

## Deliverable D15.1

### Requirements for the deployment of TMS linked with ATO/C-DAS

<b>Project acronym:</b>	MOTIONAL
<b>Starting date:</b>	01/12/2022
<b>Duration (in months):</b>	46
<b>Call (part) identifier:</b>	HORIZON-ER-JU-2022-01
<b>Grant agreement no:</b>	101101973
<b>Due date of deliverable:</b>	September 2023
<b>Actual submission date:</b>	29/09/2023
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<b>Dissemination level:</b>	PUB
<b>Status:</b>	Issued

Reviewed: yes

Document history		
Revision	Date	Description
0.9	2023-08-25	Preliminary version sent for review 1. Section 9 not finished.
0.91	2023-08-31	Version sent for review 1. All text in doc, comments still exist.
1.0	2023-09-29	Submitted document.
2.0	2024-04-24	Revision considering review comments from the ERJU, SP and the SFERA working group

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## 1 Executive Summary

This document constitutes the Deliverable D15.1 “Requirements for the deployment of TMS linked with ATO/C-DAS” in the framework of Flagship Project FP1 – MOTIONAL as described in the EU-RAIL MAWP. This deliverable is from Work Package (WP) 15 “Linking TMS to ATO/C-DAS for optimised operations” and is based on the outcome of task T15.2 and initial results of task T15.3. It is setting up requirements for innovations in TMS – ATO/C-DAS including relevant background information.

The focus of WP15 is to study and enhance the link between TMS and ATO/C-DAS in order to, e.g., enhance operations, improve feedback loops, and increase standardization. This report lays out the ground for the continued work in WP15/16 of FP1 Motional in EU-RAIL. The objective of the report is to present the current situation both as “state-of-the-art” and “state-of-practice”, describe the needed development and innovations that will be target of future work in WP15/16, and to capture the requirements that are important to consider in the development work.

The “state-of-the-art” study shows that there are important concepts and standards that are evolving in the area, like SFERA, ERTMS/ATO subsets, and the RCA. There is important knowledge to build upon regarding, e.g., energy optimisation, train trajectory optimisation, communication, and data models. The “state-of-practice” overview shows that several countries have made important implementations (both trial and “real”) of C-DAS with important conclusions valid for both C-DAS and ATO operations. There are fewer implementations and tests regarding ATO, but also in that area important experience has been made to further build upon.

For the system architecture in the area, design and analysis principles are proposed, both to get harmonization and also to help a common understanding. Communication platforms provide important bases, like the Integration Layer and the standardized data format of the Conceptual Data Model (CDM). But further developments are necessary to adapt them for the relevant area.

The continued work of WP15/16 will be very much based on the partners’ previous experience in the area and on the evolving standards. This certifies both that the work will be relevant, reusable, and move the state-of-the-art forward. The planned work has a broad base for important improvements and includes, e.g., improved RTTP and TPE construction for better ATO/C-DAS efficiency, architectural and communication developments for standardization, and better adaptation to human factor aspects of TMS - ATO/C-DAS systems.

The development work will both consider and contribute to the standards in the area and will adhere to important concepts setting up requirements on the development, such as SFERA, relevant ERTMS/ATO “subsets”, RCA, and concepts under development, such as the Integration Layer and Conceptual Data Model, as well as other types of requirements such as human factors, correctness of information, and response times.

## 2 Abbreviations and Acronyms

Abbreviation / Acronym	Description
AoE	ATO over ETCS
API	Application Programming Interface
ARS	Automatic Route Setting
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
CBTC	Communication-Based Train Control
CCS	Control, Command, and Signalling
C-DAS	Connected Driver Advisory System
CDM	Conceptual Data Model
CI	Common Interface (TAF/TAP TSI)
CMS	Capacity Management System
CTC	Centralized Traffic Control system
DAS	Driver Advisory System
DMI	Driver Machine Interface
EGNOS	European Geostationary Navigation Overlay Service
EMU	Electric Multiple Unit
ERJU	Europe's Rail Joint Undertaking, EU-RAIL
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
FFFIS	Form Fit Function Interface Specification
FP	Flagship Project
FRMCS	Future Rail Mobile Communication System
GNSS	Global Navigation Satellite Systems
GoA	Grade of Automation
IL	Integration Layer
IM	Infrastructure Manager
IMU	Inertial Measurement Units
JP	Journey Profile
LA	Logical Architecture
LTE-R	LTE (Long-Term Evolution) for Railways
LZB	LinienZugBeinflussung
MQTT	Message Queue Telemetry Transport
N-DAS	Networked Driver Advisory System
OA	Operational Analysis
OB	On-board (system)
PSM	Platform Specific Data Model
RCA	Reference CCS Architecture
RTTP	Real-Time Traffic Plan
RU	Railway Undertaking

SA	System Analysis
SCI	Standard Communication Interface
SCI-OP	Standard Communication Interface Operational Plan
S-DAS	Standalone Driver Advisory System
SFERA	Smart Communications for Efficient Rail Activities
SP	Segment Profile
STR	Status Report
SSA	Subsystem Architecture
TAF	Telematics Applications for Freight services
TAP	Telematics Applications for Passenger services
TCMS	Train Control and Monitoring System
TCS	Traffic Control and Supervision system
TMS	Traffic Management System
TP	Timing Point
TPE	Train Path Envelope
TS	Trackside (system)
TSI	Technical Specifications for Interoperability
UI	User Interface
UNISIG	Union of Signalling Industry
UWB	Ultra-Wide Band
WATO	Wayside ATO

### 3 Introduction

The present document constitutes the Deliverable D15.1 “Requirements for the deployment of TMS linked with ATO/C-DAS” in the framework of Flagship Project FP1 – MOTIONAL as described in the EU-RAIL MAWP. This deliverable is based on the outcome of tasks T15.2 and T15.3 from Work Package (WP) 15 “Linking TMS to ATO/C-DAS for optimised operations”. It is setting up requirements for innovations in TMS – ATO/C-DAS including relevant and needed state-of-the-art.

Within the framework of the Innovation Pillar FP 1: “Network management planning and control & Mobility Management in a multimodal environment and digital enablers” (MOTIONAL) of Europe’s Rail Joint Undertaking (ERJU), WP15 focuses on the integration of TMS systems with connected driving advisory systems (C-DAS) and/or automatic train operation systems (ATO). The combination of TMS with C-DAS and ATO is expected to contribute to increased energy efficient driving, network capacity utilization, punctuality, robustness, and performance during disturbances. The aspects of the TMS systems that are in focus in WP15 are aspects that are related to C-DAS and ATO.

WP15 covers the following technical enablers (TE) from the Multi-Annual Work Program (MAWP) of the ERJU:

- Technical Enabler 12 (TE 12): Real-time convergence between planning & feedback loop from operations [TRL 4/5].
- Technical Enabler 15 (TE 15): TMS speed regulation of trains, precise routes, and target times for ATO and dynamic timetables [TRL 4/5].

#### 3.1 WP15 Linking TMS to ATO/C-DAS for Optimised Operations

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. WP15/16 is about linking TMS to ATO/C-DAS for optimised operations.

For efficient operation of ATO/C-DAS, the TMS should provide a Real-Time Traffic Plan (RTTP) specifying the exact routes for each train as well as times at scheduled timing points. This RTTP is the basis for both the timely route setting by the Traffic Control and Supervision 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.

The train trajectory describes the time and speed profile over distance. A TPE must guarantee that a drivable and conflict-free train trajectory exists and the TPE should also provide sufficient flexibility for energy efficient driving and other optimisations. The TPE is used to provide constraints to the train trajectory generation algorithm of the ATO/C-DAS. A C-DAS then translates this train trajectory to driving advice for the driver, while ATO (from GoA 2 onwards) uses the train trajectory as reference to a train trajectory tracking algorithm to provide automatic control commands to the traction and braking systems.

The functions of ATO/C-DAS are divided into a Trackside (TS) and an Onboard (OB) system, with the TMS connected to the ATO/C-DAS TS. The ATO/C-DAS OB of the connected trains get information from the TS and report their status as feedback back to the TS. This feedback can be used to optimise the TPEs and RTTP automatically or via the traffic controller.



The essence of WP15/16 is to identify the various feedback loops and their use in dynamically updating the RTTP and TPEs to optimise capacity, punctuality, and energy efficiency. Further, another important part is also to identify how the traffic controller should be involved in this feedback and what information is needed and how it should be presented in the TMS. For the traffic controller to be able to maintain an updated RTTP with high quality, WP15/16 will also look at what functions in the TMS will be needed. This includes both manual tools and automatic support.

### 3.2 Objective/Aim

The aim of this document is to report the results of task T15.2 and initial results from task T15.3 of WP15 of the Europe's Rail project FP1 Motional. In short, the scope of the document includes defining important concepts, short description of state-of-practice and state-of-the-art in the area and draw up guidelines for the continued activities in WP15.

Formally, the tasks are described as<sup>1</sup>:

**Task 15.2 Requirements for innovations TMS – ATO/C-DAS**

*To set up requirements for innovations in TMS – ATO/C-DAS. The requirements are based on state of the art and current dialogue with SFERA group and System Pillar to form the evolution and transition towards TMS – ATO. To form a common view of the functionality of TMS – ATO/C-DAS.*

**Task 15.3 Requirements for TMS and ATO/C-DAS timetable development**

*Definition and outline of requirements to model TMS-ATO/C-DAS operated trains in timetables and simulation. Included here is the identification of types/grades of TMS for optimal linking with ATO/C-DAS and applying algorithms to them. Next, the development of guidelines for train path envelopes TMS – ATO/C-DAS, including distribution strategies for dynamic and optimised capacity, punctuality, and energy consumption.*

Further, this deliverable D15.1 is described as<sup>1</sup>:

*This report is based on the input of Tasks 15.2 and 15.3. It is setting up requirements for innovations in TMS – ATO/C-DAS including relevant and needed state-of-the-art.*

Since Task T15.3 continues 14 months after this deliverable D15.1 is due, it only includes initial and partial results from that task.

This report forms a basis for the continued work in WP15, by analysing and concluding the research needs in the area, point out the development direction that WP15 will continue in, and give background and motivations for the prioritized research directions.

### 3.3 Outline

This document starts in chapter 4 with a description of important concepts related to the subject: C-DAS, ATO, and their linkage to TMS. Chapter 5 gives an overview of the state-of-the-art based on both the academical and industrial status. Chapter 6 includes a description of the state-of-practice related to C-DAS, ATO and relevant TMS functions, describing the current and planned status of the countries involved in this work package. The status of some other countries has also

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<sup>1</sup> As defined in the Grant Agreement.

been added in case it is of special interest to the work package. Chapter 7 corresponds the first results from Task 15.3 and describes a principal structure of the linkage between TMS and ATO/C-DAS containing several design options, that could be used as a reference. Towards the end, chapter 8 describes the required innovations for developing the TMS – ATO/C-DAS linkage, including a description of the continued work in WP15/16, and in chapter 9 we summarize requirements that the development work in WP15/16 should take into account. Finally, the deliverable is concluded in chapter 10.

## 4 Important Concepts

Before going in depth into the interaction between TMS and ATO/C-DAS, it is necessary to clarify concepts that help to get a broad vision of the system. This includes sharing the same terminology and identifying those actors and systems focusing on the railway operation. This chapter includes a description of key concepts that arise in the relevant area for this report.

### 4.1 General Overview

Figure 1 gives an overview of the actors, systems, and information concepts that will be described in the following subsections. There are other concepts that are excluded in this overview, such as the train characteristics.

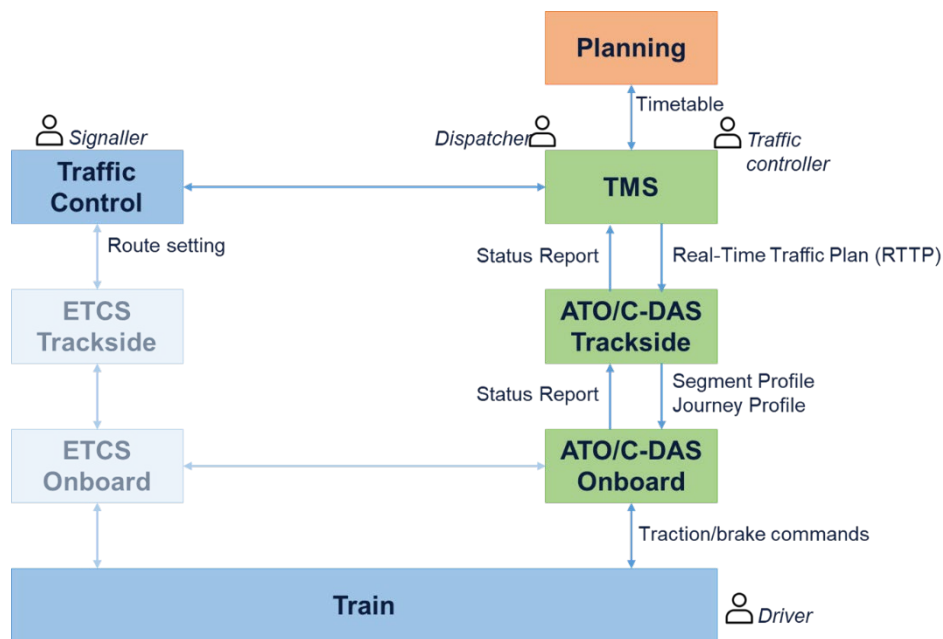


Figure 1: Overview Actors, Systems, and Information concepts

#### 4.1.1 C-DAS Benefits

C-DAS brings the following expected benefits supported by continuous data from TMS:

- Optimise 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 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 utilising data collected by C-DAS.
- Reduction in operational disturbances by limiting the number of restrictive signals encountered.
- Better overall user experience when the driver gets the present plan and the train has verified that it will follow the plan to the traffic controller. Also, better passenger information can be given when it is based on a verified plan

### 4.1.2 ATO Benefits

ATO provides similar expected benefits as C-DAS, intensified by the autonomous features (Jeiziner, (2020)):

- Enhanced infrastructure and transport capacity by decreasing headways.
- Improved timetable stability and punctuality by means of consistent driving behaviour.
- Energy savings by means of an optimised driving strategy.
- Reduced mechanical wear and tear and less noise by means of homogeneous driving with less braking.
- Increased passenger comfort by means of smoother, homogeneous driving.
- Reduced rolling stock and staff need due to increased robustness.
- With GoA4, reduced number of staff onboard operating trains.

### 4.2 Actors

The following roles at a traffic control centre can be distinguished (one person can fulfil more than one role):

- **Signaller** (or Centralized Traffic Control (CTC) operator)
  - Responsible for safe routes both in normal and degraded operations.
  - Authorizes train movements by commands to interlockings over remote control areas (routes).
  - Conducts safety communication, for instance in case of European Instructions or alarm calls.
  - Controls shunting over main tracks.
- **Dispatcher (or local traffic controller)**
  - Responsible for a feasible route plan according to the (working) timetable.
  - Monitors train path deviations and updates train timings, orders, and routes.
  - Contacts train drivers in case of disturbances and disruptions.
- **Traffic controller (or network traffic controller)**
  - Coordinates network traffic (national or large traffic control areas).
  - For large delays or disruptions, coordinates network traffic in cooperation with transport controller of the railway undertakings.

How these roles are implemented differs per country. In some countries (e.g., Sweden, the Netherlands, and Spain) the roles of Signaller and Dispatcher are executed by one person, often denoted Traffic controller.

At the side of the Railway Undertakings (RUs) the relevant actors for C-DAS and ATO are:

- **Driver**
  - Train drivers are responsible for driving trains in a safe, punctual, and economic manner over various routes in accordance with rail rules, regulations, and procedures. With ATO GoA3/4, there is no driver onboard the train.

- **Attendant**
  - In ATO GoA3 there is no driver in the cab under normal conditions, but a train attendant is present onboard who can take over the driving in case of disruptions.

### 4.3 Systems

The systems that interact in this environment are described below. Only the systems with direct involvement in the operation are described. Other subsystems and modules with different functions are not considered in this scope. We also focus on digital systems of the future and discard legacy systems that are mostly still in place.

In order to control and monitoring the network, these are the main systems:

- **ETCS:** The European Train Control System (ETCS) is the signalling and control component of the European Rail Traffic Management System (ERTMS). It is a replacement for legacy train protection systems and designed to replace the many incompatible safety systems currently used by European railways. The standard is also adopted outside Europe and is an option for worldwide application.
- **CMS / Timetable Planning System:** CMS (Capacity Management System) is a system or set of systems for scheduling or planning. Based on infrastructure data, rolling stock characteristics, and planning rules it provides timetables for both passenger and freight train operation.
- **TMS (Traffic Management System):** This is the system for monitoring and managing the traffic and the signalling system from the control centres. It covers a broad range of functionalities and, therefore, it is expressed in some cases as multi-actor system, which includes several actors. The TMS will be in charge for updating the Real-Time Traffic Plan (RTTP), which is the base for route setting in the TCS and for train operation by ATO/C-DAS. Traffic management systems will be able to receive status reports via the TCS from connected ATO/C-DAS systems in the managed area, such as position, speed and expected arrival times at timing points. This information from ATO/C-DAS can be used to improve traffic prediction and provide a better accuracy in the conflict detection. In particular, ATO/C-DAS can send its estimated forecast when the plan received from TMS is considered not feasible.
- **TCS (Traffic Control and Supervision system):** System or set of systems that commands signalling systems, sets routes or takes safety measures in case of infra withdrawal or in case of incidents. TCS is responsible for Automatic Route Setting (ARS), if available.

In addition, these are the systems related to automatic train operation:

- **ATO (Automatic Train Operation):** A mode of operation in which different train operation tasks are automated, according to the Grade of Automation (GoA) level present, up to GoA level 4, where the train operation is fully automated without the presence of staff on board. It is in charge of commanding the driving (traction and braking) and additional services (doors control, coupling control, fire detection, inner lightning, etc.) of the train

according to traffic control and regulation decisions and commands. It is composed of two separated subsystems (ATO TS and ATO OB) with an interface between them.

- **ATO TS (Trackside):** A set of functions that communicates with the TMS and the ATO OB of connected ATO trains. Based on the RTTP received from the TMS, the ATO TS generates segment profiles and journey profiles, and sends these to the ATO OB of all connected trains. It also receives status reports from the ATO OB and sends status reports to the TMS.

**ATO OB (On-Board):** A set of functions that translates the information contained in the journey and segment profiles received from the ATO TS into train trajectories and controls the traction and braking systems for automated train runs. This system is deployed on-board train units and has bi-directional communication with the Trackside equipment. It is able to optimise the performance of one train and command the train unit running without driver intervention.

These are the systems related to the C-DAS operation:

- **Connected DAS (C-DAS):** A driver advisory system with a communication link to external traffic management 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, and also receipt of information from trains to these systems to improve regulation decisions. C-DAS (Connected Driver Advisory System) consists of two main systems: the Trackside (TS) system and the Onboard (OB) system. These systems work together to provide real-time information and advisory recommendations to train drivers.
- **C-DAS TS (Trackside):** A set of functions that communicates with the TMS and the C-DAS OB of connected DAS trains. Based on the RTTP received from the TMS, the C-DAS TS generates segment profiles and journey profiles, and sends these to the C-DAS OB of all connected trains. It also receives status reports from the C-DAS OB and sends status reports to the TMS. **C-DAS OB (On-Board):** On-Board unit that receives the data from the ground (C-DAS TS), performs the calculation for the driving advice (if not done previously on the ground by RU or IM), and sends the driving advice to the user interface to be displayed. This device can either be integrated into the train or on a portable unit.
- **C-DAS DMI (Driver Machine Interface):** Subsystem that displays the driving advice to the drivers and permits data entry by a driver.

C-DAS can be built with different architectures:

- **C-DAS-C:** A C-DAS architecture in which driving advice are calculated centrally by C-DAS Trackside and sent to the trains. The C-DAS TS then needs to have high precision of the location of the train.
- **C-DAS-O:** A C-DAS architecture in which conditions and requirements for train driving are sent to C-DAS Onboard, which then calculates the driving advice. The C-DAS OB then typically has the position via a Global Navigation Satellite Systems (GNSS).

Finally, in difference to C-DAS there are non-connected versions of driver advisory systems:

- **Standalone DAS (S-DAS or DAS):** A driver advisory system which has all data downloaded to the train at or prior to journey start.

- **Networked DAS (N-DAS):** A driver advisory system that is capable of communicating with one or more traffic management systems, enabling provision of data to the train, including updates for schedule or routing information, although these are generally not in near real time.

Although this deliverable refers to the integration of ATO and C-DAS with TMS, it is worth mentioning that ETCS has On-Board and Trackside elements as well. The TSI CCS with ETCS Baseline 4 also includes the ATO-over-ETCS Baseline 1, which amongst others defines the interfaces between the ETCS and ATO Onboard systems, see Section 5.1.6. From ETCS L2 onwards, the ETCS Trackside can already communicate with TMS.

#### 4.4 Information Concepts

These data bring together information exchanged by the systems and basic elements when linking TMS to ATO/C-DAS:

- **RTTP (Real-Time Traffic Plan):** RTTP is the operational timetable based on planned routes and timing points, updated according to current traffic situation and potential delays. An RTTP includes the detailed train routing. This is implemented as Operational Plan in the RCA.
- **Segment Profile (SP):** Set of static infrastructure data associated to the Journey Profile and required by the ATO/C-DAS on-board as reference for the train trajectory. In the segment profile the timing point locations are defined.
- **Timing Point (TP):** A location defined in the segment profile to which a type (stopping or passing point) and a specific time target or time window can be attributed in the journey profile. This time may be an arrival time, a departure time, or in the case of a train not scheduled to stop at that location, the passing time.
- **Journey Profile (JP):** The JP contains references to the infrastructure data along the journey (segment profiles) and operational data required by the ATO/C-DAS OB to follow the RTTP. The operational data contains a list of timing points that the train must adhere to along its journey. The list of timing points can be defined in real time on the basis of the scheduled timetable and on-line traffic regulation (i.e., RTTP). The JP may be updated during the journey. The JP can also include additional driving information, such as adhesion information.
- **Train Path Envelope (TPE):** A list of timing points attributed with a time target or window, and/or speed target or window, used as constraints to the Train Trajectory generation onboard in C-DAS or ATO. The TPE is communicated to the OB as part of the JP.
- **Train Trajectory:** The time and speed profile over distance for a specific route complying with train, track and operational constraints, generated by the C-DAS or ATO system. The train trajectory must fit within the TPE to guarantee conflict-free operation.

#### 4.5 C-DAS and ATO Similarities and Differences

Both C-DAS and ATO technologies need information provided from a TMS that has to be translated

into train path envelope constraints for the trajectory computation. They both also need a train trajectory generation algorithm, which implicitly includes traction/braking commands. But there are key differences between C-DAS and ATO.

The main difference is that for C-DAS there is a driver who is supposed to follow the speed advice given by the C-DAS DMI. That is, C-DAS is primarily an advisory system that provides real-time guidance and suggestions to train drivers, who retain control over the train's operation. On the other side, ATO systems are designed to fully automate train operations, including acceleration, braking, and stopping at stations. ATO is classified as GoA2 (Grade of Automation, level 2) or higher and sends the brake and traction commands directly to the train.

Therefore, human aspects form the essential difference: ATO systems aim to minimise the reliance on human intervention, whereas C-DAS actively involves the train driver in the decision-making process. The drivers can choose to follow the advisory recommendations or exercise their judgment based on the situation.

