 15 km/h
Value of most restrictive speed profile where difference between Permitted and Emergency Brake Intervention speed starts to increase to the maximum value, and where it stops	110 km/h - 210 km/h
Speed difference between Permitted speed and Service Brake Intervention supervision limits, minimum and maximum value	5.5 km/h - 10 km/h
Value of most restrictive speed profile where difference between Permitted and Service Brake Intervention speed starts to increase to the maximum value, and where it stops	110 km/h - 210 km/h
Speed difference between Permitted speed and Warning supervision limits, minimum and maximum value	4 km/h - 5 km/h
Value of most restrictive speed profile where difference between Permitted and Warning supervision speed starts to increase to the maximum value, and where it stops	110 km/h - 140 km/h
Time between Warning supervision limit and Service Brake Intervention	2 s
Time between the pre-indication location and the indication supervision limit valid for most restrictive speed profile speed	7 s (subset 3.4.0), 0 s (subset 3.6.0)
Minimum and maximum possible rotating mass as a percentage of total weight of the train	2% - 15%
Compensation of the inaccuracy of the speed measurement of the train for the calculation of speed restrictions and for securing a sufficient braking distance	5 km/h
Driver reaction time between Permitted speed supervision limit and Service Brake Intervention	4 s

To correctly represent ETCS braking behaviour, RailSys calculates the ETCS braking curves automatically when it simulates a train run. This requires input on whether the train is gamma or lambda, as well as a set of input parameters in accordance with the list of parameters mentioned in the developed methods subchapter above, aside from the ones already mentioned in tables 2 and 3 above. Specifically, the Timetable and Simulation Manager within RailSys contains a rolling stock menu in which one can input specific ETCS braking settings for each rolling stock type including gamma and lambda options, alongside the physical characteristics of the train that also impact braking, such as weight, braking weight, train length, and maximum speed.

Overall, RailSys already integrates ETCS L2 to the extent that it can incorporate all the developed methods. No further development of the software is needed. Nonetheless, a limitation exists concerning specific braking coefficients called "guidance gammas" on high-speed services, which may be used to preserve brake components at high speeds. These guidance gammas lead to a guidance curve that is generally more severe than the ETCS emergency and service brake curves at high speeds. For example, guidance gammas may be –0.35 m/s^2 for speeds between 230 km/h and 320 km/h, and –0.60 m/s^2 for speeds below 230 km/h. The guidance curves cannot be automatically generated in RailSys. Instead, one has to laboriously modify the gamma braking settings, high-speed line profile settings and traction force curves for high-speed rolling stock.

A final concern in modelling ETCS level 2 is how to simulate transitions between ETCS level 2 and other signalling systems. This is critical when one wants to determine the capacity effect of an ETCS level 2 implementation on a subsection of the network. In RailSys, one solves this by overlaying signals and block sections of ETCS level 2 and the respective other type.

VTI Train Driver Simulator

The effect of a new Trafikverket ETCS implementation strategy will be examined in the VTI train driver simulator. Documents of the implementation strategy from Trafikverket served as the basis for the simulator software implementation, conducted by VTI. A reference group with experts from the Swedish Transport Administration, three operators, and VTI have participated in the implementation phase. The group have met at regular intervals to discuss and develop methods and validate the simulator development.

EPA and HESE

Recall that the EPA-Tool measures real-life train and track information sent between RBC and ETCS onboard equipment, to establish real-life evidence of braking curves compared to standardized ERA braking curves. They distinguish between different rolling stock types. Swedish partners will use the real-life data obtained in this tool as input for the ETCS national values and fixed values within RailSys, to obtain a locally even more accurate simulation of braking curves under ETCS L2, especially for freight trains. Since the tool uses real-life data, there is no direct relation to the above developed simulation methods for ETCS L2.

HESE tool varies track characteristic and marker board locations. It then generates ETCS L2 braking curves according to specifications described in ERA Subset 26-3 (ERA, 2016). Results have been verified with ERA Braking Curve Simulation Tool (ERA, 2018). Since these braking curves also form the basis of the developed simulation methods for braking under ETCS L2, the tool complies with our developed simulation methods. Eventually, HESE computes technical headways.

7.1.4. TRL4 validation

The developed simulation methods are, in short, to microscopically model marker boards and block sections into the infrastructure, to define braking parameters and curves accurately for all relevant rolling stock, and to accurately implement a set of generic parameters related to safety and interlocking, that are native to ETCS L2.

Within RailSys, the described functionality all exists and is commercially available, theoretically validating the developed simulation methods to TRL9. However, their mere inclusion in the software does not mean they are necessarily already used in production. For TRL4, the requirement is that a first version of the method is validated using at least some basic fictive case. Here, we can confidently conclude that our methods reached TRL4. Namely, some exploratory studies that implement ETCS L2 for capacity analysis using RailSys are Jansen *et al.* (2019), Sipilä (2022) and Knutsen *et al.* (2024). These studies apply the described developed simulation methods on a representative real-life case, and therefore validate them beyond TRL4.

By contrast, the Swedish tools VTI TDS, EPA and HESE are not widely commercially available. Nonetheless, they all have existing studies that validate their functionality to a high level of confidence, to the extent that they reliably may provide input data for RailSys capacity simulations. They also satisfy the developed methods.

First, several ETCS L2 studies prior to this project used the VTI train driver simulator. For example, Rosberg *et al.* (2022) investigated the effect of ETCS speed filtering on train driver braking behaviour. In Kircher *et al.* (2022), the effect of ETCS on driver visual behaviour was examined. The simulator development in this project has been validated internally by VTI and Trafikverket experts, and a demonstration was performed at Innotrans 2024 (ERJU, 2024).

Second, the EPA tool was validated with geographical position measurements, and in one main existing study focused on how drivers follow the ETCS braking curves. Through the usage of real-world data, they automatically include the relevant ETCS L2 simulation methods, as these methods follow real-life dynamics. The main result was that both EMU (lambda) and freight train (lambda) drivers follow the resulting ETCS Indication curve more closely than the Permitted curve. Figure 11 below presents these results.

Finally, KTH verified HESE tool, both against the ERA Braking Curve Simulation Tool (ERA, 2018) and against RailSys (Sipilä, 2022). This has been done in steps by first verifying that the train run module (which calculates train dynamic speed profiles) gives similar results as RailSys with the same line scenarios and train types. In the next step, the modelling of ETCS curves was implemented, and these were verified against the ERA tool for different scenarios. The third step consisted of combining train dynamic speed profile calculation modules, but using ETCS curves instead. The verification here was done by comparing total running times and running time development over distance against RailSys. The purpose was to check that trains are obeying the relevant curves. In the last step, calculation of technical headway was implemented and results from the tool verified against RailSys for a set of scenarios. So far, the tool has not been used in relation to any other project.

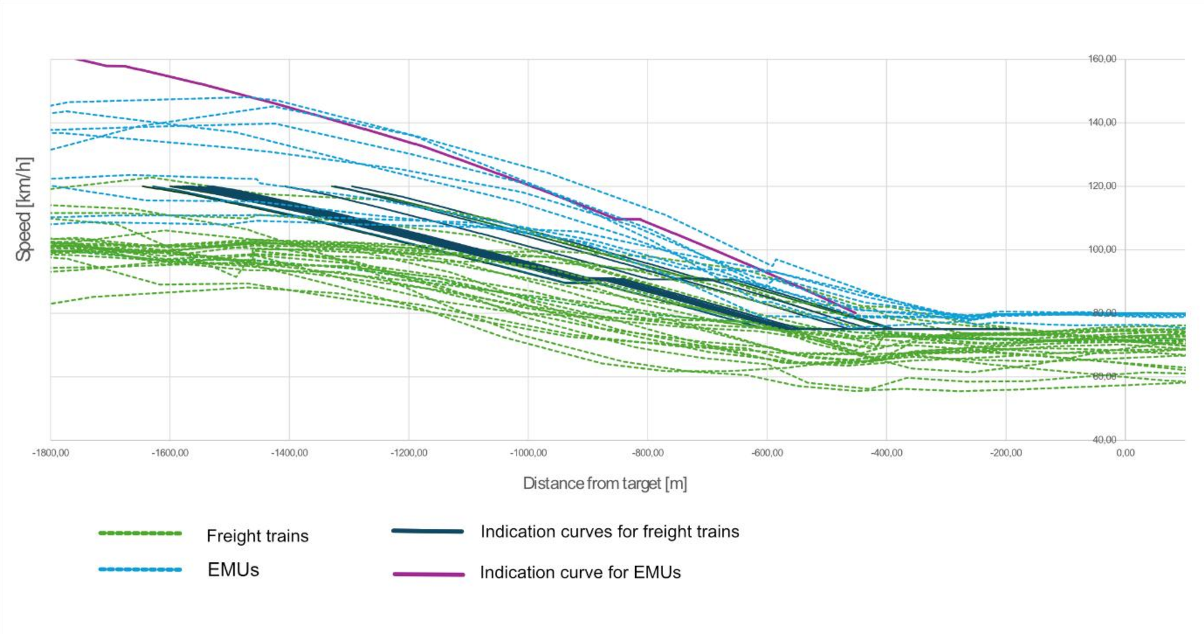


Figure 12. Speed-distance Curves and Indication Braking Curves for Freight Trains and EMUs at Ådalsbanan, Sweden – EPA Tool Output

7.2. ETCS HTD (formerly HL3)

7.2.1. Description of concept

ETCS HTD (Hybrid Train Detection, formerly known as HL3, Hybrid Level 3) is in principle an

ETCS level 2 fixed block (trackside train detection, TTD) layout with additional virtual blocks (virtual sub-sections, VSS). The virtual blocks are not monitored by trackside detection. For safety reasons, the clearing of the virtual blocks is only possible by trains that have a train integrity module, as they ensure that the entire train is still integer, or whole, when it passes between virtual sub-sections. For a more extensive explanation of ETCS HTD, we refer to FP2-WP37 deliverable 37.3 (Aoun *et al*., 2024).

The level 2 blocks have track detection systems and physical detection systems that cover at least switches, level crossings and movable bridges. Besides that, a regular interval of physical detection systems is needed to ensure a desired headway for non-integer (level 2 only) trains. In practice, passenger Diesel Multiple Units (DMUs) / Electric Multiple Units (EMUs) are relatively easily equipped with a train integrity module that continuously measures and transmits that the train is in one piece. Specifically, the ETCS module communicates to the Radio Block Centre (RBC) where the rear end of the train is located. These integer trains will safely be able to use virtual sub-sections under ETCS HTD. As a result, for these trains, shorter headways may be available. Thus, capacity theoretically increases, without increasing, and often even allowing for a decrease in, the number of physical assets along the track.

7.2.2. Developed simulation methods

To model HTD in an infrastructure model aimed at capacity analysis, one needs to define where the edges between virtual subsections are. This means that in some way, one has to define virtual marker-boards or virtual axle-counters at fixed or varying locations along tracks in a microscopic model. These virtual subsections should function the same way fixed blocks would, but only for certainly integer trains. Hence, in case one differentiates between trains with an integrity module and trains without one, one also needs to at least be able to set whether a train shall follow ETCS L2 (proxy for the train integrity status being unknown) or ETCS HTD (proxy for the train integrity being confirmed) during the simulation.

The simulation of HTD can use two methods to calculate capacity: studying the headway of two trains running under HTD, or studying the effect of using HTD signalling at the network scale on capacity (punctuality, capacity utilization, etc.). For a headway analysis, the headway time (or distance) between two trains may be studied. This can be conducted using simpler calculations (for example in Excel or developed tools), or more advanced simulation tools (like RailSys).

The simulation method for the network scale can be both deterministic (capacity utilization) and stochastic (punctuality). For the capacity utilization, one can use the UIC-406 compression method (UIC, 2013). For simulations of punctuality, one requires delay data. Relevant variables for these studies are the lengths of VSS and the share of trains with train integrity. For the simulations of HTD, the following extra parameters (in addition to the aforementioned required parameters to simulate ETCS-L2) need to be specified:

- Setting and Release time: these must be defined such that the difference between the release times of VSS and TTD blocks are captured in the simulations
- The length of the VSS blocks: this length is specific for each simulation, and depends on the purpose of the study.

7.2.3. Implementation in software

RailSys

For the purpose of simulations of HTD in RailSys, Level 2 is used as a starting point (see 7.1.2). Currently, HTD block sections and marker boards exist as a separate signalling type in RailSys. This means that the TTD block sections should have the L2-type and relevant interlocking settings for TTD, and the VSS blocks should have the HTD(HL3)-type and relevant interlock settings for VSS. Indeed, one needs to either manually enter all VSS marker boards and block sections in the Infrastructure Manager, or generate block sections and marker boards automatically at linear intervals between two predefined marker boards.

The same ETCS boards are used for both TTD and VSS blocks. However, the Level 2 blocks need to have axle counters or release contacts next to them, and the interlocking setting for Level 2 needs to have *Block release* set to *Next axle counter*. This makes it possible for the Level 2-train to use the VSS ahead of it, but only release the blocks at the end of the TTD block section.

In the timetable and simulations manager of RailSys, the user can then define which train has an integrity module by changing its signalling setting from *L2* to *HL3*. If one wants to simulate a train that goes from integer to non-integer, one can run the HTD (HL3) version of the train to the point where the integrity status changes, then run another version of the train (the L2 version) from that point onwards.

Indeed, the current method in RailSys for using HTD (former HL3) is to use a second signalling system and a second set of block sections. While this satisfies the developed simulation methods for ETCS HTD outlined above, this implementation requires a lot of manual work, is harder to check with the standard visual tools and is relatively sensitive to errors. Therefore, the RailSys using partners of this Work Package defined the following specifications to the RailSys developer, and are in ongoing talks on developing them:

- Eliminate the necessity of a second signalling system and second set of block sections by making ETCS able to handle both types of blocks at the same time.
- Facilitate a multi-edit function to reconfigure blocks from fixed to virtual blocks and to

generate new virtual blocks automatically.

- To be able to run a train with or without train integrity, the train itself should be able to use the virtual and/or fixed block within the same train version.

CAF-Tool

Regarding the developments that CAF has made to its tool, it should be noted that it is an extension of this in which the HTD functionality is added in order to be able to make capacity calculations, assessing the possibility of having different ETCS levels (L1, L2 and HL3).

For CAF, the implementation of an ETCS L3 system offers several advantages, such as improving line capacity and reducing field elements to increase reliability and reduce maintenance costs.

There are two approaches to an ETCS L3 system: by FMB (Full Moving Block), where the system issues movement authorisations based on the location of the preceding train's queue, or by FVB (Fixed Virtual Blocks), where the system generates movement authorisations to predefined points. Both approaches can be implemented with or without TTD. HTD uses pre-configured fixed blocks for train separation, and the integrity status included in the position reports to determine the status of the virtual blocks.

In an HTD application, the integrity and train length information can be used to release the track behind the train, thus allowing the generation of a new movement authorisation to a chasing train. The HTD concept can offer equivalent performance to an FMB implementation if the virtual block sections are small enough. HTD is based on the TSI CCS and is compatible with the ETCS OB 2.2 and 3.0 having as additional requirement for the onboard 2.0/2.1, the implementation of the CR940 and CR1304.

After this analysis we can consider that the objectives to be achieved with the CAF tool would be:

- Obtain the capacity analysis of an existing line operated with HTD principles.
- Validate the HTD engineering rules resulting from FP2-R2DATO D37.3. As the conclusions of the task will not be known before the CAF Tool delta has been developed, this objective is partially achievable.
- Obtain capacity analysis in theoretical situations on lines operated with HTD principles.
- To provide a tool to help pre-projects to carry out track dimensioning for tenders under HTD parameters.

HESE

HESE tool will be further developed to handle HTD scenarios. This is planned to be implemented by setting an extra attribute for marker board locations in input data sheets. This will identify marker boards as either true marker boards, which defines the level 2 block sections, or as virtual boards which will split level 2 sections into HTD sections. Development is also needed for the parts in the tool that handle release of sections, such that trains indicated for HTD or L2 are releasing sections accordingly. The basic functionality will still be two trains running in same direction.

7.2.4. TRL4 validation

For ETCS L2, the current commercially available RailSys functionality for HTD already allows for the developed simulation methods. In addition, all the partners of this Work Package that will carry out capacity simulations in RailSys have validated HTD up to the TRL4 level in own studies, described below.

First, VTI and Trafikverket have looked at a fictive case of HTD implementation, with real infrastructure data and a current timetable. Figure 12 below presents a resulting blocking time diagram, in which one can see that the VSS blocks work as intended.

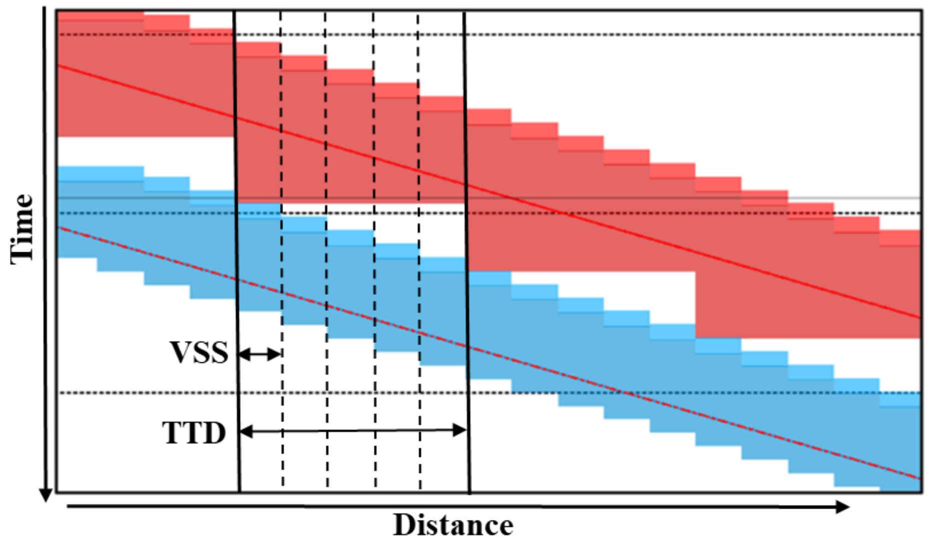


Figure 13. Blocking time diagram for two trains (not-integer L2 train and integer HTD train) in RailSys

Second, PR co-supervised two studies on fictive cases of HTD implementation with real infrastructure data and a current timetable. These studies are Jansen *et al.* (2019) and Vergroesen (2020). These studies confirmed that HTD in RailSys functioned correctly.

Third, SNCF have tested and validated the simulation methods of HTD in RailSys on the intended Lille case study, which is further described in chapter 8.2.17. The rest of this section will explain the results from this test and validate them. The Lille case studies have looked at a realistic case of HTD implementation with infrastructure data and a planned timetable. Figure 13 below presents the projected timetable modelled in RailSys.

Specifically, this case study defined three scenarios. Scenario one is a reference scenario, which models solely ETCS L2 block sections, at 1500 m apart, with shorter block sections up to 400 m apart in station areas. Scenario two models virtual subsections on top of this reference scenario that are at most 750 m apart, dividing the TTD sections by two. Scenario three models virtual subsections on top of the reference scenario that are at most 375 m apart, dividing the TTD sections by four. Figures 14 and 15 below present the infrastructure models for these scenarios. Tables 4 and 5 below present results. Figures 16, 17 and 18 below present blocking time diagrams that show headway differences between the different scenarios.

The following graphs in figures 13, 16, 17 and 18 show the timetable designed for the studied line. The x-axis represents the infrastructure (stations), and the y-axis represent the time. The occupation of the infrastructure according to the signalling system by different trains are shown in different colours. The longer the trains occupy the infrastructure, the larger the coloured squares will be.

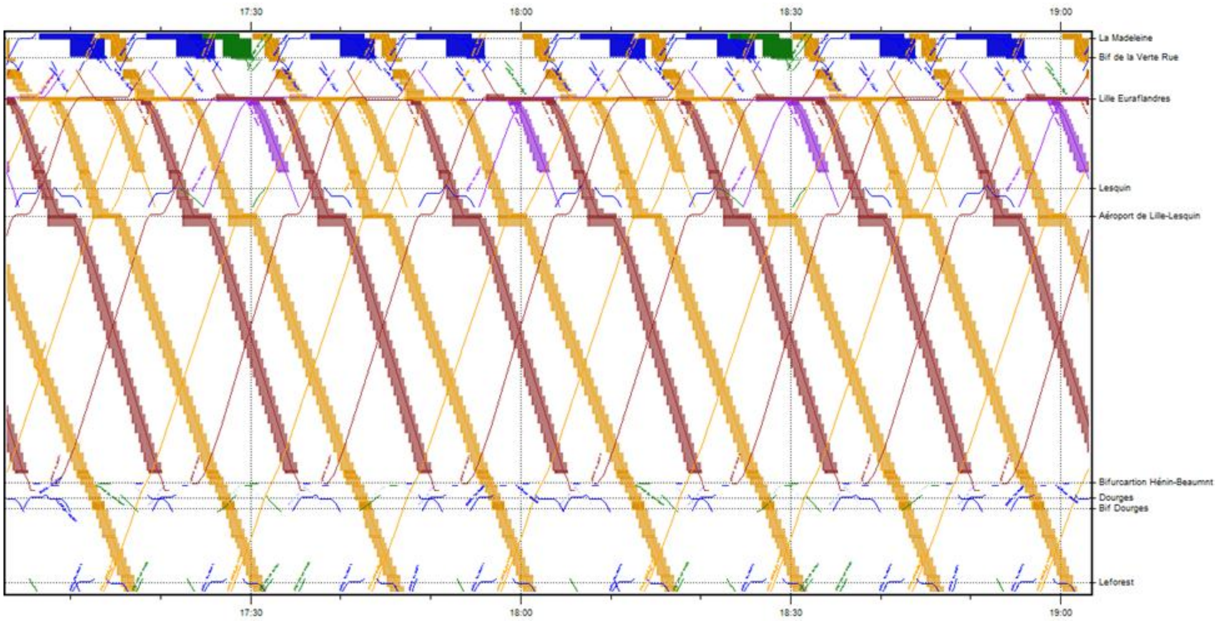


Figure 14. Projected Timetable (block-time diagram) for Lille case study, Modelled in RailSys.

Table 4. First Results for Headways for evening peak hour (17h-18h)

Scenario	Maximum length of bloc section (virtual or track-side)	Headway for 2 trains departing from Lille EuraFlandres Southbound (section A)	Headway for 2 trains arriving at Lille EuraFlandres Southbound (section A)	Headway on main REHF line southbound (including 1min stop at the Airport) (section B)	Headway on main REHF line northbound (including 1min stop at the Airport) (section B)
ETCS L2	1500m	1min 53s	2min38s	3min50s	3min54s
ETCS HTD Long	750m	1min 35s	1min51s	3min23s	3min33s
ETCS HTD Short	375m	1min24s	1min39s	3min14s	3min14s

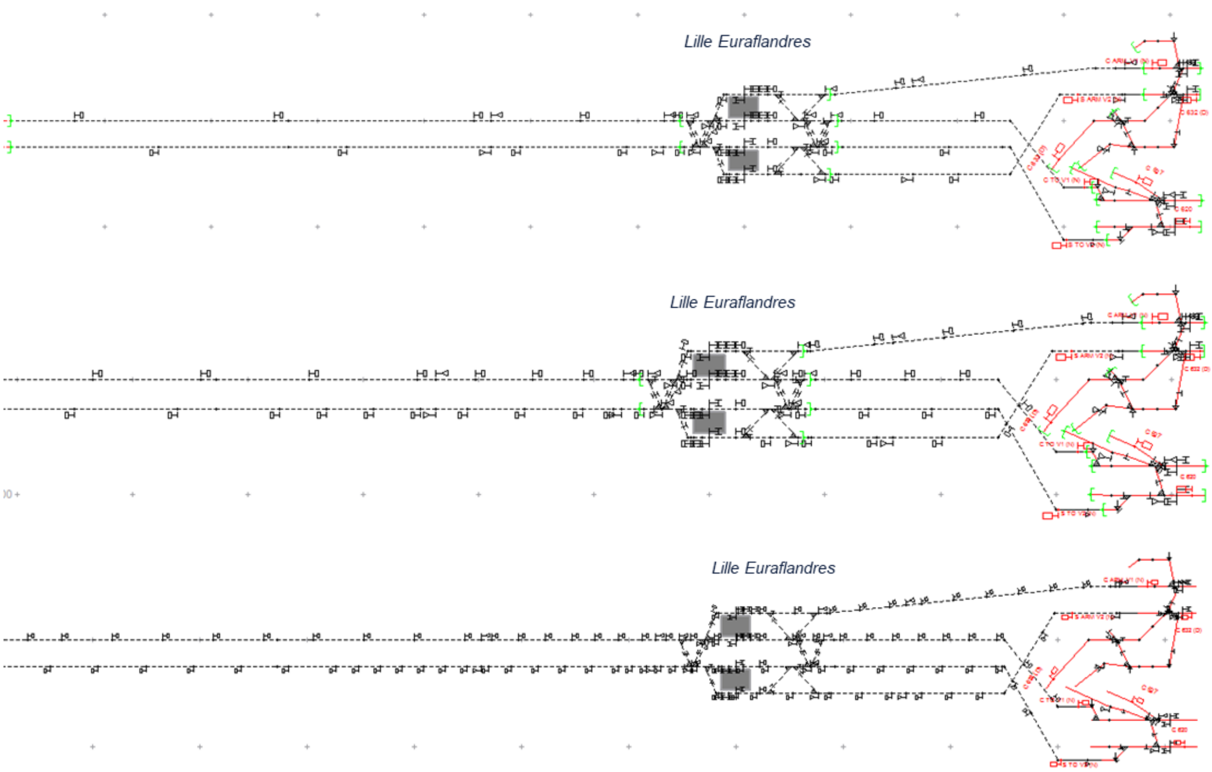


Figure 15. Infrastructure models with TTD, VSS (½*TTD length), VSS (¼*TTD length).