In addition, there is a set of less-obvious differences between C-DAS and ATO that deserve to be mentioned:

- **Integration with existing infrastructure:** C-DAS systems can be more easily integrated with existing railway infrastructure and rolling stock. They leverage the existing train control systems, onboard sensors, and communication infrastructure to provide real-time guidance to the driver. ATO systems often require significant infrastructure modifications and in particular advanced automatic train protection like ERTMS to guarantee safe train operation (although ATO applications to lines not yet equipped with ERTMS/ETCS are under investigation by railway undertakings) and specialized train and track equipment to enable full automation, such as obstacle detection.
- **Cost and implementation:** Implementing C-DAS typically incurs lower costs compared to ATO. C-DAS leverages existing infrastructure and primarily involves software upgrades and integration efforts. E.g., a hand-held equipment (tablet) could be used. ATO, on the other hand, requires significant investments in infrastructure modifications, train equipment upgrades, and safety certifications.
- **Training requirements:** Introducing C-DAS into an existing railway system generally requires less training for train drivers compared to implementing ATO (GoA 2). Train drivers need to familiarize themselves with the C-DAS interface and understand how to interpret and utilize the provided information. ATO systems, however, require extensive training to ensure drivers are well-versed in the system's operation, emergency procedures, and handling exceptional situations.
- **Human-machine interaction:** C-DAS systems rely on effective human-machine interaction, ensuring that the train driver understands the recommendations and can easily interact with the system. ATO systems, being fully automated, focus more on monitoring and supervisory interactions rather than active control input from the driver.

On the other hand, ATO has additional benefits over C-DAS. In particular, driving variation is reduced with ATO, train running is more predictable, and reaction times to the supervised braking



curves from the ETCS (or other ATP system) can be shorter. Therefore, ATO will have a higher impact on capacity gains with in particular shorter buffer time requirements. C-DAS can therefore also be seen as a first step towards ATO (GoA2 or higher).

#### 4.5.1 GoA for ATO

The definition of Grade of Automation (GoA) arises from apportioning responsibility for the given functions of railway operations between operational staff and involved technical railway systems. Table 1 provides an overview of the different GoAs<sup>2</sup>.

Table 1: Definitions of Grades of Automation

GoA	GoA Name	Train Operator	Description
GoA0	<b>On-sight train operation</b>	Train driver in the cab	In this grade of automation, the driver has full responsibility and no system is required to supervise his activities. However, points and single tracks can be partially supervised by the system.
GoA1	<b>Non automated train operation</b>	Train driver in the cab	The train is driven manually; but protected by automatic train protection (ATP). This GoA can also include providing advisory information to assist manual driving.
GoA2	<b>Semi-automated train operation</b>	Train driver in the cab	The train is driven automatically but a train driver is still responsible. Stopping is automated but a driver in the cab is required to start automatic driving of the train, the driver can operate the doors (although this can also be done automatically), and the driver checks that the track ahead is clear and carries out other manual functions. The driver can take over in emergency or degraded situations.
GoA3	<b>Driverless train operation</b>	Train attendant on-board the train	The train is operated automatically including automatic departure, a train attendant has some operational tasks, e.g., operating the train doors (although this can also be done automatically) and can assume control in case of emergency or degraded situations.
GoA4	<b>Unattended train operation</b>	No staff on-board competent to operate the train	Unattended train operation; all functions of train operation are automated with no staff on-board to assume control in case of emergencies or degraded situations.

While mainline railway applications mostly still apply non-automated train operation, i.e., GoA1, Urban Transport Systems are demonstrating across the world the capability of Automated Train Operation to increase line capacity and to reduce energy consumption, compared to manual train operation. The GoAs also originate from urban transport. With the ATO-over-ETCS developments, ATO also become within reach of mainline railways, including freight trains.

<sup>2</sup> This information was obtained from document *SUBSET 125. System Requirements Specification*. (ERA \* UNISIG \* EEIG ERTMS USERS GROUP (2022a)). In view of the TSI CCS 2023 that has just been published, level 3 no longer exists and everything is now considered level 2.

## 5 State-of-the-Art

In recent years, the railway industry has witnessed significant advances in the integration of the TMS with systems such as C-DAS or ATO to enhance operational efficiency and improve passenger experience. This integration aims to create a seamless and intelligent railway network by combining real-time data, automation, and decision-making algorithms to allow a synchronized flow of information between the train, the control centre, and other trains, leading to optimised train movements and reduced delays.

The TMS acts as the central control hub for the entire railway network, collecting data from various sources to monitor train movements, track conditions, and other operational parameters. By analysing this data, TMS can make informed decisions in real-time, such as optimising train schedules, avoiding train path conflicts, and responding to disruptions. The integration of these systems allows seamless coordination and communication between all components, enabling the railway network to function as a unified and intelligent system. C-DAS and ATO systems should work smoothly with TMS to create an intelligent and adaptive railway network capable of efficiently managing traffic, minimising delays, and improving overall capacity.

On the one hand, C-DAS leverages real-time data to provide drivers with precise and up-to-date information, enabling them to make informed decisions regarding speed profiles, braking points, and energy consumption. On the other hand, ATO systems aim at automating driver tasks, including acceleration, deceleration, and stopping based on predefined algorithms and real-time data. When C-DAS and ATO systems are integrated with TMS, they can receive accurate information about track conditions and up-to-date targets to avoid potential conflicts with other trains, allowing them to adjust train operations in real-time. This integration not only increases the precision and reliability of train operations, but also optimises energy consumption and reduces maintenance costs.

Recent advances in different key technologies are playing a crucial role in the implementation of C-DAS and ATO systems. Wireless communication systems and onboard data networks enable seamless data exchange between trains, control centres, and infrastructure. This facilitates the transmission of real-time information regarding speed restrictions, train delays, and other operational parameters, allowing for dynamic speed profile adjustments. By leveraging this connectivity, operators or automated systems can make informed decisions to optimise speed and energy consumption while maintaining safety and adherence to regulations. Additionally, accurate positioning and signalling systems are of utmost importance in ecodriving and optimal speed profile generation in railways as they provide precise information about train location, track conditions, and speed restrictions, enabling the algorithms and control systems to make informed decisions for energy-efficient operations. Together these systems ensure the safety of train movements, prevent unnecessary acceleration or deceleration, and facilitate the implementation of optimised speed profiles, resulting in reduced energy consumption, improved punctuality, and enhanced overall operational efficiency.

The following subsections will examine the state of the art of the different technologies and current standards that facilitate the integration of C-DAS and ATO with the TMS to enhance operational efficiency.

## System Pillar

A challenge regarding innovations and changes to the systems are very difficult and costly to achieve. Ultimately this undermines the performance and competitiveness of rail transportation. Therefore, the System Pillar (SP) aims to improve the European railway system to offer better services for European passengers and freight, delivering a unified operational concept and a functional, safe and secure system architecture. The System Pillar, in fact, is designed to be the “generic system integrator” for the Europe’s Rail Joint Undertakings (EU-RAIL), and the architect of the future European railway system. The System Pillar can be seen as a layer between state-of-the-art and applied practices, aimed to harmonize and standardize the innovations and developments.

The architectural process of System Pillar comprises four steps:

- Operational analysis (OA): this analysis focuses on the processes, not taking any specific technical system architecture into account.
- System analysis (SA): this analysis captures the needs for the future system.
- Logical architecture (LA): This step defines with which solution concepts and which architectural patterns the system needs shall be fulfilled.
- Subsystem architecture (SSA): This step integrates all considerations on the intended structure of subsystems and interfaces, as well as all open technical aspects, into a consistent architectural definition.

A central task of the System Pillar is not only to define target system architectures and operational concepts, but also coordinate and deliver the means for implementation through inputs to Technical Specifications for Interoperability (TSI) and harmonised standards.

## 5.1 C-DAS and ATO

### 5.1.1 Energy Optimisation

Although the railway sector is on the right path and ahead of all other transportation modes in reducing energy demand and emissions, there is still work to be done to fulfil the International Union of Railway’s (UIC) Low Carbon Rail Challenge for the years 2030 and 2050 (UIC and CER (2012)). Decarbonisation policies are shifting transport modes to those that are less dependent on carbon, and therefore significant growth in the use of railway for freight and passengers transport is expected. In addition, the global population is growing at a high rate, which exponentially increases the demand for urban mobility. These two effects together give the railway sector great growth potential for the next years and decades, requiring a bigger effort to further improve railway efficiency.

The energy demanded during train operation from the vehicle’s point of view is mainly composed of the energy balance between traction and regenerative braking (if it exists) and the energy demanded by all the auxiliary equipment. Therefore, the best option for optimising a vehicle from the energy point of view is to improve efficiency on both fronts.

According to González-Gil et al. (2014), the different strategies for reducing energy consumption in railway operations can be divided into three major groups:

- Increase efficiency by means of vehicle design optimisation. This strategy aims to increase efficiency at the design stage by improving the global design and individual components of the vehicle, such as reducing the total mass of the vehicle, improving aerodynamic resistance, improving the efficiency of traction equipment and reducing the power demand of auxiliary equipment such as heating or cooling systems.
- Energy recovery strategies. These are mainly focused on recovering the braking energy by transforming the vehicle's inertia into electricity, which can be either stored on the train, used by a nearby vehicle, or restored to the electric grid. Although regenerative braking is commonly used in many countries, there is still great potential for increasing the share of recovered energy.
- Reduce energy consumption by optimising train operation. These techniques try to reduce global energy demand by adjusting timetables and individual speed profiles for each vehicle, which is also known as ecodriving.

Although all of the above-mentioned actions are required in the mid-term for a greater reduction in energy demand, the first two strategies require a high initial investment, and they are normally taken into account when planning a new route or renewing the rolling stock. However, ecodriving presents a real opportunity for railway undertakings to minimise energy consumption without the need for expensive technological investments or major changes to current operations.

The core principles of ecodriving include smooth acceleration, optimal speed control, coasting, energy recovery, and intelligent power management (Su et al., 2023). Consistent speeds within recommended limits reduce energy losses and synchronize with traffic patterns and signal systems. Coasting allows trains to glide without power usage, harnessing kinetic energy and regenerating power. Efficient braking techniques, such as dynamic or regenerative braking, convert kinetic energy into electrical energy, reducing wear on mechanical brake systems. Intelligent power management ensures that energy consumption is adjusted based on operational requirements, train load, and track conditions.

The implementation of ecodriving techniques in railways brings several benefits. First and foremost, it saves energy and improves operational efficiency, resulting in cost savings. This, in turn, reduces greenhouse gas emissions, positively impacting the environment and contributing to a more sustainable transport system. Ecodriving also extends the life of equipment, as smoother acceleration, controlled speed profiles, and reduced braking wear minimise maintenance costs. Punctuality is enhanced as ecodriving practices improve schedule adherence, reducing delays and improving the reliability of railway services. However, implementing ecodriving does come with its challenges. Adequate driver training and awareness programs are essential to ensure that train drivers understand ecodriving techniques and their importance in energy optimisation. Infrastructure support, such as suitable signalling systems, track maintenance, and energy recovery systems, is necessary to facilitate ecodriving practices. Operational constraints, such as strict schedules or congestion, can sometimes make it challenging to apply ecodriving techniques consistently. Balancing energy efficiency with operational demands is crucial. Finally, the utilization of technologies such as C-DAS and ATO, along with their integration into the TMS, is necessary to incorporate ecodriving principles and fully leverage their potential.

C-DAS utilizes real-time data collection and analysis to provide intelligent advice to train drivers. By leveraging various sensors, communication infrastructure, and connectivity, C-DAS systems continuously monitor train and track conditions. They consider factors such as track characteristics (speed limits, gradients, etc.) (Howlett, et al. (2009)), efficient use of driving strategies such as coasting (Guastafierro et al. (2016), Tian et al. (2019), Morea et al. (2021), Pröhl, et al. (2021)), weather conditions (Blanco-Castillo et al. (2022)), or traffic status (Rao (2015), Liebhold et al. (2023)) to provide optimal driving strategies to train operators. C-DAS systems help drivers make informed decisions, such as adjusting speed, braking, or coasting, to achieve energy-efficient operations without compromising safety. ATO takes energy optimisation a step further by incorporating automation and control mechanisms into train operation. ATO systems use precise positioning, signalling, and control algorithms to operate trains automatically, reducing human error and further optimising energy consumption. These systems can manage train acceleration, cruising, coasting, deceleration, and braking profiles more efficiently than manual operations, resulting in reduced energy waste. ATO systems are capable of maintaining optimal speeds, minimising unnecessary stops, and ensuring smooth and efficient train operations.

Furthermore, the linking of C-DAS and ATO with a TMS creates a comprehensive and coordinated approach to energy optimisation in railway operations. A TMS acts as a centralized control system that oversees the entire railway network, monitoring train movements, track conditions, and schedules. By linking C-DAS and ATO with the TMS via the TCS, real-time data from the trains can be used by the TMS. In particular, ATO/C-DAS can send arrival time forecasts when a received plan from the TMS is considered infeasible. The TMS can then include this information in an improved train forecast.

The integration of C-DAS, ATO, and TMS holds immense potential for energy optimisation in railways. By combining real-time data, intelligent decision-making, and automation, these systems create a synergistic effect, resulting in reduced energy consumption, improved punctuality, and enhanced operational efficiency.

Ecodriving could be defined as the group of techniques intended to operate rail vehicles as efficiently as possible while ensuring the safety and punctuality of services. Apart from energy consumption reduction, ecodriving strategies may also improve passenger comfort through smoother driving and reduce the wear of rolling components. The intelligent use and combination of traction, cruising, coasting and braking driving modes are the basic practices in ecodriving. Track gradients, acceleration profiles and maximum speed limits are critical factors determining the traction energy consumption in rail services. Hence, their optimisation within safety and schedule restrictions may lead to important energy savings.

Although some common strategies or practises can be found, solutions in the literature largely vary according to the type of rail transport studied, namely metro, regional, high speed or freight, as the specific characteristic of each sector largely affects driving strategies. Similarly, the characteristics in terms of track gradients and traffic characteristics have a big influence on the results. Related to this, an extensive review of the literature was made in Scheepmaker et al. (2017), studying the different approaches used in energy-efficient train control and energy-efficient train timetabling.

Although multiple studies have approached the optimisation of the driving profile for a single train, a more complex but also more promising scenario arises when trying to optimise the speed profile

of several trains at the same time, combining the energy-efficient timetabling and energy efficient operation of multiple trains (Wang and Goverde (2019); Zhang et al. (2021)). These approaches compute multi-train trajectories simultaneously with a shared objective of minimising multi-train energy consumption as well as avoiding conflicts between trains. Additionally, they try to adjust train schedules to adjust train arrivals and departures to use the energy regenerated by the braking trains by the trains that are accelerating and are demanding power.

Much of the research in the field of DAS is done on speed profile optimisation with the aim of minimising energy consumption. Different theoretical solutions are available in the literature that solve this problem either as a coasting control problem or as an optimal control problem. Except from a few published studies that consider some of the characteristics of the railway network (Haar et al. (2017)), most of the solutions only consider one single train in operation in a simulation environment, comparing the calculated speed profile with the maximum performance one. Reported improved energy efficiency in simulation environments is around maximum 30% (Haar et al. (2017)). In case of one DAS, 5-15% fuel saving for freight transport and 22% energy saving on high-speed passenger trains are reported during extensive trial runs (Howlett et al. (2019)). There are also reports of 15% reduction in fuel consumption and improvement in punctuality because of application of a DAS on metro lines in Australia (Baier et al. (2008)).

### 5.1.2 Train Trajectory Calculation

A train trajectory defines the speed and time over a given route of a train. It can be represented as a speed profile over distance or in a time-distance diagram, where the time over distance corresponds to a given speed profile. The train trajectory calculation is a key element in the interaction between TMS and ATO/C-DAS. In particular, the driving strategy should be consistent amongst the TMS and ATO/C-DAS. Moreover, the parameters used in the running time calculations within the planning and TMS to compute the scheduled train paths may deviate from the ones used in the train trajectory calculations in ATO/C-DAS due to assumed conditions (e.g., mass, tractive power, wind). Also, the characteristics of specific ATO/C-DAS algorithms may not be known or modelled in the TMS. In addition, most TMS algorithms are not based on the detailed level of train trajectories, so that conflict detection and resolution algorithms may fail when actual train trajectories deviate from the assumed running times. This will mainly become an issue for dense traffic conditions and close following at bottlenecks. For these reasons, the ATO/C-DAS Trackside can play an intermediate role to check the RTPs from the TMS at the level of train trajectories and add extra targets or constraints in the Journey Profiles that are sent to the trains.

Two types of train trajectory calculations are particularly relevant:

- Minimum-time train trajectory: the fastest speed profile on a given route corresponding to the (minimum) technical running time.
- Energy-efficient train trajectory: the energy-optimal speed profile on a given route for a given running time, including running time supplement.

A train trajectory is the solution of an optimal control problem, which consists of dynamic equations for speed and time as a function of distance (or speed and distance as function of time) that depends on the traction and brake controls. The controls must be computed such that the resulting train trajectory optimises a given objective function, i.e., total running time in the case of the minimum-time problem and energy consumption in the case of the energy-efficient train

trajectory problem. Moreover, the problem includes constraints to the (speed and time) state and (traction and brake) control variables. The train trajectory optimisation problems should consider train characteristics (mass, length, maximum speed, resistance, traction, brake), route-specific track characteristics (speed limits, gradients, curves, tunnels), and operational characteristics (stop locations, signalling, temporary speed restrictions, adhesion). The (real-time) scheduled running time contains some time allowance over the minimum running time, called the running time supplement. To arrive on time at the next timing point (i.e., not too early and not too late), the available running time supplement must be translated into a 'slower' speed profile corresponding to the scheduled running time. The exact speed profile determines the resulting energy consumption. The aim of the energy-efficient train trajectory problem is to minimise this energy consumption while satisfying all constraints such as arriving on time. Scheepmaker et al. (2017) give an extensive literature review of energy-efficient train control and timetabling. The book by Su et al. (2023) gives an overview of the various possibilities of energy-efficient train operation including energy-efficient train driving strategies, timetabling, and regenerative braking.

A driving strategy consists of a sequence of the following driving regimes:

- Acceleration
- Cruising (speed holding)
- Coasting (no traction or braking)
- Braking.

The optimal driving regimes with the corresponding optimal traction and braking controls can be derived using optimal control theory, and in particular Pontryagin's Maximum Principle (Albrecht et al. (2016ab); Scheepmaker et al. (2021)). The energy-efficient train operation makes use of optimal cruising speeds and coasting points (cut-off traction) to save energy, whilst accelerating as fast as possible to reach the optimal cruising or coasting speed, and (service) braking as fast as possible before speed restrictions and stops (see Figure 2). The optimal sequence and switching points between these four energy-efficient driving regimes –maximum acceleration, cruising by partial traction, coasting, and maximum braking– depend on the available running time supplement. If the optimal cruising speed exceeds the speed limit, then cruising at the speed limit becomes optimal with a later coasting point. For short distances, the cruising regime may be absent when the optimal cruising speed cannot be reached before coasting should already start. When regenerative braking can be applied another cruising regime by partial regenerative braking on declines can also be used. Moreover, in this case the optimal cruise speed is lower and coasting starts later while braking from a higher speed is used to benefit from the regenerative braking (Scheepmaker and Goverde (2020)). For steep inclines (where maximum tractive effort is not sufficient to maintain speed) it is optimal to switch to maximum acceleration proactively before the incline when the cruise speed is below the speed limit, while the switching point back to cruising is located after the slope when the optimal cruise speed is reached again. Likewise, for steep declines (where speed increases while coasting), it is optimal to switch to coasting proactively before the decline when the speed could reach the speed limit on the decline, and also here the switching point back to cruising is located after the slope when the optimal cruise speed is reached again.

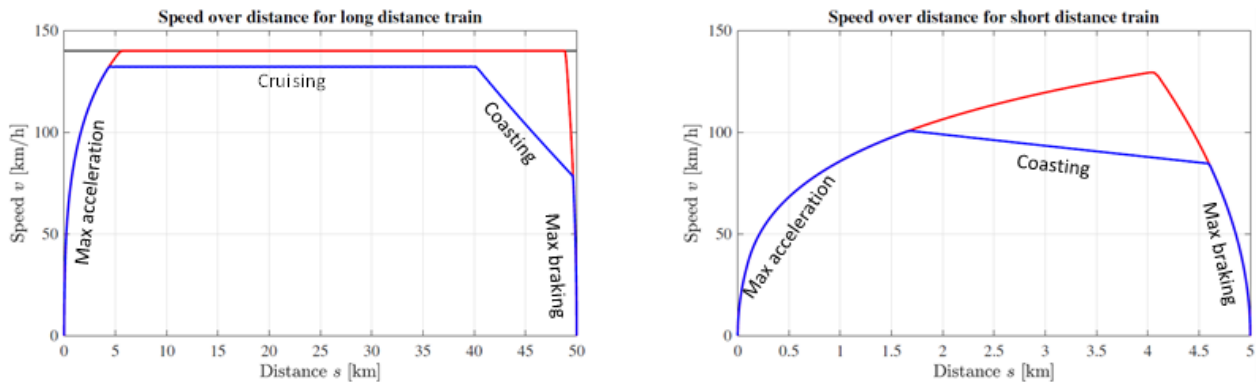


Figure 2: Minimum time (red) and energy-efficient (blue) train trajectories for long-distance (left) and short distance (right)

The main challenge in the energy-efficient train trajectory optimisation problem is the determination of the optimal switching points between driving regimes. In particular, for a varying gradient profile and/or varying speed limit profile several sequences of cruising and coasting/acceleration may be applicable. Pontryagin’s Maximum Principle defines two adjoint co-state variables that satisfy two additional problem-specific dynamic equations which together with the state dynamic equations determine the optimal switching points between regimes. This approach has been used to design efficient algorithms (Albrecht et al. (2016ab)). In addition, constructive heuristic methods have been applied using the implicit knowledge of the optimal control structure. These solution methods are indirect methods in the sense that they are based on solving the derived optimality conditions from Pontryagin’s Maximum Principle. An alternative is given by direct solution methods that transcribe the continuous optimal control problem into a discrete nonlinear programming problem by discretizing the state and control variables, the dynamic equations and the integral objective function. The resulting nonlinear problem can then be solved using efficient nonlinear optimisation algorithms without a priori knowledge of the control structure. In particular, pseudospectral methods have been developed for train trajectory optimisation problems (Goverde et al. (2021); Wang and Goverde (2016)). Metaheuristics such as Genetic Algorithms and simulation are a third class of algorithms that have been developed for approximately solving energy-efficient train trajectory optimisation problems. These later methods usually rely on model simplifications and do not provide the exact optimal solutions (Scheepmaker et al. (2017)).

Train trajectory optimisation can also be used to compute the optimal energy-efficient speed profile over multiple stops, including the optimal arrival and departure times at the intermediate stops (Scheepmaker et al. (2020); Wang and Goverde (2016, 2017)). In particular, this can be used for energy-efficient delay recovery, where instead of running as fast as possible until a delay has been recovered, an energy-efficient train trajectory is computed over multiple stops to a critical station or timing point (e.g., at the end of a corridor) using the remaining available running time supplement to this target station (Wang and Goverde (2016)).

When multiple trains are considered timing or headway constraints must be modelled to avoid path conflicts, which can take the form of time windows at timing points. All operational constraints including time targets, time windows and speed windows at timing points can be



collected in a Train Path Envelope (TPE) that is added to the optimal control problem (Albrecht et al. (2013); Quaglietta et al. (2016); Wang and Goverde (2016, 2017)). The TPE was developed in the European ON-TIME project as addition to the concept of the Real-Time Traffic Plan (RTTP) that maintains the (real-time) scheduled routes, train target times and train orders of all trains. In the ON-TIME project, a Conflict Detection and Resolution algorithm computed the RTTP in a Traffic Management System. Based on the RTTP, a TPE was calculated that was used for train trajectory optimisation in a Connected Driver Advisory System (Quaglietta et al. (2016)). The TPE and its use in train trajectory optimisation was developed further by Wang and Goverde (2016, 2017).

The ON-TIME project also developed three architectures for C-DAS. The differentiation is based on whether the train trajectory generation and the advice for the driver (target speed or suggested driving mode: traction, cruising, coasting or braking) are generated at the trackside or onboard (Panou et al. (2013)):

- Central DAS (DAS-C): both train trajectory generation and advice definition computed centrally at the trackside.
- Intermediate DAS (DAS-I): train trajectory generation computed centrally and advice definition onboard.
- Onboard DAS (DAS-O): both train trajectory generation and advice definition computed onboard.

These three alternative architectures were adopted in the SFERA standard for DAS (UIC (2020)). Wang et al. (2023) extended these three architectures to ATO. The proposed ERTMS/ATO standard is based on the ATO Onboard architecture with the train trajectory computed onboard given the constraints of an TPE computed on the ATO Trackside. The TPE in its turn corresponds to an RTTP computed by the traffic management system.

Alternative optimisation models have been developed that integrate the traffic management (or timetabling) problem and the speed profile problem, where the speed profiles are linearized or otherwise simplified to keep the resulting optimisation problem tractable (Luan et al., (2018ab); Zhou, (2017)). Rao et al. (2016) proposed an interacting model for traffic management and train operation, including alternative schemes for Central and Onboard Connected DAS and for ATO. Yin et al. (2017) provides a survey on ATO including a literature review on train trajectory optimisation and tracking. These papers do not explicitly consider a Trackside DAS or ATO, which have been proposed in more recent years.

### 5.1.3 HMI and Human Factors

Considering Human Factor aspects is very important in the design of all system discussed in this deliverable, both to secure that the systems can perform its tasks in a real setting, are well designed from an ergonomic and work perspective, and that the systems can be accepted by the users. For example, in the design of HMI for a DAS, drivers' needs should be put at high priority, as well as the needs of TMS-users interacting with the DAS from a traffic control perspective. For this purpose, two points should be considered: the process of making decisions and problems that might arise from the application of an advisory system (Panou et al. (2013)). The process of a user taking a decision based on the instruction from an advisory system is done in four stages:

- Receiving the information
- Understanding the information

- Deciding on the suitable action based on the information
- Applying the decision

Advisory information supplied by the system to the user may cause different problems in case of poor integration of the system. The following are common problems that may happen in presence of an advice system:

- Ignoring the instructions
- Misinterpretation
- Over reliance
- Misuse
- Inappropriate prioritisation
- Distraction.

Thus, the HF aspects need to be addressed in detail during the design, testing and implementation for any decision support systems, e.g., TMS and C-DAS.

#### 5.1.4 Positioning

Accurate positioning plays an important role in enhancing the efficiency and safety of both C-DAS and ATO. In the case of C-DAS, precise positioning information enables the system to accurately track the train's location and speed, allowing it to provide real-time advice and optimise driving strategies accordingly. With accurate positioning, C-DAS can take into account factors such as track conditions, gradients, speed limits, and upcoming signals to deliver precise recommendations to the driver, leading to smoother operations, reduced energy consumption, and improved punctuality. Similarly, by utilizing accurate positioning data, ATO systems can precisely control train speed, acceleration, and braking, resulting in increased capacity, reduced delays, and enhanced operation. Furthermore, the impact of train positioning inaccuracies has also been studied from the point of view of its impact on the TMS functions (Hamid et al. (2020)).

Train on-board positioning was addressed in various Shift2Rail Innovation Programmes (IP), specifically in IP2 and IP5. These programmes focus on control and communication systems, and rail freight, respectively. In the former, control, command and communication systems will go beyond merely contributing to the control and safe separation of trains to become a flexible, real-time, intelligent traffic management and decision support system. In the latter case, the main challenge is to develop a new service-oriented profile for rail freight services, based on excellence in punctuality at competitive prices, intermodality with other transport modes and responsiveness to end-user needs, including innovative value-added services. In both cases, one of the enablers is the on-board Global Navigation Satellite System (GNSS) positioning system, improving its performance and combining it with other technologies to meet the requirements of any business case. For example, these new services resulting from the IP2 and IP5 roadmaps will have an important impact on the migration from the European Train Control System, ETCS Level 2, to ETCS Level 3. This migration will allow infrastructure costs to be reduced by up to 25% on regional and dedicated freight lines and efficiency improvements of more than 50% (Ramdas et al. (2010)).

As a basis, the suitability of GNSS systems for railway applications is being or has been analysed by several European projects:

- ERSAT-EAV (ERSAT-EAV (2017)) aims to re-use ETCS odometry and the virtual balise concept to eliminate fixed balises. Augmentation networks such as EGNOS (European Geostationary Navigation Overlay Service) are also being evaluated to verify and validate different GNSS solutions in order to guarantee positioning functions in areas where the GNSS signal is not sufficiently accurate.
- FR8RAIL (FR8RAIL (2015)) project was part of the Shift2Rail research and innovation action. The main objective of the project was to develop the functional requirements for sustainable European rail freight. Its objectives were to reduce costs by 10%, to reduce time variations during the journey by 20% and to increase the information system of the logistics chain to 100%. The objectives of the project were achieved through the development of six different areas (Business Analytics, Key Performance Indicators (KPIs), Top Level Requirements; Condition Based and Predictive Maintenance; Telematics & Electrification; Running Gear, Core and Extended Market Wagon; Automatic Coupling and High-level System Architecture and Integration) where positioning was included in the Telematics and Electrification part.
- X2RAIL-2 (X2RAIL-2 (2017)) aims to improve performance at the railway system level by introducing new functionalities that will revolutionise signalling and automation concepts in the future. The key technologies cover GNSS applications in railways and their combination with other advanced technologies to implement new signalling functionalities.

The use of on-board satellite positioning systems in the listed projects is mainly focused on positioning solutions for the Virtual Balise [6]. In this case, the focus is on solving the problems of the GNSS-based positioning system for continuous positioning. The on-board satellite positioning systems have coverage problems in urban environments or in difficult orography such as tunnels or canyons.

In order to address the limitations of GNSS positioning systems, alternative sensors such as Inertial Measurement Units (IMUs) and Ultra-Wide Band (UWB) have been proposed, along with software-based positioning enhancement techniques like maps. These sensors offer better availability than GNSS systems, but they come with certain drawbacks. IMUs, for example, exhibit poorer accuracy and reliability, while UWB has limited coverage. To fulfil the requirements of the railway industry, it is necessary to present a positioning technique that incorporates additional sensors alongside GNSS and IMU, such as UWB. This combined approach would enable continuous positioning throughout a journey, along with the use of software-based positioning augmentation techniques like map aided positioning. By integrating these various components, the proposed technique can overcome the limitations of individual sensors and meet the needs of the railway industry.

Taking into account the Automatic Train Operation (ATO) architecture presented in X2R4 (X2RAIL-4 (2022a)), see Figure 3, positioning is a key element. It is intended to be part of the solution that allows a safe train operation along with the new concepts of perception on-board the train. In this way, the aim is that the train is independent of the track and the equipment installed in it.

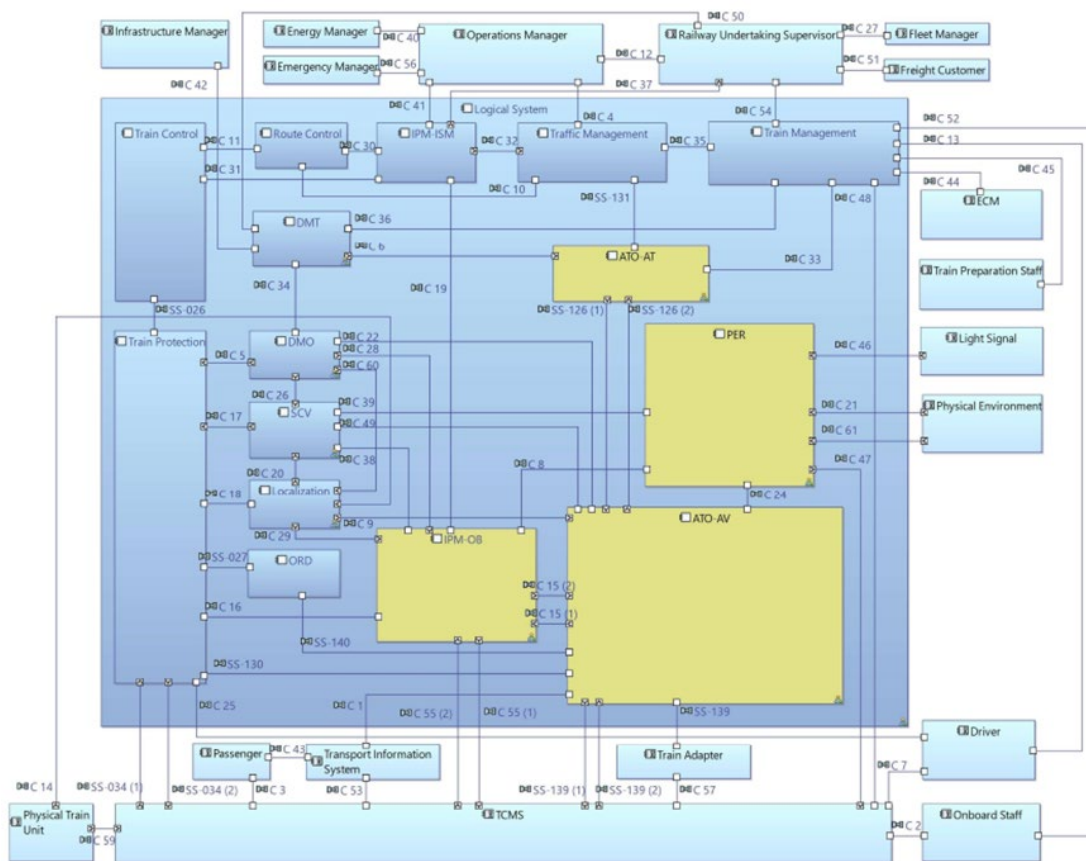


Figure 3: ATO logical architecture (X2RAIL-4 (2022a))

### 5.1.5 Reliable Communications

Effective and reliable communication technologies play a crucial role in enhancing the functionality and safety of both C-DAS and ATO in the railway industry. In the case of C-DAS, constant communication between the system and the driver enables real-time transmission of essential information, such as speed limits, track conditions, and potential hazards, allowing the driver to make informed decisions. Additionally, communication between the C-DAS and the centralized control system facilitates the exchange of data, enabling the system to provide accurate and timely advice to the driver. Similarly, in ATO systems, reliable communication between the train/ATO OB and the ATO TS and TMS, ensures seamless coordination and synchronization of operations. It enables the transmission of targets at timing points and speed adjustments, while providing the control centre with vital train status updates.

Many railway-oriented communication systems, based on different technologies and standards, have been used to transfer information from applications in several usage scenarios. Part of these systems are directly oriented to signalling and/or train control (Shafiullah et al. (2007)). Communication-based train control (CBTC) is a modern and widely used radio-communication-based signalling system. In spite of the fact that communication-based train control is a broad term, nowadays CBTC refers specifically to systems utilized in mass transit, relying on IEEE 802.11 Wireless LAN for wireless communication (Farooq and Soler (2017)).

CBTC uses high-capacity radio communication to facilitate the exchange of train control

information between the train and the wayside. This enables the implementation of Automatic Train Supervision (ATS) functionalities, Automatic Train Protection (ATP), and Automatic Train Operation (ATO). CBTC used to have the following traffic requirements:

- Control message size: 400-500 bytes
- Message transmission time: < 100 ms
- Bit rate: < 100 kbps (typically 20-40 kbps).

A typical CBTC system is composed of three integrated networks. The train onboard network, the train-to-trackside radio network, and the trackside backbone network. The train's onboard network and the trackside backbone network make use of Ethernet, whereas the train-to-trackside radio network typically utilizes Wi-Fi. The selection of Wi-Fi for the train-to-trackside link obeys to some advantages of this radio technology, such as the easy scalability, the use of the freely available ISM band, and the interoperability among multiple vendors together with a large vendor market and industry support.

GSM-R, LTE-R, and 5GRail are other communications technologies oriented to train control (and support other services according to their data throughput). GSM-R, an international wireless communication system that is a sub-system of ERTMS, was specifically developed for European rail companies with the aim of replacing the traditional railway communication system. Its purpose is to ensure seamless and reliable communication for trains traveling across different countries, mitigating any potential communication issues along the way. It is utilized for various purposes such as voice calls, data transmission, and traffic control in the railway system, especially for ETCS. One of its key advantages is the secure communication it provides for drivers and signallers, thanks to its extensive coverage across the rail network (Gheth et al. (2021)). GSM-R base stations use frequency bands around 800-900 MHz, with a peak data rate of 172 kb/s (Ai et al. (2020)). With this transmission rate, the system can hardly support real time applications. Also, the handover due to the connection with different base stations along the train movement is the most crucial process that can affect the QoS.

Some limitations of GSM-R are attended by LTE-R, increasing the speed and the capacity of the wireless networks. The main improvements of LTE-R are related to the use of an IP-based network architecture and a different modulation scheme together with orthogonal frequency-division multiple access, allowing better spectral efficiency. Also, the packet/information loss is mitigated thanks to a softer "make-before-break" handover strategy, instead of the "break-before-make" strategy used in GSM-R handover. LTE-R could provide data rates of 50 Mbps for the downlink and 10 Mbps for the uplink.

Future Rail Mobile Communication System (FRMCS) is another successor of GSM-R. FRMCS can be based on the 5th generation of mobile communications (Pencheva et al. (2022)); which brings more reliable, low latency, high data throughput systems. 5GRAIL is a fundamental element of the overall FRMCS program. The 5GRAIL project is on Mission Critical Services and 5G capabilities relevant for Mission Critical communications. Among the 5G features developed and tested in the context of 5GRAIL we can find (Nikolopoulou et al. (2023)):

- 5G Standalone Core
- 5G QoS
- 5G unicast IP-based PDU session

- Session continuity over 5G Systems for cross border use cases
- 5G User Equipment supporting 5G New Radio bands relevant for FRMCS.

The current prototypes of FRMCS/5GRAIL are composed of applications (similar to GSM-R and new ones, i.e., ATO, Train Control & Management System (TCMS) applications, and video application) and gateways (on-board and trackside). The gateways aim to decoupling applications and communication services/transport strata. The fundamental principle is the decoupling between railway application and transport strata, so that the transport stratum can evolve without impacting the application stratum, ensuring improved performance and service availability (enabling variety of bearers or Radio Access Technologies simultaneously) and resource sharing (providing transport services for multiple applications considering the individual QoS requirements of the application and possibly priorities among applications).

The above listed technologies (from GSM-R to FRMCS) support the use of ERTMS at least in its second level; implementing continuous radio signalling. The precise positions of trains, along with other essential information, are automatically transmitted at regular intervals or when specific events occur in the system. The movement authority, which includes static speed profiles associated with track characteristics, conditions, speed restrictions, and other relevant details, is transmitted to the train at any given time. This ensures that trains receive comprehensive information necessary for their safe and efficient operation (Di Meo et al. (2020)).

The communication technologies commented above play a major role in both C-DAS and ATO systems, that heavily rely on communications between onboard and trackside subsystems. C-DAS corresponds to automation level GoA1 and it is leading the way in assisted train operation, and various implementations of different C-DAS architectures can be observed worldwide (Wang et al. (2022)). Mainly, we can distinguish three categories of C-DAS, starting with a division in a trackside subsystem (DAS TS) and an onboard subsystem (DAS OB) and the distribution of the intelligence and the functions between these:

- Central (DAS-C): The train trajectory and the corresponding speed advice are centrally computed in the DAS TS. The only function of the DAS OB is to display the advice. The Admirail/AF used in the Lötschberg base tunnel in Switzerland relies on this category.
- Intermediate (DAS-I): The computation is divided between the subsystems. The DAS TS calculates the train trajectory and subsequently sends it to the DAS OB. The DAS OB then converts the train trajectory into driving advice based on successive regimes and displays it to the train driver. An example is the ZLR train control system tested by Deutsche Bahn.
- Onboard (DAS-O): The computation of the train trajectory and the generation of speed advice are both handled within the DAS OB. The DAS TS solely transmits the Train Path Envelope (spatial-temporal information from the trackside) to the DAS OB. An application of this category is the Computer Aided Train Operation (CATO) system (Lagos (2011)) in Sweden.

The Smart Communication For Efficient Rail Activities (SFERA) protocol, denoted IRS 90940 (UIC (2022)), developed by the International Union of Railways (UIC), serves the purpose of standardizing data exchange between Traffic Management Systems (TMS) and DAS from various suppliers, also enabling interoperability, even between the TS and OB subsystems.

Both systems, ATO and C-DAS, aim to automate or aid human driving to improve operational efficiency. C-DAS is comparable with ATO, and it can be considered as a potential transitional phase toward full ATO implementation. The primary distinction lies in the fact that with C-DAS, the driver is responsible for following the speed advice provided, whereas in higher levels of automation, the ATO OB directly sends brake and traction commands to the train. Additionally, both technologies rely on information provided by a TMS, which needs to be translated into constraints (JP/TPE) for trajectory computation, trajectory generation, and subsequent translation into traction/brake advice or commands.

In order to promote interoperability and facilitate the implementation of ATO (Automatic Train Operation) across Europe, the European Union Agency for Railways (ERA) has been actively working on the development of a comprehensive set of technical specifications. These specifications focus on integrating ATO functionality with ETCS, ensuring seamless compatibility and harmonization throughout the region.

Within the ATO-over-ETCS (AoE) framework, a dedicated ATO architecture has been established, outlining the functions and information exchange between the trackside subsystem (ATO TS) and the onboard subsystem (ATO OB). This defined architecture is set to become a mandatory requirement for European railways, ensuring standardized implementation and interoperability across the region. The ATO TS uses the spatial-temporal information from the trackside to construct the Segment Profiles (SP, consisting of the length of the segments, static speed profiles, curvatures, timing points, etc.) and the Journey Profile (JP, consisting of a list of SP and timing constraints) while the ATO OB takes care of Traction/Brake control. The rest of the functions are distributed between the subsystems, similarly to C-DAS. Attending to that, Figure 4 shows three possible architectures proposed in (Wang et al. (2022)).

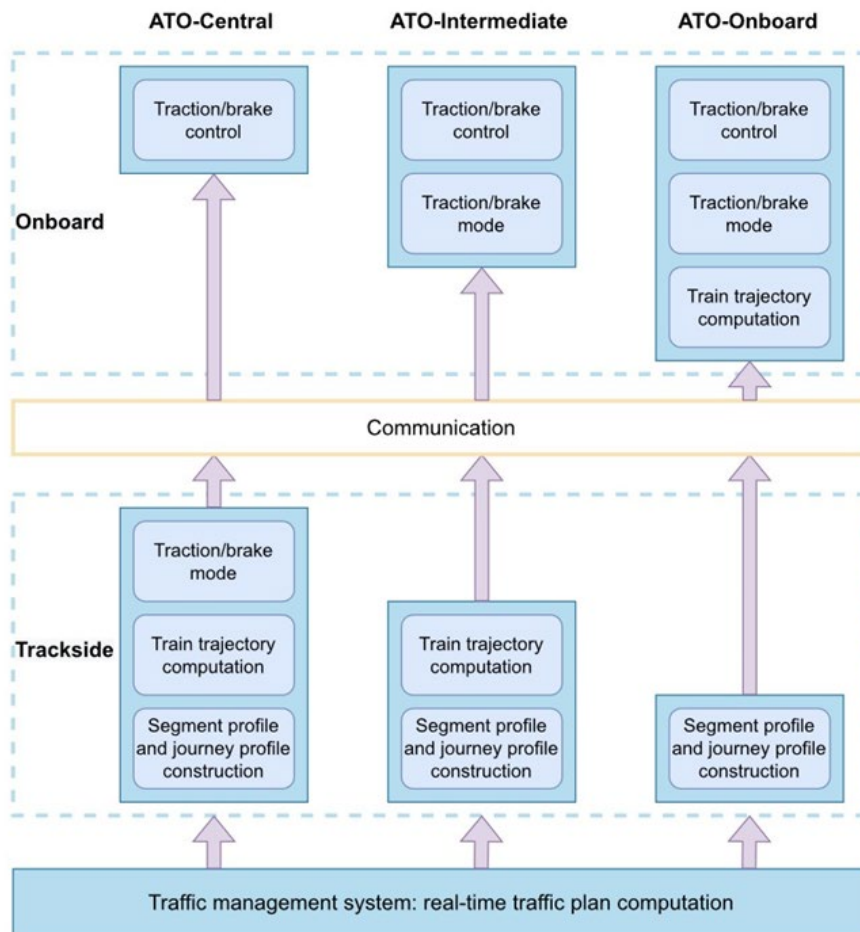


Figure 4: Distribution of functions for the ATO architecture alternatives (Wang et al., 2022)

1. **Central (ATO-C):** The ATO OB's primary responsibility is limited to the control of traction and brakes. On the other hand, the ATO TS centrally computes crucial aspects such as the construction of SP and JP, the determination of the optimal train trajectory, and the selection of the appropriate traction/brake mode (these modes consist of maximum acceleration, traction/brake power controlled, no traction/brake power and maximum brake power). Effective communication between ATO TS and ATO OB is crucial for the overall process and plays a vital role in managing driving deviations. Therefore, the success of ATO-C relies heavily on the quality of data transmission, the precision of train parameters, and the accuracy of state measurements. This approach essentially involves remote control from the trackside, where the train obediently follows orders determined by the trackside system. From the communications point of view, ATO-C requires low communication volume but with a low latency and high frequency between trackside and onboard communications.
2. **Intermediate (ATO-I):** In this scenario, the ATO TS is responsible for constructing the SP and JP, as well as determining the optimal train trajectory. These are then transmitted to the train borne unit. Unlike the previous architecture, in this case, the traction/brake mode



is determined based on the trackside trajectory information but computed onboard. Also, the traction/brake control system generates the appropriate tracking commands to ensure accurate train movement. To maintain consistency in the overall system, it is crucial to provide feedback on train parameters to the trackside and share them with the TMS. This ensures the coherence of parameters throughout the entire loop, including Real-Time Traffic Plan (RTTP) and JP or SP construction. If there is inconsistency or a delayed feedback loop to the central system, it can result in unnecessary re-computations of train trajectories at the trackside or even reevaluating JPs by the TMS. Therefore, ATO-I is suitable for environments characterized by stable, predictable train dynamics, and straightforward train trajectories that can be easily tracked. This approach still involves remote control from the trackside, but with some intelligence in the train to determine the appropriate traction/braking mode based on the given train trajectory. From the communications point of view, ATO-I requires medium communication volume with low latency and medium frequent communications between the trackside and onboard.