Note: The top panel represents scenario one with only ETCS L2 blocks, the middle panel represents scenario two with ETCS HTD blocks at half distances of the ETCS L2 blocks, and the lower panel represents scenario three with ETCS HTD blocks at quarter distances of the ETCS L2 blocks.

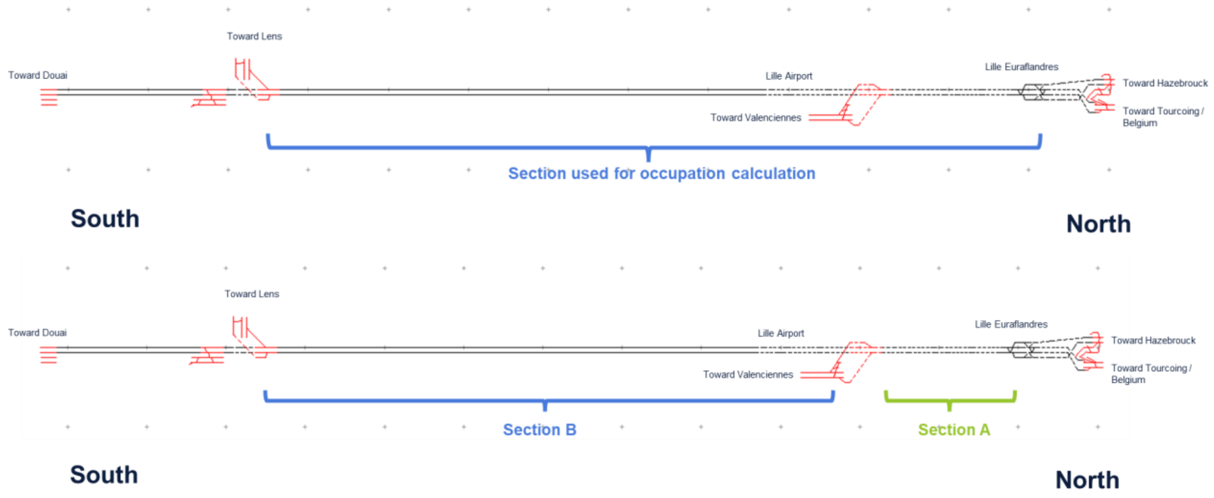


Figure 16. Graphical description of the compared infrastructure sections

Table 5. Infrastructure occupation for evening peak hour (17h-18h)

Scenario	Maximum length of block section	Occupation southbound	Occupation northbound
ETCS L2	1500m	60,0%	58,8%
ETCS HTD Long	750m	47,9%	49,4%
ETCS HTD Short	375m	43,4%	41,8%

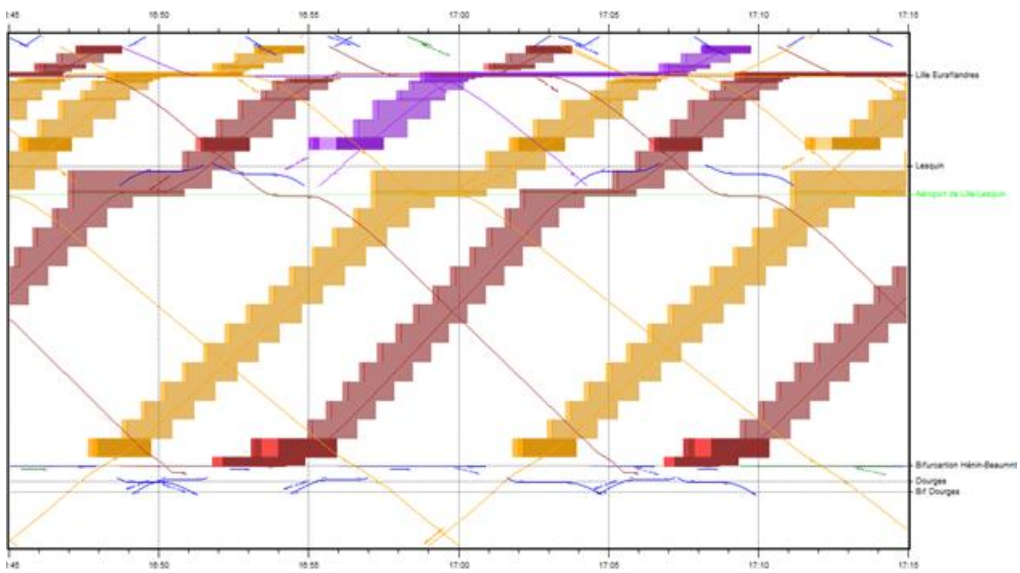


Figure 17. Headway diagram for ETCS L2, 1500m max

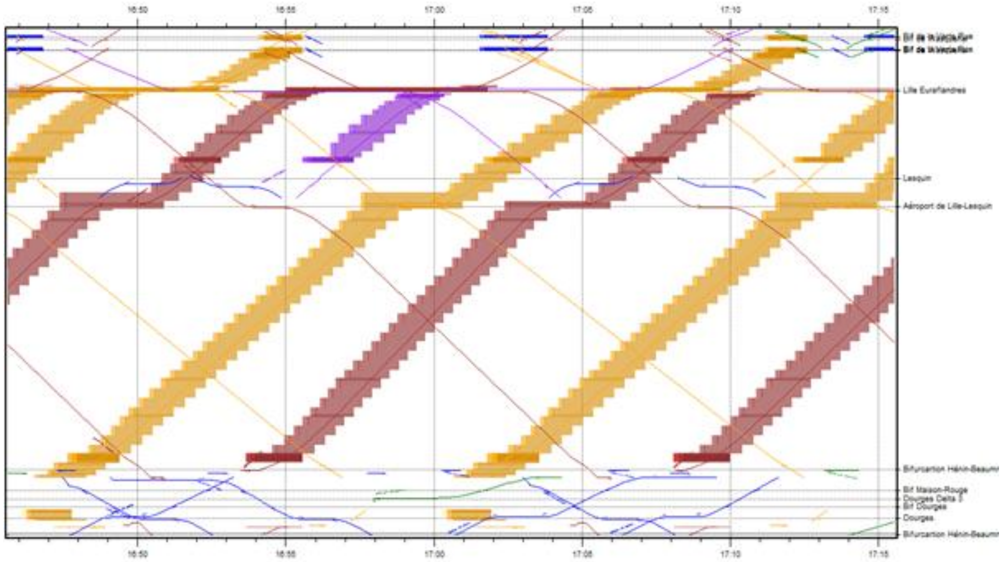


Figure 18. Headway diagram for ETCS HTD, 750m max

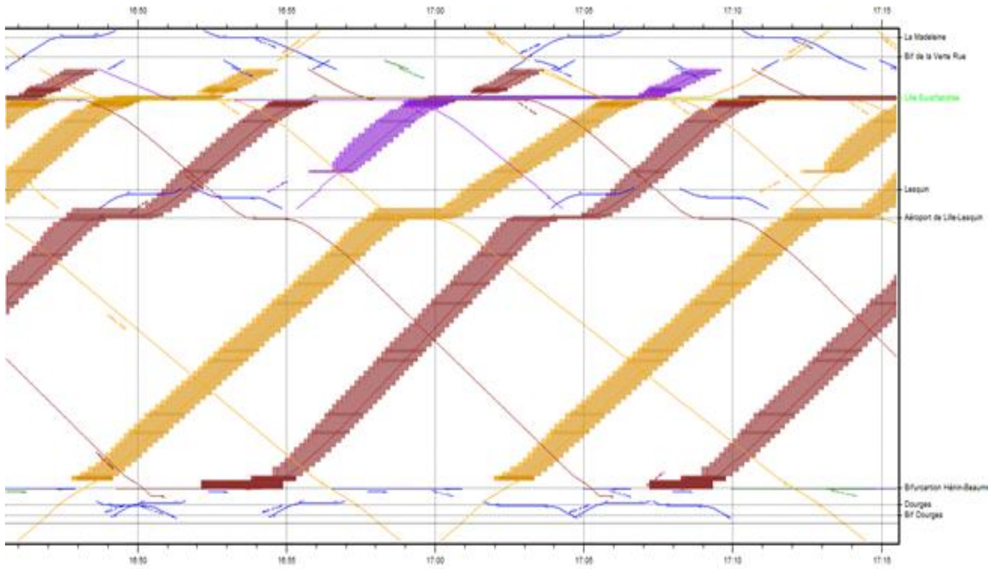


Figure 19. Headway diagram for ETCS HTD, 375m max

The results SNCF obtained from this use case are coherent with what is expected for ETCS HTD capacity behaviour. In line with other studies, SNCF finds an improvement of headways and infrastructure occupation with ETCS HTD. They also compared the time/distance graph and noticed that the block occupations are less capacity-consuming for ETCS HL3. Figures 19 and 20 below depict the accompanying speed distance graph and ETCS braking curves respectively. The conclusion based on expert judgement of the results is that the expected behaviour is reproduced by the model.

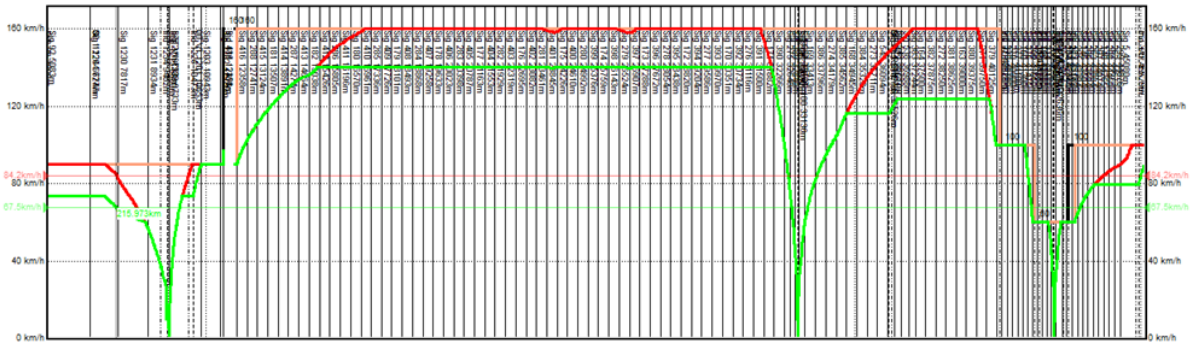


Figure 20. Speed-distance graph from a simulation including braking point, acceleration, respect of the speed limit etc.

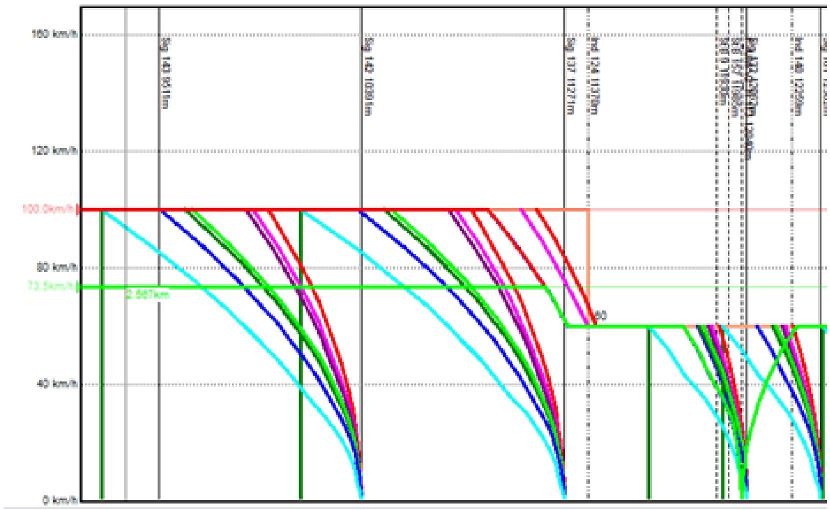


Figure 21. ETCS Braking Curves from a simulation including braking point, deceleration, length of the curve, correspondence with the ERA simulator etc.

7.3. NG-Brake

7.3.1. Description of concept

The work on Next Generation (NG) brake systems in FP2-R2DATO deals with Brake and Adhesion Management System (BAMS). In short, this system combines Adhesion Detection System (ADS) between trains, through communication with other onboard systems like the ATO onboard module or the ETCS system. This communication might pass through other trackside systems which store the adhesion values and share them with other trains, such as the ATO Trackside and TMS. The detailed architecture will be defined in FP2-WP17 (Next

Generation Brake Systems with adhesion management functions – Phase 1: Demonstrator preparation and pre-validation).

In a future realization, the BAMS onboard will determine the current adhesion or receive the predicted adhesion of the railway line ahead. Based on this, the BAMS will determine the maximum available deceleration and supply current K_{dry} and K_{wet} values to the ETCS unit and/or available adhesion information to the ATO onboard unit. This will activate adhesion related functions, *e.g.* sanding units when the track is too slippery.

The improved knowledge on the current situation and the better system performance will result in more predictable and shorter deceleration distances in wet and dry conditions.

7.3.2. Developed simulation methods

Acceleration and braking are limited by the traction force and braking force that can be applied to the track. This force is generally represented by the factor μ, representing the maximum horizontal component of the traction or braking force on a wheel. In slippery conditions, the value of μ is lower. The effect of lower traction and braking forces can be modelled. This requires a simulation in which it is possible to adjust rolling stock parameters representing tractive effort and maximum deceleration, as well as accurate modelling of the effect of these curves on driving behaviour, including microscopic track geometry. To model the effect of adhesion on tractive and braking effort curves, one may calculate these parameters externally or internally with respect to the train simulation software. This calculation follows the method below.

Braking

Better adhesion management is intended to be modelled by using the Gamma braking model and adjusting the K_{wet} parameter. This is because the BAMS, according to current development, intends to do exactly that. The NG Brake functionality fits best to multiple unit trains, which are mostly Gamma trains. One limitation posed by the current development of the technique is that it restricts application, and hence also simulation of NG Brake, to gamma trains only, as lambda trains do not use K_{dry} and K_{wet} (see chapter 7.1 above). For trains using the Gamma braking model, the safe emergency brake deceleration $A_{brake_{safe}}$ (in $\frac{m}{s^2}$) on flat track can be expressed as follows:

$$A_{brake_{safe}} = K_{dry}\big(K_{wet} + M_{NVAVADH}(1 - K_{wet})\big) \cdot A_{brake_{emergency}} \qquad (1)$$

where K_{dry} is the braking degradation coefficient in normal adhesion conditions, K_{wet} is the braking degradation coefficient in low-adhesion conditions, $M_{NVAVADH}$ is a nationally determined value describing an available adhesion weighting factor, and $A_{brake_{emergency}}$ is the deceleration rate for emergency braking.

More precisely, the onboard correction factor K_{dry} quantifies the dispersion of the emergency braking performance on dry rails as a factor of $A_{brake_{emergency}}$. The onboard correction factor K_{wet} quantifies the loss of emergency braking performance on a reference reduced wheel/track adhesion value (e.g., wet rails). The national value $M_{NVAVADH}$ (available adhesion weighting factor) is currently set to 0 in Sweden. Possible values for this value are in the range $[0,1]$ in steps of 0,05. Some other countries, such as the Netherlands, use $M_{NVAVADH} = 1$, which implies that K_{wet} does not affect the calculation of $A_{brake_{safe}}$ in this case. Since $A_{brake_{emergency}}$, K_{dry} and K_{wet} are speed interval dependent, $A_{brake_{safe}}$ is defined for the same speed intervals. From this, A_{safe}, the safe emergency brake rate that takes track gradient into account, is expressed in a simplified form either as equation 2 for locations (sections of track) without reduced adhesion or as equation 3 for locations with reduced adhesion:

$$A_{safe} = A_{brake_{safe}} + A_{gradient} \tag{2}$$

$$A_{safe} = \min\left(A_{brake_{safe}}, A_{MAXREDADH}\right) + A_{gradient} \tag{3}$$

$A_{MAXREDADH}$ comes from a national value and depends on the train category used. This value will be changed in cooperation with FP2-WP17 Next Generation Braking Systems, as they decide whether the NG Brake systems shall enhance this value. $A_{gradient}$ represents the acceleration/deceleration due to gradient of the railway track. A_{safe} is calculated with respect to (1) speed and (2) position with respect to target. Thus, A_{safe} can be calculated from a mix of the two expressions if there are sections of track indicated as reduced adhesion. From this, the emergency brake deceleration (EBD) curve can be calculated which, together with the service brake deceleration (SBD) curve, heavily influence the calculation of the other intervention and warning curves.

The aim is to alter K_{wet} factors in relevant use cases and for relevant trains to model improved adhesion management, with input from FP2-WP17 Next Generation Brake Systems. One can then compare to cases without assuming this improvement, with elements of reduced adhesion conditions in both.

The new braking curves under reduced adhesion conditions will be compared with the driver behaviour under reduced adhesion conditions. Based on experience, the driver will approach a zone with reduced adhesion cautiously.

Traction

The tractive effort curve under slippery conditions will be constrained by the maximum force the axles with traction can apply to the track. This force is dependent on the weight resting on the motorized axles, as well as the value of μ. The value of μ is speed dependent, and will behave according to the factorized Curtius-Kniffler formula:

$$\mu = P\left(\frac{7.5}{v + 44}\right) + 0.161 \qquad (4)$$

where v is the speed in kilometres per hour and factor P determines the relative position of the curve.

To compare the situation with NG Brake trains to a situation without NG Brake trains, one shall repeat the NG Brake simulation with one that models existing (human) low-adhesion traction and braking behaviour. For this, we present a list of scenario variations, limitations and assumptions below.

Variations

- Braking:
    - Reference: Manual driver behaviour with slippery conditions, since ATO is not working under slippery conditions. Driver is aware of slippery conditions due to a notice of traffic control or experience and drive carefully with a reduced percentage of maximum braking rake. This value will be defined in WP9.
    - NG Brake: Braking with NG Brake, to be defined in accordance with FP2-WP17 Next Generation Brake Systems and following the method above
- Slippery condition scenarios:
    - Network wide bad conditions. For this, we assume a value of $\mu = 0.05$. This would lead to a braking rate of 0.5 m/s², plus the effect of the Eddy-Current (Magnetic Track Brakes are not considered) brake if all axles are braked. For higher μ's, the available braking rate will generally exceed the braking rate used in regular operations, so they do not need to be considered. For traction, higher values would matter to the acceleration potential, but these are still not relevant in a simulation that aims to estimate the capacity effect of an NG Brake traction system. Namely, a driver and an NG Brake traction system both drive at the maximum adhesion limit with slip detection.
    - Local leaves on the track. For this, we assume a value of $\mu = 0.03$. This would lead to a braking rate of 0.3 m/s² plus the effect of the Eddy-Current brake.
- Deterministic vs. Stochastic
    - The Dutch SAAL simulation will be deterministic only. The Swedish Eastern link will go up to stochastic.

Limitations and assumptions

- The ETCS curve in dry conditions ($\mu > 0.15$) does not change
- Traction and acceleration are both modelled.
- Values measured at braking are also applicable for traction and vice versa.
- The between-train adhesion prediction system is not explicitly modelled, only the effect of more accurate braking and the specific location of slippery track.
- Without NG brake, drivers in trains with ATO GoA2 will switch to manual driving.
- Without NG Brake systems, drivers are notified for slippery track by traffic control or know by experience and drive carefully with reduced braking effort as long as a notice is applied. Slippery track notices are applied form station to station, as this makes the simulation much more convenient while also offering maximum comparability with the current situation.

7.3.3. Implementation in software

RailSys

There is no need to adjust RailSys to model the described method, as one can alter tractive effort curves as well as the relevant braking parameters for individual trains within the Timetable and Simulation Manager. One can then simulate separate trains of the same rolling stock type individually, one with low adhesion and one with normal adhesion, to proxy a section of track having reduced adhesion conditions for some period of time.

Specifically, for acceleration, one defines two rolling stock types per train, with different traction curves for normal and low-adhesion conditions. To calculate this traction curve, one can use scripts written outside RailSys, then import these traction curves in the Timetable and Evaluation manager. For braking, one can make changes to the relevant discussed parameters (K_{dry}, K_{wet}, μ, and derived braking effort A_{safe} in m/s^2). Using this functionality, one can design specific cases where some trains in a timetable are set to experience reduced adhesion conditions in some area. The size of this area will be iteratively adjusted during the respective simulation studies to ensure capturing the correct granularity. Finally, to compare this situation with NG Brake trains to a situation without NG Brake trains, one repeats the simulation with trains that one models with existing low-adhesion traction and braking behaviour.

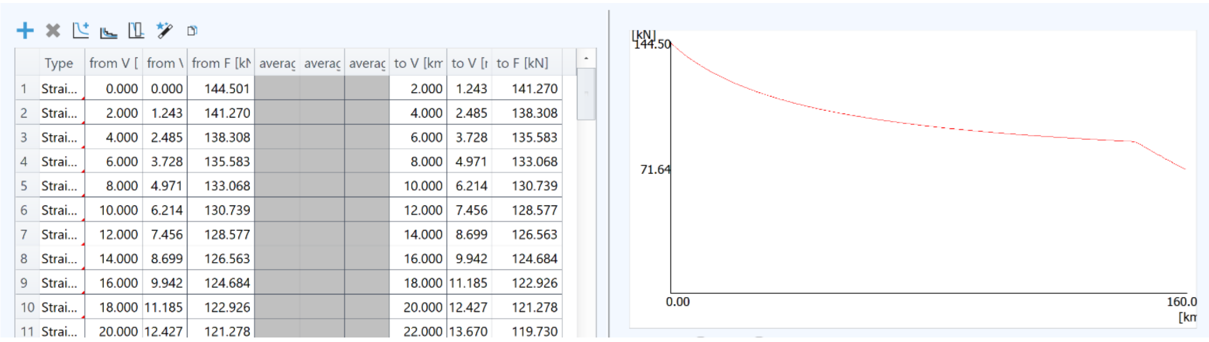
HESE

HESE tool does not require modifications or development for handling headway calculations with and without NG brakes. The effect will mainly be handled by adjusting Gamma parameters (K_{dry} and K_{wet}) in train model data, which enters the software exogenously.

7.3.4. TRL4 validation

To validate the NG Brake simulation methods described above, previous studies do not exist. Hence, in accordance with the TRL4 standard required, ProRail carried out a simple RailSys case study on a few-kilometre line between two train stations in the Netherlands – *Almere Parkwijk* and *Almere Buiten*, with fictive ETCS L2 block sections.

Specifically, this validation models train 1, of the rolling stock type SNG12(4+4+4), with a manually calculated tractive effort curve for low-adhesion conditions ($\mu = 0.04$). Correspondingly, this validation limits service and emergency braking to 0.4m/s², assuming all axles are fit with brakes. It inputs the tractive efforts in kN for each 2 km/h interval up to the maximum speed of 160 km/h. Figure 21 below shows how this looks in Railsys, in the Timetable and Simulation manager *Edit Unit Types* submenu. The validation then schedules train 2, also of the type SNG12(4+4+4), with its standard tractive effort and braking curves (tractive efforts with up to three-times higher kN values at low speeds, service braking of 0.7m/s², and emergency braking of 1.0m/s²).



	Type	from V [	from \	from F [kN	averag	averag	averag	to V [km	to V [r	to F [kN]
1	Strai...	0.000	0.000	144.501				2.000	1.243	141.270
2	Strai...	2.000	1.243	141.270				4.000	2.485	138.308
3	Strai...	4.000	2.485	138.308				6.000	3.728	135.583
4	Strai...	6.000	3.728	135.583				8.000	4.971	133.068
5	Strai...	8.000	4.971	133.068				10.000	6.214	130.739
6	Strai...	10.000	6.214	130.739				12.000	7.456	128.577
7	Strai...	12.000	7.456	128.577				14.000	8.699	126.563
8	Strai...	14.000	8.699	126.563				16.000	9.942	124.684
9	Strai...	16.000	9.942	124.684				18.000	11.185	122.926
10	Strai...	18.000	11.185	122.926				20.000	12.427	121.278
11	Strai...	20.000	12.427	121.278				22.000	13.670	119.730

Figure 22. Input Traction Curve for Low Adhesion in RailSys

To verify that this method leads to different driving behaviour, this validation then consecutively models both trains to run a section between the two train stations. Indeed, changing the traction and braking parameters in accordance with the developed simulation methods leads to a difference in output speed distance graphs, as shown in figure 22 below. This proves that adjusting the adhesion and braking parameters, as per the method outlined in chapter 7.3.2, allows for accurate simulation of low-adhesion conditions, which in turn allows for capacity analysis of the effect of NG Brake.

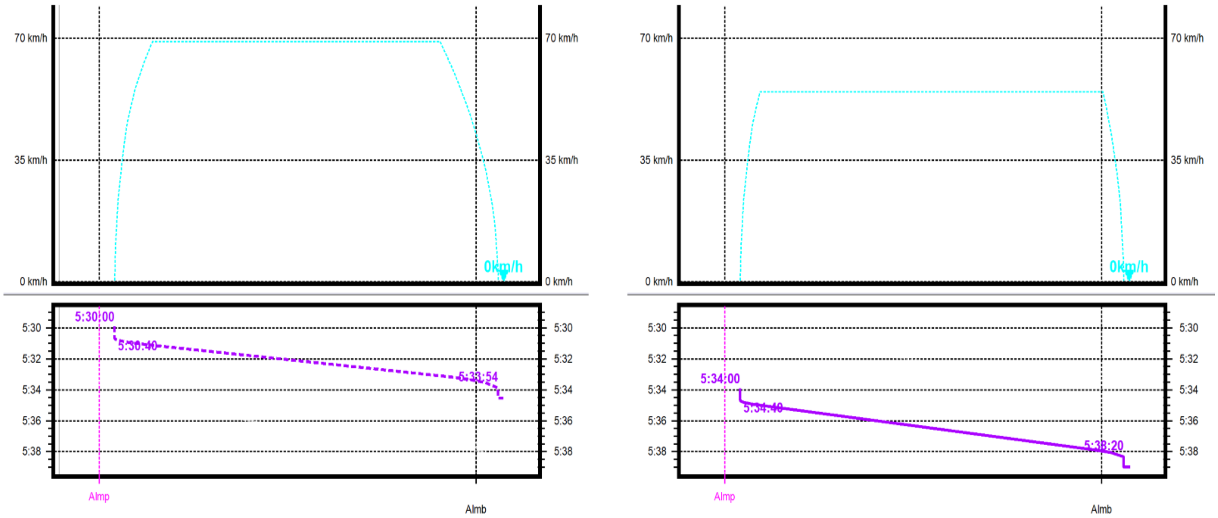


Figure 23. Speed- and Time-distance diagrams for low (left) and normal adhesion (right)

Note: for the above validation, both trains have the same scheduled runtime. We use running time supplement to show that a normal adhesion train (right panel) has a different traction and braking curve when compared to a low adhesion train (left panel), meaning that the trains have the same scheduled runtime between departure and arrival. This is why the maximum obtained speeds between stations differ.

7.4. C-DAS

7.4.1. Description of concept

As described in higher detail in FP1-MOTIONAL Deliverable 15.1, C-DAS (Connected-Driver Advisory System) is a driver advisory system with a communication link to external control systems in each controlled area in which the train operates. This enables the provision of schedule, routing, and speed-restriction updates to trains in near real-time. It also enables the transmission of information from trains to these systems to improve regulation decisions.

C-DAS consists of two main systems: the Trackside (TS) system and the Onboard (OB) system. These systems work together to provide real-time information and recommendations to train drivers. The OB subsystem of a C-DAS can be integrated on the train driving desk itself or it can be a hand-held equipment (tablet). It receives the recommendations generated by the TS system and provides them to the train driver in real-time, displaying the recommendations on the driver's interface, typically through visual displays or audio alerts. The OB system can also provide the driver with other useful information such as track gradients, distance or estimate time to upcoming important points or position against scheduled. In return, the OB system may also collect onboard data, such as train performance metrics, and transmit it back to the TS system for further analysis. The system can give advice for example on punctual execution of the timetable and energy optimal driving. However, the system heavily relies on the train driver following the output from the C-DAS. C-DAS brings the following expected benefits supported by continuous data from TMS:

- Optimize the use of capacity and/or increase the regularity of a network by increasing the predictability of train runs.
- Improve safety by limiting the number of restrictive signals encountered and reducing braking phases.
- Utilize the running time supplements to reduce energy consumption, carbon emissions, and wear and tear, while still operate punctual.
- Improved driver guidance with updated information for the journey and disturbance investigations by utilizing data collected by C-DAS.
- Reduction in operational disturbances by limiting the number of restrictive signals encountered.

7.4.2. Developed simulation methods

The development and use of a C-DAS functionality in the simulation tools should enable the user to estimate the capacity effect of C-DAS. This means that trains should be simulated microscopically. It also means that it should be possible to alter the driving profiles, or the input parameters leading to certain driving profiles, for individual trains. Therefore, the developed simulation methods will address how exactly to model different driving profiles and how this links to capacity effects. Note that the same reasoning holds for ATO – theoretically, C-DAS functions as ATO GoA1 (see chapter 7.5.1 below), and ATO requires similar driving-style-related adaptations in simulation models.

More specific simulation requirements are as follows. The capacity effects of C-DAS by using a coasting driving strategy should be considered. Therefore, the simulation tool should consider this driving strategy during simulation that can be adjusted for various purposes on a (partial) network. C-DAS aims to arrive exactly on-time at the next stop, critical timetable point or other timing points as defined by the simulation expert, which should also be the aim for this driving strategy in the simulation tool. The simulation expert should be able to analyse the simulation results for instance regarding the running times, timetable stability, robustness (e.g., model punctuality or recovery time), and energy consumption. Not all train drivers in practice apply the C-DAS and even during a single train run C-DAS might not be completely used, thus, the driving strategy should be adjusted per train and timetable points to vary the percentage of C-DAS trains. For each individual train the amount and distribution of the running time supplements and the braking behaviour can be adjusted to see the effects of the C-DAS driving behaviour on evaluation criteria such as capacity utilization, robustness and energy consumption. The usage of the C-DAS also might influence the driver's reaction time, which should be adjustable in the simulation tool.

The simulation studies with C-DAS are focused to analyse the effect of different driving strategies on the infrastructure capacity utilization, timetable robustness and traction energy consumption of trains. The driving strategy of trains is changed during different simulation runs. Basically, the different scenarios as described in the paragraph above are analysed, such as varying the percentage of C-DAS trains, and varying the amount of running time supplement and their distribution across the different stages of a train run.

Compliance to C-DAS

When modelling Connected Driving Advisory Systems (C-DAS) for timetable planning, several limitations and assumptions must be considered, as C-DAS systems face the complexity of real-world railway operations, which may not always align perfectly with the assumptions made in the models. These advisory systems rely on the assumption that drivers will consistently adhere to the suggestions provided, overlooking potential human factors such as fatigue, distraction, or individual driving styles that may influence adherence. Additionally, the effectiveness of C-DAS is contingent upon accurate predictive modelling of driver behaviour, which may be challenging due to the complexity of human decision-making processes and the variability in individual driver responses. Thus, this intermediate link between the C-DAS and the train introduces different uncertainties in terms of delay in applying the suggested command, poor precision following a reference speed or driving commands suggested, or not following advices at all. These human-related aspects are difficult to model in simulation.

Driving strategy with C-DAS

C-DAS aims to influence the driving strategy of a train driver by speed or coasting advice. Therefore, during simulation, one should include the driving strategy of C-DAS. A train driver can apply different driving strategies to run a train. Figure 23 below gives some examples of different driving strategies that this section discusses, where the left panel shows the speed profile for long distance between stops and the right panel shows the speed profile for short distance between two stops. The first driving strategy is the minimum time train control (MTTC), where the aim is to minimize the total running time of a train (i.e., run as fast as possible). In practice this driving strategy can be applied if a train is delayed. During MTTC the train driver accelerates as fast as possible (maximum acceleration) to the speed limit. Afterwards, the speed limit is maintained by cruising or speed-holding. In the end, maximum braking is applied to come to a standstill.

However, the timetable includes running time supplements that are the extra time above the technical minimum running time in the timetable to cope with running time variations and to recover from small delays (Scheepmaker and Goverde, 2015). If the train is running on time (i.e., not too early and not too late), then the train can apply different eco-driving strategies in order to save energy and arrive on time at the next stop or critical passing point in the timetable.

The train driver can apply cruise control to drive according to a reduced maximum speed or RMS below the speed limit. The driving strategy consists of the driving regimes maximum acceleration, cruising, and maximum braking, see Figure 23. Another driving strategy that saves in general more energy than RMS is maximum coasting (MC). During MC the train applies maximum acceleration, cruising at the speed limit (if possible), coasting, and maximum braking, see the left picture in Figure 23. During coasting the train rolls over the infrastructure and no traction or braking control is applied (only train resistance). Trains do have a big potential for coasting, due to the very low rolling resistance (i.e., low friction between steel wheels and steel tracks) and due to the heavy train load. If the distance between two stops is too short, the train directly starts from acceleration to coasting, see right picture in Figure 23.

Energy savings, compared to *e.g.* the MTTC driving strategy, depend on the distance between stops and the amount of running time supplements. Scheepmaker, et al. (2020) showed that energy savings of about 13%—18% are possible for a long-distance train, while for a short-distance train savings of about 24%—28% are possible with the eco-driving strategies with 5% running time supplements compared to the MTTC driving strategy. More background information regarding the RMS and MC driving strategy can be found in Scheepmaker, et al. (2020).

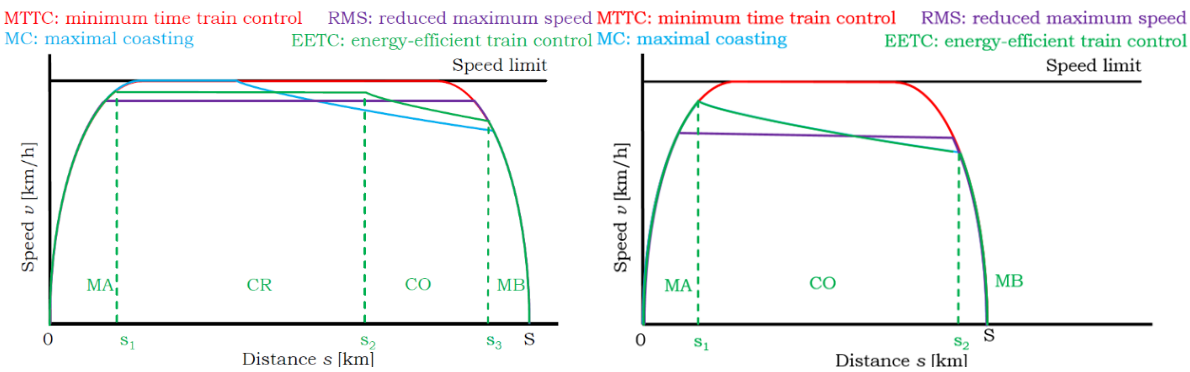


Figure 24. Different (energy-efficient) train driving strategies for different driving regimes

Note: the energy-efficient driving regimes (MA, CR, CO and MB) are depicted as they would look on flat track. Left picture: long distance between two stops. Right picture: short distance between two stops (MA = maximum acceleration, CR = cruising, CO = coasting, MB = maximum braking, s_1, s_2, s_3 = switching points between driving regimes).

Eco-driving is normally not considered during timetable design and simulation, but should be involved when considering C-DAS during simulation, because C-DAS is focused on giving eco-driving advice. Normally a RMS driving strategy is considered in timetable design and simulation to consume the running time supplements. If a train in practice applies the MC driving strategy, it means that it will run ahead of schedule. This can be seen from the time-distance diagrams (right-above) in Figures 24 and 25 below.

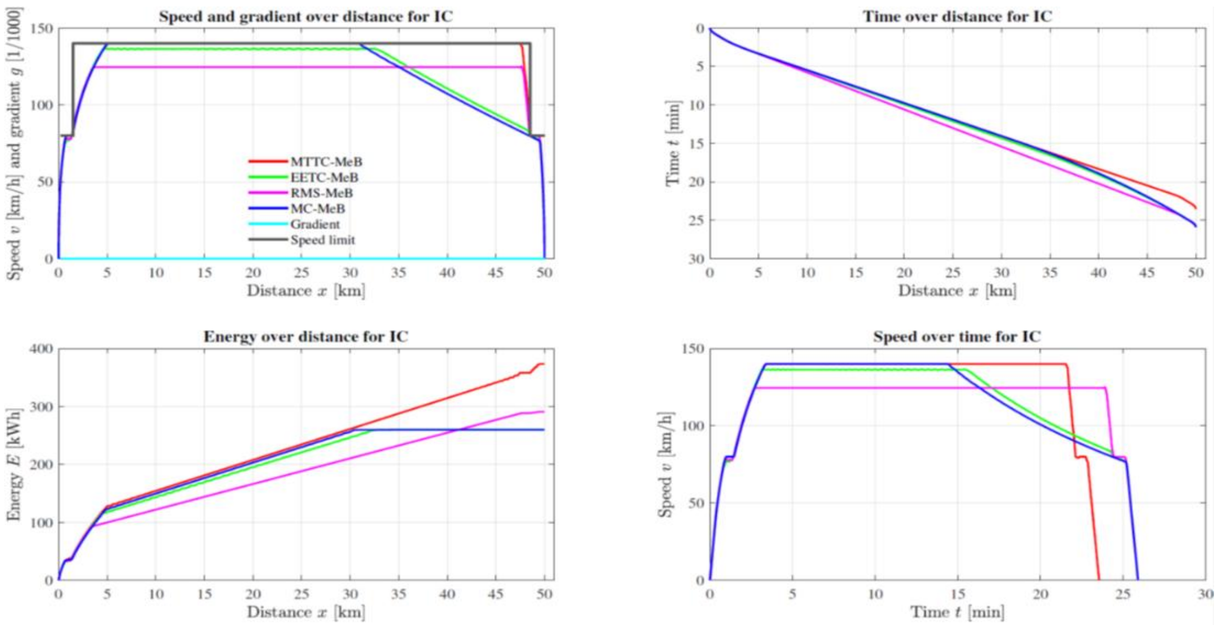


Figure 25. Speed-distance, time-distance, energy-distance and speed-time diagrams, express train

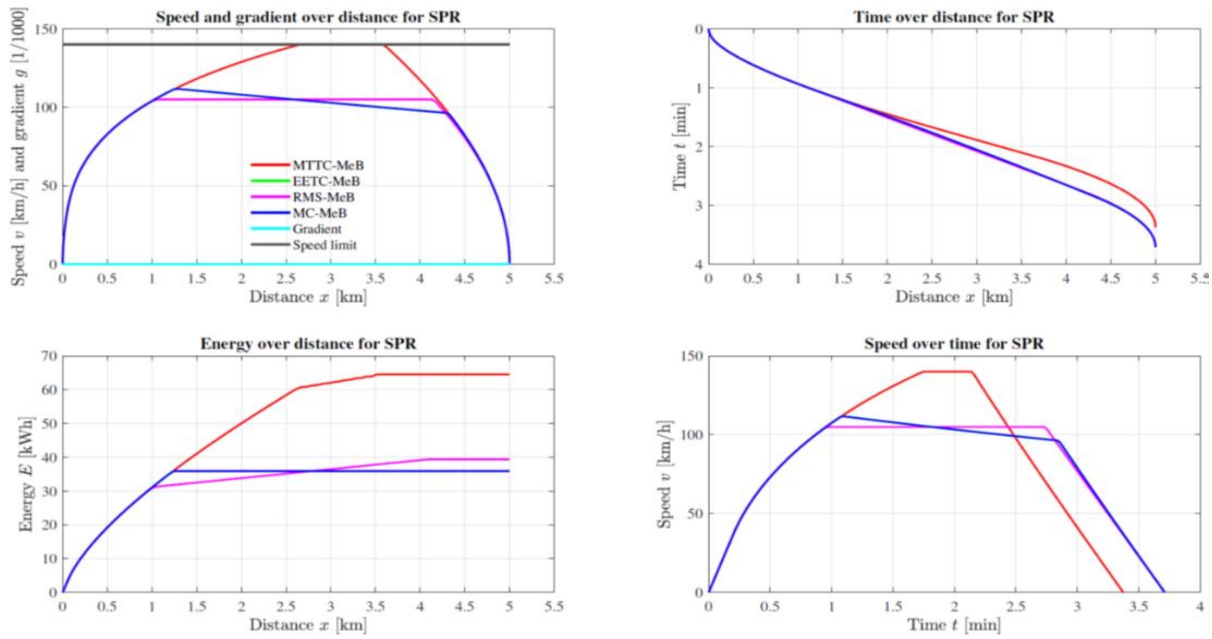


Figure 26. Speed-distance, time-distance, energy-distance and speed-time diagrams, commuter train

7.4.3. Implementation in software

RailSys

Within RailSys, one can alter the driving strategy in the settings of a train when one sets up the individual timetable run of that train. Currently, RailSys trains maximize the cruising time, while they switch to a maximum speed driving regime upon suffering a delay. This means that RailSys does already contain a way to adapt the driving style within its system architecture. However, RailSys does not yet, but probably will soon, include the MC eco-driving strategy. Note that these driving strategies will not be dynamic, that is, a new max cruising optimum will not be calculated for each clock tick in the simulation. For our developed methods, this suffices.

The MC driving strategy also means that trains can run ahead of schedule, but this is limitedly possible in RailSys. Trains should be forced to run before schedule independent from a scheduled stop minimum stopping time or a skipped operational stop (both functionalities of the existing RailSys solution). Trains in RailSys are unable to apply the minimum running time driving strategy if they run on-time and RailSys is not able to draw negative values for delays for running time delays. In addition, realization data of the Netherlands also indicates that trains run ahead of schedule, so also for validation of simulation results it is important to have the possibility in RailSys simulations to run ahead of schedule.

Partners of this Work Package that aim to use RailSys for their simulations of driving strategies, be it under C-DAS or ATO, are in ongoing talks with the developer on implementing the following functionalities:

1. Trains should be able to run ahead of their schedule (e.g., passing times) using the MC driving strategy, while arriving/passing on time at the next stop/critical timetable point.
2. Maximal coasting driving strategy should be available to approach C-DAS behaviour based on the coasting advice of the C-DAS *Roltijd* of NS, which consists of a single coasting phase between two stops/critical timetable points.

Aside from the development wants mentioned above, in the Netherlands, timetable stability and robustness are investigated without the influence of traffic control. This means that disturbances can happen during the simulation, but dispatching is not permitted. In addition, in general the interlocking system in the Netherlands keeps the order of the trains fixed according to the schedule, and that can be manually adjusted by the dispatcher if needed. To have realistic results of the simulation runs that can be validated using realization data, it is necessary that RailSys enables the option to keep the order of trains fixed according to the schedule. This option is currently not available in RailSys, and therefore, should be specified to improve RailSys.

RailVOS

Although railVOS (originally OPTICON) was initially conceived as an energy-focused tool, it is being upgraded with new functionalities, in this case towards capacity evaluation. In its origins, it was developed as an eco-driving tool, so it is already capable to generate time-compliant energy-efficient driving profiles suitable to be implemented in C-DAS systems. However, the tool required some modifications to be able to correctly model the infrastructure information needed for capacity analysis (e.g., tracks, switches, signals).

Additionally, the capacity evaluation and assessment algorithms are currently being developed, together with the integration of the existing C-DAS eco-driving algorithms with the developed capacity simulation tool.

As a summary, the following developments are being implemented:

- Updated C-DAS eco-driving algorithms with improved energy efficiency to be integrated in the new capacity tool (see Figure 26 below, left panel).
- New simulation tool railVOS (successor of OPTICON) with capacity evaluation functionalities is under development and validated up to TRL4 using synthetic data (see Figure 26 below, right panel).
- Integration of C-DAS eco-driving algorithms with the dynamic simulation tool of the trains and the capacity evaluation.

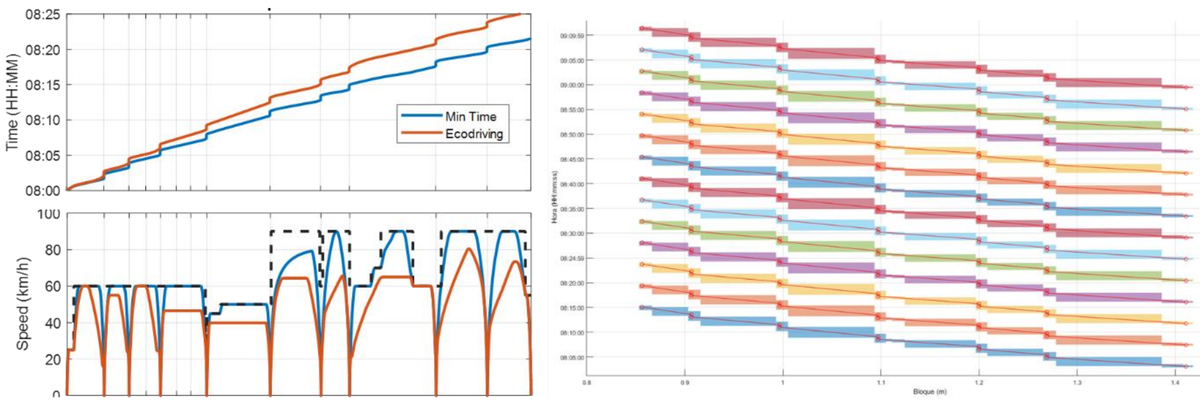


Figure 27. Example of minimum time and eco-driving speed profiles and time-distance lines (left), and track occupation calculation (right)

TMS_SIM

TMS_SIM supports the analysis of "draft" timetables prior to creating the final timetable. The addition of C-DAS simulator in the simulation environment allows to compare how the trains behave with/without C-DAS in the model. The integration of C-DAS into the Indra simulation environment will demonstrate how the route calculation process in the TMS can be enhanced through this linkage. Lastly, the considerations of different “driver modes” in relation with the C-DAS recommendations compliance provides a better characterization of the model.

The C-DAS simulator communicates with the TMS (Traffic Management System) and with the driver simulator to offer drivers optimal speed profiles and routing strategies based on real-time conditions of the rail network.

In this scenario TMS + C-DAS + Driver / Train simulators functionality, we simulate in order to compare two scenarios:

1. Current functionality (without C-DAS simulation): This scenario incudes train simulator that run following the timetable taking in account infrastructure and train features.
2. With C-DAS functionality: This scenario integrates C-DAS in the simulation environment being responsible of the Movement Authorities sent to the Driver Simulator.

This incorporation of the C-DAS simulator will enable improvements in the INDRA simulation environment improving the current route calculation process and assessing how the trains would behave with C-DAS deployment in specific infrastructure networks.

TMS_SIM provides views to monitor the train movements in the network. In figure 27 below, we can see the simulated train in synoptic view. Figure 28 below shows how the software represents interlockings.