3. **Onboard (ATO-O):** In this setup, the ATO TS focuses solely on determining the SP and JP. On the other hand, the ATO OB takes responsibility for computing the optimal train trajectory, making decisions regarding the traction/brake mode, and executing the corresponding traction/brake control. The onboard sensors play a crucial role in monitoring the train's state and relaying this information to both the ATO OB and ATO TS. Similar to ATO-I, it is advisable to implement an online dynamic train model parameter calibration system to achieve a more precise real-time computation and adjustment of the train trajectory. If the monitored parameters deviate from the pre-defined values then the updated parameter values can be communicated back to the JP/SP computation and to the TMS. In this alternative, all the intelligence resides onboard the train, while the trackside system primarily provides targets and constraints to ensure conflict-free train movement. From the communications point of view, ATO-O requires high communication volume due to the JP and SP transmission (SPs are more static and can be cached OB), but they can work with higher latency and less frequent communications between trackside and onboard.

### 5.1.6 Interaction with Signalling Systems

Metro systems are typically based on an automatic train control (ATC) system that integrates all vital and non-vital functions to guarantee the safe and efficient operation of trains (see Figure 5). An ATC system is defined by three subsystems: Automatic Train Protection (ATP), Automatic Train Operation (ATO), and Automatic Train Supervision (ATS), which include onboard and track-side equipment (Lagay and Adell (2018)).

- ATP is a fail-safe system, which performs the safety critical function of enforcing the movement authority. The ATP system provides information on the speed limits, current speed, and current position.
- ATO is a system to drive the train automatically. In addition, it is responsible for all the train traction and braking control commands; thus, it is a key to the operational efficiency and profitability of train operation systems.

- ATS' main task is to act as an interface between the operator and the system. In addition, it is responsible for managing traffic according to specific regulatory criteria.

Notably, the ATS provides train routing and schedule adherence instructions to the ATO according to the train's current status. On the other hand, ATO collects information related to the train speed, programmed stop, and dwell time, and then decides the brake or acceleration action of the train. Meanwhile, ATP monitors the real-time train running status and intervenes whenever the train exceeds its movement authority or triggers emergency braking, if necessary (Yin et al. (2017)).

In other words, safety is guaranteed by the ATP system, which guarantees over-speed protection, ATS keeps the trains in the predetermined schedule, and ATO is concerned with the train operational strategies for automatic operation and regulating the train's braking/traction system in accordance with ATP's goal speed.

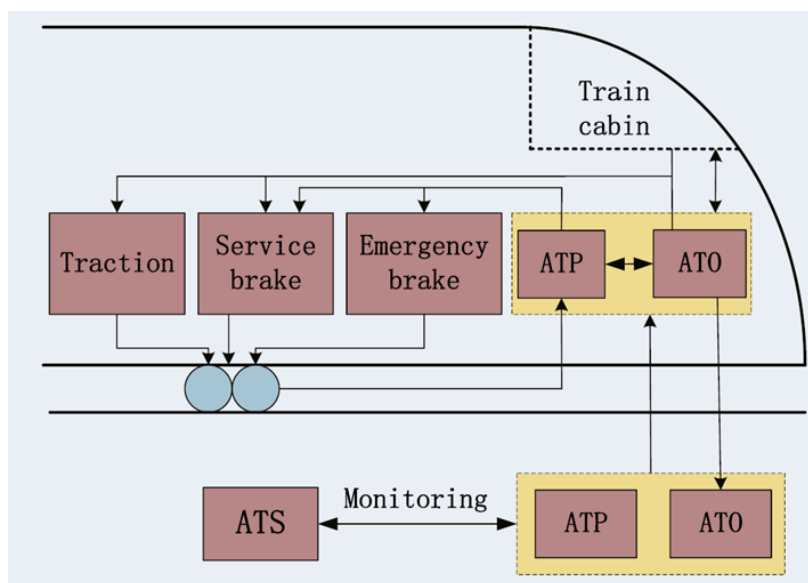


Figure 5: ATC structure in metro systems (Yin et al. 2017).

For railway systems other than metro systems the ATS is usually called the TMS, and ETCS corresponds to ATP. With ATO-over-ETCS also ATO is introduced in connection to the ATP.

As we have mentioned before, ATO is usually composed by an ATO TS and an ATO OB. An alternative is that ATO is composed of an ATO OB standalone only. The main characteristics of such an ATO is that it does not need to communicate with the infrastructure as it has the timetable preloaded. This ATO OB standalone is more suitable for non-mixed operations. One example of this type of ATO can be found in some city Electric Multiple Units (EMUs) in Auckland (New Zealand). These trains are composed by ETCS On-board and ATO over ERTMS standalone.

#### ATO over ETCS reference architecture

In Europe, the ATO-over-ETCS system (AoE) is the key concept for the future automation of mainline railway operations (see Figure 6). The application of ATO in conjunction with ETCS

includes operational functions such as speed control, accurate stopping, door operation, and other functionalities that are traditionally the duties of drivers.

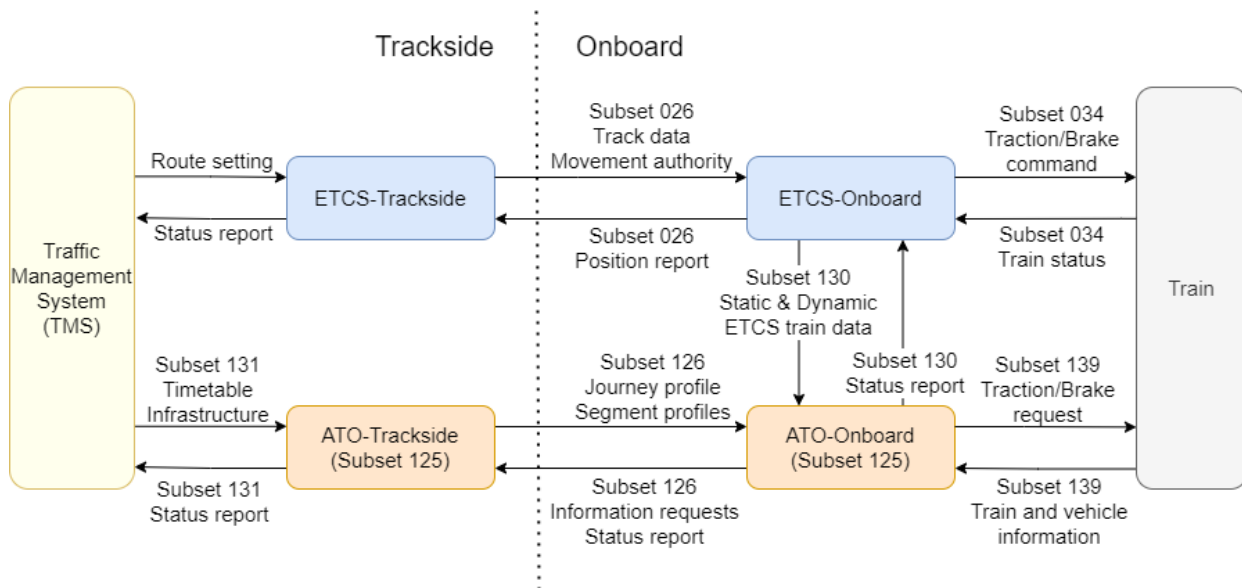


Figure 6: ATO over ETCS reference architecture (Wang et al. (2022))

The components of the ATO over the ETCS architecture and the information exchange between them are presented as follows. ATO contains two components of the railway control system: ATO Trackside (ATO TS) and ATO Onboard (ATO OB). ATO OB is called the heart of ATO over the ETCS architecture. It determines and tracks train trajectories and corresponding traction/braking commands based on the journey and segment profiles (JPs and SPs), ETCS operational data (static and dynamic train data), and the train characteristics. The journey and segment profiles are obtained from the ATO TS. The ETCS onboard (ETCS OB) system delivers the parameters of the ETCS operational data. The train itself, by means of the Train Control and Management System (TCMS), delivers train characteristics to the ATO OB. Furthermore, position information is delivered to ATO OB using the ETCS system (Yin et al. (2017); Wang et al. (2022); Buurmans (2019)).

Another component is the Traffic Management System (TMS). The TMS sends infrastructure and timetable information about the route, targets at Timing Points (e.g., arrival time, departure time, and minimum dwell time), temporary speed restrictions, and low adhesion (if applicable) to the ATO TS (UNISIG (2014)). Information related to infrastructure and timetables is transformed into a list of SPs and JPs at the ATO TS and then forwarded to empower the ATO OB driving functions (UNISIG (2018, 2020)). The static SP carries the most up-to-date infrastructure details, such as segment length, static speed profile, gradient, and curve data. The dynamic JP encloses a list of SPs (route data), Timing Point (TP) constraints (e.g., stopping or passing point and acceptable time allowance to be earlier at the TP), and temporary constraints (e.g., additional speed restrictions and adhesion conditions), representing the current timetable. If the timetable is changed during a journey without rerouting, the timing point information in the JP should be updated correspondingly while the SPs are maintained. If new routes are given in the rescheduled timetable, a new JP with a new set of SPs must be provided. In addition, the TCS sends the route setting to the interlocking system in alignment with route requests from the ETCS TS. This

information allows the ETCS TS system to compute the movement authority. The ETCS TS then sends this new information to the ETCS OB system.

Furthermore, the TCMS is an on-board system that controls and monitors train equipment and functional processes. This component is based on a control and monitoring architecture; thus, it centralizes all information related to the operating status of all intelligent train equipment.

### 5.1.7 Standardisation

This section provides insight into several standards that offer voluntary, detailed requirements, and related assessment criteria for achieving compliance with the mandatory requirements of the TSIs (UIC (2016)).

**Note:** The Subsets related to the ERTMS/ATO mentioned below are included in the “List of mandatory specifications” of the new Control, Command and Signalling TSI 2023 (CCS TSI). Therefore, they will no longer be voluntary requirements. They include the specification for the ATO-over-ETCS GoA2.

#### 5.1.7.1 UNISIG Standards

##### **Standard Interfaces (subsets) in ATO over ETCS architecture**

ATO over ETCS (AoE) is composed of different interfaces and standards that define its components and relations (Figure 7):

- Interface ATO TS and ATO OB: Subset-126 defines the interoperable interface between the ATO-Trackside and ATO-Onboard. Journey profiles, segment profiles, and the status reports are exchanged between the ATO TS and ATO OB.
- Interface ETCS OB and ATO OB: The interface between the ETCS OB and the ATO OB is laid down in subset-130 (UNISIG, 2018c). This subset describes four groups of data which are sent from the ETCS-Onboard to the ATO-Onboard: static train data, dynamic train data, supervision data, and positioning data.
- Interface TCMS and ATO OB: Subset-139 (UNISIG, 2018d) specifies the interface between the ATO onboard and the train control management system. The following set of information is exchanged between the ATO onboard and the train: traction and brake control, odometry, door control, and train characteristics.
- System Requirements Specification: Subset-125 specifies the system functional requirements that must be fulfilled in order to provide an interoperable solution for ERTMS/ATO for GoA2. This standard defines the following: ATO related functions (including DAS), Driver Machine Interfaces principles, ATO operation states, and ERTMS/ATO architecture.
- Train interface: Subset-034 specifies the functional requirements on all information which is exchanged between the ETCS OB equipment and the vehicle via the train interface.

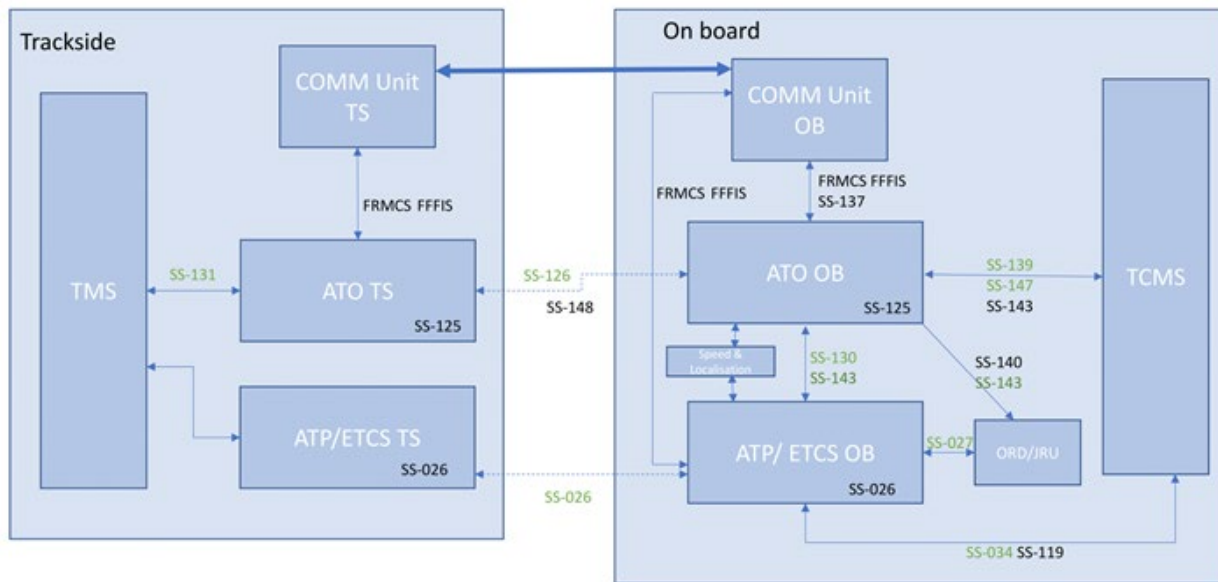


Figure 7: Standard interfaces diagram

The interface between the TMS and the ATO TS is designated to Subset 131, but this has not been developed yet.

UNISIG Standards Subset 125 and Subset 126 (SS125 and SS126) are technical documents which describe the ATO over ETCS (AoE):

- SS125: AoE System Requirement Specification.
- SS126: AoE Interface Specification between ATO Onboard (OB) and ATO Trackside (TS).

SS126 defines the packets to be exchanged between ATO OB and ATO TS, but it does not contain the communication requirements relative to this interface. This information is included in SS125 "ERTMS/ATO System Requirements Specification". In addition, SS148 ("ATO OB / ATO TS Interface Specification Transport Layer") includes details about the communication, as well as some new subsets almost ready to be published: SS146 "ERTMS/ETCS End to End Security", SS37-1 "EuroRadio FIS CS/PS Communication Functional Module" and SS037-3 "EuroRadio FIS FRMCS Communication Functional Module".

Understanding the concepts of these documents is highly beneficial to properly define C-DAS functionality. Both concepts, ATO and C-DAS, are very similar in terms of data requirements. ATO data packages are structured in three blocks:

- Application Header:
  - Standard ETCS header generated by the subsystem which sends the package ATO OB or ATO TS,
  - can be Application Train To Track Header or Application Track To Train Header,
  - normally with 3 variables: Package ID, Qualifier Direction and Package Length.
- Specific ATO Header:
  - Normally generated by the subsystem which sends the package ATO OB or ATO TS,
  - can be Application Train To Track Header or Application Track To Train Header,

- provides a unique Identifier to the package based on combinations of variables: Operational ID, Date Time Stamp, Seconds Time Stamp.
- Applicable content:
  - Core of the package information, details of the packages exchanged,
  - can be formed by several subblocks with different variables within each of them.

Communication between ATO OB and ATO TS is bidirectional and currently based on the communication channel managed by the ETCS.

In subset 126 the application-level communication packages are defined and are as follows:

Packet Number (NID_PACKET_ATO)	Packet Name	Source	Sink
0	Handshake Request	ATO OB	ATO TS
1	Handshake Acknowledgement	ATO TS	ATO OB
2	Handshake Reject	ATO TS	ATO OB
3	Journey Profile Request	ATO OB	ATO TS
4	Journey Profile	ATO TS	ATO OB
5	Journey Profile Acknowledgement	ATO OB	ATO TS
6	Segment Profile Request	ATO OB	ATO TS
7	Segment Profile	ATO TS	ATO OB
8	Status Report	ATO OB	ATO TS
9	Status Report Acknowledgement	ATO TS	ATO OB
10	Session Termination Request	ATO TS	ATO OB
11	Session Termination	ATO OB	ATO TS

**Note:** The ATO over ETCS subsets for GoA2 mentioned in this chapter will not be a UNISIG Standard anymore after they are included as part of the new CCS TSI 2023.

### 5.1.7.2 SFERA

Smart communications For Efficient Rail Activities (SFERA) is an ongoing UIC-project started in 2017 (UIC (2017)). The aim of the project is to facilitate data handling and communication between DAS and TMS. The project involves major infrastructure managers and railway undertakings interested in C-DAS implementation. Results of SFERA will facilitate the use of C-DAS for international traffic by defining a standard format and protocol for data exchange between DAS and TMS. Nevertheless, a unique standard also helps on national lines with different RUs because the IM only has to feed one interface. The SFERA format shall cover ERTMS/ETCS and class B train protection systems. SFERA format is also going to be useful for standalone DAS and ATO. (Panou et al. (2013))

In the first two years, data required for the exchange between DAS and TMS was defined. Moreover, in October 2018 and April 2019 tests adopting the SFERA protocol were carried out on Thalys trains operating through France, Belgium, and the Netherlands. Results of the tests proved that the protocol can be used in different countries with different DAS (Global Railway Review (2019)). In the next phase of SFERA, the project members delivered a draft version of the protocol and data exchange format that has gone through internal and external review process. The SFERA

guidelines was published in UIC International Railway Solution (IRS) 90940 after UIC approval in 2020 (UIC, 2019) and a second edition was published in 2022 (UIC, 2022).

As SFERA is structured after the AoE model and already largely uses the ATO architecture, it allows railways to already align their data and systems with the future AoE structure and prepare for a migration to ATO when a line is being fitted with ETCS Full Supervision. This is realised by:

- Implementing a similar architecture in close alignment to UNISIG Subset 126,
- aligning the technical architecture of the ground-to-onboard messages,
- integrating all data elements used in Subset 126 specifications into the SFERA protocol.

The technical architecture of the SFERA messages has a very similar composition to the AoE data structure and is designed to portray a complete train journey with the timetable, the infrastructure, and the train's physical data, see Figure 8.



Figure 8: Illustration of AoE Data Packets

- **Journey Profiles** contain the most dynamic data and describe the timetable and temporary restrictions. They reference to both segment profiles and train characteristics. They describe the individual train service on the network of an IM. This data set is largely equal to AoE.
- **Segment Profiles** are mostly static and contain the information about the terrain and the infrastructure. Additional data elements, mainly for infrastructure, were added in SFERA like signal and ATP aspects for running trains on legacy systems and positioning information due to the absence of balises.
- **Train Characteristics** describe the train's features such as its length, weight and the traction power. In addition to planned characteristics information on degraded functions are introduced. This data group does not exist in the AoE ground to onboard messages and is unique to the SFERA protocol.

The SFERA architecture is extremely flexible to fit most national requirements and different evolution steps of DAS. Only a small amount of data is mandatory to operate a simple DAS. Many optional data elements can be added when available to realise a more sophisticated driving advice generation.

### 5.1.7.3 Wayside ATO (WATO)

The Wayside ATO (WATO) (X2RAIL-4 (2022c)) is considered as a kind of ATO TS based on the Integration Layer. It reads timetable, infrastructure, restriction, weather and rolling-stock data broadcasted via the Integration Layer and receives inputs from a driver UI.

WATO creates JPs and command messages for the train defining its journey with expected arrival

and departure times at stopping or passing points according to the production timetable. The WATO also reads static Segment Profiles via the Communication Infrastructure, adapt actual segment data if restrictions have been set and broadcast the updated version via the Integration Layer. The WATO sends all information to the Integration Layer and not directly to a Communication Module. This implies that messages from the train via the Communication Module are also stored on the Integration Layer to be available for the WATO.

All data on the Integration Layer are following the interoperable platform specific data model format implemented on the Integration Layer (Figure 9). The communication module reads and broadcast messages directly from the Integration Layer. This allows to reduce the built-in functionality to the translation between PSM and Application Data Format and the communication to other ATO TS or Communication Modules.

The concept assumes the existence of three major systems involved in ATO wayside operations:

- WATO business application (WATO) – to produce and deliver ATO related data structures like JP and SP and monitor trains / formations movements in ATO mode,
- Integration Layer – a communication platform allowing to exchange information in the ATO area but also in other railway specific areas to support data exchange in ATO related areas like infrastructure, timetable, rolling stock and others,
- Track to Train Communication Manager – responsible for establishing technical communication with the train, exchanging information with the train and communicating with WATO business application via the Integration Layer.



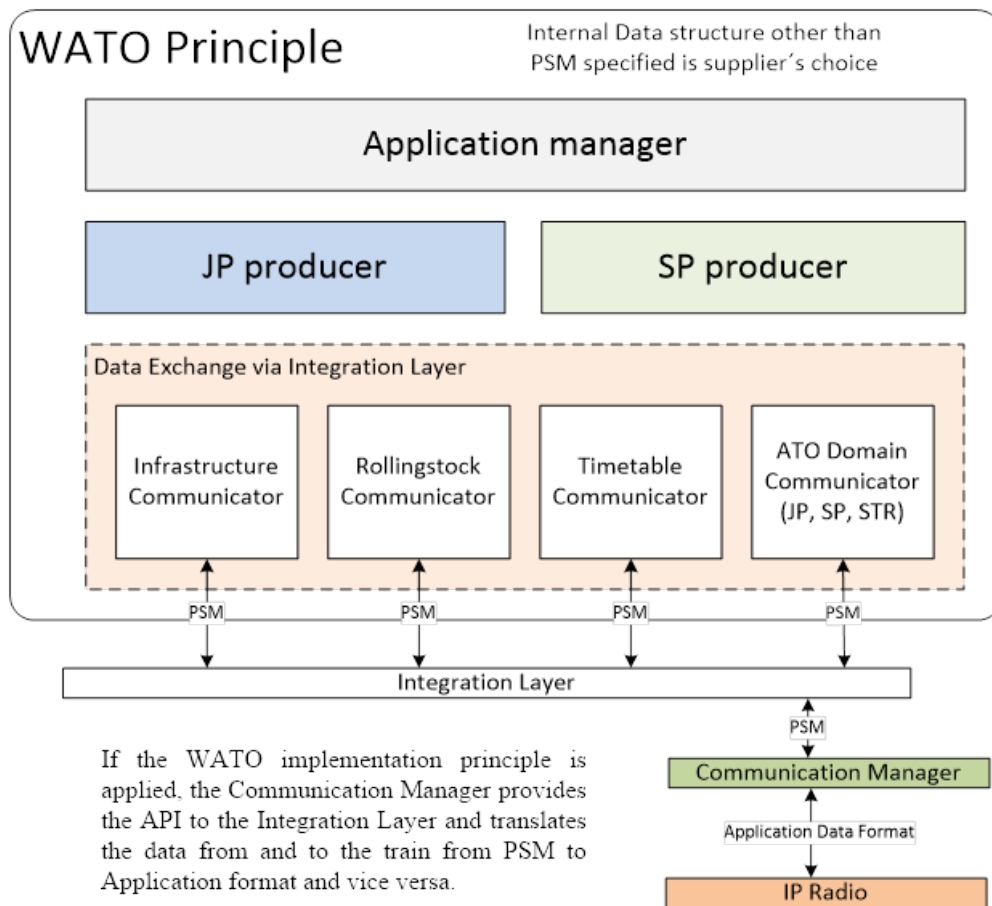


Figure 9: WATO Principle

#### 5.1.7.4 ATO Trackside (ATO TS)

The ATO TS is an alternative implementation strategy compared to the WATO approach. The difference is that the ATO TS reads the infrastructure data, timetable and other information from the Integration Layer or any other communication infrastructure or storage produces and produces the SPs and JPs. The ATO does not communicate messages for the train via an Integration Layer to the Communication Manager but has a direct connection to the radio (Figure 10).

If TMS and ATO TS are linked with an Integration Layer, the ATO TS will send Status Reports and other messages from the train to the Integration Layer. In case that no communication platform, such as the Integration Layer with an interoperable data format (PSM) is used, the Interface between ATO TS and TMS is of project specific nature.

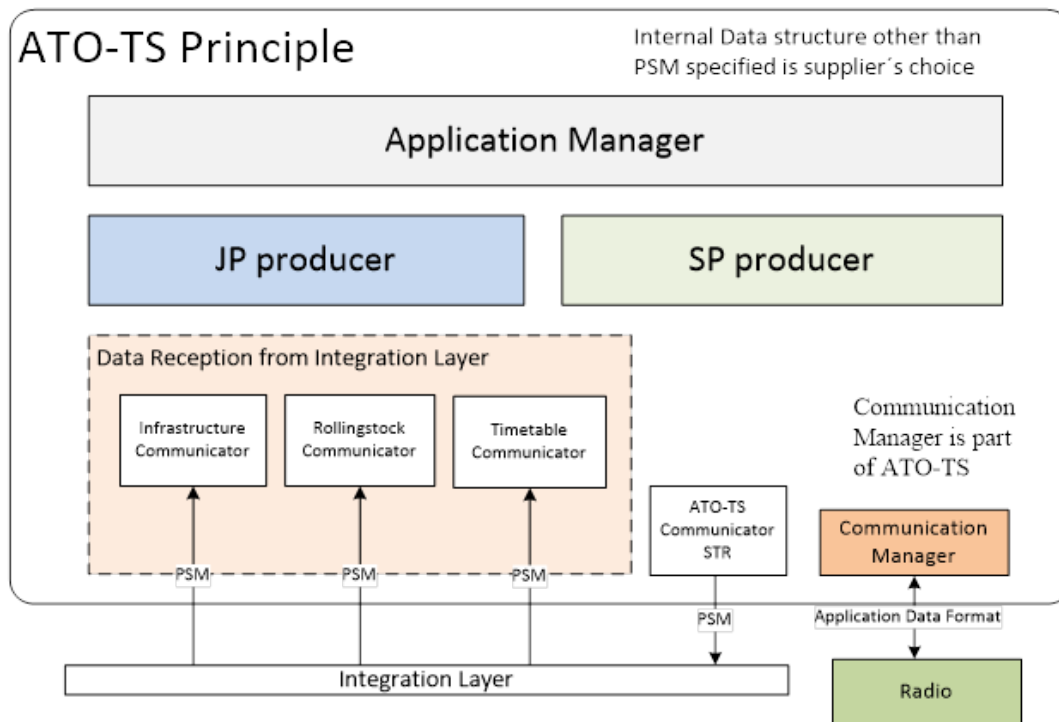


Figure 10: ATO TS Principle

### 5.1.7.5 Reference CCS Architecture (RCA)

The members of the ERTMS Users Group and the EULYNX Consortium are together formulating a collaborative approach to Control, Command, and Signalling systems (CCS) and are therefore jointly developing of a future 'Reference CCS Architecture' (RCA) that will have many benefits.

RCA includes ATO but the TMS is considered an external system and is part of the Planning System (PAS) in RCA terminology. The RCA includes the subsystems ATO Execution (AE) and Plan Execution (PE), corresponding to functionally related to the ATO Trackside and Automatic Route Setting, respectively. These subsystems are connected to the external Planning System via the bi-directional Standard Communication Interface Operational Plan (SCI-OP). Hence, the SCI-OP is located at the system border of RCA and connects the RCA with the Planning System (i.e., the TMS).

The subsystem ATO Execution generates instructions for ATO based on the information taken from the Operational Plan, so that Train Units autonomously drive the Operational Movements as planned. ATO Execution and Plan Execution report the execution progress of the Operational Plan back to the Planning System via the Operational Plan Execution Report and the Train Unit Report. The Operational Plan is defined per train movement and includes amongst others the operational movement, consist, passage and stop events, event times, and event links (dependencies) in RCA terminology. The relevant RCA documents are (see ERTMS, EULYNX (2022)):

- RCA: Terms and Abstract Concepts, RCA.Doc 14
- RCA: Concept: SCI-OP (Standard Communication Interface Operational Plan), RCA.Doc 31
- RCA: ATO – Concept, RCA.Doc 72
- RCA: System Concept ATO Execution, RCA.Doc 73.

The interface specification of SCI-OP is not finalized yet. The RCA also refers to X-RAIL-131 as a placeholder for the TMS-ATO interface but does not provide any information on it.

## 5.2 TMS-Aspects Related to C-DAS and ATO

With respect to ATO and C-DAS, an important function of the TMS is to define timing requirements in real time with regards to scheduling and adherence to the timetable, while the C-DAS and ATO define the optimum driving style within the limits of the timing requirements. Scheduling, routing, and speed restriction updates are communicated to the train in real time, while information from the train enhances traffic regulation decisions at the TMS end.

A particular goal of the Shift2Rail Multi-Annual Action Plan (2015) within its Innovation Program IP2 was to develop and implement new technologies for Traffic Management Systems (TMS), including the development of a new TMS based on standardized frameworks, data structures, real time data management, messaging, and communication infrastructure including interfaces for internal and external communication between different subsystems, applications and clients. This aims at significant higher integration of status information of the wayside infrastructure, trains, and maintenance services together with management of energy and other resources.

### 5.2.1 Human Factors and Human-in-the-Loop Simulation

Human factors studies for heavy rail on ATO GoA2 and GoA4 have predominantly been focused on the effects for train drivers. Very little research has been done involving the Traffic Management System and ATO design, support and impact for dispatchers and signallers and the interaction between them and the train drivers.

Research and validity requirements for a human-in-the-loop simulation environment as a tool/environment to conduct human factors studies has been extensively done in the Dutch rail context (Middelkoop et al. (2012); Lo (2020)).

### 5.2.2 System Architecture

The high levels of automation required by C-DAS and, especially, ATO require a significant level of standardization of data and communication procedures. This demand highlights the need for a new model of TMS. The new TMS model relies on the digitalization of all inputs and outputs, enabling the implementation of new features such as advanced automated decision-making and optimisation of traffic management. However, the current interconnections between TMS, energy management, maintenance management, and signalling systems are incomplete and inefficient due to the lack of standardized interfaces. For example, connecting the maintenance system to TMS significantly enhances efficiency, particularly for cross-border traffic. Sharing maintenance information related to rolling stock is crucial in minimising disruptions and ensuring safety more effectively. Furthermore, the existing interfaces of TMS were not developed with scalability in mind and were generally limited to the core TMS functionality (Krsak et al. (2010)). Another drawback of the current TMS is the lack of standardization in their interfaces, which prevents the potential benefits of TMS interoperability from being realized.

A preliminary attempt to address these issues was undertaken in the OPTIMA project (OPTIMA (2019)), conducted as part of the Shift2Rail innovation program IP2. The primary strategic objective of this project is to develop a new communication platform that integrates traffic

management, traffic control, asset management, maintenance operations, energy (grid) control systems, signalling field infrastructure, and vehicles for signalling purposes (ETCS). The central component of this platform is the integration layer, which acts as a middleware, facilitating seamless and standardized communication and data exchange between TMS services on one side and Rail Business Services and External Services on the other side (Cecchetti et al. (2021)). The overall architecture proposed in the OPTIMA project is illustrated in Figure 11.

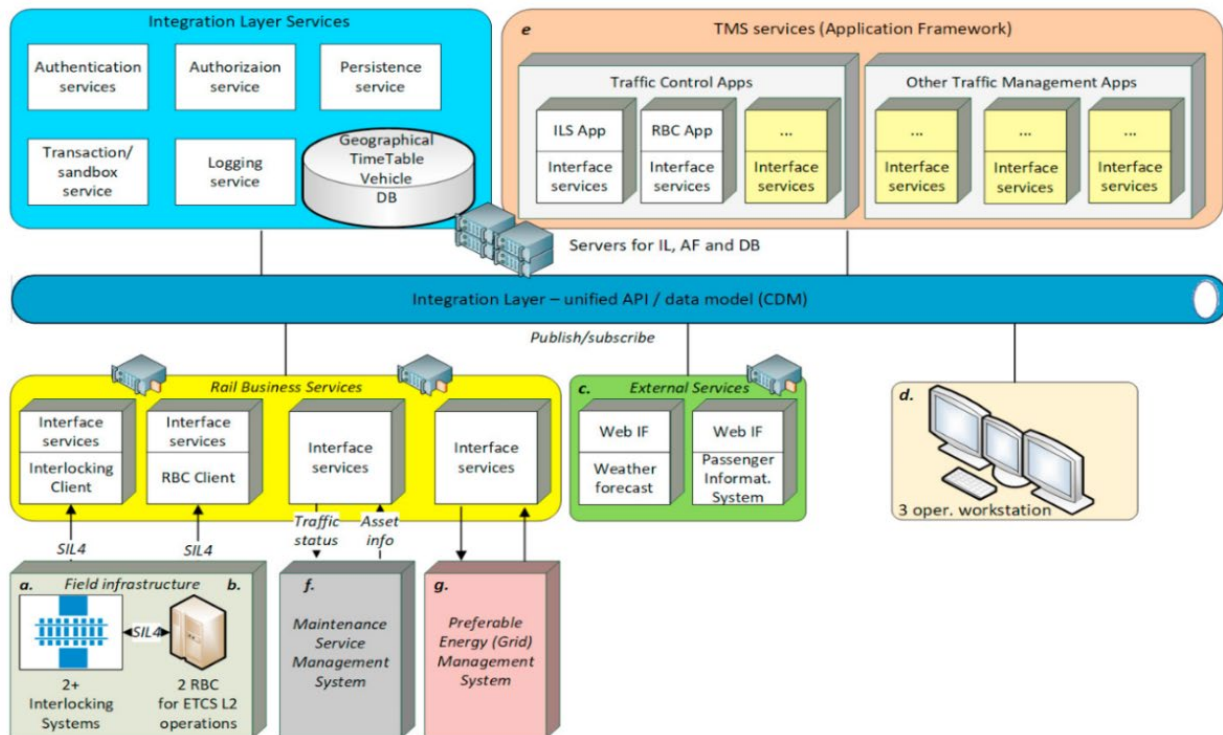


Figure 11: General architecture of the OPTIMA communication platform for TMS

### 5.2.2.1 Integration Layer

IN2RAIL (IN2RAIL (2015)) and X2RAIL-2 (X2RAIL-2 (2017)) projects have delivered the main functional and non-functional requirements and the characteristics of the Integration Layer (Figure 12). The Integration Layer can be defined as a scalable and interoperable data layer providing the data exchange between internal Rail Operation Services (in the first step TMS, Asset Management) and external services either leveraging on the available Information and/or sourcing required Information. This information has a standardized structure and follow an overall data model, called Conceptual Data Model (CDM).

The system has standardized Interfaces, supports high-speed data transmission and can be extended in the future for topics (data-lines) carrying specific information of different complementing services/clients: each client is connected to the Integration Layer via an API (Application Programming Interface).

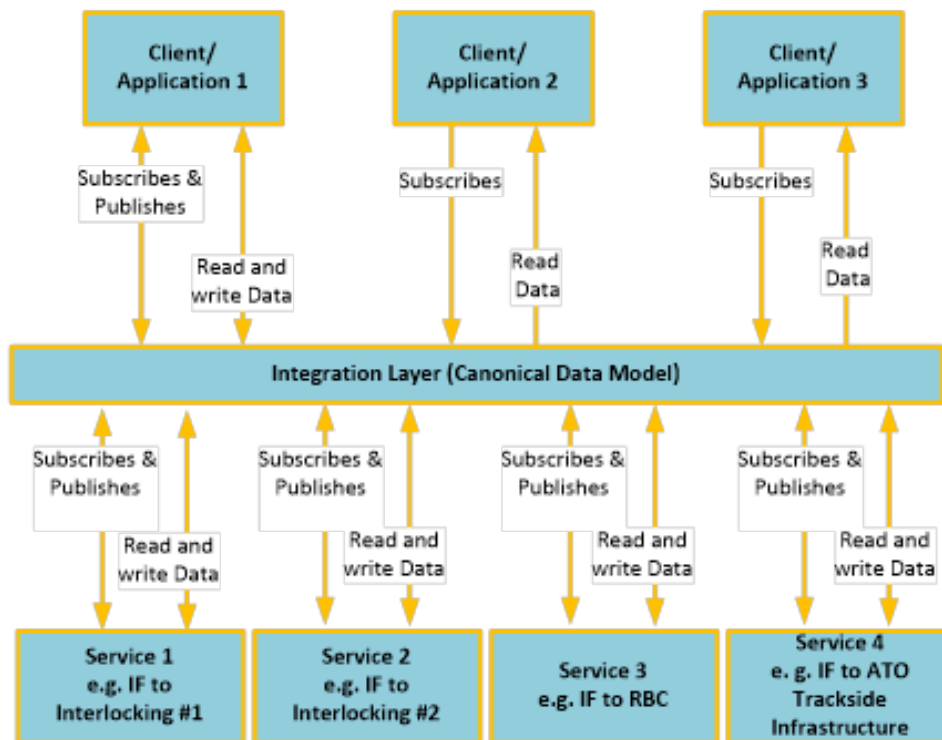


Figure 12: Integration of Applications/Clients through the Integration Layer

### 5.2.2.2 CDM

The CDM (Conceptual Data Model) is an essential enabler of the interoperability between the services of the Integration Layer, developed in Shift2Rail Linx4Rail-project (LINX4RAIL (2023)). System components may have different data representations internally, but whenever exporting or importing data to/from other components, they must translate this data to the canonical form. The result is that new communication paths may easily be added, as both end points are independent of the other end points internal data model. There is always one way of unambiguous translation and interpretation of data from the CDM to the connecting data models and vice versa, which is precondition for standardisation.

The CDM is defined starting from conceptual data models in the context of database design: in such a context, in fact, to minimise development risks, databases are normally designed at three stages, conceptual, logical, and physical:

- The Conceptual Data Model represents business entities and determines what kinds of relationships exist between them. It suppresses details to provide the big picture.
- The Logical Model takes these entities a step further and works out the details as attributes and relationships.
- The Physical Model makes decisions about database management technology, the design of tables, keys etc.

The purpose of the conceptual data model is to make the IT-specialist designing a database familiar with the domain knowledge, to ask questions, consult with stakeholders, analyse business requirements. In (Nalimov (2021)) is a set of characteristics given, describing a good conceptual data model:

1. Provide a high-level overview of the system to be built.
2. Define the scope of the data to be represented.
3. Create a blueprint that can be referred to throughout the project.
4. Diagram entities and relationships rather than attributes.
5. Avoid dealing with technical considerations or terminology.
6. Prevent the model from already being tied to a particular database management system.
7. Be used to get feedback from non-technical stakeholders.
8. Focus on the business requirements the database needs to solve.
9. Provide a solid foundation for creating logical and physical models.

To further leverage on the benefits of the CDM, the same model shall be applied to the Integration Layer and application framework. There will for sure be some information items that only apply to one of the environments – nevertheless, they are still part of the same CDM.

Each application has basically three options how to adapt to the CDM:

- Apply the CDM format also for internal data representation. This may be suitable in case of new developments.
- Implement a Messaging Mapper ([EIP]), i.e., an internal module which maps data between the applications domain objects and the CDM. This may be suitable for migrating existing applications to the IL/AF context.
- Implement a Message Translator ([EIP]), i.e., an external adaptor, receiving data according to CDM which it relays according to some other interface specification, and vice versa. This is suitable for adapting legacy systems without changing them at all internally.

### 5.2.3 Energy Optimisation

The energy optimisation capabilities provided by the TMS can be divided into two main categories: intelligent management of timetables and delays, and real-time capabilities for applying ecodriving techniques to C-DAS and ATO technologies.

In the first category, it has been demonstrated that making small modifications to the operating timetable can offer a cost-effective solution to maximize the utilization of regenerative energy. This can be achieved by synchronizing the braking and accelerating phases of vehicles. Synchronization not only maximizes the use of regenerative energy but also provides additional benefits to the power system. By limiting the simultaneous acceleration of a large number of vehicles, it becomes possible to keep the peak voltage of the supply line within acceptable limits and prevent substation overloads (Yang et al. (2013)). The reduction in power peaks also leads to decreased power supply losses, thereby reducing the operational and investment costs of the network (Albrecht (2010)). Other authors have explored the benefits of optimal train trajectory calculation with special emphasis on avoiding unplanned stops to prevent potential traffic conflicts and improve traffic flow (Rao et al. (2016)).

Regarding the second category, combining TMS with DAS is an effective way to maximize energy savings in delayed scenarios. Connected DAS (C-DAS) can react to real-time information provided by dispatchers and recalculate the most efficient profile under disturbances, improving reliability

and energy savings. Research on rescheduling in urban and high-speed systems is limited due to network characteristics such as single traffic type, similar train trajectories, and few interactions. However, the introduction of coasting on the Paris metro, combined with a Communications Based Train Control System (CBTC) that allows for real-time updates, demonstrated average savings of 16% (Urien (2013)). Another system, which utilizes DAS and real-time communication between trains and a central control centre, has been successfully implemented in Sweden (Yang (2013)). The combination of ATO and TMS could further maximize energy savings in delayed scenarios, as driver variance is eliminated.

Furthermore, by combining both of the aforementioned strategies, applying intelligent strategies from the TMS side in disturbed scenarios or during delay handling can further reduce energy consumption during the recovery process in these perturbed situations (Umiliacchi et al. (2016); Naldini et al. (2022)). Other studies (Liu et al. (2019)) reveal the potential for savings of up to 9% when correctly managing the movement of two trains, especially when one of them is delayed.

#### 5.2.4 Train Path Coordination

In order to achieve the full benefits of ATO/C-DAS, it is necessary to coordinate the movements of several trains. The coordination of trains in this sense includes small scale RTTP-adjustments to improve the train system performance with respect to, e.g., energy consumption or robustness. ATO/C-DAS gives the traffic management the possibility to coordinate the train movements in detail to achieve such system optimality. A typical example of this is a meeting between two C-DAS trains on a single-track line, where the exact planned time of the meeting has an influence on both the energy consumption and the (time) robustness of the transport. In a larger scale, there can be a system of meetings between several involved trains along a single-track line, and the total energy consumption and timetable robustness depend on the detailed planning of each train meeting. In the ON-TIME project (ON-TIME (2014)), the optimisation of minor RTTP adjustments for a system of C-DAS trains were studied.

## 6 State-of-Practice

Whilst most individual railway systems have views of the future railway architecture, there is no common EU railway system view that is used today. The railways have traditionally approached systems architecture following a national – even regional – technical approach, leading to a heterogeneous picture at a European level. In this chapter we collected the inputs from WP15 participants about their countries' state-of-practice and about other countries in which they are involved.

### 6.1 ATO

This section provides an overview of the ATO state of practice in the countries of this WP's members where an ATO is available or research programs have been started/planned, and also in other countries where an ATO system was developed, and this WP's members were involved.

#### Czech Republic

In the Czech Republic, a GoA2 ATO system, denoted AVV, has been in commercial operation for 30 years. History of AVV:

- 1960s – Beginning of research & development on the field of automatic train control systems (using analogue devices only).
- 1970s – Automatic speed regulation system “**ARR**” was released (keeps, accelerates or brakes the train to a speed given by the driver via keyboard).
- 1980 – Target braking system “**CB**” implemented on Prague metro (subway) line “**C**” (ASR + stopping at stopping points) + testing on railway.
- 1980s – Development and testing of energy optimisation system “**OJV**” – energy efficiency, fuel / electricity savings, emission reduction.
- 1990 – Transfer from analogue to digital control, research & development on the field of railway automation and control systems transferred from state to a commercial company AZD.
- 1991 – GoA2 ATO system “**AVV**” released for testing (**AVV = ARR + CB + OJV**).
- 1993 - First commercial deployment of **AVV** ATO on class 470 EMUs.

Current state:

- 600+ railway vehicles equipped with AVV GoA2 system.
- 3000+ kilometres of tracks equipped with AVV localisation points (magnetic „balises“ or GPS).
- Ongoing integration with ETCS
  - AVV over ETCS – original AVV adapted for localisation using ETCS balises, following the speed curves and driving under its supervision.
  - ATO over ETCS – European interoperable implementation of ATO to ETCS guidelines
    - Implemented and tested at „Plum line“ (regional line in commercial operation) and „Kopidlno line“ (AZD test track).
  - GoA3 / GoA4 research based on ATO over ETCS and Shift2Rail outputs.



## Italy

In the Italian network, ATO systems are not yet integrated. However, STS Italian division installed an ATO system in Australia, in collaboration with Rio Tinto: the project started in 2012 and the first run was in 2018. The system covers more than 1700 km of track. It is based on ERTMS protocol defined within the scope of X2RAIL-3.

## Sweden

In Sweden there are no installations of ATO on mainlines and there are no plans to implement ATO at the moment. An initiative to at least see what the railway industry, mainly the RUs, think about ATO started in spring 2023.

There are still very few lines installed with ERTMS and it will take a very long time to have most of the lines equipped with ERTMS. In this perspective the focus for Sweden is C-DAS and to improve the TMS capabilities to support C-DAS with RTTPs of high quality.

## Spain

In the Spanish network there are no lines equipped with fully operational and functional ATO (neither ATO over ERTMS). There are lines equipped with ERTMS Level 2 and Level 1 and with national legacy systems as such the LZB.

The closest to ATO is the C5 commuter line in Madrid, which is equipped with LZB with more than 25 years in service (it is planned to be replaced by ERTMS). In the Spanish network, there are currently installed different CCS Class B systems (ASFA, EBICAB 900 and LZB). The LZB system is one of these existing national legacy systems (class B system). This is a safety system for rail traffic control (an ATP), which is used on certain high-speed lines in Germany, Austria and Spain (HSL Madrid-Seville and Madrid-Toledo, although it is also used on the C-5 Commuter Line in Madrid). The LZB continuously monitors the speed with bidirectional data transmission between track and train.

In on-board systems, there is a similar situation.

With respect to future schedule, there are currently no ATO deployment plans in Spain in the short or medium term. ADIF is aware of the advantages that the ATO would bring but not currently a forecast to start implementing this system.

In the new CSS TSI 2023, the specifications for the ATO over ERTMS (ERTMS/ATO) for GoA2 are included. Therefore, it is understood that this should be the starting point to continue developing the ATO.

## The Netherlands

In The Netherlands there are no real-life implementations of ATO yet. However, the potential of ATO is of high interest to The Netherlands. The Netherlands has a dense train network where passenger and freight trains mostly run together. The network is reaching capacity limitations and space to build new infrastructure is very limited. At the same time, train transport both for passengers and freight is considered as the way forward from a sustainability point of view.

The research for the potential of ATO in the Netherlands is a shared effort in the railway sector,

where railway undertakings, the national ministry, local authorities and the infrastructure manager work together to organise tests and research activities. This has resulted in a sector ambition (ProRail et al. (2021)) and a sector program plan for the research phase between 2022 and 2026 (ProRail (2023)). The aim of the research phase is to use simulations, experiments, tests and pilots to create insights in costs, benefits and feasibility of application of ATO. This is not only focussing on the technical systems, but also on processes and human factors. The scope of the research is on GoA2, GoA3 and GoA4, both on mainline and for shunting.

An overview of performed and planned tests is given in Table 2 and described in the paragraphs below.

Table 2: ATO-tests in the Netherlands.