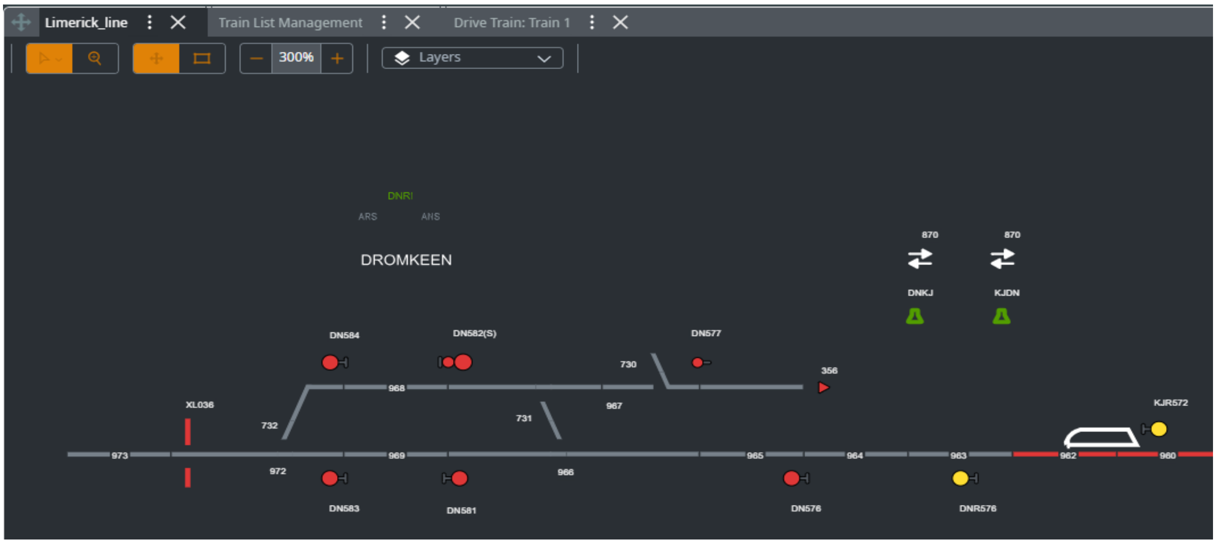


Figure 28. TMS_SIM synoptic view

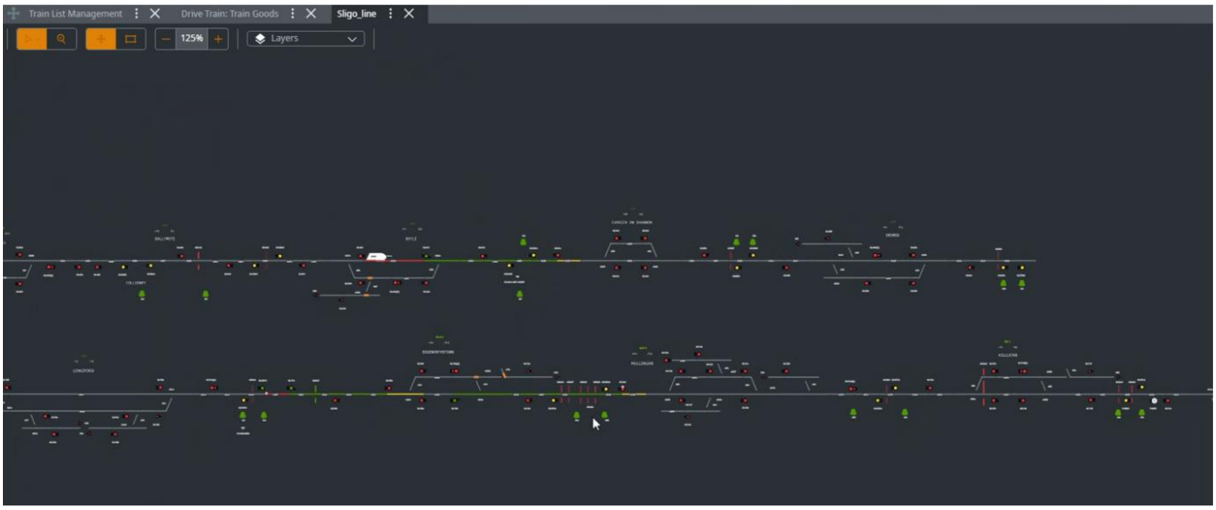


Figure 29. Several interlockings in the TMS_SIM

TMS_SIM allows the configuration of scenarios either with an initial timetable or even launching unscheduled trains. To include C-DAS, INDRA added a "Semi-automatic" function that defines the "C-DAS driving mode". The functionality includes the speed restriction provided by the C-DAS ("Cruise" in "Active speed restriction" section) that is received by the C-DAS OB and processed by the TMS_SIM. Figure 29 below shows what the corresponding menu interface looks like.

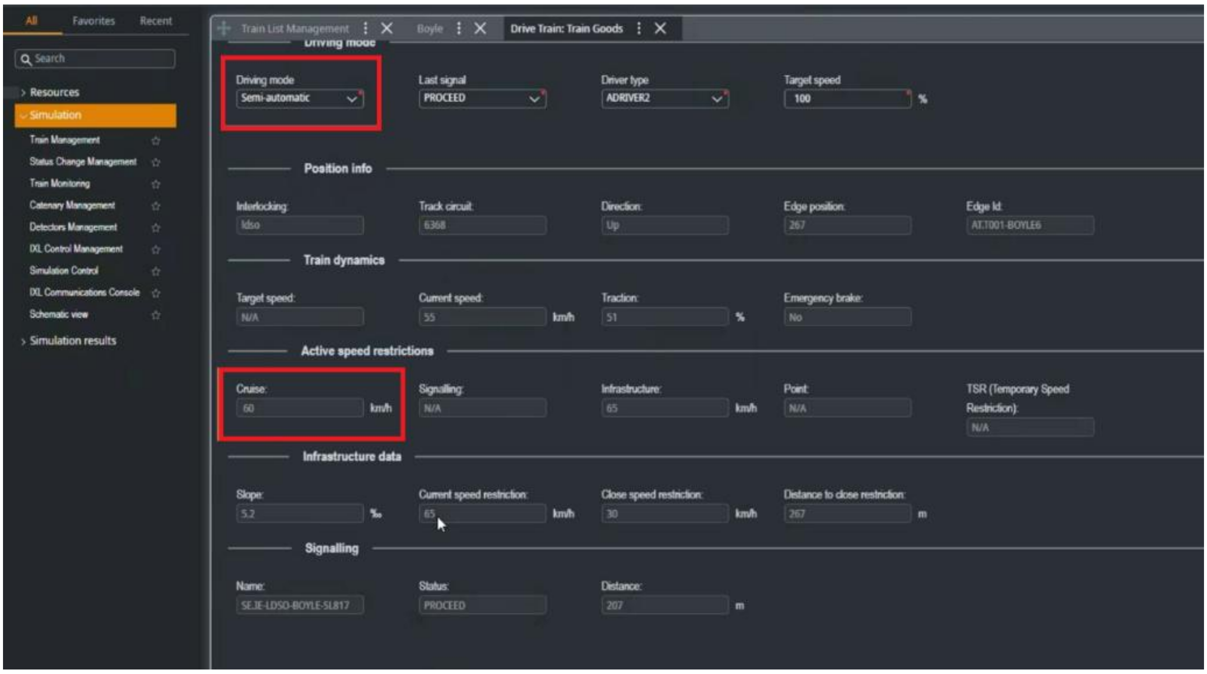


Figure 30. Train path information in the TMS_SIM

Future tests will be based on the driver mode in relation with C-DAS information testing with different topologies networks and the effects of TSRs.

7.4.4. TRL4 validation

TRL4 validation method applied in RailSys

This section considers the TRL4 validation for the methods of the coasting driving strategy, running ahead of schedule and keeping the order of trains as scheduled by using RailSys.

First the validation of the coasting driving behaviour is discussed. The validation of the coasting driving strategy by using RailSys will be performed by both static timetable analysis as well as deterministic simulation runs. In the static analysis different train categories will be scheduled with a coasting driving strategy. The speed/gradient-distance diagrams will be analysed for the coasting behaviour and it will be checked if the trains arrive exactly on-time at the next stop or critical timetable point. An example of these diagrams from RailSys can be found in Figure 30 below.

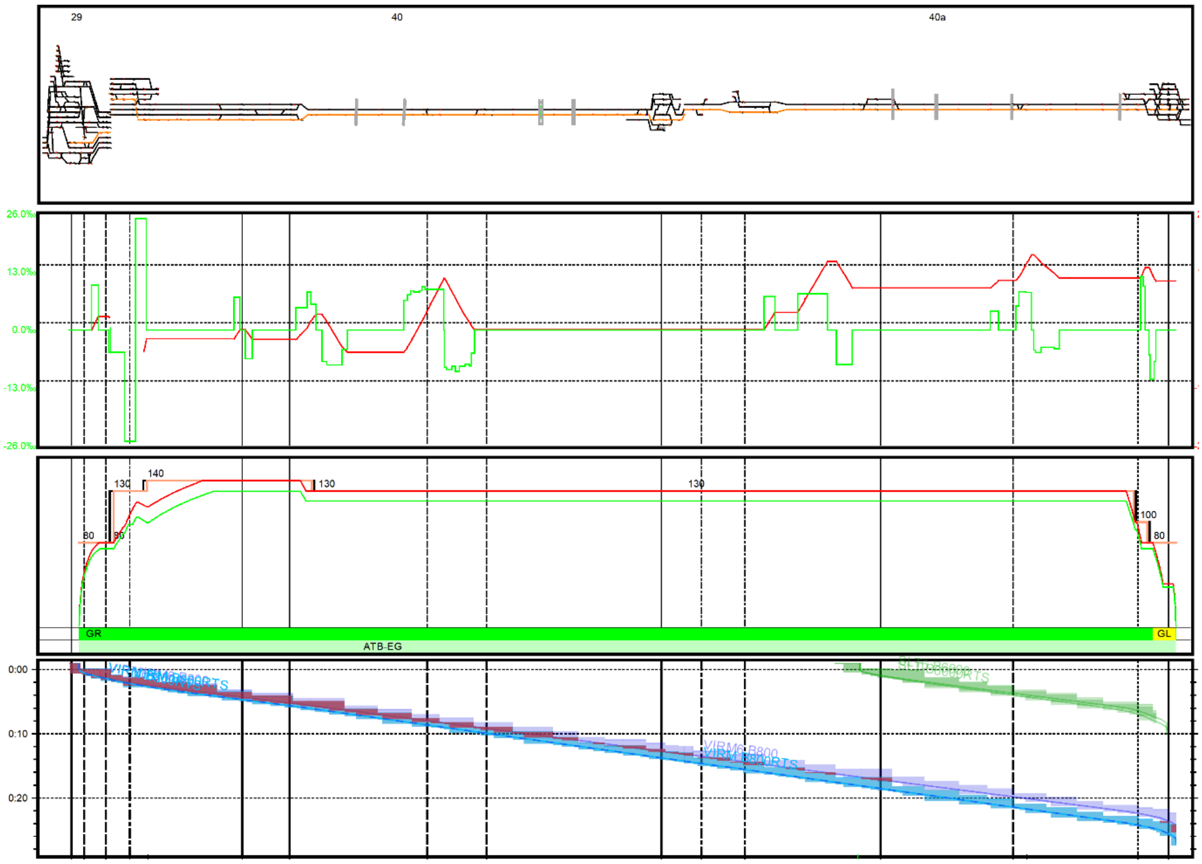


Figure 31. Example of an infra-distance (above), gradient-distance (row 2), speed-distance (row 3) and time-distance (below) diagram from RailSys for Coasting Validation

During the deterministic simulation runs the dynamic behaviour of the coasting driving strategy will be tested, especially to see the effects of delays on the driving strategy by switching between coasting and running as fast as possible. Similar to the static analysis, the speed/gradient-distance diagrams will be analysed. Furthermore, the simulated time-distance diagrams will be analysed and compared with the scheduled diagrams.

Second, the method for trains running ahead of schedule will be validated using RailSys. The coasting driving strategy will be used to evaluate the deterministic simulation run to see if trains run ahead of schedule at intermediate timing points. Furthermore, the passing times at critical timetable points (i.e., interaction with other trains) and the arrival times at the next scheduled stop will be analysed to see if trains are on-time. The running time computation tables and time-distance diagrams of RailSys will be used to validate the method.

Third, the method of keeping the scheduled order of trains during simulation will be validated by using RailSys. Specifically, deterministic simulation runs will be applied and junctions will be analysed, where different trains merge and diverge in different directions. Around those locations the scheduled order of trains will be compared to the scheduled order by analyzing time-distance diagrams as well as the visualization of simulation runs (i.e., trains running over the network, see example in figure 31 below).

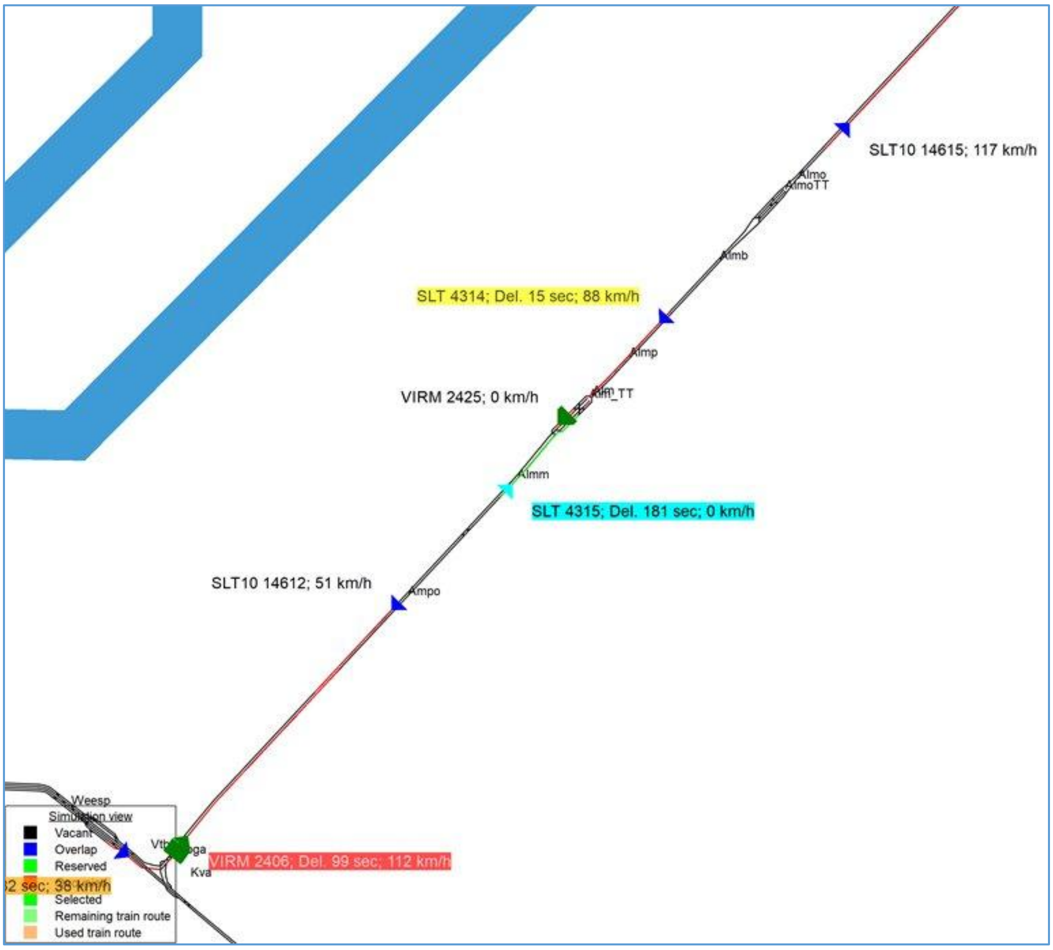


Figure 32. Example from RailSys visualisation of simulation run

TRL4 validation method applied in railVOS

The validation up to TRL4 of the developed capacity evaluation algorithms is made through the evaluation of simulations in controlled synthetic scenarios to analyse its results. Synthetic and controlled input data provides the advantage of easy access to multiple scenarios to validate the output and study how the algorithms behave in different controlled conditions. This involves conducting simulations and small-scale testing under realistic conditions to validate the algorithm functionality and reliability.

In a first run, the capacity analysis algorithms are tested with different synthetic scenarios and checking the results manually using the time-distance diagrams and calculated occupation rates (Figure 32 below). In a second step, the eco-driving algorithms have been tested, varying the driving strategies and running time margins and checking that the results are coherent by analyzing the time-distance diagrams and distance-speed graphs of the individual trains, together with the energy consumption values obtained and the characteristics of the rolling stock and the route characteristics (Figure 33 below).

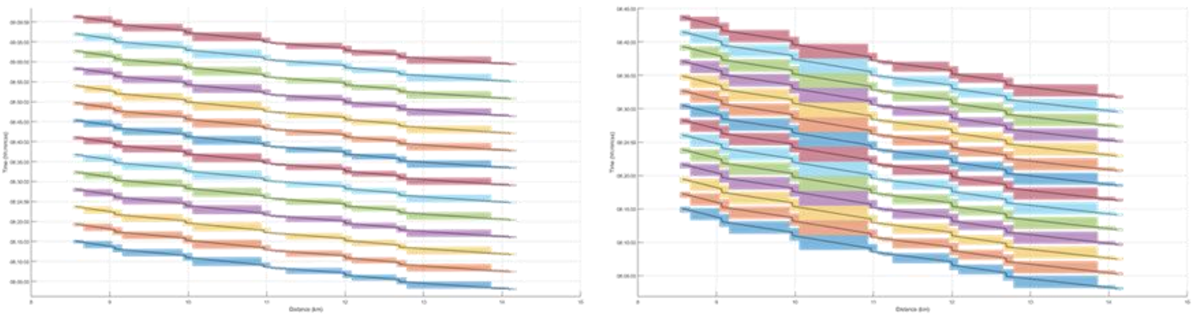


Figure 33. Example of reference timetable (left) and compressed timetable (right) for capacity evaluation of a double-track line

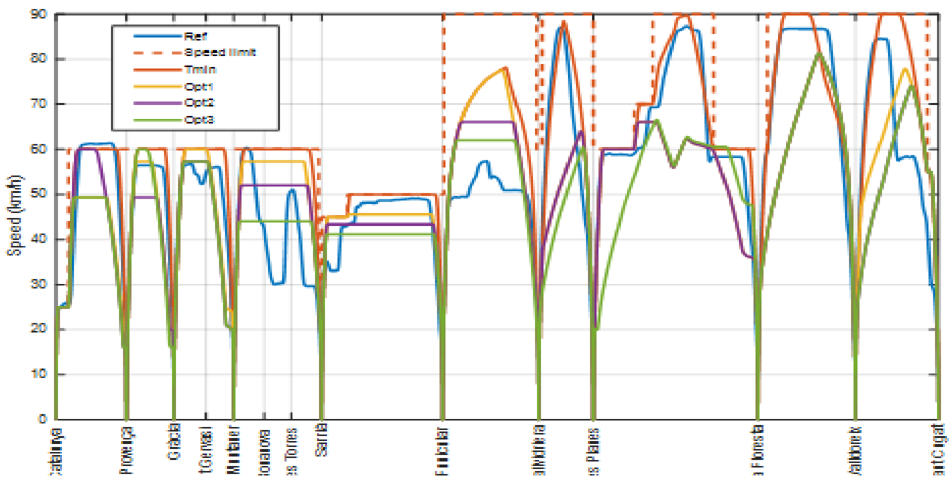


Figure 34. Examples of minimum and energy-efficient speed profiles with different running time requirements

7.5. ATO

7.5.1. Description of concept

The term "ATO" stands for Automatic Train Operation, which is an overarching concept. There are four different levels of automation referred to as GoA levels (Grades of Automation). Table 6 below describes the GoA levels. They are defined in the international standard IEC 62290-1:

- GoA1: The train driver operates the train manually, possibly with the assistance of driving advisory systems.
- GoA2: Acceleration, deceleration, and stopping are automated. The train driver remains responsible, monitors the ATO system, and intervenes if necessary.
- GoA3: The ATO system operates the train independently. There is a train attendant onboard the train that can handle the door closing process and different types of tasks.
- GoA4: The ATO system operates the train independently and intervenes in case of (potential) incidents. No personnel are present on the train. Disruptions are managed through remote control and/or by a maintenance team.

Table 6. ATO Grades of Automation (OTIV, 2024)

OTIV

Grade of automation	Train operation	Setting the train in motion	Driving and stopping the train	Opening and closing the doors	Operation in case of disruptions
0 Line of Sight	Just the driver	Driver	Driver	Driver	Driver
1 Non-automatic	ATP with a driver	Driver	Driver	Driver	Driver
2 Semi-automatic	ATP and ATO with a driver	Driver / Automatic	Automatic	Driver	Driver
3* Driverless	ATP and ATO without a driver	Automatic	Automatic	Driver / Attendant	Attendant
4 Unattended	ATP and ATO without a driver and attendant	Automatic	Automatic	Automatic	Automatic

* Only applicable on passenger trains

GoA1 represents the current manual train operation in many countries with an ATP system monitoring the train movement, which serves as the reference point against which the benefits of higher GoA levels are evaluated. The addition of a C-DAS to GoA1 (sometimes referred to as GoA1.5) is treated as a distinct DATO concept in Chapter 7.4 above.

In this study, we consider GoA3 out-of-scope as a separate concept, and take a more in-depth look at GoA4. As such, the business case, WP32 in R2DATO, includes the two extremes of DATO implementation levels in sense of estimated benefits and costs. The scoping for the baseline is GoA level 1, which represents a minimal level of automation. On the other end of the scope, GoA level 4 is included representing the most advanced technical level for DATO in which the full benefits of DATO can be realised. GoA level 2 is included in the scope as an intermediate level, representing the highest level from which empirical data is available at the time of writing.

ATO GoA2

In essence, ATO GoA2 consists of two systems: ATO trackside and ATO onboard. ATO trackside serves as a mailbox. It constructs a journey profile and segment profile based on the train's current status, timing points, and the timetable and route planning from the TMS. This constructed plan is then delivered to the ATO system on the train. ATO onboard influences the train's traction and braking. This system takes into account various factors such as the timetable, infrastructure characteristics, train characteristics, safety limits, comfort limits, current time, speed, and train position. It uses this information to determine the desired speed profile, translating it into brake/acceleration/coasting commands for the train.

The standard ATO solution within the European Train Control System (ETCS) framework was developed by a European working group under the Shift2Rail partnership (TD 2.2). The objectives were to create an interoperable ATO extension for the ETCS system, establish a common standard, and become the primary solution for ATO on mainlines in the EU. This effort resulted in the ATO GoA2 over ETCS specification in the Technical Specifications for Interoperability (TSI) 2022.

With ATO GoA2, drivers are in the cabin and have to be capable of driving the train manually and have a safety task in observing the tracks and the system. The expectation is that in this situation ATO will not always be engaged, due to keeping experience and avoid the risk of distraction. In the simulation, choices have to be made where or when ATO is used or turned off.

As the driver can turn off ATO, the ATO driving style should be accepted and trusted by the drivers. The assumption at NS is that this can limit the ATO driving style, especially when braking. The standard braking rate or the buffer to the ETCS braking curves in the simulation should be chosen at a level that drivers will be comfortable with.

ATO GoA4

In contrast to ATO GoA2, ATO GoA4 operates without a train driver present in the train cab and no personnel on board the train. The most significant difference is that ATO GoA4 has to fulfil additional functions, requiring the incorporation of extra systems. These functions include monitoring and responding to hazards on and around the track. For ATO GoA4, an obstacle detection system must be added, comprising sensors on the train (such as camera, lidar, etc.) and an image recognition model to detect and respond to obstacles. In the event of disrupted situations, the system must be capable of handling them autonomously. Persistent disruptions can be addressed by deploying a mobile maintenance team or by taking remote control of the train from a remote operation centre.

With ATO GoA 4, the trains will always use ATO and could potentially brake later, because the limitations of GoA 2 related to driver's acceptance are no longer necessary. Also, minimal turnaround times could be lower as the driver doesn't have to walk to the other cabin.

7.5.2. Developed simulation methods

Much like C-DAS, the simulation of ATO mainly requires adaptations to the driving regimes that trains follow. In addition, one would require functionality to assess differences in driving style across time in an individual train run or across multiple train runs. Also, the driving regimes should reflect the expected, more energy-efficient driving regimes that ATO will offer, as well as the current human driving regimes for comparison.

Consequently, a capacity simulation of ATO should be able to register changes in punctuality, recovery times, and capacity through timetable changes. For the latter category, softwares that instantaneously calculate a timetable and signal conflicts as result of entered train runs with input driving styles, such as RailSys, seem most efficient. For capacity-adjacent studies into infrastructure wear and energy savings, a software should also be able to register acceleration/braking actions and energy consumption respectively as a result of the differences in simulated driving behaviour.

Driving strategy with ATO

Energy-efficient train control or train trajectory optimization is aimed to derive the driving strategy with the least amount of traction energy consumption. In addition, regenerative braking can also be considered in the optimization. After deriving the objective, dynamic constraints, path constraints, and boundary constraints, Pontryagin's Maximum Principle (PMP) is used to derive the necessary optimality conditions (Pontryagin, et al., 1962). Afterwards, the Karush-Kuhn-Tucker conditions are applied to derive the optimal control structure including the indications of the costate values that determine the switching points between different driving regimes. The optimal control structure consists of the following driving regimes: maximum acceleration, cruising, coasting, and maximum braking. Note that the optimal control results in maximum acceleration and maximum braking. This is different to road transport due to the higher efficiency of an electrical engine of the train as well as the high train mass and low rolling resistance of the train. Therefore, the extra energy for fast acceleration is compensated by earlier coasting. A simple example of the EETC driving strategy for both a long and short distance between two stops can be found in Figures 23 and 24 above. Efficient algorithms can be used to solve the optimal control problem. There are basically three different ways to solve the optimal control problem: indirect solution methods, direct solution methods and heuristics (Scheepmaker, et al., 2017). Indirect methods use a boundary value problem to solve the problem and constructive methods are applied that use the knowledge of the optimal control structure to solve the problem. Direct solution methods discretise the problem to a nonlinear programming problem that is then solved. Heuristics determine iteratively a solution, but cannot guarantee that the solution is the absolute optimal. More background information regarding the topic of energy-efficient train operation can be found in Scheepmaker et al. (2017) and Su et al. (2023).

An ATO is able to run according to the energy-optimal driving strategy, if the input data is accurate enough. Therefore, in the simulation study trains running under ATO GoA 2 and GoA4 should apply the EETC driving strategy.

Method of estimating simulation parameters with ATO

With ATO-controlled trains, there will no longer be a human driver that controls the trains. In order to simulate ATO trains the simulation setup needs to be changed compared to human driven trains. In the next section the identified parameters that need to be changed are described. The estimation of these parameters is a challenge when simulating ATO in a realistic way as there are few ATO systems on the mainlines. In this work package, insights from ATO GoA2 test runs for a passenger train at NS can be used, including a test with different driving characteristics and braking rates for a passenger train with GoA2 with passengers onboard that evaluated the comfort level.