Year of test	Topic	Involved parties	Location	Type of ATO
2018	Technical running of freight locomotive under ATO	Rotterdam Rail Feeding, Alstom, ProRail	Betuweroute	GoA2 mainline, ERTMS, freight
2019, 2020, 2021	Technical running of passenger train under ATO, passenger experience with running under ATO, capability to handle changes in routes and delays	Arriva, Stadler, ProRail	Groningen – Buitenpost	GoA2 mainline, ABT-NG, passengers
2025 (planned)	Running of freight trains in various compositions and situations	DB Cargo, ProRail	Betuweroute	GoA2 and GoA4 mainline, ERTMS, freight
2022	Automatic shunting	Lineas, Alstom, ProRail	Oosterhout	GoA4 shunting, non-signalled, freight
2023 (going on)	Shunting and stabling	NS, ProRail (see ATO Research program at NS; part of WP38)	Groningen – De Vork	GoA up to GoA4

#### *2018 Betuweroute*

In 2018, the first tests with ATO were performed in The Netherlands. In a joint project between infrastructure manager ProRail, railway undertakings Rotterdam Rail Feeding (RRF) and system supplier Alstom, test rides were performed on the freight-only line Betuweroute. This line is equipped with ERTMS. The tests were a combination of live tests on the Betuweroute and human factors research about the impact of ATO GoA2 on the train driver. Results are reported in (Van den Band et al., 2020, Betuweroute). The general conclusion was that it is possible to retrofit a locomotive with an ATO system and to run test rides. The ATO on-board system proved promising technology, but in combination with the used locomotive it required further development.

#### *2019-2022 Groningen-Buitenpost*

In 2019, 2020 and 2021 a series of test runs has been performed between Groningen and Buitenpost, focussing on mainline passenger transport with ATO GoA2. The initiative for these tests came from the Provincie Groningen (regional government of the province of Groningen), as they want to be the first region in The Netherlands to implement ATO. The tests were performed in corporation between railway undertakings Arriva, system supplier Stadler and infrastructure manager ProRail. The project was a combination of live test rides, human factors research, passenger research and timetable simulations. In 2019 technical tests with the system were performed. In 2020, passengers were invited to join the test rides, to experience driving under ATO. It was a blind test, in the sense that some of the rides were driven by a driver, while in other rides ATO was driving the train. The passengers were afterwards requested to provide their experiences. In general, differences between driver driven and ATO driven rides were small, but a jerkier driving style of ATO compared to drivers, made the experience with ATO slightly less comfortable. The results of the test in 2019 and 2020 are reported in (Van den Band et al., 2020, Groningen). In 2021 an additional set of test rides is performed with a focus on timetable aspects, such as driving according to plan and responses of ATO to changing routes and delays. The results of these tests were promising. However, a main topic of attention was that there was no ETCS available in the testing area, which makes it very complex to have ATO performing stable and reliable (Van den Band et al., 2022, Groningen).

#### *2025 Betuweroute (planned)*

At the moment of writing of this report, the railway undertakings DB Cargo and infrastructure manager ProRail are preparing a yearlong test period in 2025 with ATO freight trains on the Betuweroute. The plan is to make 200 test runs on the mainline between Kijfhoek and Valburg. The aim is to gather insides in the performance of loaded freight trains in various compositions and in all types of external conditions while driving under ATO GoA2 and GoA4. Operational processes will be tested, as the test trains will run mixed with commercial trains. Therefore, a Proof of Concept of a trackside system will be developed and tested during the test year. As part of this, research will also be done after the human factors of an ATO interface for traffic controllers and traffic managers. Furthermore, specific incident scenarios will be tested, especially for the situation of running under GoA4.

#### *2022 Automatic Shunting*

Next to the above mainline tests, also a test with automatic shunting has been performed. This was the first test with ATO GoA4 in The Netherlands. The project was a corporation between railway undertakings Lineas, system supplier Alstom and infrastructure manager ProRail. In the years 2021 and 2022 several testing phases have been carried out on a non-signalled shunting yard in Oosterhout (ProRail, 2022, Oosterhout). During these phases, a locomotive has been retrofitted with an ATO module and an obstacle detection system. After a training period for the obstacle detection system and the ATO system, in November 2022 a demonstration has been given where the ATO system could run the train, detect correct positions of switches, detect obstacles and stop the train at a designated place or in case of an obstacle present. The tests show the potential of GoA4 for shunting. However, important recommendation of the project was that, to determine the required precision, also the driving systems of the locomotive are of importance. An older type of locomotive was used, where potentially a more modern locomotive could provide better results. Next to this, the application of ATO on a non-signalled shunting yard comes with a lot of challenges (Katstra et al. (2023)).

### *ATO research program at NS*

Besides ProRail, also NS started their ATO research program. At the end of 2019, NS executed their first experiments with ATO GoA2 over ETCS on the Hanzelijn (Caf Signaling (2019)). This was the first step in learning how to run with ATO and to gain insight in its sub-technologies. During the experiments it was experienced that ATO is able to drive very accurately according to schedule. This is also confirmed by other European carriers and rail parties. However, given the small number of trips driven and the circumstances in which the experiments took place, it was not yet possible to draw conclusive conclusions about ATO's performance in the Dutch context.

Human factors research during the experiments has showed that in order to achieve optimal performance with ATO, the interaction between driver and system must be explicitly designed. The tested ATO-over-ETCS solution did not yet sufficiently take into account the human need from the driver.

In 2020 NS executed their first experiments with ATO over STM ATB-EG. This testing project was completed in 2021. The reason NS wants to experiment with ATO on a class B system is because of the long-planned lead time of ERTMS rollout on the infrastructure in the Netherlands (ERTMS NL). NS investigate ATO over STM as a potential migration step towards ATO over ETCS. The first tests confirmed the technical feasibility of the concept and showed sufficient potential for NS to continue developing and testing the solution.

Follow up endurance tests (200 test runs) with both ATO GoA2 over ETCS and STM are planned in 2023 with a retrofitted SNG train in cooperation with CAF. This will include a more mature and further integrated ATO solution compared to our earlier testing solutions. The same train is also equipped with technology to conduct our first experiments in a shunting context using remote train operation (RTO) with GoA1, RTO with GoA2 and GoA4. These experiments are also planned in 2023 (Spoorpro (2023)).

## 6.2 C-DAS

This section presents an overview of the C-DAS state-of-practice in the countries of this WP's members where a C-DAS is available or research programs have been started/planned, and also in other countries where a C-DAS has been developed and this WP's members were involved.

### **Italy**

In Italy, there are no C-DAS in operation yet. C-DAS experimentation started with X2Rail-4 project: STS developed an ERTMS prototype which was tested on the Adriatic Line, on a journey of about 30 km. The prototype communicates through radio MLCP (LTE, GSM-R) using the subset 126 with an ATO TS, which is connected to a simulated TMS through an Integration Layer. The system communicates, also, with ETCS to get the real odometry of the train. The driving directives produced by the C-DAS, lastly, are sent to a DMI tablet in use of the driver.

### **Germany**

In Shift2Rail project FR8RAIL-2, Knorr-Bremse developed a C-DAS prototype based on a non-commercial version of "LEADER" product, whose installation and test started within the 2020. A special aspect of this prototype is that it uses a feature which is not defined in ETCS subset 125/126 nor in the initial version of SFERA UIC IRS 90940 but could be considered as a proposed

enhancement of the abovementioned standardization. It is based on information presenting to the driver related information about the position and features of the train immediately ahead and immediately behind. In FR8RAIL-2 context the optional message is called “Farsight – Rearview” message (Figure 13) and it contains the following information:

- Rear / Front train type.
- Rear / Front train average speed.
- Rear / Front train distance in number of free blocks.
- Length of free blocks.

This information is expected to be provided by the TMS / IM and is meant to be used by C-DAS as an optional feature, in order to inform the driver about neighbourhood traffic conditions. Note that this information, besides optional in C-DAS, is not an actual DAS recommendation; it is not an advice provided by internal DAS calculations (is not part of the optimal DAS calculated driving profile). It is, indeed, extra information for the driver to operate on his/her own based on his/her experience and knowledge. This information is not a driving advice but allows the driver to choose his own reaction based on real traffic context. This additional information could be useful since many times drivers with DAS technology ignore driving advices considering them inappropriate for timetable observance.

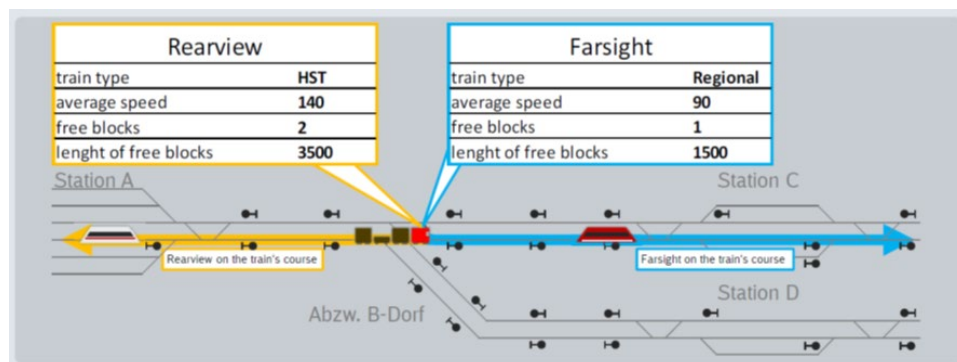


Figure 13: Option for “Farsight - Rearview” message

### Sweden

Between 2010 and 2015, a large-scale trial run of C-DAS was in operation on the Iron Ore line in the north of Sweden. It was a cooperation between the IM Trafikverket and the mining company LKAB, using the CATO system from Transrail (Leander, Törnblom (2019)). The deployment area was the Swedish part of the single-track line from the port of Luleå to the Norwegian border in Bjørnfjell, about 450 km. CATO was installed in all LKAB’s engines. Some conclusions from the C-DAS-installation at the iron ore line are reported in (FR8RAIL II (2020)).

The TMS used in this installation was the application Steg that is developed in-house at Trafikverket. The information exchange between Steg and the CATO trackside system was made with an in-house developed protocol and messages via web services. With Steg, the traffic controller kept the RTTP updated and conflict free, but Steg didn’t include any specific support or automation to facilitate the RTTP adjustments.

Some important conclusions from the large-scale C-DAS trail at LKAB were:

- The traffic controller is central. It is very important to give him/her the right understanding and the right support tool to handle the traffic. The information presented in the UI of the TMS must be adequately designed and relevant.
- The demands on the traffic controller increases since it becomes more important to have an RTTP that is correct and of high quality down to every detail with very high precision and some reasonable foresight. This is in particular true in situations with a mixture of C-DAS and non-C-DAS trains, since even very small deviations from the RTTP of a non-C-DAS train may cause a C-DAS train to have an unexpected stop (red signal) even if it follows its JP.
- The mixture of C-DAS-trains and non-C-DAS trains is a challenge since these give different planning and operational conditions.
- The non-C-DAS trains risk to significantly reduce the advantages of having C-DAS since they create uncertainties in the RTTP – you don't know if the non-C-DAS trains really follow their RTTP. Thus, for non-C-DAS trains, the RTTP must be updated (in very detail) so that it reflects the train's estimated run.
- To keep the RTTP properly updated with good foresight, the traffic controller needs some decision support or automation – in particular in the mixed traffic situation with both C-DAS and non-C-DAS trains. The traffic controller should (and wants to) focus on the larger decisions (where to have meetings, which train to prioritize, etc.) and not on minor adjustments to keep the RTTP in perfect shape. Thus, minor adjustments of RTTP to keep it optimal should be automatized.
- High quality RTTPs (with resulting good JPs) are essential to motivate the drivers to really follow the advices of the C-DAS. There should never be an unexpected red signal and the driving advices from the C-DAS must be smart and correct.

From 2019, a new C-DAS project was started at Trafikverket (in a smaller scale than the previous on the Iron Ore line) with pilots running for some parts of the railway network with different railway undertakings and C-DAS systems from Railit and Transrail for both passenger and freight trains. During the second half of 2022, an adaption to the SFERA standard (UIC (2017)) was started. Trafikverket is implementing the C-DAS-O architecture and have a clear division of the responsibilities between Trafikverket and the RUs according to SFERA. That is, Trafikverket handles the IM C-DAS TS part and setup the interface via CI, while the RUs handles the RU DAS TS and the equipment in the trains or for the drivers including the communication over air.

The plan for 2023 is to have some parts of the SFERA standard implemented via CI so it could be possible to run C-DAS with at least the most rudimentary functionality and data. This will then be further developed during the coming years and hopefully with more RUs joining and in growing parts of the network.

### **Spain**

Currently, ATO/C-DAS is not implemented in the Spanish network, therefore it is not integrated in the TMS platform although this could be in the future.

## The Netherlands

Energy-efficiency is an important topic for NS since the steam engines, where train drivers were financially compensated if less coals were used for their journey. In 1968, NS distributed leaflets for the train drivers to promote energy-efficient train driving. Later (1989), NS investigated providing fixed locations in the timetable (at specific signals or sign) to start coasting if the train was running on-time. A simple (stand-alone) *driver advisory system* (DAS) was developed in 1991 called the “Blue Lamp”. This light turned blue if the train could start coasting, while arriving on-time at the next station. Around 2001 the Energy Barometer was developed in trains. This meter measured the consumed energy and compared it with a reference. More details regarding the history of energy-efficient train driving at NS (including references) can be found in Luijt et al. (2017).

Most focus until 2010 was on the technique for energy-efficient train driving and on a top-down implementation approach (from management to train driver). Unfortunately, due to this approach most energy-efficiency innovations were not successfully implemented in operation at NS. The old top-down approach changed in 2010, because the management recognized that successful implementation depends strongly on the acceptance rate of the train drivers who use the system. Therefore, in the new EZR (energy-efficient train driving) approach, NS considered the human as crucial element for successful implementation of energy-efficient train driving and used a bottom-up approach (start with the train driver and then involve the management) to bring a change in the organization.

In 2011, NS implemented a simple manual UZI-method (universal energy-efficient driving idea) based on static tables for energy-driving (Scheepmaker and Goverde (2015)). The method was developed by a train driver of NS and is based on coasting depending on the available running time in the timetable and speed limit between two stops. The main benefits are the low investment costs, relatively high energy savings, lower workload for the train driver, and the high acceptance rate by the train drivers (Luijt, et al. (2017)). Furthermore, Scheepmaker et al. (2020) showed that the coasting strategy of NS leads to higher energy savings than reduced cruising speed, due to the relative short distance between stops in the Netherlands. For more details on the EZR approach, see Luijt et al. (2017).

The bottom-up approach inspires train drivers to apply the UZI-method and they asked themselves for further digital assistance with energy-efficient train driving. This led to the internal development of the (stand-alone) DAS called *Roltijd*, which is an app on the tablet of all train drivers for NS (implemented in July 2019). *Roltijd* computes the coasting curves dynamically real-time. It calculates the expected arrival time using GPS data and compares the expected arrival time with the target arrival time. When the expected time is equal or earlier to the target time, coasting is advised by showing a blue screen to the driver (see example in Figure 14). More details of *Roltijd* can be found in (Cunillera, et al. 2023). The basic idea of the method is to keep it simple (high acceptance rate by train drivers) and to assist the train driver in his craftsmanship. For instance, this means that the current version of *Roltijd* does not consider varying gradients. About 70% of all train drivers at NS currently use *Roltijd*, while energy-efficient train driving and using *Roltijd* is not mandatory. The yearly energy savings of the energy-efficient driving strategy at NS are about 9%, of which about 2% are achieved by the use of *Roltijd*.

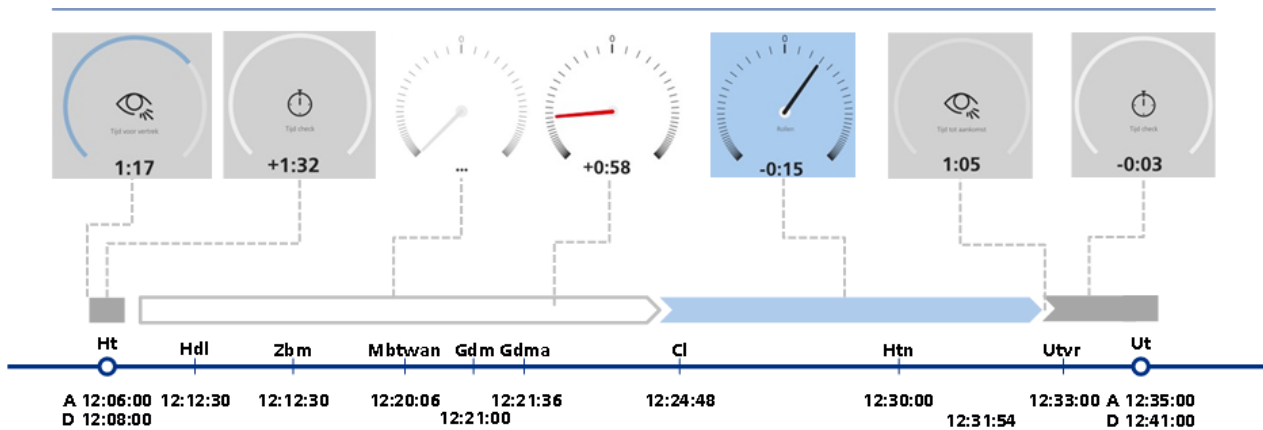


Figure 14: *Roltijd* coasting advice during a long-distance train run between the stops Ht (‘s-Hertogenbosch) and Ut (Utrecht Central). The blue screen (number 5 from right) indicates the train can start coasting and will be 15 s too early (Cunillera et al. (2023)).

### Routelint

ProRail offers all Railway Undertakings the possibility to let train drivers use the Routelint app. Routelint provides the driver with dynamic information of his journey and provides information on inserting, branching and intersecting trains on his route. The idea is that the driver him/herself is able to determine an optimal speed profile using this context information.

### Czech Republic

C-DAS systems have never been widely used in the Czech Republic, due to a 30-year history of commercial operation of the GoA2 ATO system “AVV”.

### Switzerland

The major infrastructure holder in Switzerland, SBB AG, has implemented and rolled-out a nationwide C-DAS system, denoted ADL, for both passenger and freight trains. ADL was developed in 2014 and builds upon a C-DAS-C architecture, in which all the driving advices and train trajectories are calculated centrally, and speed advices are pushed out to the trains. Positioning is based on passage of signals and balises in the sense that new driving advices are pushed to the trains after signal/balise passages. The onboard system shows speed advices rounded to the nearest 5km/h together with information about how long this speed should be held. The speed advice can be shown to the drivers on different kind of onboard units, like CAB radio, iPad or Smart phone.

ADL is closely integrated with the Swiss TMS-system, denoted RCS. The RCS-system forecasts and indicates line conflicts and is capable of automatically adjusting the RTTP to resolve many conflicts, which in turn is reflected in the ADL’s speed advice. ADL creates energy savings by avoiding unnecessary stops and energy efficient speed advice; 3-5% energy savings are reported.

The Swiss railway system is operated with very high precision compared to many other European countries. To increase the precision even more and to further save energy and reduce the variability in the driving styles, SBB has implemented a complementary DAS system (Graffagnino et al. (2019); Graffagnino (2021)), denoted vPRO, also aimed at passenger trains. The DAS system compares the current driving with the ideal, precomputed, train trajectory and indicates the



deviation (in seconds) to the driver (together with other relevant timetable information). The system has received high acceptance among the drivers and creates about 4-5% energy savings (on top of savings from ADL).

### 6.3 TMS

This section gives an overview of the TMS state of practice in the countries of this WP's members where a TMS is available or research programs have been started/planned, and also in other countries where a TMS was developed and this WP's members were involved. The focus is on TMS-aspects that are related to ATO/C-DAS.

#### **Australia**

STS Italian division is working on a project to install a TMS in Queensland, Australia, in the next few years. The system will be based on ERTMS protocol and architecture defined in Shift2Rail projects, and it will be used for metro application. Further, transport for NSW/Sydney Trains are implementing a TMS (Siemens as a supplier), in parallel with the ETCS L2 deployment.

#### **Sweden**

The TCS system used in Sweden by IM Trafikverket is the Ebicos 900. It is installed at eight traffic centrals, and it is used national-wide on all tracks that are remotely controlled. When using only the Ebicos 900 the replanning of the RTTP is made on paper graph with ruler and pencil. The TLS module of Ebicos is used to set the routes automatically for trains that are on time.

Trafikverket also have a system called Steg that is an in-house developed system built as a layer on top of the Ebicos 900. Steg provides a time-distance graph for RTTP planning and also ARS functionality. Based on the RTTP, route setting orders are sent to Ebicos 900. The changes made to trains in the RTTP are exported from Steg using an in-house developed protocol and messages. Steg development started in 2006 and was installed in one traffic central in 2009.

The system Steg is currently in the process of being installed at most traffic control centres, the aim is that 80% of the traffic will be short-term planned via Steg. Steg implements the concept *Control by Planning*, which includes that the traffic controller should be more proactive in his/her actions to make the train traffic follow the plan (RTTP), in contrast to the previous general approach which is more reactive. Steg replace the paper graph, and it also assists the users by conflict detection, but the conflict resolution is made manually through RTTP-adjustments by the traffic controllers. Based on the RTTP, basic C-DAS information is calculated by IM C-DAS TS and sent to RU C-DAS TS and C-DAS OB.

An important design paradigm in Steg has been to keep the traffic controller in pole position. This includes both the Control by Planning concept, and also that "human-in-the-loop" aspects are very important, and that the system should never give users "automation surprises" by ill designed automation functionality. In fact, this far, the RTTP-updating is very manual. However, previous Swedish experience with C-DAS shows that large scale C-DAS systems requires many detailed RTTP adjustments to really achieve the desired flow in the traffic, and this kind of detailed adjustments can be a heavy workload for the traffic controllers (FR8RAIL II (2020)). In particular, this is the case when only a part of the train fleet is equipped with C-DAS, since the non-C-DAS-trains don't necessarily follow the RTTP while the C-DAS trains do. This can lead to less good JP, for C-DAS trains, since unexpected conflicts with non-C-DAS trains may arise. Therefore, Trafikverket has concluded that some automation in the RTTP handling is necessary both to make sure that traffic

controllers are not overloaded, and to secure that the benefits from C-DAS are achieved already at initial stages when only a part of the trains have C-DAS. A design principle regarding C-DAS in Steg has been that the traffic controller should only plan RTTP, and he/she should not have to care how the JP and TPE is created. Though, it has turned out that it is important for the traffic controllers to know whether a train is operated with C-DAS or not, since it creates special requirements on the RTTP.

## Spain

Currently, in Spanish rail network there are three types of trackside gauges (the Iberian gauge (1668mm), the Standard European gauge (1435mm) and the narrow gauge (1000mm)) which are operated by two different types of traffic management systems:

- The first system is called Davinci and is mainly implemented for high-speed railways lines.
- The second that is called SITRA and operates the rest of the train lines which are named conventional and RAM lines.

SITRA system was implemented over 30 years ago to manage conventional lines and a major part of the high-speed rail lines. For these lines, the standard communication is handled through the centralized traffic control systems (CTCs). The SITRA regulation systems that manage crossings and overtaking points in rail traffic operate from these centres and allow information to be disseminated to the ADIF IM and the RUs on the current traffic situation and possible traffic delays. For the RAM lines, the operation of the trains is displayed through an interface integrated in a geo-positional system called Stack Rail, which is a centralized software that implements wireless communications with the vehicles to collect data on their position and signal status while sending control messages to train drivers, railway stations and stop points. The Stack Rail system is based on current geolocation technologies (GPS, GIS) and mobile communications (GSM-R/GPRS, satellite). Through the interface between Stack Rail and SITRA, the movements of the trains are automatically communicated (entries and exits through the established points).

Currently, in the Spanish network for high-speed lines, an advanced integrated rail traffic management system called “Davinci” from Indra is used. This is an innovative and flexible technology platform that integrates and automates all the processes and systems of the railway operations. The system provides real time information about the traffic situation and its evolution. This system:

- Monitors rail traffic and anticipates deviations.
- The system automates traffic control operations on area such as:
  - The automatic train routing
  - The integration of fixed and mobile telephony (DICOM)
  - The integration with remote controls such as detectors.
- Generates operational plans with efficiency criteria on:
  - Data management from topology and rolling stock
  - Planning of times and routes.
- Integrates with other modules and operating systems (CTC, Energy, PCE, ...).
- Has constant and full control of the different operational areas (traffic, planning, incident management...).

Davinci functions as an integration environment that can manage information coming from traffic control systems (planning, regulation, management of sensor alarms in the infrastructure...), plus systems corresponding to energy and telecommunications management. Its modular architecture allows you to sectorize the operation area in different positions and locations, in a secure and interoperable environment.

### **The Netherlands**

The TMS of the Netherlands consists of two systems: VOS with a national view and 13 decentralized systems with a regional view denoted Procesleiding.

VOS (Verkeersleiding Ondersteunend Systeem) is a customized system. It originated in the 90s. VOS has been completely rebuilt in 10s. The national dispatchers at the national traffic control centre and the regional dispatchers at the regional traffic control centres use VOS to keep the national traffic plan up-to-date (RTTP without exact routes).

Procesleiding is also a custom-built system that originated in the 90s and has been further developed since. It is used at the regional traffic control centres by signallers and contains TMS and TCS functions for remotely controlled tracks:

- TMS functions: keep a routing plan that fits the RTTP (from VOS) up-to-date for the region concerned;
- TCS functions: Automatic Route Setting, operate the infra elements.

Traffic state prediction, conflict detection and conflict resolution are not yet automated in VOS and Procesleiding.

ProRail wants to further develop TMS functions to reduce workload of signallers/dispatchers and traffic controllers and to have a feasible timetable and routing plan that is basis for automatic route setting and sending information to the train (ATO/C-DAS).

ProRail has a simulation environment in which the integration of TMS functions and ATO has started.

### **Czech Republic**

In the Czech Republic, TMS decision support system “GTN” is widely used in commercial operation for 20 years. Some of the key features of “GTN” are the following:

- Provides up-to-date traffic information in real-time.
- Automatically generates traffic documentation.
- Provides data to passenger information systems.
- Provides train diagnostic information.
- Minimises the need of voice communication.
- Monitors the real-time operation of safety devices (e.g., IXL).
- Provides train traffic chart, displays and documents traffic to dispatcher on the line section and at individual stations.
- Analyse set train paths by dispatcher (using train numbers).

- Continuously updates the train positions and allows immediate evaluation of the transport situation (delay / ahead of the time schedule).
- Shows traffic forecast.
- Implements automatic route setting, according to the timetable.
- Implements trackside interface for ATO over ETCS (DriveSWing DRS-10).

## 7 Principle of Linking TMS to ATO/C-DAS

The previous chapters described the state-of-the-art and practice of ATO and TMS functions related to ATO. Still undecided is how the two should be linked to optimize traffic performance, and in particular the role of the ATO TS as link between the TMS and the ATO OB. This chapter discusses the potential future functional directions which are in line with the current architectural and standardization developments like the RCA, SFERA and ERTMS/ATO. The purpose is also to have a uniform view for all GoAs including C-DAS and higher ATO grades.

One of the main tasks of a TMS is to provide routes and event times to trains for conflict-free and punctual train operation. A TMS must provide a Real-Time Traffic Plan (RTTP) specifying the exact routes for each train as well as time targets and possibly time windows at selected timing points. This RTTP is the basis for a synchronized timely route setting by the Traffic Control system and accurate speed regulation of trains by ATO/C-DAS. In the RCA the RTTP is implemented as the Operational Plan.

The ATO/C-DAS should translate the RTTP into a TPE for each connected train, where time windows at Timing Points (TPs) on the route of the train to the next stop or beyond may be further specified, with possibly additional Timing Points. The Timing Points may be static, flexible or dynamic, which is still to be defined. A TPE must guarantee a drivable and conflict-free train trajectory, i.e., the time and speed profile over distance, while providing sufficient flexibility for energy efficient driving. The TPE provides constraints to the train trajectory generation algorithm of the ATO/C-DAS. C-DAS translates this train trajectory to driving advice for the driver, while ATO (from GoA2 onwards) uses the train trajectory as reference to a train trajectory tracking algorithm to provide automated control commands to the traction and braking systems. The manual versus automated use of the train trajectory onboard is a main difference between C-DAS (GoA 1) and ATO (GoA 2 and higher), which may have consequences for the system design choices of the linking between the TMS and ATO/C-DAS.

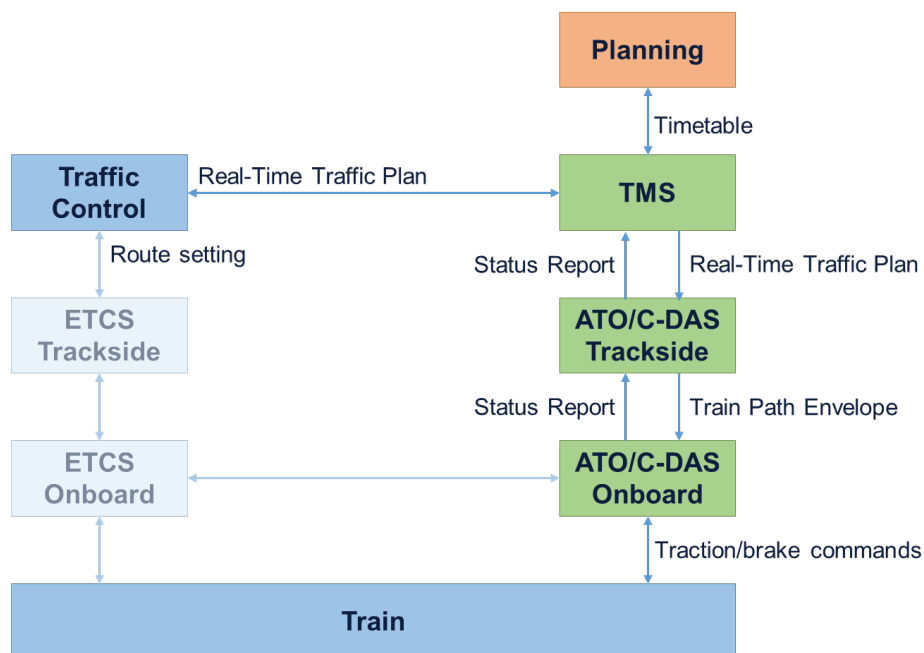


Figure 15: Interactions TMS, traffic control, ATO/C-DAS and ETCS

Figure 15 illustrates the interactions between TMS and ATO/C-DAS, as well as the interacting components of traffic control and ETCS. The functions of ATO/C-DAS are divided over a Trackside (TS) and Onboard (OB) system, with the TMS connected to the ATO/C-DAS TS. The ATO/C-DAS TS sends targets and constraints to the ATO/C-DAS OB of all connected trains in the form of Journey Profiles and corresponding Segment Profiles, while the ATO/C-DAS OBs send Status Reports back to the ATO/C-DAS TS. This feedback can be used to optimise the TPEs at the ATO/C-DAS TS or be sent further to the TMS. Different choices can be made about the various feedback loops and their use in dynamically updating the TPEs and the traffic predictions in the TMS to optimise capacity, punctuality and energy efficiency. Also, the required information in the Status Reports is still (partially) to be decided depending on the functions in the TS and TMS. For instance, the OB may send the Expected Time of Arrival at the next Timing Point(s), or more information about the preferred speed profile. Recommendations for the required feedback and how this can be used in the TS or TMS will be based on experience in future simulation environments in WP15/16.

The TMS should interact seamlessly with ATO/C-DAS, which are complementary but linked systems. The TMS is responsible for updating the RTTP corresponding to actual conditions and disturbances focusing on integral track capacity allocation of the railway traffic on the network level. On the other hand, ATO/C-DAS is responsible for regulating the trains by computing feasible and energy-efficient train trajectories (speed profiles) over the allocated routes within the allowances contained in the RTTP and following them by driver advice (C-DAS) or speed tracking algorithms (ATO GoA2 and higher). These responsibilities and their interaction can be designed in different ways, and the choice for the best alternative may depend on the level of automation, i.e., GoA1 with C-DAS or GoA2 to GoA4, the latency requirements of the feedback loops, and the traffic characteristics of the railway system, e.g., regional, urban, national, international, and high-speed rail.

The train trajectories should not exceed the supervised dynamic speed profile from the ETCS Onboard (or any other Automatic Train Protection system). Otherwise, a brake intervention will disturb the planned speed profile. Hence, the train trajectories should be aligned with the Movement Authorities (MAs) although their time horizons are different. Traffic Control executes the route setting via the interlocking systems based on the planned routes in the RTTP and route requests from the ETCS Trackside following the Position Reports from the ETCS Onboard. The set routes are translated into Movement Authorities (MAs) by the ETCS Trackside and send to the ETCS Onboard together with a track description. The ETCS Onboard calculates and supervises the corresponding braking curves and dynamic speed profile over the MA. The MAs are extended following route releases by the preceding or conflicting trains. In contrast, the ATO/C-DAS train trajectory is usually calculated from stop to stop, or beyond. For a smooth train operation, the TPEs must be conflict-free so that the successive requested routes are feasible, and the resulting MAs are aligned with the possible train trajectories.

In the absence of C-DAS or ATO, updated targets in the TMS must be communicated to the drivers in the trains by other means, which currently differs per railway. By adding ATO/C-DAS some of the tasks of the TMS may change or move towards ATO/C-DAS. The purpose of this would be to increase efficiency and timely response to minor train trajectory deviations. In particular, the time allowances contained within an RTTP, i.e., running time supplements to the train paths and buffer times between adjacent train paths, are distributed over the TPEs of the various trains and can be

influenced via (extra) Timing Points. These may be tight or more flexible depending on the choices made. Note that reordering and rerouting are dedicated TMS conflict resolution measures corresponding to bigger disturbances, next to retiming measures to resolve train path conflicts. The ATO/C-DAS is responsible for the exact speed profiles and thereby the finetuning of the train paths, which must be kept synchronized with the route setting (plan execution) as specified in the RTTP under control of the TMS. This should guarantee the alignment of the train trajectories to Movement Authorities. The TMS interacts with the underlying CCS (interlocking and ETCS TS), which includes the safety layer to check if the routes proposed by the TMS are acceptable or not. The routes in the CCS might also be valid for only a certain time determined by ETCS Movement Authority section timers. Hence, the RTTP can be affected both by feedback received from the CCS system and/or from the ATO/C-DAS. Overall, the linkage of TMS and ATO/C-DAS requires a careful architectural design and specification of functions, information exchange, and time restrictions, including the impact of the CCS.

The design alternatives correspond to the distribution of functionalities over the TMS, ATO/C-DAS TS and ATO/C-DAS OB, as follows:

- TMS-based ATO/C-DAS TS: In this case, the ATO/C-DAS TS merely translates the RTTP into separate TPEs corresponding to the various connected trains and sends them to the trains within the Journey Profiles. Status Reports from the ATO/C-DAS OBs to the TS are passed to the TMS and can be used by the TMS for traffic state prediction and conflict detection. In this case, the ATO/C-DAS TS can be viewed as being an extension of a TMS without any decision-making intelligence on its own. Here, the TMS needs to be enhanced to make the best use of the additional possibilities that the connection with the ATO/C-DAS TS/OB offers, including functionalities, update frequencies, response time, time horizon and geographical scope. For instance, the actual position and speed as well as the expected time of arrival at the Timing Point(s) in the Status Reports from the OBs can be used for specific monitoring, traffic prediction and conflict detection functionalities.
- Advanced ATO/C-DAS TS: In this case, the ATO/C-DAS TS calculates the TPEs for the various connected trains based on the constraints set by the RTTP. The TS may allocate optimised time windows to static, flexible or dynamic Timing Points of the various trains over their routes depending on real-time information from the OBs, while respecting fixed targets from the RTTP to keep aligned with the route plan execution. The ATO/C-DAS TS may now dynamically adjust TPEs of certain trains based on actual and expected train positions received from the OBs via the Status Reports, without the interference of the TMS. If the TS cannot find feasible TPEs to a given RTTP given the Status Reports from the OBs, or the performance becomes too restricted (e.g., high energy consumption, very tight buffer times at certain bottlenecks) then the TMS is requested to compute an updated RTTP respecting possible network effects. Note that any infrastructure update information like a temporary speed restriction will affect the feasibility of the RTTP and thus will go via the TMS for an updated RTTP. This way speed restrictions known to the ETCS OB stay aligned with the ATO/C-DAS OB information contained in the TPE. Timing and speed regulation functionalities are distributed to ATO/C-DAS for fast and optimal response to small

disturbances of the trains that stay within the bandwidths provided in the RTTP, while the TMS focuses on larger disturbances and disruptions. The exact threshold for the TMS to come into play depends on the geographical scope, traffic mix and actual time allowances. This will also affect how and when the human in the loop will have to act. In principle, the TMS does not have to be updated about the actual train positions and expected train trajectories as long as they are consistent with the RTTP, although regular updates of the train positions can be used in the TMS for monitoring, traffic prediction and information provision on the background, as well as for conflict detection and resolution concerning trains connected to different ATO/C-DAS systems or for non-equipped trains.

- The allowed flexibility of the ATO/C-DAS OB provides an additional choice corresponding to the alternative architectural design alternatives of Central, Intermediate or Onboard C-DAS or ATO, see Chapter 5.2. In line with SFERA version 2, we will not further consider the Intermediate OB alternative and focus on the Central and Onboard ATO/C-DAS. The first essentially provides a remote train control from the TS with train trajectories calculated by the TS, which are translated into traction/brake advice or commands that are sent directly from the TS to the OB. The latter offers the most flexibility to the OBs to respond to (slight) deviations in the train trajectory tracking without relying on a feedback loop to the TS (or TMS) to tell how the train should respond, corresponding to an adaptive (cruise) control. The TS will be informed when the OB is not able to find a train trajectory within the constraints of the TPE with additional information about critical timing points that can be used to derive better TPEs. Note that the TS is still responsible for computing the TPEs to the various connected trains, so that the Timing Points and their time windows within each TPE can still be optimised over all connected trains.

Table 3 gives an overview of the four resulting ATO/C-DAS functional design options depending on the functionalities on the trackside and onboard. The most rigid is the left-upper corner with a Simple Central architecture corresponding to remote control from the TMS. The most flexible is the right-lower corner corresponding to three feedback loops each dealing with an increased deviation from the train path from slight deviations that can be handled by the OBs within a given TPE, medium deviations that can be solved by the TS by adjusting adjacent TPEs, to large deviations that need to be escalated to the TMS to provide new RTTPs. These options need to be analysed on performance both for normal and disturbed conditions, with the latter including delays and operational restrictions.



Table 3: Distribution of decision-making intelligence over ATO/C-DAS TS and OB

	<b>Central ATO/C-DAS OB</b>	<b>Onboard ATO/C-DAS OB</b>
<b>TMS-based ATO/C-DAS TS</b>	<b>Remote Control</b> Train Trajectory derived from the RTTP and sent to the OB to be used directly	<b>Onboard Intelligence</b> TPE derived from the RTTP and sent to the OB for Train Trajectory calculation
<b>Advanced ATO/C-DAS TS</b>	<b>Centralized Intelligence</b> Train Trajectory optimized from the RTTP and OB Status Reports and sent to the OB to be used directly	<b>Distributed Intelligence</b> TPE optimized from the RTTP and OB Status Reports and sent to the OB for Train Trajectory calculation

This scheme can be further worked out for C-DAS and the various ATO GoAs separately, where ATO leads to full automated driving within the context of specific GoAs. The type (static, flexible, dynamic), amount and location of timing points for the TMS and the ATO/C-DAS TS may be different depending on the decision power given to the ATO/C-DAS TS. Advanced ATO/C-DAS TS should facilitate more flexible or dynamic options to the TS to control the TPE by for instance adding Timing Points at critical locations for smooth operations, while the TMS can be restricted to main Timing Points such as at stop locations or home signals. This is particularly relevant to dense traffic where a different choice of driving strategy or capability by one train may already result in train path conflicts or energy inefficient operation when sticking to pre-allocated TPEs. Controlling this effectively needs faster response times triggered by real-time positions and deviations of the various trains in a corridor that is expected from ATO/C-DAS TS.

The various options may generate different requirements and dynamics to various functions in the components of TMS, ATO/C-DAS TS and ATO/C-DAS OB that need to be checked and analysed within state-of-the-art simulation environments. A preliminary list of points is as follows.

- Functions and requirements for TMS, ATO/C-DAS TS and ATO/C-DAS OB
  - Dynamically updating RTTPs by the TMS
  - Dynamically updating TPEs by the ATO/C-DAS TS for given RTTP
  - Dynamically updating train trajectories by the ATO/C-DAS OBs for given TPE
- Feedback information
  - Required feedback by ATO/C-DAS TS from ATO/C-DAS OBs (e.g., status and predicted trajectory)
  - Required feedback by TMS from ATO/C-DAS TS (e.g., arrival time forecasts in case of infeasible RTTPs)
- Requirements on RTTP and TPE depending on the feedback control loops
  - Robustness/flexibility of RTTP computed by TMS for ATO/C-DAS TS
  - Robustness/flexibility of TPE computed by ATO/C-DAS TS for ATO/C-DAS OB
- Different TMS functional levels for various ATO/C-DAS TS/OB flexibilities and GoAs
  - C-DAS (GoA1), GoA2, GoA3, GoA4

- Different automation levels (human versus automation) of the various functional components in the TMS, ATO/C-DAS TS, ATO/C-DAS OB.

In WP15/WP16 several promising alternatives will be developed and analysed in detail, including C-DAS and ATO for higher GoAs.

## 8 Required and Prioritized Innovations

Based on the descriptions in previous chapters, in this chapter we point out prioritized innovations that are approached in the continuation of Motional WP15/16. The innovations are first summarized in an overview, then there is a description of each partner's contributions.

### 8.1 Overview

This section provides a summarized description of the development and innovation work that will be performed with WP15. The demonstrators developed in WP16 are further described in Deliverable 10.1 (Motional (2023)).

Table 4 summarizes the prioritized development areas for linking TMS to ATO/C-DAS, the areas are further described below. In the next section, the contributions from each partner are detailed.

Table 4: Prioritized development areas in WP15/WP16

Area	Subareas	Main contributor(s)
Requirements on TMS - ATO	TMS decomposition and components	TUD, NRD, INECO
	Feedback loops	TUD, INECO
	Content of RTTP	TUD, PR, STS, TRV
	Modelling TMS-ATO/C-DAS operated trains in timetables and simulation	TUD
Operational aspects	System scope and purpose	INECO, TUD, PR, TRV
TMS functions focused on RTTP	Traffic prediction	Indra, CAF, TRV, RISE
	Traffic regulation for different traffic conditions	CAF
	TMS forecast and operational plan update	Mermec
	RTTP finetuning for C-DAS	TRV, RISE
Train Path Envelopes	TPE Generation	TUD, NSR
	TPE handling in C-DAS TS	CEIT
TMS – ATO/C-DAS platforms	ATO-TMS integration platform	STS, AZD
	C-DAS TS	CEIT
	ATO-OB	CAF
Human factors	HF for TMS-ATO system	PR, UT, NSR
	HF for TMS-C-DAS system	TRV, VTI
Simulation environments and feedback loops	Automated components and interactions	PR, TUD, NSR, CAF
	C-DAS components of TMS	TRV, RISE
	Human-in-the-loop-simulator	PR, UT, NSR

Some partners in WP15 will focus their contribution to reviewing and/or providing data; this is valid for ADIF, INECO, NRD, and ÖBB Infra. The list of contributors is not exclusive but lists the major contributors while minor can be active as well.

### **Requirements on TMS – ATO**

This area relates to new requirements on the TMS-ATO/C-DAS concept that evolve as the linkage of the systems are developed. The components and functions of the TMS in relation to ATO/C-DAS should be established as a basis for defining architectural aspects of the whole system, like the distribution of functions over subsystems and components. This includes the identification of types/grades of TMS for optimal linking with ATO/C-DAS and applying algorithms to them. The feedback loops between different components needs to be defined as well as the data interchanged between components. The RTTP is a central concept in TMS in relation to ATO/C-DAS and its definition and format need to be well defined. ATO/C-DAS operated trains will have an impact on the train performance and capacity utilization, and it should be investigated how these trains should be modelled in simulations and planned in the timetables.

### **TMS functions focused on RTTP**

The RTTP is a central part of the operational planning in the TMS. ATO/C-DAS have an impact on how the RTTP should be constructed, and the functionality of the TMS should be enhanced in order to reach the full potential of ATO/C-DAS. A high quality RTTP is dependent on a prediction of the train movements and train traffic with high accuracy and the detection and resolution of potential conflicts. An interesting case is when there is a mixture of trains that are equipped with ATO/C-DAS and trains without, in which case many of the benefits of ATO/C-DAS is at risk due to the lack of coordination. The RTTP should take the fact that trains are equipped into account, and in the TMS there is a need for automatic finetuning of the RTTP to reduce the planning burden of the TMS operators. The traffic regulation could also take into account the different operational conditions that occurs during the day, as the traffic situation in rush-hour needs other planning priorities than outside rush-hour.

### **Train Path Envelopes**

The train path envelopes are a basis for the train coordination in an ATO/C-DAS-system and the creation of TPE is a key function of the ATO/C-DAS TS. Thus, the generation of the TPE and its handling in ATO/C-DAS TS are central functions that need further investigation. In particular, guidelines for distribution strategies of TPs in the TPE for dynamic and optimised capacity, punctuality, and energy consumption will be developed.

### **TMS – ATO/C-DAS platforms**

The Integration Layer is a central interface of the future system environment, and it should also cover the specific needs related to ATO/C-DAS. Thus, further development of the Integration Layer is of great importance. Further, data converters at the trackside and on-board units of ATO/C-DAS are important elements of the ATO/C-DAS-systems, which are further investigated.

### **Human factors**

To any system that interact with users, the human factor aspects are of importance, both from an ergonomical perspective and to certify that the system is accepted and used in the intended way. The situation can be even more complicated when several humans in different roles interacts via systems. This also relates to the TMS-ATO/C-DAS with interacting train drivers and TMS-operators. To investigate and elaborate around this, a human-in-the-loop-simulator with HF analysis functionalities is developed in order to study and enhance the human factor aspects of TMS-ATO. C-DAS also put specific requirements on the TMS-operators and the handling of these from a

human factor perspective is important to achieve the expected benefits of C-DAS.

### **Simulation environments and feedback loops**

To place the developments in a larger setting, simulation and evaluation environments are constructed. Some environments will test specific components and functions, as described above, while other takes a more holistic perspective to include the feedback loops between subsystems or include humans in the simulation environment. The simulation environments will also be a basis for the demonstrations in WP16.

## 8.2 Contributions from the Partners

In this section the contributions from the different partners in WP15/16 are outlined.