In other studies, assumptions have been made regarding reaction time, buffer times, and braking rate. Vergroesen (2020) for example set the braking to 2 s before the EBI curve in ETCS L2, and the normal buffer time of 60 s between trains in the Netherlands was reduced to 30 s. This assumption of less buffer time needed is not validated yet in a mainline simulation study and can be checked in WP9.

Reference Driver's profile

Two different methods for including the driver behaviour are tested. The first method is to create different train types based on identified driver profiles. The second method is to use run time extensions to simulate different driver profiles. The data contains speed and GPS location on a 2 second interval. Similar data from different countries could be used.

The first method of identifying different driver profiles can be made by cluster analysis regarding acceleration, cruising, coasting, and deceleration patterns. Based on the cluster analysis average acceleration and deceleration rates can be implemented into different vehicle types in simulation software. The share of the identified driver profiles can be equal to the share of the vehicle type. In order to make this process easier, a script for the timetable editing can be made.

The second method of using run time extensions is based on the actual running time between two stations and subtracted with the minimum technical running time in RailSys. The differences of all the different train runs are inserted as a run time extension on that specific route as a delay distribution.

Delay distributions - GoA3 and GoA4

In a future with automatic train operation (ATO) and especially a high grade of automation (GoA) and unattended train operation, the delays and punctuality could look different from today. A study by Jansson (2020) shows that driver-related causes such as the driver being late or missing account for 1% of the total delay time for passenger trains and 5% of the total delay time for freight trains. These types of delays could be reduced with unattended train operation as there is no longer a train driver onboard the train. However, other types of delays could instead increase in situations where the train driver could perform tasks that resolve the problem. Jansson et al. (2023a) conducted a study based on the delay data and free-text descriptions of the causes of delays and the tasks of train drivers. The study found that train drivers perform six different types of tasks during unplanned events; detect, report, inspect, adjust, manage passengers, and respond to train orders. The task of adjusting could be the most difficult to perform without a train driver on-board and thus these situations could take much longer to resolve with unattended train operation. One such situation is when turnouts do not function properly due to ice and snow and the traffic controllers ask train drivers to clean the switches. In a system with unattended train operation, this type of failure could take a longer time to resolve due to the need to send a service team to the location and add the response time to the delay.

Another type of situation that impacts the delays is trackside sensor alarms. Trackside sensors are located along the Swedish railway network and monitor the passing trains. Most of the sensors control the area around the wheels but there are also some sensors that monitor the pantograph. When a certain threshold value has been breached the traffic controller receives an alarm and then contacts the train driver who needs to stop the train and manually inspect the vehicles. Jansson et al. (2023b) studied trackside sensor alarms during one year in Sweden and found that there are statistically significant differences in terms of affected trains due to train type, climate zone, and month of the year. Freight trains in colder climate zones during winter months have the highest frequency of a trackside sensor alarm. A trackside sensor alarm entails 20-25 minutes of delays (The Railway Industry Cooperation Forum (JBS), 2022).

In order to specify which unplanned events that could lead to longer delay time different types of data sources have been used. The data sources are from the Swedish railway network. The first data source is delay data containing information about the delayed train, including one of around 200 codes assigned by the traffic controller as the reason for the delay. The codes are described in the Network statement for the Swedish railway (Trafikverket, 2023a). The second data source is vehicle failure logs from commuter trains in southern Sweden and contains information about the type of failure and also information to the driver on how to handle the situation. The third data source is track-sensor alarms. The final data source is response times from the contractors today in Sweden and will be used to estimate the response time on different locations in the railway network.

There are also delays that would disappear in GoA3 and GoA4 systems. The delays caused by personnel onboard the trains would no longer be relevant and thus should be removed in stochastic simulations.

The details of delay causes vary in different countries and this method of identifying delays causes that will be affected in GoA2 and GoA4 will be somewhat different. In Germany (DB Netz, 2023) there are 34 different causes while in Norway (Bane NOR, 2022) there are 17 different causes.

High Density Lines

On high density lines the focus on delays will be different. With higher frequencies, longer disturbances will lead to cancellations which are out of the scope of the planned microscopic simulations. On high density lines with mixed traffic, the exactness of driving with ATO and the effects of ATO on acceleration and braking, especially of commuter trains, are more interesting. When stochastic simulation is used for these situations, delay distributions will be focused on dwell times and human driving behaviour.

This subsection concludes with a general overview of the parameters and simulation settings required to simulate ATO.

General

With ATO GoA2, scenarios with partly ATO employed (based on location or % of runs) are realistic. With ATO GoA4 the expectation should be that ATO will be engaged all time for trains fitted with ATO. The buffer time is another parameter that could be influenced by ATO and adjusted accordingly.

Braking

The braking is a parameter that needs to be adjusted to ATO simulation. The parameter can be adjusted both in term of braking rate at different speeds and also by following different types of established braking curves in ETCS. The braking parameters for the reference scenario should incorporate the driver variation.

Acceleration

The acceleration parameter will be adjusted for the ATO-equipped vehicles and this can be done in the settings for the specific vehicles. The acceleration parameter should take into account the driver variation for the reference scenario.

Delay distributions

In stochastic ATO simulations especially with a high grade of automation a different delay distribution could be expected and should be derived by analysing the delay causes. Depending on the different GoA different delay distributions will be used in the simulation software as an input parameter. As a reference scenario a distribution for manual driving should also be added in order to represent the driver variation.

Timetable settings

The ATO parameters for acceleration and braking are in most cases set to a higher value than for trains driven by humans. This would result in shorter running times. This could be used to either implement more buffer time in the timetable or insert more trains in the timetable. The choices made should be clearly stated in the presentation of the simulation results.

7.5.3. Implementation in software

ATO improvements RailSys

As mentioned in the Section 7.4.3 of C-DAS, the eco-driving strategies and running ahead of schedule is missing in RailSys. For ATO, the EETC driving strategy is required to be implemented in RailSys. Therefore, the following specifications are wanted to improve RailSys:

1. Trains should be able to run ahead of their schedule (e.g., passing times) using the EETC driving strategy, while arriving/passing on time at the next stop/critical timetable point.
2. Energy-efficient train control driving strategy should be available to approach ATO behaviour: combination of optimal cruising speed and coasting.

Ongoing discussions with the developer indicate that these developments will arrive in time for the simulation studies in Work Package 9.

CAF Parameters

One of the main features of the extension we have made to the CAF capacity tool is that we have migrated the ATO algorithm that was being used.

Previously, a basic algorithm was used, but it was decided that in order to have more realistic results, the real one, implemented by CAF, should be used so that when simulations were carried out, it would reduce the margin of error that could appear.

This tool will also allow the user to carry out capacity analysis taking into account whether the type of driving is that of a driver or whether it is the ATO GoA2 that carries out the driving.

Related to efficient driving, CAF's capacity tool is focused on satisfying the needs of the operator and therefore has implemented the possibility of defining the energy demand that the train may have.

PROTON

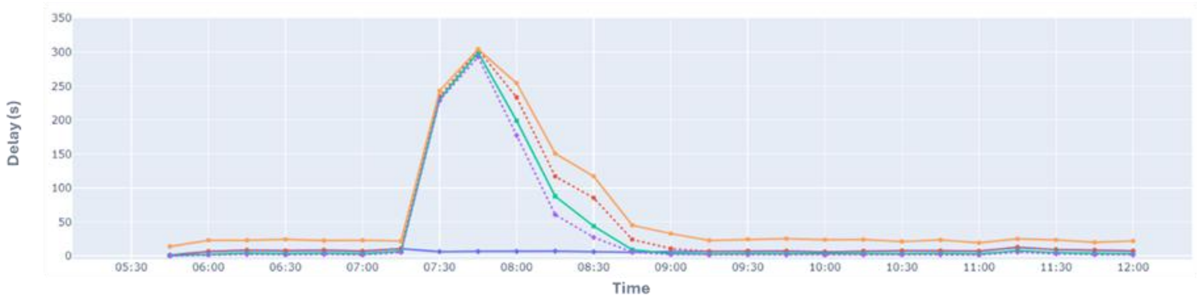
PROTON will be used to simulate a GoA4 scenario on a rural single-track line. The delay distribution used will contain long delays and thus a macroscopic simulation tool is prefered. A transformed delay distribution will be used based on the method explained in 7.5.2. The running times in PROTON are given as an input and not calculated in the tool itself. There new running times will be used based on the acceleration and braking rate for ATO trains.

7.5.4. TRL4 validation

ATO study Netherlands

In different studies in the Netherlands it is shown that changing driving parameters and reducing driving variation does have benefits in punctuality or robustness. In Figure 34 below, the effect of driving with ATO with different braking parameters do have effect on the robustness in a simulation of a train with an unplanned standstill of 15 minutes.

In the same study, 1-minute train punctuality is measured with different percentage of trains running with ATO in a standard timetable and an optimized timetable. Difference in driving behaviour and difference in the timetable do have an effect on punctuality as is shown in Figure 35 below. Validation of this effects with realisation data is yet not possible, the tool that was used had been validated for non-ATO driving. In this (fictive) study, the difference between ATO and manual driving was a combination of more exact driving and driving faster when cruising, closer to the allowed maximum speed.



Scenario	No ATO, 0.5m/s²	All ATO, 0.5m/s²	All ATO, 0.7m/s²	All ATO, 1m/s²
Back to normal at	9:12	09:11	08:42	08:34

Figure 35. Recovery from disruption (15 min stand-still) with ATO (harder braking)

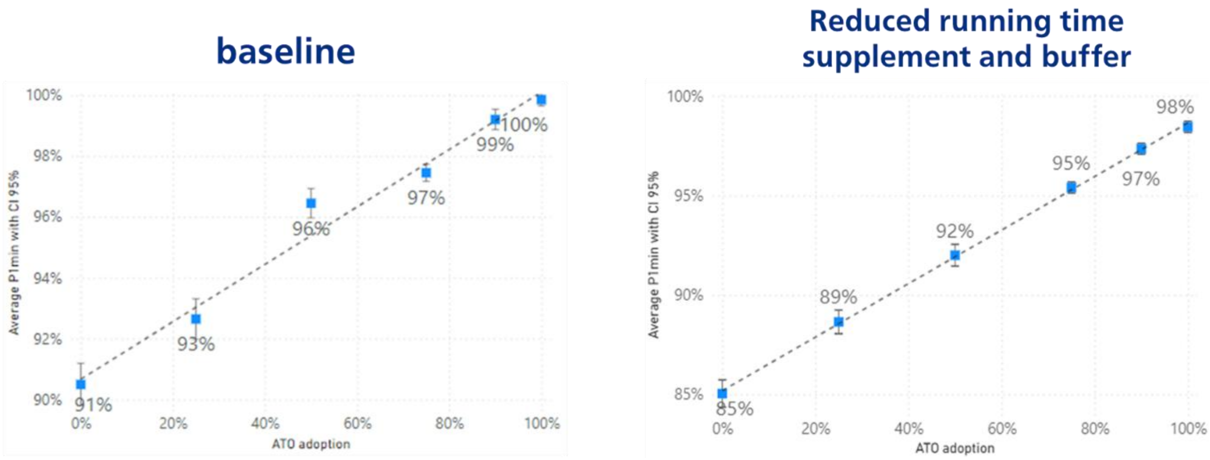


Figure 36. Punctuality outcomes of a fictive case study, manual driving versus ATO

Note: Based on fictive data. Percentages indicate punctuality ≤ 1 minute at endpoints of simulation area.

The study uses a coasting driving strategy, which is less energy efficient as the EETC driving strategy as an EETC driving strategy was not available in the software tool used for the study. Coasting is also used as part of a EETC driving style. Figure 36 below shows that coasting is possible as a driving style in a ATO simulation study and energy consumption (power usage) can be measured. The train is coasting in the area's where power consumption is zero and the speed (red line) is reduced slowly (around 45 degrees decent in this graph).

ATO driving could be compared to manual driving, with or without C-DAS. This manual driving can be modelled (amongst other options) using a deviation on the arrival time, where ATO is expected to arrive exactly on time when possible. In Figure 37 below the deviation uses a Gamma distribution, based on realisation data. An example is shown of one of many graphs that are used to validate the simulation with realisation data. With a perfect distribution, the difference between realisation and modelling should be 0, which is impossible for a generic distribution for a train type. In the picture you can see that the median between simulation and realisation is around zero and the deviations are relatively small.

Figure 37. Speed (red) and acceleration (orange) versus distance for a coasting (ATO) train

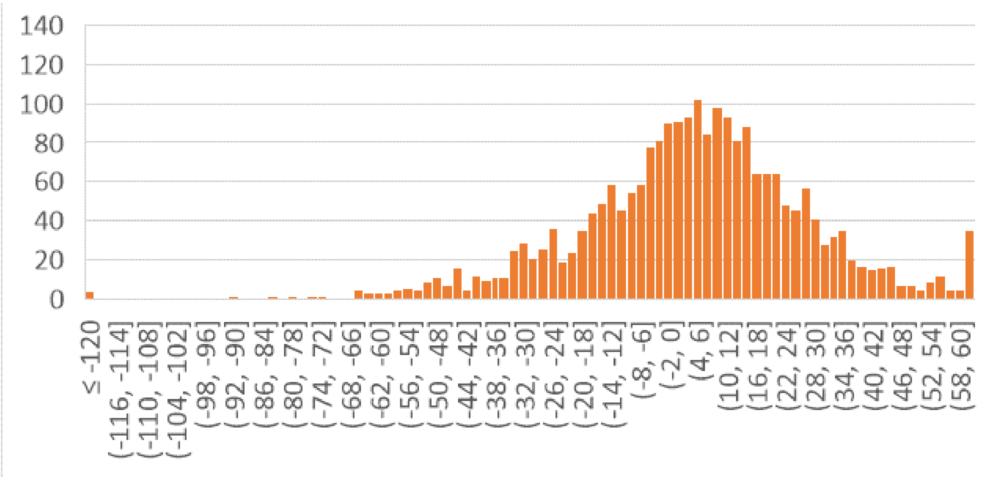


Figure 38. Deviation of approximated human driving (Gamma distribution) to real human driving, Dutch case, km/h

Delay distributions in GoA3 and GoA4

The validation of the delay distributions is done by using real delay data and transforming it according to method explained in Section 7.5.2. Stochastic simulations are performed with the original data and with the transformed data. The method and the original data have been validated in a previous study (Palmqvist et al., 2023). The simulation results in terms of delays have been compared and evaluated with empirical data. Another part of validation has been done by identifying the affected delay causes based on expert judgements.

RailSys EETC driving strategy

The validation of the method of the EETC driving strategy of RailSys will be similar to the one for the coasting driving strategy as discussed in Section 7.4.4. This means that both a static analysis as well as a dynamic analysis using deterministic simulation will be performed in RailSys for different train types and running time supplements to evaluate mainly the generated speed profile. The resulting speed/gradient-distance profiles will be analysed. The validation of trains running ahead of schedule and keeping the scheduled order already discussed in Section 7.4.4.

7.6. TMS

7.6.1. Description of concept

As described in deliverable 15.1 [Deliverable D15.1 Requirements for the deployment of TMS linked with ATO/C-DAS, 29-09-2023] from Flagship Project 1 “Development - Linking TMS to ATO/C-DAS for optimised operations” (TMS is Traffic Management System) is the global system for monitoring and controlling the traffic and the signalling systems from the control centres. It covers a broad range of functionalities and, therefore, it is expressed in some cases such as multi-actor systems, which includes several actors. Traffic management systems can subscribe to the location and speed information from C-DAS fitted trains in the managed area. Also, ATO can feedback information, namely on actual status and expected arrival times timing points. This information from C-DAS/ATO is useful in order to update the RTTP (Real Time Traffic Plan) and a better accuracy in the conflict detection.

A main task of a railway Traffic Management System (TMS) is to provide information about routes and times to trains for conflict-free and punctual train operation (See Figure 38 below).

A TMS must provide a RTTP specifying the exact routes for each train as well as target times at scheduled timing points. This RTTP is the basis for both the timely route setting by the Traffic Control System (TCS) and the accurate speed regulation of trains by ATO/C-DAS. The ATO/C-DAS translates the RTTP into a Train Path Envelope (TPE) for each connected train, which specifies both targets and possibly additional time windows at Timing Points (TPs) on the route of the train.

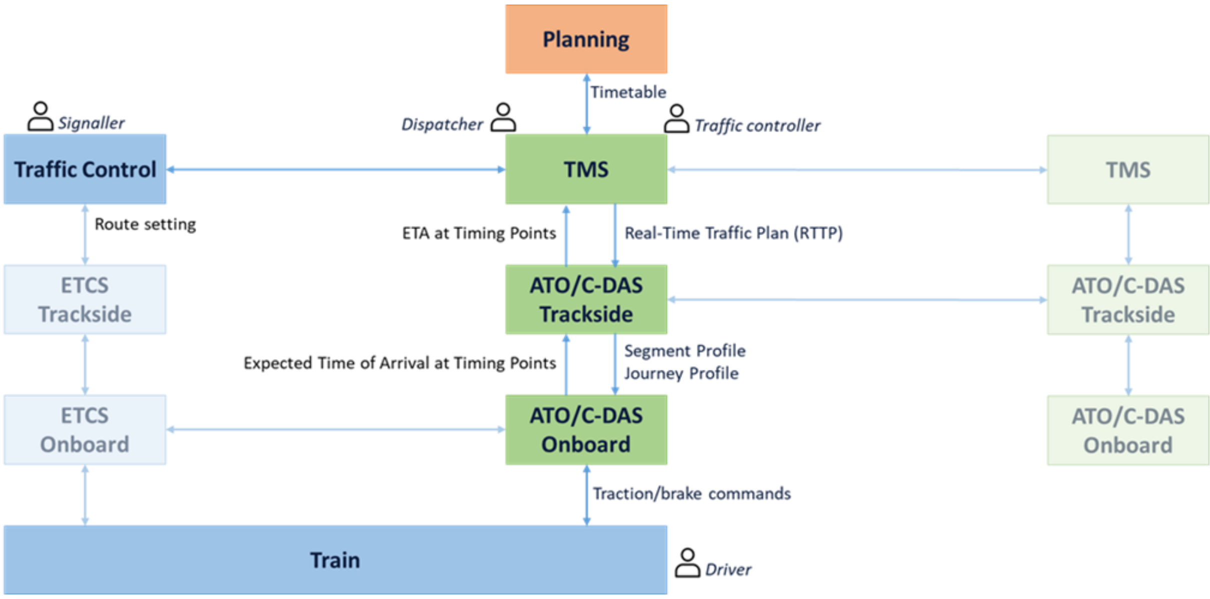


Figure 39. Explanation of TMS (source: FP1-WP15-Deliverable 15.1)

7.6.2. Developed simulation methods

Having presented the concept of TMS, we will now go on to outline a number of developments that have been carried out by different partners in order to carry out simulation methods. There exist several limitations to the development of TMS simulation methods:

- The TMS-ATO functionality is still in development within Europe's rail. Only the insights of this functionality developed in WP15 until July 2024 could be taken into account.
- The TMS will generate a feasible RTTP, not the optimal RTTP. It does not consider the TPE with optimizing the timetable.
- Development of TMS simulation methods is outside the scope of the task set out for WP8/9 as defined in the grant agreement, and as is also apparent from the title of this document – while we include it here as it is a relevant topic for other work packages within Europe's Rail and as it has strong complementary benefits with C-DAS and ATO, note that the development status of these methods and the associated software packages will be relatively less mature.

For simulation of TMS, we define the following assumptions:

- Real-time data of the railway system state, rolling stock and infrastructure is correct and available for the TMS.
- The TMS generates a feasible RTTP with the constraints of the railway infrastructure & rolling stock such as the signalling system.

- The RTTP may contain timetable speeds (lower speeds that maximum speed to ensure the plan is conflict free)
- If there is no real TMS is coupled to the simulation TMS works accurate. Therefore, no error margin of the TMS calculations is accounted for in those simulations.

In order to make sense of the limitations and assumptions set out in the previous paragraphs, and thus make sense of the TMS functionality in the simulation tools, it is necessary to define a series of user requirements we collected that serve to answer the research questions we aim to explore in this project. These user requirements are as follows:

- I want to see the effects of the TMS rescheduling of C-DAS and ATO trains in deterministic simulations
- I want to switch the TMS on and off in a premade scenario
- I want to adjust the train path envelope and detect and resolve conflicts
- I want to analyse the punctuality after the simulation to assess the robustness of the RTTP from an operational TMS
- I want to analyse the recovery times to assess the robustness of the timetable with an operational TMS
- I want to analyse the timetable to calculate the travel time gains
- I want to analyse the energy consumption to calculate the energy savings
- I want to obtain the maximum line capacity to generate optimised plannings.

7.6.3. Implementation in software

RailSys

Having C-DAS or ATO and assuming good route setting in normal situations, the value of an intelligent TMS is updating the RTTP in cases of delays or other disruptions, generating an updated feasible conflict free plan. A simulation can approach this in two ways, which figure 39 below depicts.

RailSys itself focuses on designing a good static timetable and uses simulation to verify the robustness of a timetable. If an intelligent TMS is available, it could be possible to use less buffer (gaining capacity) in the timetable and still have a good performance, or improve the performance within a given timetable.

It is possible to design and evaluate a timetable with less buffer in RailSys, but it is not yet possible to have an intelligent TMS algorithm in the simulation generating updated RTTP's during simulation. On the other hand, it is possible to adjust the timetable manually in RailSys, adapting the primary delay(s) in the timetable and resolve any conflicts by hand, changing the plan only after the moment of the delay. The primary delay(s) have to be large enough to let the train run outside the original TPE. With the same primary delay(s), you can compare the outcome of the simulation with the original plan and with the manually adjusted plan. This difference will be a good approximation of the effect of a dynamic TMS solution.

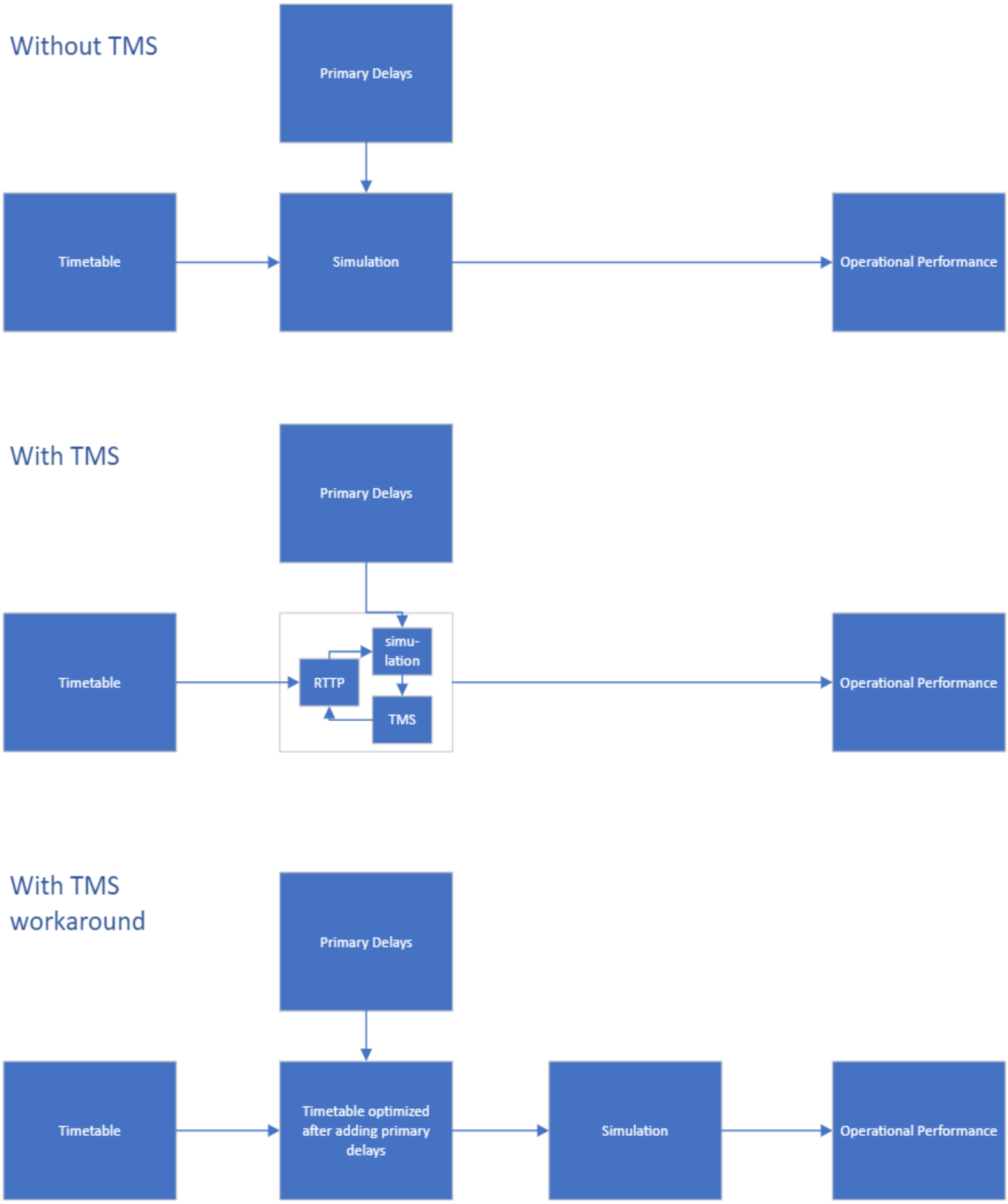


Figure 40. Different workflows with and without TMS

The main difference by adding TMS is adapting the delays in the timetable manually. In this manual process, there are no easy input parameters that can be changed. It could be possible to give different priorities to the planner like “minimize changes” or “punctuality on x minutes” or “energy efficient planning”.