### **Contribution from PR/NSR/TUD**

The experience of ProRail shows that integrating components in a scalable simulation environment, regarding TMS, ATO and Human Factor (HF) -functions, requires a sound conceptual model and description of the components, functions, communication protocols and information/data exchange and technical architectural choices. Challenges are the distribution of functions over the components, calculation efforts and information update frequencies. Time horizons of the internal used forecasts and the synchronisation and reduction of inefficient calculation effort in components have shown to include challenges. ProRail would like to enable 'live' human factors demonstrations and human factors research using a human-in-the-loop simulation environment, where traffic operators and train drivers can participate, for ATO variants with ETCS. This is linked to tasks 16.1, 16.2 and 16.4, which are led by ProRail.

The simulation environment involves the roles in the traffic control centre (signaller/dispatcher combined in one role and traffic controller) and train driver. It is intended to be able to include algorithms developed in Task 15.3 and FP2/WP39. TUD will develop TMS-ATO functions aiming at smooth ATO operated trains. In particular, algorithms will be developed to compute TPEs including Timing Point optimisation for conflict-free train movements (with FP2/WP39), as well as TMS algorithms to adjust the RTPP to optimally support the TPE calculations in reaching an overall optimal trade-off between multiple objectives (punctuality, capacity, energy efficiency). In 15.3, TUD will lead the development of feedback control loops between TMS - ATO TS and ATO TS – ATO OB, such that the ATO OB of the connected trains are up-to-date considering dynamic traffic conditions. These TMS functions and ATO TS functions will be tested and fine-tuned in 16.4. Aim is also to investigate how the feedback loops between humans in traffic control centres – TMS functions – ATO TS functions – ATO OB function work and provide input to the ATO business case in FP2/WP32.

Therefore, the following is needed:

- Clear scope from FP2/WP32.
- Choice for architecture, standards and technical aspects that should be present or applied in the simulation environment.
- The Interface description between TMS and ATO TS (for ATO TS/OB the existing TSI SS 126 is used).

- Human factors requirements to the simulation environment based on the research questions (FP2/WP32).
- Changes to our simulator platform to add new algorithms or software modules, that are developed elsewhere and should be used in simulation: (Note: feasibility of these changes still needs to be investigated.)
  - ATO Onboard module from CAF
  - TMS algorithms developed in 15.3
  - New optimised braking functionality that will be developed in FP2
- Specifications of the scenarios/use cases (ref task 16.1), including reference scenarios and aligned with scenarios of capacity studies (WP32).

The existing simulation environment must be checked on specifications and standards and potentially be adjusted. Besides the mentioned functionalities, the performance indicators of the simulation should be aligned with those from the ATO business case from FP2/WP32. As preparation for the demonstrations ProRail/NSR/TUD will contribute in Task 15.3, 15.4.1., 15.4.2 and 15.4.3.

### **Contribution from TRV/RISE**

The experience from C-DAS installations in Sweden point out some challenges that will be approached in the continuation of Motional WP15, see section 6.2 for more details on the background. The Swedish experience primarily comes from operations with C-DAS on a single-track line, but many conclusions are transferable both to double track lines and to ATO operations.

A general observation is that good C-DAS operation requires high-quality RTTP on a very detailed level – in fact the RTTP needs to be more accurate in the details when C-DAS is used than without C-DAS, since C-DAS trains can be operated exactly as RTTP prescribes (on a level of a few seconds), while without C-DAS, trains more “flow as train drivers make them proceed”. Therefore, C-DAS increases the expectations on a perfect RTTP. Furthermore, when the traffic is intense, experience shows that it can be very demanding for the traffic controllers to keep the RTTP for all trains in high-quality.

An important characteristic of the C-DAS-implementation (in Sweden) is that it will for a long time be a mixture of trains equipped with C-DAS and trains without C-DAS. It is important to give C-DAS-trains the advantages of C-DAS already at early stages to encourage that RUs equip trains with C-DAS. One such improvement is that the TMS should deliver “green wave” and smooth rides to the C-DAS-trains, which requires detailed and good predictions of the movements of trains *not* equipped with C-DAS, so that JP of C-DAS-trains are correctly adapted to all traffic.

This leads to two kinds of required innovations for improving the efficiency of the C-DAS operations and handling of those trains that will be developed in Task 15.3. Firstly, TMS and C-DAS TS must be better suited for handling traffic with a mixture of trains that are equipped and not equipped with C-DAS; the traffic controllers need better decision support for such situations so that the benefits of C-DAS are not challenged. This includes, e.g., making forecasts of the motions for non-equipped trains. Secondly, traffic controllers need automation or decision support, specifically designed for C-DAS operations, that reduce the workload while still keep the traffic controller in full control of the situation. This means that such decision support or automation

must be designed with good consideration to human factors.

The TMS system Steg will be enhanced to incorporate one or several of the required C-DAS-related innovations indicated above in a test environment of Steg, including adequately designed C-DAS-related information in the UI of Steg. Which of the innovations that is integrated in Steg depends on the reached maturity level for each respective innovation area. The developed concepts will be demonstrated in Task 16.3.

### **Contribution from Indra**

Currently, INDRA TMS offers to the dispatcher a series of tools providing a clear and advanced monitoring and visual representation of the status of the operation. There are also tools to amend (so called replanning) the current timetable to recover the service when a disruption happened and a set of automations to apply the updated timetable into the signalling systems. One of the key elements of the TMS is the forecast calculation process. This process provides the expected future times and tracks at the regulation points of the route of each train including all the temporary conditions (temporary speed restrictions, delays, etc.) using all the current information present in the system. This forecast allows the dispatcher to compare the expected behaviour against the planned journey and to detect the future conflicts than can prevent the correct performance of the train.

INDRA's objectives are based on the interfaces developed in WP11/WP12 between TMS and C-DAS, which provides standardized communication through CDMs. Its aim is to test how the information of C-DAS (basically the status reports received by the TMS) can improve the forecast calculation and consequently the dispatcher's decisions, since he/she will have better elements of judgment when replanning in the short term. Feasibility of the timetable and early detection of potential conflicts that might prevent the correct performance of trains are the main benefits. Optimisation algorithms will be developed in the TMS to improve the forecast calculation mainly in task 15.3 and will be demonstrated in 16.3.

A modular architecture is expected to manage the distribution of functionalities between C-DAS TS and C-DAS OB. Depending on the operational convenience, train trajectory and advice computation will be provided by C-DAS TS or C-DAS OB. "Central" approach requires low latency and high frequency communications between trackside and onboard. On the other side, "on board" approach can work with higher latency and less frequent communications but requires high communication volume to include complete JP and SP transmission.

Lastly, we have interest in the operational roles in TMS (dispatcher, signaller, ...) and their impact in the operation procedures knowing that (some) drivers receive real-time advice by C-DAS linked to the task 15.4.1.

### **Contribution from CEIT**

ATO/C-DAS require reliable communications and on-board positioning to achieve optimal performance in terms of driving recommendations to achieve a smoother driving and lower energy consumption. CEIT aims at adapting and connecting CEIT simulation tools related to energy (optimal driving profile), communications (communication performance) and positioning (on-board position estimate) topics related to their impact within ATO/C-DAS. This will bring more realistic behaviour to the simulations, allowing us to study the effect of the behaviour of the on-

board systems with regards to positioning and communication in the driving recommendation for C-DAS and ATO. CEIT's development efforts will be concentrated mainly in tasks 15.3 and 15.4 and will be demonstrated in 16.3.

### **Contribution from CAF**

CAF's objective in WP15 is mainly the development of an algorithm that allows to solve the small disturbances that occur during the operation of railway systems. Also, with this algorithm they expect to have different strategies for regulating the traffic depending on the time of the day, train location, degraded operational situations (i.e., low adhesion, ATO inhibition zone, current limitation), electrical substations state, and reuse of braking energy in trains. For example, during rush hours traffic the algorithm will regulate traffic primarily considering headways constraints and during off-peak hours, traffic is regulated primarily considering timetable constraints. Further, depending on the used tracks, it is determined if it is a branches zone or an urban core: in the first situation, the regulation would be done by the timetable, while in the second situation it would be done by headway. The algorithm will also take energy efficiency into account.

CAF developments will be done mainly in task 15.5, some part of the TMS-ATO integration (fulfilling Subset 125 and Subset 126) will be done in 15.4.4 and will be demonstrated in 16.5. To carry out this demonstration, an integration of our TMS solution with our emulated ATO will be performed in a laboratory environment. The ATO TS is a module within the TMS and it performs the functions of ATO TS. Through our algorithm we will be able to generate and send from TMS new JPs (if they are necessary) to our ATO OB when a situation has changed. In the opposite direction, our ATO OB will send the STR (inside it we will include the train position and the timing points estimation) and the TMS will check if the disturbance between the nominal time and the reported one are fulfilled. If it is not fulfilled, a new regulation is done, and the new JPs will be sent.

### **Contribution from ADIF/Ineco**

Adif and Ineco will propose and review the requirements on the interaction between TMS and ATO/C-DAS systems by considering their experience as the Spanish infrastructure manager and railways consultants, respectively. This will be done seeking to minimise the impact in the technological ecosystem for traffic management in Spain and maximize the complementarity, in this way simplifying the future incorporation of the ATO/C-DAS technologies when needed. A key aspect for Adif and Ineco is that the link between TMS and ATO/C-DAS should be interoperable and it should be included in the EU TSIs, e.g., the CCS TSI including the specification of ATO-over-ETCS. Ineco provides their experience on the ATO over ETCS specifications (i.e., Subset-125, subset-126, subset-148, etc.) included in the CCS TSI 2023. For example, these ATO specifications define the data provided by ATO OB to ATO TS that should be considered when defining the data that could be used by the TMS from the ATO system to update the Real-Time Traffic Plan (RTTP). The Adif and Ineco contribution are linked to the task 15.2, 15.3 and 15.5.

Regarding WP16, Adif is involved in task 16.2 and 16.5 by providing IM data, if and when data requested by another partner is available.

### **Contribution from NRD**

NRD is interested in C-DAS and in the tradeoffs to concurrently optimize for energy consumption, improve punctuality and increase traffic capacity. NRD will collaborate with their expertise from a



Norwegian perspective, and in particular on defining an overall strategy concerning C-DAS, ATO and TMS. NRD is also involved in other related FPs and WPs and will align insights from there with WP15/16. In particular, NRD is involved in WP17 in the development of traffic management algorithms, and in traffic simulations for ATO in R2DATO.

### **Contribution from STS**

In order to allow the integration between TMS with ATO/C-DAS for all the partners of the WP, STS will make an integration platform, the Integration Layer (IL), available, within the scope of the task 15.4.4.

This integration platform will allow TMS and ATO TS of different partners to communicate with each other using a common data structure, a Conceptual Data Model (CDM), to be defined with the help of the other partners of the WP. To do so, it will be necessary to collect data and interfaces requirements for all the technologies/subsystems/features that will be connected to the platform. Data requirements will be an input for WP10, that has the goal to define the common data structure to be used (task 10.3). After that, the IL will be designed and developed, starting from the data structure obtained from WP10 and its specific communication functions (e.g. API).

For WP16, finally, STS will contribute to tasks 16.3 and 16.5: the IL designed and developed in task 15.4.4 will be made available in a common platform accessible by all the WP partners.

### **Contribution from AZD**

In WP15, AZD will build on their 30-year experience on ATO research and commercial operation of GoA2 ATO system “AVV”, and a 20-year commercial operation of decision support TMS system “GTN” in the Czech Republic. Key features of “GTN” are described in chapter 6.3.

AZD have already implemented a GoA2 ATO-over-ETCS system on the “Plum line” (Regional line in Czechia in full commercial operation) a few years ago, including a GoA2 TMS-ATO platform that represents an interface between our “GTN” application and ATO-Trackside. Based on this experience, in Task 15.4 AZD intend to contribute to and review all the specifications for a new interoperable platform, keeping in mind all the new specifics of a GoA3/4 autonomous railway. Later on, based on these specifications AZD intend to develop an implementation of such a platform and use it in laboratory and/or operational testing, and share the results with the partners for further discussion and review. Finally, after the platform is successfully tested, the goal is in Task 16.5 to carry out a live demonstration of its function in cooperation with other partners, subjected to multiple testing scenarios reflecting real traffic operations, to prove their function and interoperability.

### **Contribution from MERMEC**

MERMEC/MMSTE aims to realize a TMS-CCS (RBC-IXL-ATO) loopback simulation by realizing an interface between TMS and ATO TS in which the TMS provides an operational plan with the sequence of paths to be realized. MERMEC’s goal is to improve the algorithm of conflict detection and resolution from WP17/18 by using the interaction between TMS and ATO, e.g., the operational plan sent and evaluating ATO feedbacks.

Infrastructure and alternative paths, coming from the IM, will be implemented by using the System Pillar directive (e.g. CDM and publications). The interaction between TMS and CCS will follow the System Pillar indications based on the RCA SCI-OP requirements. The TMS sends the Operational

Plan (e.g. the OP Execution Request), while the TMS receives from the ATO-TS information such as train data, train position, and train speed.

The TMS can use the physical train length and other received data, inside its regulation and optimization functions, when determining the position of the train on a platform in a station, or to decide whether the train can be allowed to stop on a platform or not, for example when solving a conflict. The TMS can display the Train status onto the Time Distance Graph (TG) or using a view containing train run data and conflicts. The TMS can use the positional reports to improve the train forecast algorithm, by using train position and speed.

## 9 Requirements for Deployment

In this chapter, we point out some important influencing concepts that puts up requirements on the innovations developed in WP15/16. Several of these are already described in previous chapters in this document. Each of the requirements mentioned here will not be described in detail here; it is to future work to in detail study the implications of these requirements and how these affects the future work of WP15/16. Also, potentially conflicting requirements will be analysed and discussed with the System Pillar how to resolve this.

### 9.1 High-Level Requirements from Technical Enablers

From the Technical Enablers 12 and 15, the following requirements should be considered in the innovation work of WP15/16:

- Req 12.1: TMS – ATO/C-DAS simulation environment to evaluate enhancements and human-factor aspects related to feedback loops
- Req 12.2: Guidelines for TMS – ATO/C-DAS feedback loops
- Req 15.1: Integration platform to support TMS – ATO train operation
- Req 15.2: Method to compute optimized TPEs to connected ATO/C-DAS trains for a given RTTP
- Req 15.3: Method to dynamically adjust an RTTP based on feedback from ATO/C-DAS
- Req 15.4: Method to dynamically adjust TPEs based on dynamic RTTPs
- Req 15.5: Method to dynamically adjust TPEs based on feedback from the ATO/C-DAS Onboard
- Req 15.6: Optimal interaction of TMS, ATO Trackside and ATO Onboard functions
- Req 15.7: TMS – ATO/C-DAS simulation environment to test and evaluate TMS – ATO/C-DAS operations.

### 9.2 Non-Functional Requirements

There are several types of non-functional requirement that the future innovation work should take into consideration. The details of such requirements can often not be specified in advance, but experience and tests are necessary for detailing, e.g., the exact level for acceptable response times. To enable the specification of such non-functional requirements, the simulation and evaluation environments are of high importance. Such specifications of requirements are important results from WP15/16. Below, we comment on some of the most important non-functional requirements.

#### **Interoperability**

As indicated above, interoperability of communications between systems is essential for infrastructure managers in general. Even some operators, such as Renfe, have expressed concern about the compatibility of communications throughout the whole process starting with the request for capacity and ending with the running of the train. The use of unified or at least mutually compatible communications protocols ensures the reliability of the process and provides all actors with a secure and stable basis.

The risk of not ensuring interoperability has well-known technical and economic impact, e.g., in the cases of Eurocabin and RBCs. At the communications level, TMSs must be able to receive information from the capacity allocation systems and report incident information to them in order to optimise the transport plan. But this is only one set of links that must be connected to each other by a single or at least compatible communications protocol. On-board and on-track C-DAS

equipment must be able to establish reliable communications with the TMSs and their respective operators, and these close the loop with the capacity allocation systems.

Ultimately, the communications protocol (one or more compatible with each other) needs to be established to ensure interoperability of the data and information exchanged between these systems. The SFERA project recommended XML as the basic protocol, but it needs to be developed into a standard specifically for cross-border capacity requests that need to be handled by several systems in different networks.

### **Human factors, including human-in-the-loop**

It is clear that all technical innovations will only work in practice when the human operators are able to work with the systems. Considering human factors is essential, and human-in-the-loop simulations are important to obtain insights in the impact of TMS-ATO/C-DAS change including the human factors. This may lead to new requirements on (1) user interface design, (2) on which TMS-ATO/C-DAS functions need to be automated and (3) on how the feedback loops need to work. Furthermore, they may lead to insights on benefits and risks of the business case.

### **Response times**

Depending on the used architecture the needed response times can differ. Response times are important to consider both in the overall interaction between the traffic controller and the train/driver but also in and between the different parts of the architecture. When looking at the change made in the Journey Profile due to a replanning this change is communicated and processed in several steps to the train which then act on the change and also updates the status which is communicated back. This feedback will need to be fast enough, so it becomes clear what change is actually active and it is clear what result that change made.

Being able to define needed response times will be important so that the system as a whole will work as intended. Both in the different feedback loops and for the human to be in control and understand what actions gives what results.

During the planned work in WP15/16 it will be possible to also get a better understanding on what response times are needed.

### **Availability**

When the train traffic becomes more and more depended on support system such as C-DAS and ATO, the availability of these systems will become increasingly important. This will also affect many of the system that provides different kind of information needed. For example, correct infrastructure data, train compositions, timetables, and detailed vehicle data.

### **Traffic safety**

Safety of the railway traffic is very important and introducing new systems like C-DAS and ATO must be looked at from a lot of different aspects. When implemented in a good way, the safety should be at least as good as it is today. Since several of the roles involved in ATO/C-DAS have a safety function by themselves, the human factors perspective becomes very important. Then the possibility to do simulations that is close to the real situation is a way to test how new systems affects the human also when it comes to, e.g., workload and situation awareness.

### **Correctness of information**

With an increasingly digitized environment with a lot of information that is both presented more directly to the different roles and also used in different automations/calculations, the correctness also becomes more important since the effect of an incorrectness can give a larger consequence.

When handling information in IT systems it then becomes important to look at data quality parameters like accuracy, completeness, consistency, etc to ensure the correctness of information. Especially for parts related to traffic safety but also to have systems that act in a reliable way so that confidence in the system is not affected.

## 9.3 Standards and Related Development

In this document we have described several standards and current development work that are both important input and also sets requirements for the developments in WP15/16. Below, we comment on the most important standards and related development that the work in WP15/16 should adhere to.

### **System Pillar**

The System Pillar is an integrated part of Europe's Rail Joint Undertaking (ERJU/EU-RAIL) which aims to improve the European railway system to offer better services for European passengers and freight, delivering a unified operational concept and a functional, safe and secure system architecture. As described above, the System Pillar, is designed to be the "generic system integrator" for the Europe's Rail Joint Undertakings (EU-RAIL), and the architect of the future European railway system. The System Pillar both defines target system architectures and operational concepts and also coordinates and delivers the means for implementation through inputs to Technical Specifications for Interoperability (TSI) and harmonised standards. Thus, there is a bidirectional collaboration between EU-RAIL Flagship Project's (FPs) and the System Pillar, where the work packages of Motional (FP1) both will receive advice to adhere to from the SP and will also provide generalizable results to the SP.

### **SFERA**

SFERA is a project aimed to facilitate data handling and communication between DAS and TMS. It is further described in section 5.2.7.2. The development work in WP15 will include the architecture principles and communication formats proposed by SFERA and also has established an active discussion with SFERA on how to make the best out of this linkage.

### **RCA**

The Reference CCS Architecture (see section 5.2.7.5) developed by ERTMS User group and EULYNX provides a proposed standard architecture relevant for ATO systems. The developments in WP15/16 will follow RCA whenever relevant.

### **Conceptual Data Model (CDM)**

The LINX4RAIL and LINX4RAIL-2 projects have initiated the definition of a Conceptual Data Model offering a project-independent railway system model with rich semantics based on a federation of UML source models (see also section 5.3.2.2). A railway semantic dictionary has been subsequently built which collects ontologies extracted from the conceptual models and allows their interlinking. Building on and extending the outcomes of LinX4Rail's Conceptual Data Model and railway semantic dictionary, the Conceptual Data Model / Common Domain Ontology is a

common standardised machine-readable model of the rail system domain formally describing syntactic and semantic data structures consistent with the System Pillar architectural guidelines.

The Conceptual Data Model will need to be expanded to increase coverage of the railway domain and/or in response to specific requirements and inputs emerging from the EU-RAIL FPs (handled within the scope of the WP30).

### **ERTMS/ATO Subsets 125, 126, and 131**

Subset 126 is defined by UNISIG, is standardized and should be used by all partners to communicate between ATO OB and ATO TS (see section 5.2.7.1). Subset 126 defines the interoperable interface between the two subsystems of the ATO System according to the ERTMS/ATO system requirements specification.

The communication requirements associated with the ATO OB/ATO TS interface are included in subset 125. The scope of subset 125 is to define the functional system requirements for an interoperable ERTMS/ATO system, limited to GoA2 (excluding GoA3 and GoA4). This specification is applicable to ETCS levels 1, 2 and 3. This subset is advisable to use, but not mandatory because it may be that, instead of using it, another communication protocol such as TCP/IP is used.

Subset 131 is an initial draft also written by UNISIG, the latest version of which is from 2014 and is not being worked on. The objective of subset 131 is to provide an interoperable interface between ATO TS and TMS to support ATO over ERTMS, and an interoperable set of data to be exchanged between the two subsystems.

As it is a draft, subset 131 it is not standardized, so it is not mandatory. There are some companies that, based on this draft, have made their own version of it for themselves, but other partners would not have to adopt it in order to use it.

## 10 Conclusions

This report lays out the ground for the continued work in WP15/16 of FP1 Motional in EU-RAIL. The focus of WP15 is to study and enhance the link between TMS and ATO/C-DAS in order to, e.g., enhance operations, improve feedback loops, and increase standardization. The objective of the report is to present the current situation both as “state-of-the-art” and “state-of-practice”, describe the needed development and innovations that will be target of future work in WP15, and also to capture the requirements that are important to consider in the development work.

The report shows that there are important concepts and standards that are evolving in the area, like SFERA and several ERTMS “subsets” for ATO-standards. There is important knowledge to build upon regarding, e.g., energy optimisation, train trajectory optimisation, communication, and data models.

Regarding the “state-of-practice”, several countries have made important implementations (both trial and “real”) of C-DAS with important conclusions that are valid for both C-DAS and ATO operations. There are fewer implementations and tests regarding ATO, but also in that area important experience has been made. The lessons learnt point out the directions of innovation that will be performed in the continuation of WP15/16. Future development should be in line with recommendations from the System Pillar of ERJU.

For the system architecture of the TMS – ATO/C-DAS linkage, design and analyse principles are proposed, both to get harmonization and also to help a common understanding. Communication platforms, like the Integration Layer, and standardized data formats, like the Conceptual Data Model, are important bases, but further developments are necessary to adapt them for the relevant area.

The continued work of WP15/16 will be very much based on the partners’ previous experience in the area and on the evolving standards. This certifies both that the work will be relevant, reusable and move the state-of-the-art forward. The planned work has a broad base for important improvements and includes, e.g., improved RTTP and TPE construction for better ATO/C-DAS efficiency, architectural and communication developments for standardization, and better adaptation to human factor aspects of TMS - ATO/C-DAS systems. The development work will both consider and contribute to the standards in the area.

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