The evaluation of the added value of TMS could include punctuality, energy consumption and effect of timetable compression. A scenario is to use a planned timetable with less buffer or more trains besides the reference timetable and compare the results with/without TMS. A possible workaround is to use the train formation specific parameter of using allowance to reduce lateness. The threshold value could vary between ATO trains and non-ATO trains. ATO trains could potentially have a lower threshold of lateness compared to non-ATO trains. This workaround would not simulate an actual TMS function but just parts of the concept, to change speed profile based on the current traffic situation.

With all the described tools the user stories in chapter 7.5.2 can all be realized. In the paragraph below all the gaps per tool are specified. As stated before, RailSys does not have an intelligent TMS functionality. A good TMS functionality could be added to the RailSys simulation, or RailSys could develop options to use an external TMS module in their simulation. Before doing this, much more consensus and maturity of TMS functionality is needed.

Train path envelope improvement RailSys

RailSys does not include train path envelopes. They should be available during timetable design in RailSys, to see potential TPE conflicts, especially considering the C-DAS and ATO eco-driving strategies. In addition, timing points included in the TPE should be flexible to add, adjust or delete. The TPEs should also be available to evaluate the output of the simulations, in order to evaluate TPE conflicts during simulation. Without these improvements, a first study will be possible but more iterations and manual corrections will be needed.

CAF

The calculation of the best service schedules that meet all needs will take into account ATO traffic. This will allow us to make a comparison between the efficiency of the planning when it is intended for ATO and when it is not intended for ATO. CAF will focus on different parameters such as energy savings, punctuality, timing points or the place in which the train need to stop in a station, amongst others.

Taking into consideration the results that our capacity tool (CAF Tool) will provide us, our planning tool will have more inputs to design proper operational plans. The idea is that our planning tool will be an offline tool that can work without being connected to any other part of the system (i.e., the regulation system). But with this tool we will generate a file that can be uploaded in the regulation system.

TMS_SIM
INDRA currently has available the TMS_SIM simulation tool. It connects to TMS interfaces for testing, simulates interlockings and train movements. TMS_SIM is crucial to test and compare the timetable and the real run of the trains (simulated).

Current planning calculation is based on the most restrictive speed among all the affecting speed restrictions. It is an approach that can be improved because trains do not usually run at maximum speed and these differences (between timetable and the real run) affect the conflict detection. TMS_SIM can include different driver behaviours based on compliance with C-DAS instructions. This is called the "C-DAS driver mode" as outlined in section 7.4.3 above.

The TMS SIM simulator is used to verify the reduction of delays or deviations of trains with respect to the planned timetable of the trains in TMS using C-DAS driver mode instead of without it. First tests indicate that less delays or deviations are produced using C-DAS driver mode, which allows the TMS to adjust the timetable with respect to the scheduled timetable better. Indra will analyse the optimal capacity in a section of the network when C-DAS driver mode is included in the INDRA simulation environment. The purpose is to compare the simulator with and without C-DAS.

It is unclear for now whether the TMS_SIM will also simulate the resulting timetable adjustment, nor whether they will manually approximate it using a similar workflow logic as the one outlined above for RailSys and the TPE.

7.6.4. TRL4 validation

While the tools are not fitted for TMS yet, the method is already used incapacity calculations. The method of the TMS-ATO link with TPE is described and proven in Wang *et al*. (2023).

RailSys
Studying the effects of TMS on capacity in RailSys is divided in two parts. First, there is a workaround to make an updated plan by hand, which in future should be done by a TMS system. This method is discussed and validated within the RailSys users in this workpackage (WP). The technique is simply to make a new timetable variant including the primary delay(s) and compare the outcome of the simulation of the original timetable and the updated timetable. To plan and simulate a timetable is a common activity that will not need a further validation.

In the second part is using Train Path Envelopes (TPE's) in RailSys when designing and updating the timetable. The main difference of TPE's in this work package is that the planner can see the different options in driving strategy a driver/C-DAS/ATO had between two points. Using this technique when planning the timetable is almost the same as planning without TPE, the planner will experience a broader infrastructure occupation as shown in Figure 40 below.

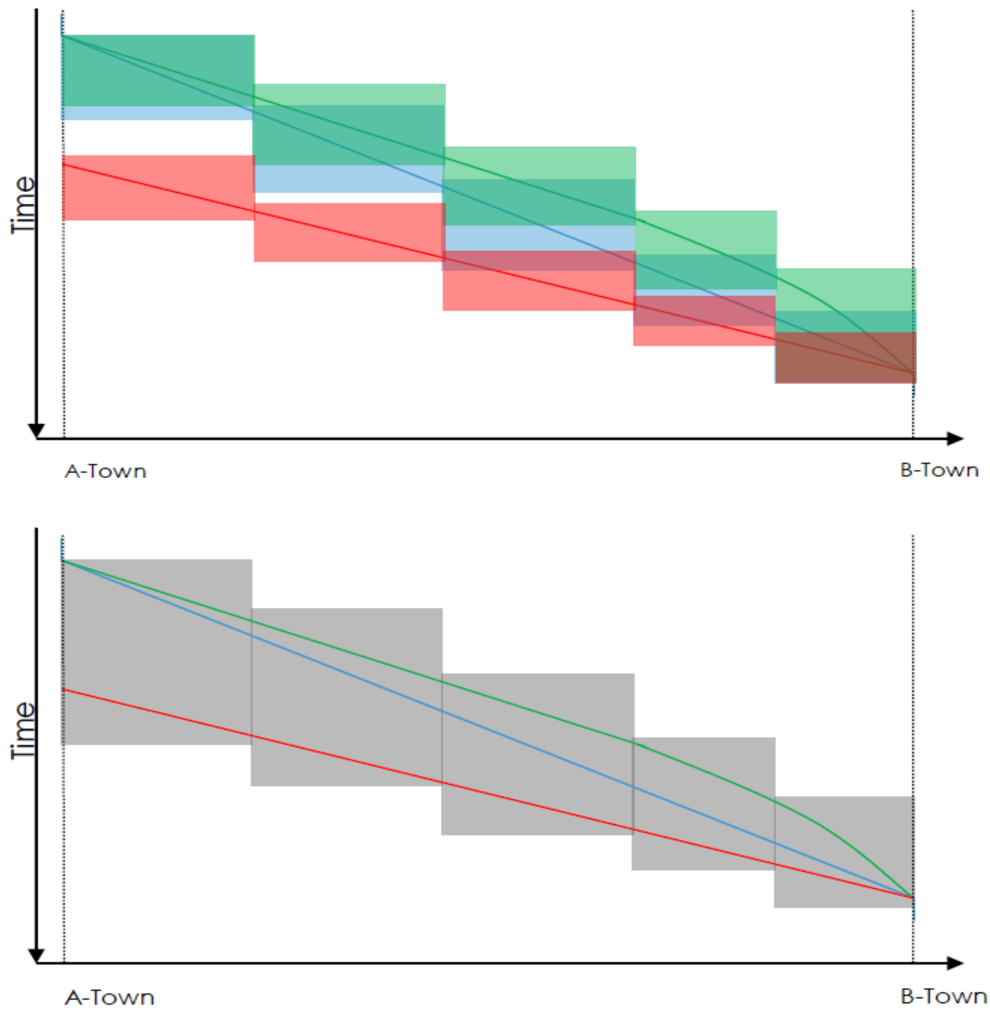


Figure 41. Time-distance diagrams with block occupancy of different driving strategies

Note: red: minimum running departure at first station, blue: standard run time using cruising, green: coasting

Instead of only one occupation (one colour) the planner will see the grey block including some information on the edge strategies. Using this information, the planner can try to avoid any overlappings or add specific timing points underway to reduce the grey area. Both options will reduce the change of hinderance between trains. As said the method is almost the same as the current situation and also discussed with the RailSys users in this Work Package. If this method will improve the quality and indirect improve capacity has to be investigated in WP9. How TPE's will work in combination with TMS and ATO will be investigated in WP15/16.

CAF Planning Tool

The validation of TRL4 in the CAF planning tool will be carried out through a series of global software tests in which the functionality of each of its modules will be verified.

The information obtained from the capacity analysis of our test scenario in Bilbao will be used as input for this tool.

These global tests are strategically thought out and defined to test all kinds of cases and situations that could happen. A first result of these tests is shown in Table 7 below.

Table 7. Modules tested

Module	Total of test	OK	KO	NA
Global Tests SW User Authentication Module	24	23	1	0
Global SW Tests Exploitation Plans Management Module	22	19	3	0
Global SW Testing Module Operation Schedule Management	22	22	0	0
Global Tests SW Module Service Management Type	49	46	3	0
Global SW Tests Commercial Service Management Module	32	29	3	0
Global Tests SW Track Strip Display Module	1	1	0	0
Global SW Testing Mesh Visualisation Module	3	3	0	0
Global Tests SW Module Conflict Detection	4	4	0	0
Global Testing SW Module Multilanguage Support	9	6	0	3
Global Tests SW Module Additional Tests	4	4	0	0

8. Developed simulation models

8.1. Overview of scenarios

This chapter provides a general overview of the geographical scenarios that will be simulated by WP9. Table 8 below lists these scenarios, together with the software tool they will be simulated in, the DATO concepts to be tested, and the traffic character of the lines.

Table 8. Simulation Models for WP9 by Software Tool, DATO Concepts tested, and Traffic

Model	Tool	ETCS L2	C-DAS	ATO GoA2	ATO GoA4	TMS	NG Brake	HTD	Traffic type
(NL) SAAL (ch 8.2.1)	RailSys	(=Reference)	(=Ref)	X	X	X (GoA2)	X (GoA2 and GoA4)	X	Dense mixed, dense passenger
(SE) Stockholm (ch 8.2.2)	RailSys	(=Reference)		X		X			Dense passenger
(SE) Malmö (ch 8.2.3)	RailSys	(=Reference)		X		X		X	Dense passenger
(SE) Southern Main Line (ch 8.2.4)	RailSys, VTI Sim	(=Reference) R+VTI		X (R)		X (R)		X (R)	Mixed mainline
(SE/NO) Kiruna-Narvik (ch 8.2.5)	Railsys, Proton	(=Reference) R+P		X (R+P)	X (P)	X			Mixed rural
(SE) Eastern Link (ch 8.2.6)	Railsys, HESE	(=Reference)					X	X	High speed
(E) Bilbao (ch 8.2.7)	CAF-Tool	(=Reference)		X		X			Dense passenger
(E) Madrid-Atocha-Tunnel (ch 8.2.8)	CAF-Tool							X	Dense passenger
(E) Mostoles-ElSoto-Humanes (ch 8.2.9+16)	CAF-Tool		X					X	Dense passenger
(E) Madrid-Torrejón (ch8.2.10)	CAF-Tool							X	Dense passenger
(E) Barcelona-Figueiras (ch8.2.11)	CAF-Tool							X	Dense passenger
(E) León-Guardo (ch8.2.12)	CAF-Tool							X	Rural
(E) Lérida-Reus (ch8.2.13)	CAF-Tool							X	Rural, mostly freight
(E) Cercanías-Barcelona (ch8.2.14)	CAF-Tool							X	Dense passenger
(E?) Indra (ch8.2.15)	TMS_SIM		X			X			Unclear; scenario not specified yet
(F) Lille (ch8.2.17)	RailSys	(=Reference)						X	Dense passenger
(F) Bretagne et Pays de Loire (ch8.2.18)	RailSys	(=Reference)						X	Mixed high speed

Note: R = RailSys, P = PROTON. The softwares VTI Sim and HESE will not be used for capacity analysis (and are not capacity-analysis-oriented software), but they will be used to estimate input data for capacity analysis in RailSys.

Notably, the focus of this phase of the project, and correspondingly this report, is on methods development. Different partners have different levels of information ready about the scenarios and its model variations. Hence, we refer to the future deliverable 9.2 for information on scenario variations, the metrics to be tested, and the approaches that will be used to evaluate the differences between reference and system implementation scenarios. Moreover, there is heterogeneity in the thoroughness and quality of the below descriptions of the geographical and logistical contexts of the scenarios.

8.2. Descriptions of geography and traffic

8.2.1. Netherlands: SAAL

The SAAL-corridor is one of the busiest railway lines in the Netherlands, situated around the city of Amsterdam, with a length of roughly 60 kilometres. SAAL is an acronym. From Schiphol airport, the line runs to the Amsterdam Zuid train station, then to Almere, and ends in Lelystad. Policymakers plan to equip this corridor as well as parts of associated connecting lines with ETCS Level 2 (release 2) in the near future, and due to projected growth in passenger numbers, ATO, TMS, NG-Brake and HTD may cost-effectively provide the required capacity as well as overall welfare gains by facilitating extra trains, faster travel times and/or cost reductions.

Therefore, we aim to investigate the capacity effect of all DATO concepts (ETCS L2, ETCS HTD, NG Brake, C-DAS, ATO and TMS). The resulting simulation demonstrator is formalized in the use case FP1-DEMO-9.5-UC-1. Our base year of simulation is the year 2030. Figure 41 below shows the geographical context.

The infrastructure consists of two sections with four parallel tracks. These sections lie between Hoofddorp and Duivendrecht Junction West, as well as between Gaasperdammerweg Junction and Weesp. On this section, the station of Schiphol Airport offers six platform tracks. Similar six-platform-track plans exist for the station of Amsterdam Zuid, but only from the year 2037 onwards. The station of Hoofddorp has six tracks, of which four are platform tracks and the remaining two are passing tracks for the high-speed line that originates there. The rest of the line is all double track. The stations of Almere Centrum, Almere Oostvaarders and Lelystad Centrum offer four platform tracks on these double-track sections. Figure 42 below presents a schematic overview of the entire corridor. It also includes connecting lines that are planned to receive the ETCS Level 2 upgrade as part of the SAAL ETCS upgrade program.

Traffic on the line is dense, and contains a mix of express, regional express and always-stopping services. Maximum speeds do not exceed 140 kilometers per hour. In addition, cargo trains run regularly on part of the corridor. They enter the corridor at Amsterdam Bijlmer ArenA turning east, and then use the level-grade Venserpolder Junction to continue towards, usually, Hilversum and Amersfoort. The Hoofddorp-Duivendrecht section does not allow cargo traffic. We expect especially interesting results for ETCS HTD on the mixed-use part of the corridor, as it will contain a mix of integer and non-integer trains. By contrast, planned headways are most critically low between Hoofddorp and Duivendrecht Junction West, so we expect especially interesting results for ATO on this part of the corridor. Figure 43 below presents the intended timetable variant schematically. This intended timetable variant was built by long-term timetable developers at ProRail based on projected capacity capabilities and predicted traffic demand.

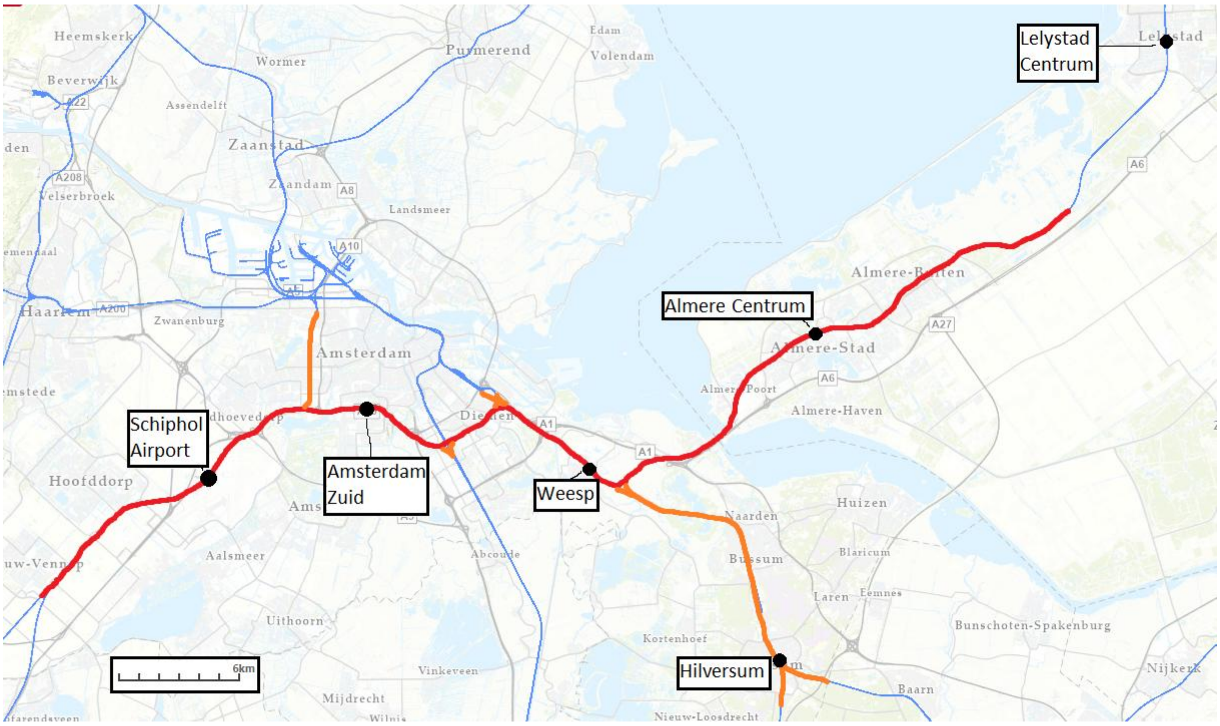


Figure 42. The SAAL Corridor: Line segments of the ETCS-L2 SAAL Program

Note: Red segments indicate the proper SAAL corridor, and orange segments indicate parts of the corridor that are upgraded as part of the SAAL ETCS-L2 upgrade program. We build both into our simulation program. Note that a part of the line between Almere and Lelystad Centrum is not highlighted. This section of line still belongs to the line from Schiphol to Lelystad, but is due to be upgraded with ETCS-L2 as part of a different program. Nonetheless, since we require known timetable points for trains entering and exiting the model area, our simulation model will include the section to Lelystad Centrum fully.

The intended timetable is named "6-basis", derived from the plan to run six intercity services per hour on certain major corridors. Within the SAAL corridor, this is visible from six intercity services running Leiden Centraal – Amsterdam Zuid – Utrecht Centraal and six intercity services running Rotterdam Centraal – Amsterdam Zuid and onwards to Almere Centrum or Hilversum each hour. Further notable lines are the *Airport Sprinter* stopping service from Amsterdam Centraal to Hoofddorp through Schiphol Airport, which will run eight times per hour. They, along with the regional express service from Lelystad Centrum to Hoofddorp through Almere Centrum and Amsterdam Zuid, will use the inner two tracks on the four-track section of the SAAL corridor, while intercity and high-speed services will use the outer two tracks. In the six-track Schiphol Airport station, intercity and high-speed services will use the outer two platform tracks on either side, and the stopping and regional express services will use the inner two platform tracks. Another notable change is the routing of the international train coming from Berlin through Amersfoort. This train will terminate at Schiphol Airport, thereby also using the SAAL corridor, instead of at Amsterdam Centraal, as it does currently.

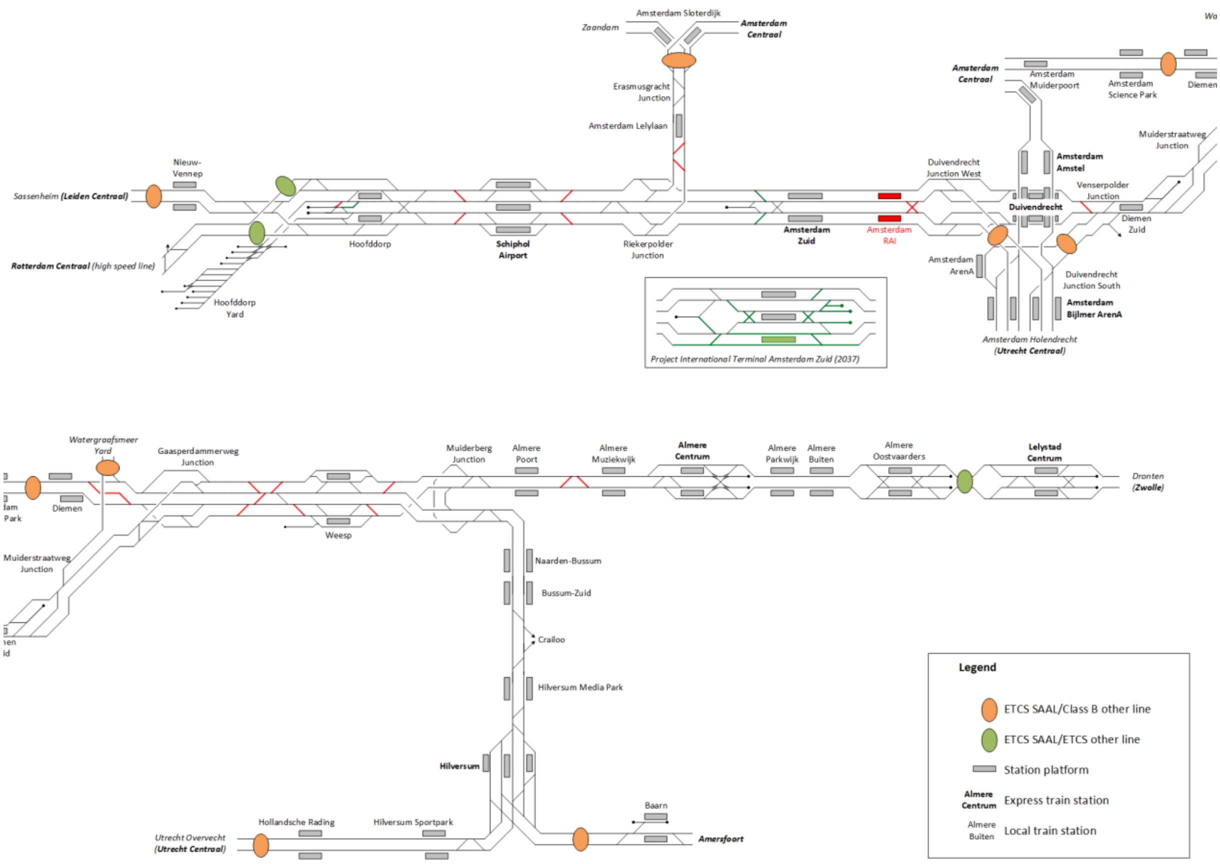


Figure 43. Schematic overview of the SAAL corridor and connecting SAAL ETCS Upgrade Program line segments, as planned for the year 2030

Note: Each line represents one track. Orange and green circles indicate the edges of the planned SAAL ETCS Level 2 implementation - orange circles represent a transition to a Dutch class B system, while green circles represent a continuation of running under ETCS outside the SAAL ETCS project area. In current plans, the connecting lines to Lelystad Centrum and Rotterdam Centraal (high speed line) continue under ETCS, while the others transition to the Dutch class B system. Express train stations are indicated in boldface. Red line segments are currently existing line segments that will be removed before our reference year (2030), while green line segments are to be added. In practice, this involves the removal of many switches, while three new switches are added (two west of Amsterdam Zuid, one in Hoofddorp). Express train stations are indicated in boldface.

In practice, the timetable we will simulate has a version with high-speed trains from Rotterdam terminating at Amsterdam Centraal, in which case the additional platform tracks at Amsterdam Zuid are not necessary, and a version with international trains terminating at

Amsterdam Zuid, in which case the additional platform tracks are necessary. Pending internal discussions will determine whether we include the extra platform tracks in our simulation model, as the required additional platform tracks will only be finished in the year 2037.

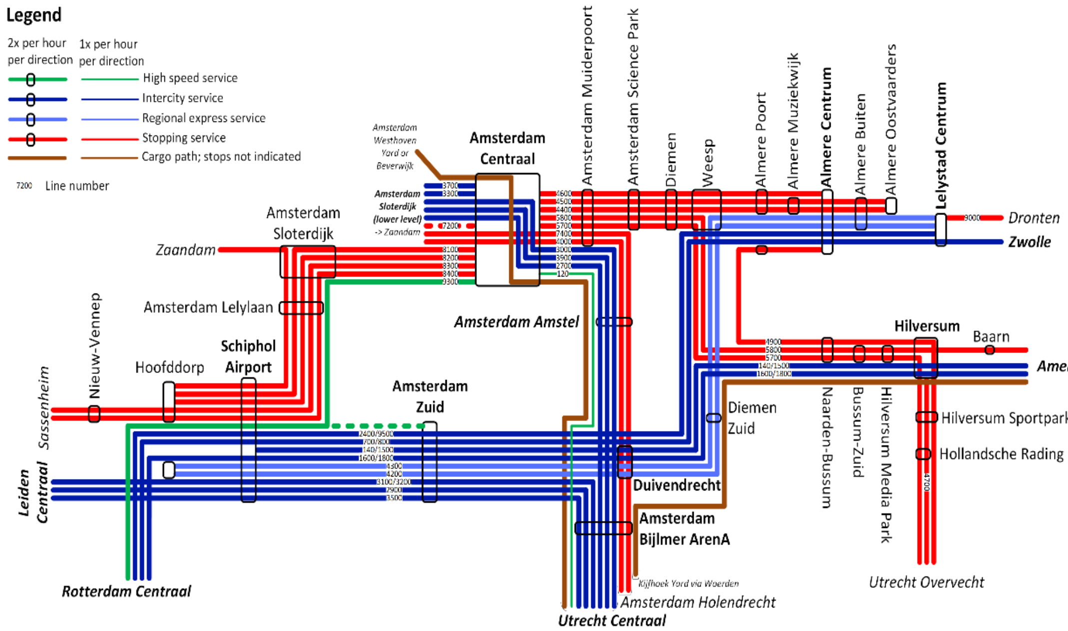


Figure 44. Timetable overview of the SAAL corridor and connecting lines

Note: Timetable variant is "6-basis" 2030. Intercity train stations are indicated in boldface. Dashed lines represent the timetable in its intended form, which the infrastructure will only allow from the year 2037 onwards: the high-speed services from Rotterdam Centraal will then terminate at Amsterdam Zuid, not Amsterdam Centraal, and the freed-up slot at Amsterdam Centraal will be used for an additional stopping service towards Zaandam.

Since this is a complex network, the simulations will be at a deterministic level, sticking to pre-defined train paths to prevent deadlocks and additional computational complexity. Nonetheless, we may introduce some stochastic driving in simulations comparing ATO to non-ATO such that the benefit of low variability in ATO running times will become clearer. We will assess the impact and recovery of disturbances with a deterministic set of disturbances. For all DATO technologies, we will assess the basic timetable of 2030.

We may also manually adjust this timetable to incorporate the benefits of ATO GoA2 and GoA4. We cannot represent a definitive model of this manually optimized timetable yet, since we would prefer to optimize the timetable through an iterative process of analysis of initial simulation results and improvement in the exact modelling of ATO driving behaviour. This would allow the causation to run from ATO behaviour to timetable adjustments, which eventually results in a well-tailored optimized timetable. Without software development to model ATO driving styles more exactly, an alternative, currently viable method is to start from an adjustment in timetable parameters, to then simulate ATO trains running that timetable instead. Concretely, following Dutch timetabling principles, we would impose a predetermined lower running time slack or supplements and lower headway buffer percentage, as in Vergroesen (2020). This method is less preferable since it offers a lesser degree of generalizable causal inference.

From the intended timetable and the infrastructure model, it follows that certain tracks shall run at a capacity of up to 14 trains per hour. This would give average headways of approximately four minutes. ATO, TMS, NG-Brake and ETCS-HTD may provide the required capacity upgrade to feasibly run this timetable, or at least to run it more stably. This is why we test these technologies on the SAAL corridor.

8.2.2. Sweden: Stockholm

The Citybanan is the commuter line through the city centre of Stockholm. This is a 6 km long double-track line for commuter trains only and has a very dense timetable. ATO GoA2 could be a solution to increase the capacity without building new infrastructure. The increase of capacity will be needed in the future in order to accommodate an increase of travellers. The line consists of four stations of which one is four-track and three are two-track. The simulation area will be between Stockholm Odenplan in the north and Årstaberg in the south. A previous study on the effects of GoA2 on Citybanan will serve as a base for the more detailed studies. The current signaling system is the Swedish legacy system ATC but will as the rest of the Swedish railway network be implemented with ETCS level 2. The time line for the ETCS implementation is under revision at the moment. The base year for the simulation will be decided together with the infrastructure manager.

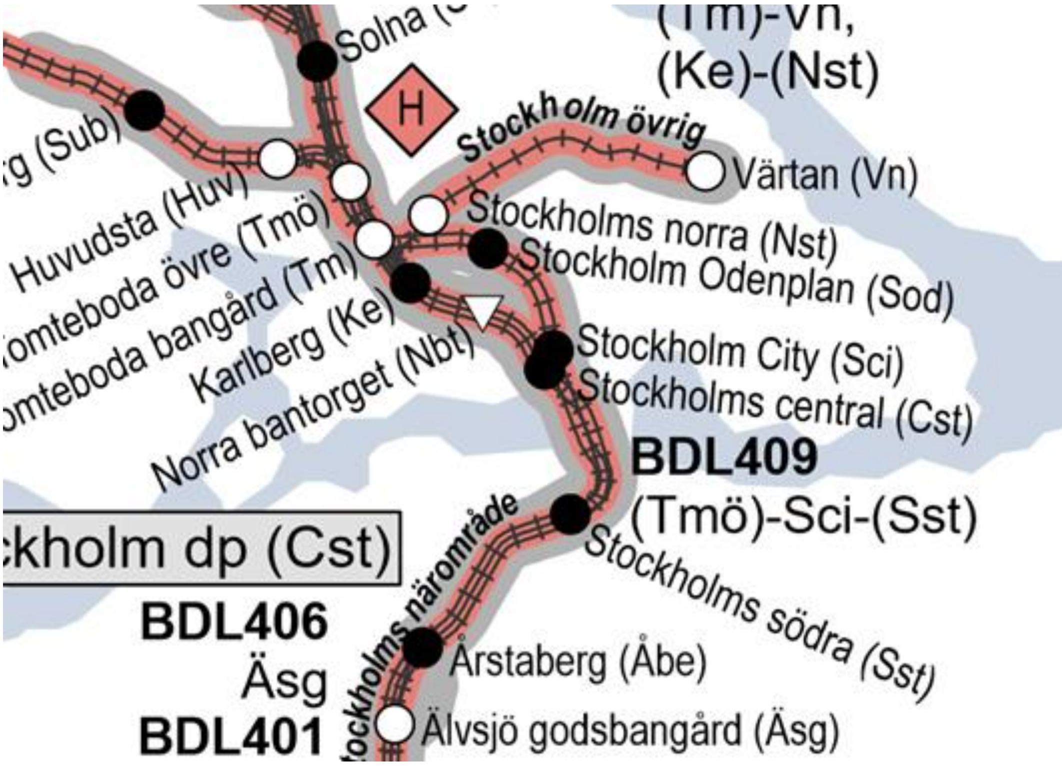


Figure 45. Stockholm Citybanan (Trafikverket 2023b).

8.2.3. Sweden: Malmö

Similar to the Citybanan in Stockholm, Citytunneln in Malmö is a 6 km double-track tunnel with only passenger traffic between Malmö Central and Hyllie. However, regional, commuter and long-distance trains operate the tunnel but no freight trains. The line consists of three stations of which two have four tracks and one has two tracks. The line is considered a bottleneck in the region and more capacity will be needed. ATO GoA2 will be analysed for the line to estimate the capacity effects. The current signalling system is the Swedish legacy system ATC but will as the rest of the Swedish railway network be implemented with ETCS level 2. The time line for the ETCS implementation is under revision at the moment. The base year for the simulation will be decided together with the infrastructure manager.

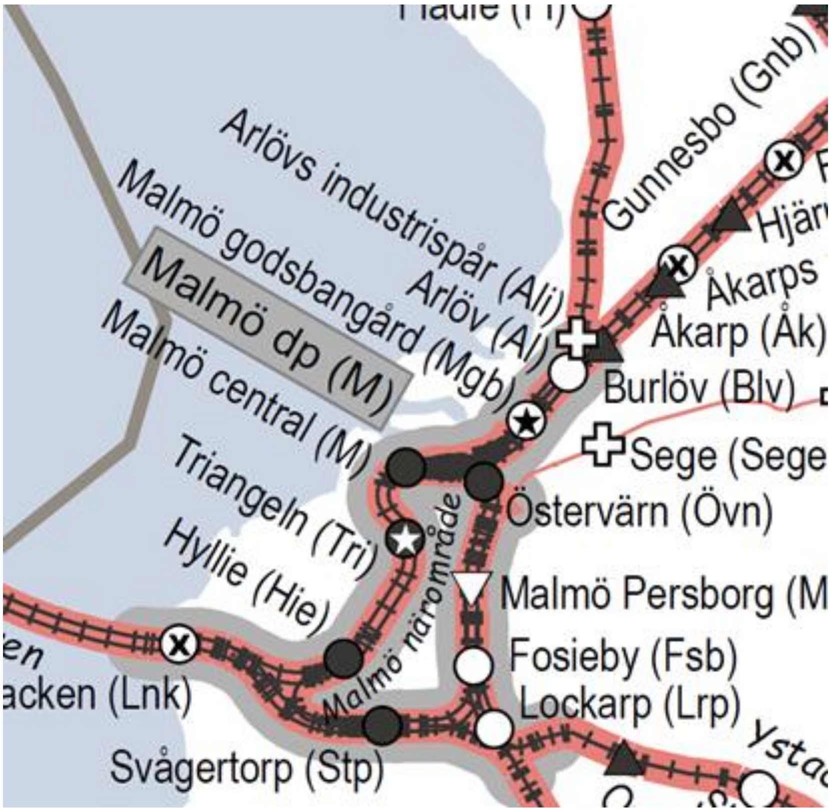


Figure 46. Malmö Citytunnel (Trafikverket, 2023b)

8.2.4. Sweden (- Norway): Kiruna – Narvik

The Iron ore line in Northern Sweden and Norway between Kiruna and Narvik is a 174 km long, single-track. There are 18 stations in between Kiruna and Narvik. The traffic is dominated by heavy 750-meter Iron ore trains and some additional freight and passenger trains. The line is at the capacity limit and more capacity would be needed. Both ATO GoA2 and GoA4 will be studied for this line to see the potential effects. For GoA2 the capacity effects will be the focus, while for GoA4 a focus will be on the punctuality. The line will be equipped with ETCS level in the upcoming years as the installation is an ongoing project. The base year for the simulation will be decided together with the infrastructure manager.

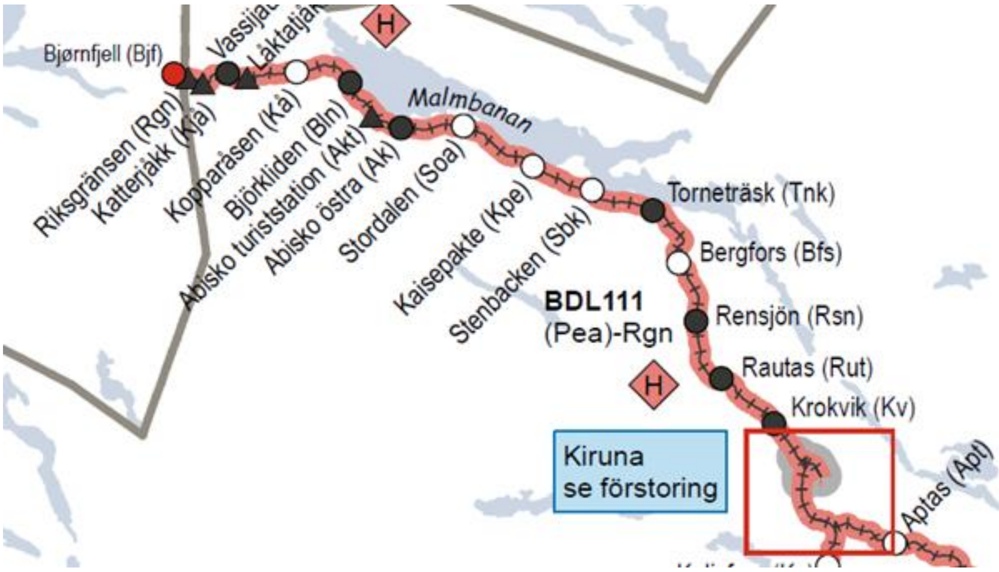


Figure 47. Iron Ore Line between Kiruna and the Swedish-Norwegian border (Trafikverket, 2023b)

8.2.5. Sweden: Southern Mainline

The Southern mainline between Norrköping and Mjölby is a 79 km long double track with mixed traffic of commuter, regional, long-distance, and freight trains. There seven stations between Norrköping and Mjölby of which five are passenger stations. Due to the mix of traffic, the line has capacity problems and the effects of GoA2 will be studied to evaluate the potential capacity gains. The current signaling system is the Swedish legacy system ATC but will as the rest of the Swedish railway network be implemented with ETCS level 2. The timeline for the ETCS implementation is under revision at the moment. The base year for the simulation will be decided together with the infrastructure manager.

VTI simulates the same track as KTH, the southern mainline (Figure 47 below). The simulation, which is equivalent to the real double-track, includes four stations and connected line. Unlike KTH, the focus is on studying capacity effects of system boundary transitions between ETCS level 2 and the Swedish lineside signalling system ATC (Automatic Train Control).

Figure 48. Southern Mainline (Sweden) between Norrköping and Mjölby (Trafikverket, 2023b)

8.2.6. Sweden: Eastern Link

The Eastern Link is a new 160 km long double-track railway line in Sweden that is under construction. It runs from Järna in the north to Linköping in the south (figure 48). Top speed will be 250 km/h, and it will be equipped with ETCS. In Järna and Linköping it will connect to existing double-track lines. In the long term, the Eastern Link will be part of a new high-speed railway network connecting Stockholm, Gothenburg and Malmö. The Eastern Link will primarily be used by long-distance trains and regional trains. Traffic density will be about 4–5 trains per hour in each direction. The simulation study will also include the existing line between Stockholm and Järna.

Figure 49. The Eastern Link (Sweden) between Järna and Linköping (Trafikverket, 2023b)

8.2.7. Spain: Bilbao Line 3

Our demonstrator will be tested on line 3 in Bilbao (Spain), a double commuter line operated by the railway operator Euskotren. The demonstrator will cover the entire length of the line, which is equivalent to a 5,885 km section consisting of 7 stops (Matiko, Uribarri, Casco Viejo, Zurbarranbarri, Txurdinaga, Otxarkoaga and Kukullaga).

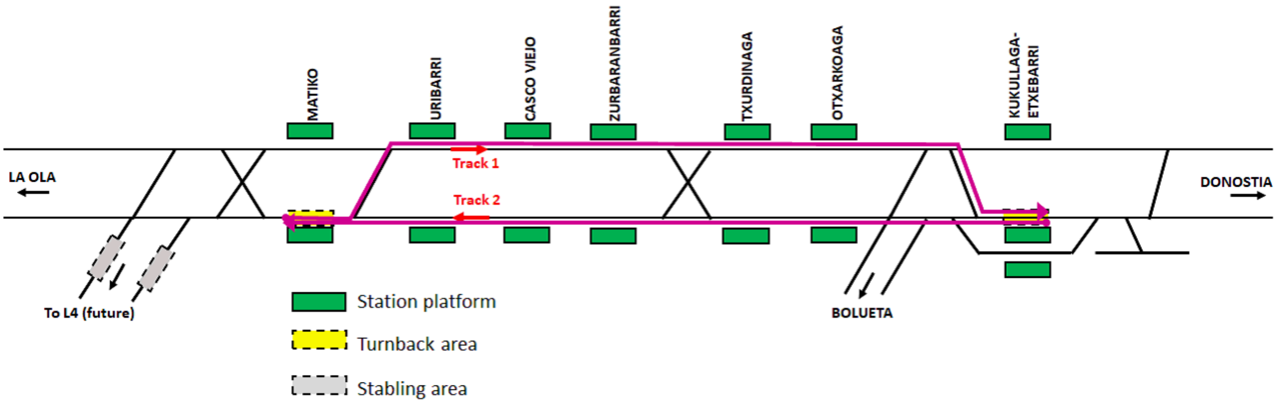


Figure 50. Schematic lay-out of Bilbao L3

Looking at the system architecture of the line, the ATO system is based on ETCS L2, as well as the protection provided by the interlocking. It consists of an RBC, which is the ETCS L2 track equipment, whose main function is to calculate movement authorisations based on the information received from the signalling system, and the ETCS-OB, which is responsible for supervising the safe movement of the train.

There are also fixed beacons whose main task is to serve as a reference for the location of the train and for the information sent by the RBC.

Figure 51.Bilbao Commuter Lines

8.2.8. Spain: Madrid Atocha Commuter Tunnels

INFRASTRUCTURE

This is a double-track ETCS Level 1 section for commuter trains between Chamartín and Atocha stations, with a length of 7.4 km, this is a central node where many lines come together, more specifically, almost all of Madrid's commuter lines.

There are 2 options for this route: through Recoletos tunnel stopping at Recoletos station (Chamartín-Nuevos Ministerios-Recoletos-Atocha) or through Sol tunnel stopping at Sol station (Chamartín-Nuevos Ministerios-Sol-Atocha).

At Nuevos Ministerios station, there are sidings on each track so that different speed trains can overtake each other if necessary.

TRAFFIC

The traffic of the line consists of commuter trains every 7 minutes on both Recoletos and Sol routes, regional trains every 45 minutes through Recoletos and every 3 hours through Sol.

SCENARIOS

For the scenarios to be simulated in this section, two objectives are pursued. On the one hand, the aim is to achieve an increase in capacity; on the other hand, the aim is to reduce costs. Considering the following described conditions, the goal is to find a balance between both, cost and capacity.

In order to achieve these objectives, different scenarios are proposed to check, by simulation, if, firstly, the defined goals are achieved and, secondly, if the results are valid.
First, the reference scenario is defined, which is the current track and traffic status, and will be used to compare the rest of the scenarios to be simulated. In this way, we will obtain an answer on whether we have improved our goals regarding the current state.

These scenarios are determined by modifying different elements: making changes in the infrastructure, modifying the integrity of the rolling stock and incorporating VSSs.
Since the objectives to be achieved for this line are both capacity improvement and cost reduction, the chosen changes are the following:

In relation to traffic and rolling stock, two alternative conditions are defined: the first is that it is assumed that commuter trains are equipped with TIMS, whereas regional trains are not equipped with it. The second condition is to consider that all the trains are equipped with TIMS. This way, differences regarding capacity between those cases can be compared, where it could be visualized whether a decrease in capacity is obtained as a result while not having TIMS equipped.

Regarding infrastructure and TTDs, a case where the current TTD layout remains with no change is defined. As mentioned, the cost reduction goal is also pursued, therefore, a case where TTDs are reduced between stations to the minimum is defined. By removing physical TTDs, a cost reduction could be obtained as a result of not installing them while designing a track.

This is intended to achieve the objective of cost reduction. However, if we only reduce the TTDs, this could be reflected in a decrease in capacity, hence, VSSs are incorporated. For the length of these, a methodology for optimal VSS lengths for each specific line should be followed.

However, in the absence of such methodology, it is intended to make an engineering study of the line, where the most critical sections of the track will be identified and analyzed. Firstly, a minimum VSS length of 25 meters (if possible) is implemented, then, a simulation is runned and a new VSS size increased by 25 meters [2] is simulated. Several iterations are performed increasing it by multiples of 25 through simulations until a size is reached from where the results improve in a non-significant way concerning the objective of the defined scenario, cost reduction and capacity increase for this case, so the optimal length of such scenario is established.

Table 9. Definition of variants Madrid Atocha Commuter tunnels

4.0	**Reference (ETCS Level 1 and Class B)**		
ID	Rolling Stock	TTD	VSS
4.1	Passengers with and without TIMS	Current	From 25 m to max. TTD length
4.2	Passengers with and without TIMS	Reduction of TTD between stations	From 25 m to max. TTD length
4.3	All trains with TIMS	Current	From 25 m to max. TTD length
4.4	All trains with TIMS	Reduction of TTD between stations	From 25 m to max. TTD length

8.2.9. Spain: Móstoles-El Soto – Humanes

INFRASTRUCTURE

This is a double-track commuter line between Mostoles-El Soto and Humanes with 21 stations in between them, with a length of 45.1 km.

Stations are closer to each other than the rest of the Madrid commuter lines and it has a particular signalling and supervision system, the LZB, a train protection system with continuous transmission of information and monitoring of the vehicle speed.

This is the only line in Spain working with automatic driving, where it is expected to eliminate this LZB and install ETCS level 2.

TRAFFIC

Unlike the rest of the commuter network, the C-5 line has similar frequencies to the Madrid Metro lines. The traffic consists of commuter trains every 5 minutes during peak hours and every 10 minutes during off-peak hours.

SCENARIOS

The objectives of this scenario are also cost reduction and capacity increase.. Regarding rolling stock, it is defined a case where all the trains are equipped with TIMS and another case where trains are not equipped with TIMS. This way, we could compare the two situations in terms of capacity.

Concerning trackside conditions and in order to get a cost reduction, a case where TTDs are reduced between stations with no change in stations is defined while there is another case where the current TTD layout is maintained.

In the case of VSSs, once the knowledge acquired in the first scenario for determining the most critical sections can be applied while using the previously mentioned methodology for determining the optimal VSS size for each case, several simulating iterations starting from the minimum possible VSS length will be carried out.

Table 10. Definition of variants Móstoles-El Soto – Humanes

5.0	**Reference (Class B - LZB)**		
ID	**Rolling Stock**	**TTD**	**VSS**
5.1	Only trains with TIMS	Reduction of TTD between stations	From 25 m to max. TTD length
5.2	Only trains with TIMS	Current	From 25 m to max. TTD length
5.3	Trains without TIMS	Reduction of TTD between stations	From 25 m to max. TTD length
5.4	Trains without TIMS	Current	From 25 m to max. TTD length

8.2.10. Spain: Madrid - Torrejón de Velasco

INFRASTRUCTURE
This is a high-speed line between Madrid and Torrejón de Velasco with a length of 35.85 km.

TRAFFIC
This line consists of high-speed trains from Chamartín towards Levante every 20 minutes.

SCENARIOS
The objective set for this line is to improve capacity as well as reducing costs, for which rolling stock, TTD and VSS conditions are defined. Regarding rolling stock, it is only proposed a case where all the trains are equipped with TIMS.

A case where the TTDs are reduced between stations for reducing costs is defined and another where the TTDs remain as they are now in the reference scenario. However, VSSs are incorporated in order to get a possible increase in capacity. The plan for the VSS length is the same as in the other scenarios, to develop a methodology for reaching the optimal size, from the capacity increase point of view, once an engineering study of this concrete line has been done.

Table 11. Definition of variants Madrid – Torrejón de Velasco

6.0	**Reference (ETCS Level 1/Level 2)**		
ID	**Rolling Stock**	**TTD**	**VSS**
6.1	Only trains with TIMS	Current	From 25 m to max. TTD length
6.2	Only trains with TIMS	Reduction of TTD between stations	From 25 m to max. TTD length

8.2.11. Spain: Barcelona - Figueres

INFRASTRUCTURE

This is a high-speed line between Barcelona and Figueres with a length of 130 km.

TRAFFIC

The traffic of the line consists on mixed traffic: freight trains every 1.5 hours, regional trains (200-250 km/h) every 2 hours and high-speed trains (250-350 km/h) every 3 hours.

SCENARIOS

The objective to reach by this simulating experiment is to get an increase in capacity. This is also a high-speed line as Madrid - Torrejón de Velasco, however, the difference between them is that this is a mixed traffic line so freight trains are also operating in it.

Concerning rolling stock, passenger trains will remain all equipped with TIMS as it is more critical because of punctuality and other possible service problems while freight trains will not be equipped with it.

The TTDs remain as they are now in the reference scenario, however, VSSs are incorporated in order to get an increase in capacity. The VSS lengths will be the ones taken from the methodolgy for reaching optimal sizes through iterations by simulating this specific scenario taking into account the critical sections and the increase in capacity objective.

Table 12. Definition of variants Barcelona - Figueres

7.0	Reference (ETCS Level 1/Level 2)		
ID	**Rolling Stock**	**TTD**	**VSS**
7.1	Passenger trains with TIMS and freight without TIMS	Current	From 25 m to max. TTD length

8.2.12. Spain: León-Guardo

INFRASTRUCTURE
This is a single regional line from Asunción Universidad to Guardo with a length of 93,82 km. In this case, a 26 km section from Asunción Universidad to Matallana will be studied. There are sidings in some stations in between them where trains can overtake and come across each other. It is expected to have demonstrators for ATO, ASTP, FRMCS and Level 3 in this line for the next call.

TRAFFIC
The traffic of the line consists of regional trains every 1.5 hours from Asunción Universidad,12 commuter trains per day and 2 long distance trains per day towards Bilbao.

SCENARIOS
The main objective for this line is to reduce costs, hence, conditions for rolling stock, TTD and VSS are determined. With respect to rolling stock conditions, passenger trains are all equipped with TIMS whereas freight trains are not.

Regarding TTDs, there is a situation in which only one TTD remains between stations with no changes in stations. Additionally, another case where also one TTD remains between stations and one TTD in stations is defined.

The strategy for the VSS length is the same as in the other scenarios, to use the developed methodology for reaching the optimal size from the cost reduction point of view once an engineering study for this concrete line has been done.

Table 13. Definition of variants Léon - Guardo

8.0	Reference (Class B)		
ID	**Rolling Stock**	**TTD**	**VSS**
8.1	Passenger trains with TIMS	Minimum (1 TTD between stations, 1 TTD	From 25 m to max. TTD length

	in stations)	

8.2.13. Spain: Lérida - Reus

INFRASTRUCTURE

This is a single regional line from Lérida to Barcelona covering a length of 64 km.

TRAFFIC

The traffic consists on mainly freight trains and 2 passenger trains per day. These freight trains could typically be organized in batteries of trains that all the group runs towards the same direction in order to increase capacity.

SCENARIOS

The objective set for this line is to improve capacity, for which rolling stock, TTD and VSS conditions are defined.

Regarding rolling stock, both passengers and freight trains will be equipped with TIMS. The TTDs remain as they are now in the reference scenario, however, VSSs are incorporated in order to get an increase in capacity. The VSS lengths will be the ones taken from the methodology for reaching optimal sizes through iterations by simulating.

Table 14. Definition of variants Lérida - Reus

10.0	**Reference (ETCS Level 1/Level 2)**		
ID	**Rolling Stock**	**TTD**	**VSS**
10.1	Only trains with TIMS	Current	From 25 m to max. TTD length

8.2.14. Spain: Cercanías Barcelona

INFRASTRUCTURE

For this case, some sections of the Barcelona commuter network will be taken into account, more concretely: El Prat de Llobregat-Paseo de Gracia (Paseo de Gracia tunnel), Hospitalet-Aragó (Plaza Cataluña tunnel) and Sagrera-Granollers (Montmeló tunnel).

TRAFFIC

The Montmeló tunnel, is node where commuter, regional and freight trains converge.

SCENARIOS

The main objective for this line is to improve capacity, hence, conditions for rolling stock, TTD and VSS are determined.

Regarding rolling stock, a case where passenger trains are equipped with TIMS and freight trains are not is defined and another case where both passengers and freight trains will be equipped with TIMS is also defined. The TTDs remain as they are now in the reference scenario, however, VSSs are incorporated in order to get an increase in capacity. The VSS lengths will be the ones taken from the methodology for reaching optimal sizes through iterations by simulating.

Table 15. Definition of variants Cercanías Barcelona

11.0	**Reference (ETCS Level 1/Level 2)**		
ID	**Rolling Stock**	**TTD**	**VSS**
11.1	Passenger trains with TIMS and freight without TIMS	Current	From 25 m to max. TTD length
11.2	All trains with TIMS	Current	From 25 m to max. TTD length

8.2.15. Indra

For this case, using this line will enable us to simulate real-world conditions and suitable environment to evaluate the tool's capabilities comprehensively, without involving real-world infrastructure.

The simulation will focus on a specific railway line within a larger control area that consists of seven lines in total. This particular line has been selected due to its unique operational challenges and diverse traffic patterns, which will provide valuable insights for the pilot. The layout of the line is a single track, adding complexity to the management of mixed traffic flows. As the sole route for both passenger and freight services, careful coordination will be required to ensure efficient and safe operation, especially during peak times or when managing freight with specific scheduling requirements.

The line features six stations, each varying in complexity, from smaller stops to potentially larger interchange stations. This diversity in station design and capacity adds another layer of operational challenge, especially when it comes to the efficient management of both passenger boarding and freight handling. The interplay between station complexity and single-track layout will be critical in determining optimal traffic flows and minimizing delays.

The traffic on this line is a mix of both passenger and freight services, representing a key element of the simulation's scope. In 2024, the base year for the simulation, the line operates with ETCS level 0, which implies a more conventional signalling system compared to higher ETCS levels. This will require precise traffic planning and careful coordination between trains to ensure safety and efficiency. By modelling this complex environment, the simulation will serve as a critical preparatory step for future improvements and potential upgrades, ensuring the line can accommodate the increasing demands of both passenger and freight services.

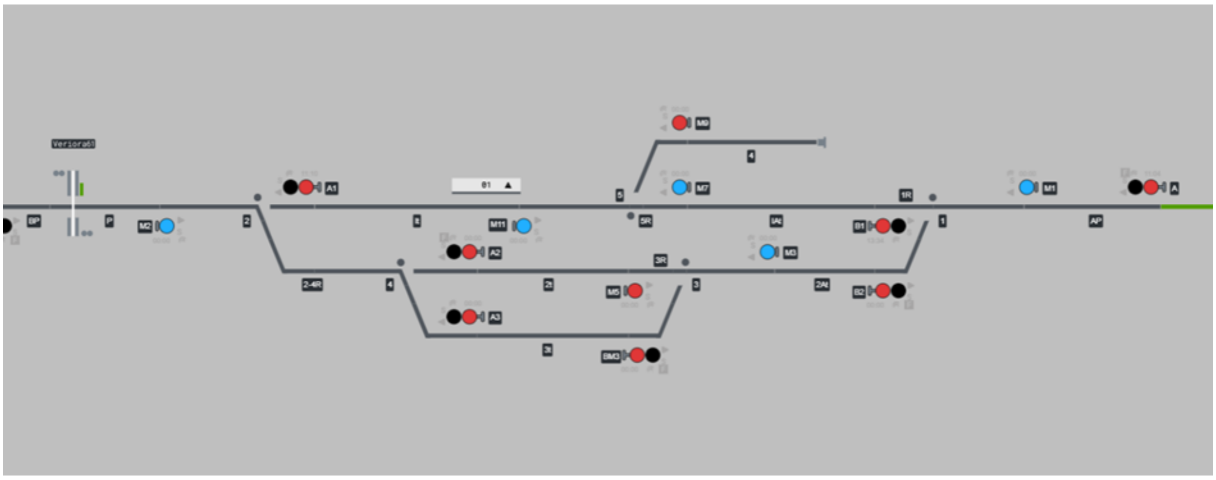


Figure 52. Schematic layout of a station on the modelled railway line

8.2.16. Spain: CEIT (C5: Móstoles-El Soto – Humanes)

The description of the geography of the line and the kind of traffic circulating can been seen in Section 8.2.9. The scenarios or conditions for the simulations are as follows.

Table 16. Definition of variants Móstoles-El Soto – Humanes, CEIT

Description	Period	% C-DAS
Off-peak hour | 100% C-DAS	Off-peak	100%
Off-peak hour | 50% C-DAS	Off-peak	50%
Peak hour | 100% C-DAS	Peak	100%
Peak hour | 50% C-DAS	Peak	50%

8.2.17. France: Lille

The Lille Metropolitan Regional Express Service (SERM) is part of the French SERM development policy announced by the French President at the end of 2022. Currently planned for 2040, this new service should meet the following objectives:
- Intensification of services with a doubling of frequencies on all routes to/from Lille (¼ hour frequency targeted)
- Creation of suburban services (omnibus) separate from regional services (fast non-stop services)
- Extended operating hours (5am-11pm)
- Service from the Lille hub to the ‘2nd ring’ bounded by Valenciennes, Douai, Arras, Lens, Béthune and Hazebrouck.

In order to meet these service objectives, infrastructure development projects are planned:

- Capacity treatment of sensitive areas of the existing infrastructure
- Creation of a new double-track line on the Hénin-Beaumont to Lille route, dedicated to high-speed regional train traffic. This section, known as REHF (Réseau Express Haut de France), will involve the construction of an underground station in Lille ‘Euraflandres’ to handle the traffic targeted via this section (12 trains per hour in each direction). A new station at the Airport and connections to the existing lines are also planned at Rougebarre, Lesquin and Hénin-Beaumont.

The new line “REHF” is planned to be equiped with ETCS. We want to determine the capacity effect of ETCS HTD compared with ETCS level 2.

The objective of this use case is to demonstrate the method for implementing ETCS HL3 into RailSys and determining the capacity effect of ETCS HL3.
It’s a relatively simple use case that will validate the methodology defined for the modelisation of ETCS HTD.

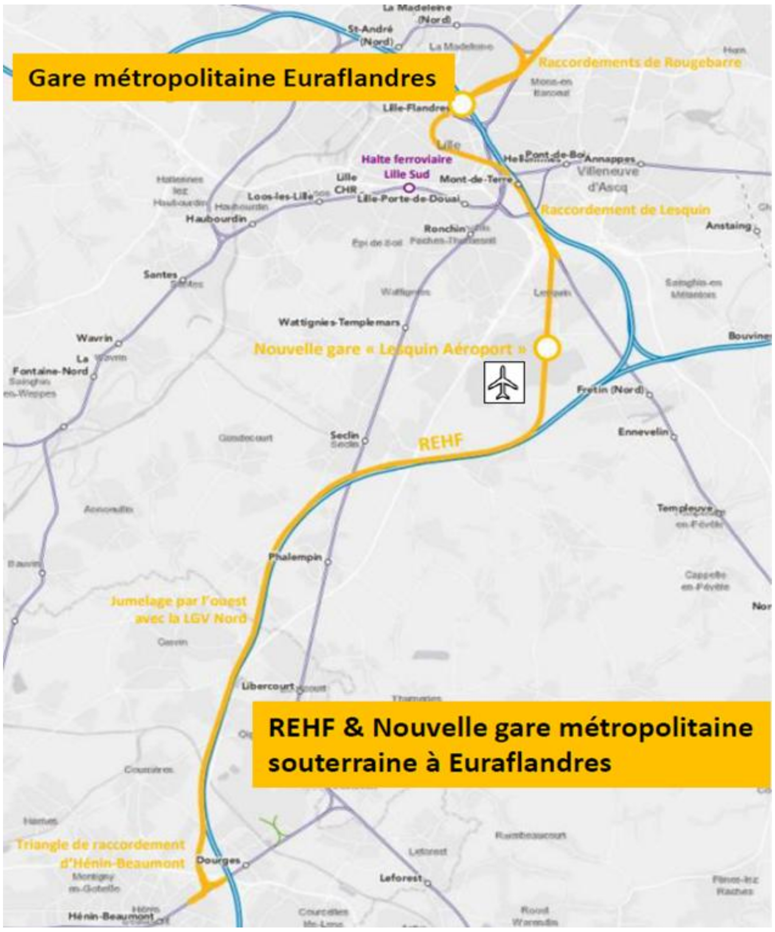


Figure 53. Location of the Lille – Euraflandres line

For this WP8/9 use case:

- The simulation area will be the REHF (new line between Lille and Henin Beaumont)
- This is a full double track line with 2 stations and some connexions with 4 connections to the existing network. The "Lesquin Aeroport" station is double track, and the Euraflandres station will have 4 tracks.
- Only regional and suburban trafic will run on this line
- We will simulate ETCS L2 and ETCS HTD on the line
- The horizon for putting the infrastructure into service, and therefore for the study, is 2040.

  The different scenarios that will be studied in this use case are :

Table 17. Definition of variants

Scenario	Signalling system	Maximum lenght of block section (virtual or track-side)	Rolling stock integrity detection
Reference	ETCS L2	1500m	0%
Sc 1	ETCS HTD	750m	100% (all trains)
Sc 2	ETCS HTD	375m	100% (all trains)

We will only run suburban trains supposed to be equipped with train integrity detection. Therefore, for this use case, no scenario will take into account the superposition of trains running with ETCS L2 and ETCS HTD.

The KPI for this use case will be for each scenarios :

- Minimal headways on different part of the infrastructure and for different configurations
- Infrastructure occupation percentage for the whole infrastructure

8.2.18. France: Bretagne and Pays de Loire

This demonstration will be carried out in WP9.

The various parties involved in the west of France want to improve rail links in Brittany and Pays de la Loire. The aim is to improve metropolitan services, inter-regional services, and high speed links to/from Paris by increasing rail capacity and improving journey times, while supporting the development of rail freight.

Several infrastructure development scenarios are possible in these regions, including new high-speed line, capacity treatment of sensitive areas of the existing infrastructure and implementation of ETCS on existing lines. In this context, the equipment of existing and new lines with ETCS HTD can be an option. So, we want to determine the capacity effect of ETCS HTD on the different sections of the infrastructure planned to be equipped with ETCS.

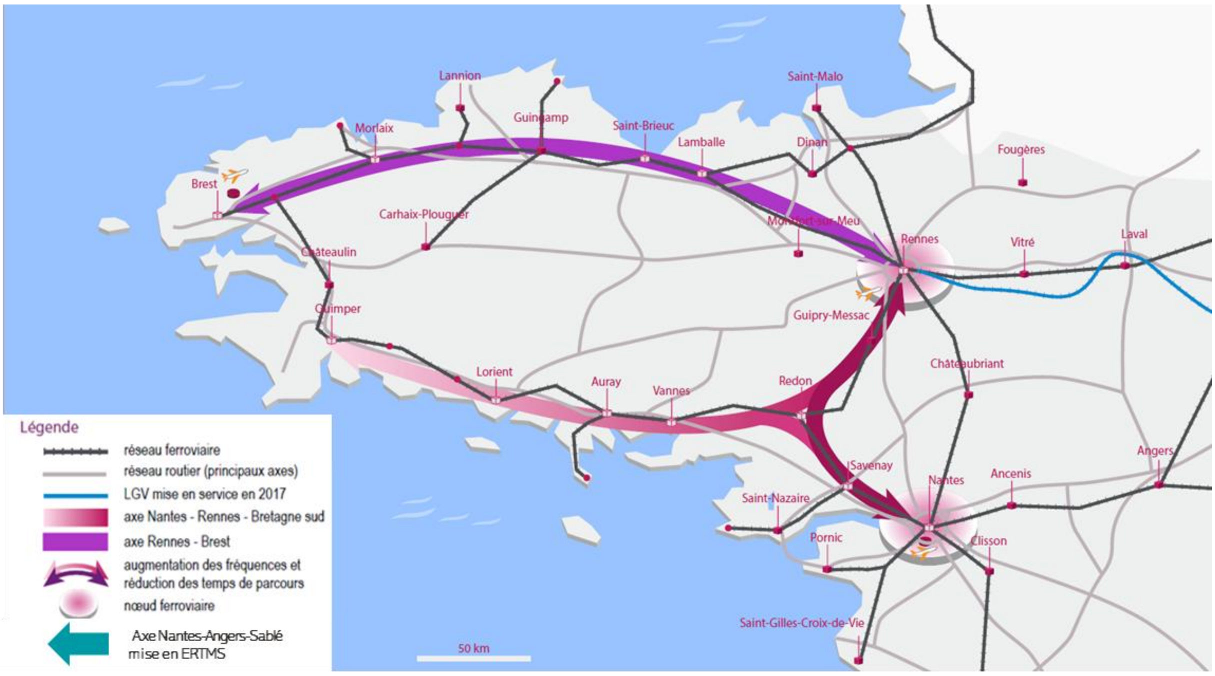


Figure 54.Location of the railway lines Bretagne and Pays de Loire

For this WP8/9 use case:

- The simulation area will be the Britany and/or Pays de la Loire network. The study will focus on the existing line that are planned to be equipped with ETCS. These lines have high-capacity requirement as they support mixed traffic (regional, suburban, high speed and freight trains) The exact relevant lines of the network where the study will be carried out are still to be determined. The lines for the simulations are mostly double track line.
  Several stations have high-capacity requirement. The two main stations of the network are Rennes and Nantes with more than 10 tracks for each station and link with the maintenance facilities. Several other stations have some capacity requirement such as Vannes, Lorient or Messac. These are mostly the terminus stations for regional and suburban services.
- We will simulate ETCS L2 and ETCS HTD on this use case
- The horizon for putting the infrastructure into service, and therefore for the study, is 2035/2040.

For this use case, we are currently planning of simulating the following scenarios, change may occur later during WP9, if others scenarios appear relevant:

Table 18. Definition of variants Bretagne and Pays de Loire

Scenario	Signalling system	Length of block section (virtual or track-side)	Rolling stock integrity detection
Reference	ETCS L2	According to the actual project - TBD	0%
Sc 1a	ETCS L2 ETCS HTD	**Light virtual subdivision –** exact length TBD in WP according to discussion with partners and WP37	Only suburban trains equipped, others trains non equipped
Sc 1b	ETCS L2 ETCS HTD	**Light virtual subdivision –** exact length TBD in WP according to discussion with partners and WP37	All trains equipped except long distance / high speed trains and freight train
Sc 1c	ETCS L2 ETCS HTD	**Light virtual subdivision –** exact length TBD in WP according to discussion with partners and WP37	All trains equipped except freight train
Sc 2a	ETCS L3H ETCS HTD	**heavy virtual subdivision –** exact length TBD in WP according to discussion with partners and WP37	Only suburban trains equipped, others trains non equipped
Sc 2b	ETCS L3H ETCS HTD	**heavy virtual subdivision –** exact length TBD in WP according to discussion with partners and WP37	All trains equipped except long distance / high speed trains and freight train
Sc 2c	ETCS L3H ETCS HTD	**heavy virtual subdivision –** exact length TBD in WP according to discussion with partners and WP37	All trains equipped except freight train

The KPI for this use case will be for each scenario:

- Minimal headways on different part of the infrastructure and on different configurations
- Maximal number of trains on different part of the infrastructure depending on the expected service
- Infrastructure occupation percentage for the whole infrastructure.

9. Interaction with other Flagship Projects

As mentioned in several locations in this report, there are relations with multiple other work packages of Europe's Rail. In order to create an overview of those connections, they will be summed up and described briefly here. Usually, information goes in two directions: information is received in the past two years to this work package 8 and used in the deliverable at hand for describing new technologies and their simulation methods. Information on simulation methods and results of the scenarios will be sent back during the upcoming two years when working on work package 9. Notably, we do not focus on scenario variations and parameter settings in this document, as the focus is on methods development. A summary of parameter setting inputs from the associated work packages, most of which were already delivered, will be described in the future Deliverable 9.2.

FP1-MOTIONAL

Within Europe's Rail Flagship Project 1 Motional, two work packages relate to the current deliverable:

- WP15 Development - Linking TMS to ATO/C-DAS for optimised operations
- WP16 Demonstration - Linking TMS to ATO/C-DAS for optimised operations.

Namely, this deliverable described C-DAS and TMS methods and scenarios that partly built on knowledge gathered in both deliverables of WP15:

- D15.1 – Requirements for the deployment of TMS linked with ATO/C-DAS
- D15.2 – TMS and ATO/C-DAS timetable test & simulation environment

Theoretically, we use the developed knowledge on RTTP and TPE as a basis for chapter 7.6, in which we concede that the contemporary development of the technology is not mature enough to have been implemented into software tools with more advanced capacity measurement capabilities yet, though we do describe the functions that such a software development would need to achieve. Also, we describe how the Spanish software tools were developed with specifically WP15/16 in mind.

In terms of software and scenarios, there are varying levels of correspondence depending on the partners associated. CAF and Indra are in both sets of work packages, with the same staff working on both, and the tools they develop are co-intended for use in both WP15/16 and in WP8/9. Automatically, this means that the future simulations of C-DAS and TMS are exactly aligned across work packages for the Spanish use cases, although it must be noted that the extent of capacity measures testable within these tools is limited (i.e., headways only). Namely, the modelling of a dynamic TMS is computationally intensive, and the focus divergent between capacity effects (WP9) and operational insights as well as technological development (WP16). Hence, from a certain threshold onwards, it becomes logical that software characteristics for dedicated TMS-ATO/C-DAS interaction diverge from capacity analysis from a certain level of detail onwards. Indeed, for the Dutch use case, the software tools and associated staff differ. Nonetheless, the intention is to match the scenario (as described in chapter 8.2) as much as possible, i.e. following the same infrastructure model and the same timetable. Finally, Swedish C-DAS simulations are not matched between WP8/9 and WP15/16.

Accordingly, the scenarios defined in this document may be mirrored in:

- D16.2 – Demonstrations of TMS functionality for improved C-DAS operations
- D16.3 – Report on ATO – TMS integration platform demonstrator

FP2-R2DATO

Within Europe's Rail Flagship Project 2 R2DATO, there are three related work packages that are listed below, each with their relevant deliverables. Since topics in R2DATO are not spread over two work packages, the deliverables giving information and receiving information might overlap.

- WP17 Next Generation Brake Systems with adhesion management functions – Phase 1: Demonstrator preparation and pre-validation
  - D17.1 – ATO impact of brake/ adhesion management systems including considerations on certification methods; resume on adhesion determination methods
  - (pending grant agreement adaptations): D18.1 – Summary of ATP impact of BAMS including considerations on certification methods, ADS and long term perspective of dynamic braking curves adaptation
- WP37 ETCS HL3 Deployment Strategies
  - D37.3 – Requirements specification to FA1 WP 8/9
  - D37.4 – Determining ETCS HL3 capacity impact analysis using simulations
  - D37.2 – Methodology for optimised placement of (virtual) blocks.
- WP32 DATO Assessment and Potential identification.
  - Information has been received based on D32.2 – DATO business case outline & required inputs specifications and scheme
  - Information will be given back for analysis to D32.5 – DATO capacity and impact simulations report.
  - Information will thereafter be used in the concluding report to evaluate different DATO-techniques, titled D32.1 – DATO Business Case.

Chapter 7.3 of this deliverable pulls theoretical insight on the NG Brake technology from work package 17. The simulation methods we designed are in accordance with the ways NG Brake are predicted to affect traction and braking behaviour. The results of our simulations for NG Brake will be shared with work package 18 in a later stage. Alignment on exact parameter settings and scenario variations took place, and will be described in FP1-D9.2 (i.e., the follow-up work package of this project).

Next, work package 37 describes ETCS HTD deployment strategies. Of specific interest to our work package was their deliverable D37.3, which determined the required scenario setups and its VSS block length variations for our simulations in work package 9. The scenario descriptions for HTD scenarios in chapter 8 match the ones described in that deliverable. In the future, information on our methodology and our results in work package 9 will be analysed in D37.4 and generalised into broader conclusions about optimised virtual block design in D37.2.

Finally, work package 32 will integrate the capacity results of some of the simulations outlined in this deliverable within a new DATO business case framework. Especially relevant, here, is deliverable 32.5, which uses an interface model to transform the simulation results into economic and business impacts through aggregation into capacity indicators and then processing them further. Notably, the transmitted simulation results are limited to the Dutch (all DATO concepts described in this deliverable), Swedish (ATO and HTD), and CAF as tasked by Adif (HTD) scenarios, as the WP32 deadline lies before the one of work package 9, and only the partners deliberately participating in both work packages could commit to such result transmission deadlines.

Indeed, formally, WP32 supplied requirements for tested DATO concepts to WP8/9, which the scenarios outlined in chapter 8 conform to. Informally, this process was more horizontal, as there is considerable overlap in the people working on the simulations in WP8/9 as well as the capacity team in WP32.

The D32.5 output economic and business impacts of capacity effects will be input to deliverable 32.1, which aggregates capacity impacts into a broad business case framework that considers all relevant impacts, also outside the scope of capacity. In such, work package 32 represents an important link with this work package in inferring the real-world consequences of the capacity effects we will find for the different system developments.

10. Conclusions

Railway operations are constrained by limited capacity on railway networks and by available financial budgets. New technologies may make railway operations more cost-efficient, and they may also decongest and add capacity to existing networks without the need to build more infrastructure. However, little is known about the exact effect sizes of capacity effects for many new technologies. This raises the need to evaluate the capacity effect of these new technologies in different logistical contexts.

Capacity simulation methods, applied in railway simulation software, will give us a comprehensive insight into these capacity effects. However, for many new technologies that will become mature in the next few decades, there are no established simulation methods for this aim, and parameter settings for simulation need to be adjusted. In this report, we developed these methods for six DATO-techniques: ETCS, HTD, NG-Brake, C-DAS, ATO and TMS. We developed the methods up to TRL4. We will apply these methods in WP9, and this report also outlined the corresponding application scenarios and software choices.

Chapter 5 explained that we mostly require microscopic, deterministic and synchronous modelling of a railway network and timetable in order to properly test the capacity effect of these new technologies. Chapter 6 described corresponding software choices at each respective partner of this WP. In general, Swedish, Dutch and French simulations centre around RailSys, while Spanish simulations use tools that they developed in-house.

Chapter 7 then defined the developed simulation methods for each DATO technique. Generally, DATO techniques require careful modelling of the signalling system for ETCS and HTD, and of the driving regime for C-DAS/ATO/NG-Brake. The report described several parameter settings or key functionalities that simulation of these techniques should have to properly represent their real-life effects on capacity. We also explained how the software tools will implement, or implemented, these parameter settings or key functionalities.

Finally, for application of our methods in the next work package, chapter 8 of this report described 17 scenarios covering a wide array of logistical situations across different EU countries. Naturally, these scenarios will be simulated using the methods developed and software tools explained in this deliverable.

Overall, the developed methods in this deliverable give guidance on the necessary functions and parameter settings to simulate capacity effects of DATO techniques. This represents an important theoretical step towards evaluating the potential for contemporary technical advances to increase the capacity and cost-efficiency of rail networks in Europe.

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