Rail to Digital automated up to autonomous train operation

D39.2 – Best practices report from mainline capacity assessment, including testing Operational Concept (OC) for mainline operations

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Disclaimer

EXECUTIVE SUMMARY

European railway networks are facing increasing pressure to accommodate growing transport demand while simultaneously improving punctuality, operational reliability, energy efficiency, and overall network resilience. In many mainline corridors, infrastructure capacity is already heavily constrained, particularly in dense and heterogeneous traffic environments where high-speed, regional, commuter, and freight services share the same infrastructure. At the same time, the railway sector is expected to contribute significantly to European sustainability and decarbonisation objectives by enabling a modal shift from road and air transport towards rail.

Traditional approaches for increasing railway capacity often rely on major infrastructure investments, including additional tracks, signalling upgrades, and station expansions. However, such measures typically require long implementation times, high costs, and substantial operational disruption. As a result, increasing attention is being given to digitalisation, automation and advanced traffic management solutions capable of improving the utilisation of existing infrastructure while maintaining high levels of safety and operational robustness.

Within this context, Automated Train Operation (ATO) over the European Rail Traffic Management System (ERTMS) is considered one of the key technological enablers for the future railway system. By combining automated driving functions with advanced traffic management and signalling systems, ATO has the potential to reduce operational variability, improve train path adherence, optimise energy consumption, enhance traffic predictability and support more efficient capacity utilisation. Furthermore, the integration of Traffic Management Systems (TMS), Train Path Envelope (TPE) generation and onboard automation creates opportunities for more adaptive and coordinated railway operations in increasingly complex traffic environments.

Despite these expected benefits, the introduction of higher levels of railway automation also raises important technical, operational, organisational and human factors challenges. The deployment of ATO over ERTMS requires reliable interoperability between multiple systems, robust operational procedures, high-quality operational data and clear allocation of responsibilities between automated systems and operational staff. In addition, railway operators and infrastructure managers must ensure that automation solutions remain transparent, trustworthy and operationally manageable under both nominal and degraded operational conditions.

To this end, this deliverable presents the best practices identified from the mainline capacity assessment and the testing of the Operational Concept (OC) performed within R2DATO WP39 "ATO over ERTMS demonstration on mainline". The deliverable consolidates results from two complementary activities carried out in FP1 WP9 "Demonstration – Simulation and operational feedback for improved planning" and FP1 WP16 "Demonstration – Linking TMS to ATO/C-DAS for optimised operations". First, the mainline capacity assessment evaluated the potential impact of ATO GoA2 and GoA4 on railway capacity, running times, operational stability, and timetable robustness through simulation studies performed on the SAAL corridor in the Netherlands and the Southern Main Line in Sweden. Second, the Operational Concept testing validated the interaction between Traffic Management Systems (TMS), TPE generation, ETCS, and ATO through Human-in-the-Loop (HITL) demonstrations and technical simulations in realistic operational environments.

The performed studies demonstrate that ATO can significantly improve railway operations by reducing running times, decreasing headway allowances, increasing timetable flexibility and improving operational predictability. The simulations indicate measurable reductions in capacity utilisation and running time, particularly for stopping and commuter services operating in dense traffic

conditions. The results further show that TPE-based coordination between TMS and ATO enables dynamic conflict detection and trajectory adaptation while supporting energy-efficient train operation and operational stability.

The Human Factors demonstrations highlighted both the opportunities and challenges associated with introducing higher levels of automation into railway operations. The results show that operators generally recognise the operational benefits of ATO, including improved consistency, predictability and support for traffic management. At the same time, the demonstrations identified several implementation challenges related to workload distribution, trust in automation, operational procedures, interface design and organisational readiness.

The set of best practices included TPE generation, conflict management, data quality, simulation methodologies and implementation strategies for ATO over ERTMS. Particular emphasis is placed on the use of microscopic simulation tools with integrated ETCS functionality, realistic operational scenarios, iterative validation through Human-in-the-Loop simulations and the importance of harmonising planning and operational time resolutions. The study confirms the importance of maintaining clear allocation of responsibilities between traffic management and onboard automation while ensuring that operators remain sufficiently informed and supported during operational decision-making.

ABBREVIATIONS AND ACRONYMS

ATO	Automatic Train Operation
ATO-OB	ATO On-Board
ATO-TS	ATO Trackside
C-DAS	Connected Driver Advisory System
DATO	Digital Automatic Train Operation
EETC	Energy-Efficient Train Control
ERTMS	European Rail Traffic Management System
ETA	Estimated Time of Arrival
ETCS L	ETCS Level
FP	Flagship Project
FRISO	Flexible Rail Infrastructure Simulation of Operations
GoA	Grade of Automation
HITL	Human-in-the-Loop
HLA	High-Level Architecture
IC	InterCity
IM	Infrastructure Manager
JP	Journey Profile
KPI	Key Performance Indicator
MA	Movement Authority
MOTIONAL	MObility managemenT multImodal envirOnment aNd digitAl enabLers
MTTC	Minimum-Time Train Control
OC	Operational Concept
R2DATO	Rail to Digital and Automated up to Autonomous Train Operation
RMS	Reduced Maximum Speed
RTTP	Real-Time Traffic Plan
RU	Railway Undertaking
SAAL	Schiphol – Amsterdam Zuid – Almere – Lelystad
SP	Segment Profile
SPR	Sprinter
TMS	Traffic Management System
TPE	Train Path Envelope

TRL	Technology Readiness Level
TRV	Trafikverket
UC	Use Case
WP	Work Package

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1 INTRODUCTION

Deliverable D39.2 belongs to WP39 'ATO over ERTMS demonstration on mainline'. It relates to task T39.1 'Preparatory work to demonstrate ATO-solutions for main line bottlenecks' with the goal of preparing to demonstrate the solutions that DATO over ERTMS technology can bring to relieve bottlenecks in mainlines, i.e., high-density networks with heterogeneous traffic. This complexity is typically present in nodes and junctions where multiple lines come together. D39.2 is dependent on D39.1 which is about on the test specification for DATO and TMS interface in mainline operations. In D39.1, the test specification is defined for FP1 WP8/9 regarding capacity simulations and FP1 WP15/16 for the demonstration of the Operational Concept, including human-in-the-loop simulations.

The deliverable describes the best practices from mainline capacity assessment and the testing of the Operational Concept (OC) for mainline operations. It builds upon the test specification defined in Deliverable D39.1, as well as upon the activities performed in FP1 WP9 "Demonstration – Simulation and operational feedback for improved planning" and FP1 WP16 "Demonstration – Linking TMS to ATO/C-DAS for optimised operations". The work in this deliverable contributes to the broader objectives of Europe's Rail regarding the digitalisation and automation of railway operations through ATO over ERTMS and Traffic Management Systems (TMS).

The increasing demand for railway capacity, operational reliability, and sustainable transport requires new operational concepts capable of improving network performance while maintaining high levels of safety and robustness. In this context, Automated Train Operation (ATO) over ERTMS is considered a key technological enabler for enhancing capacity utilisation, reducing operational variability, improving energy efficiency and supporting more resilient railway operations. However, the introduction of higher levels of automation also introduces important operational, technical and human factors challenges that must be carefully assessed before large-scale deployment.

The objective of this deliverable is therefore twofold. First, it aims to identify and evaluate best practices for assessing the impact of ATO on mainline railway capacity through simulation-based studies. Second, it aims to define best practices for testing and validating the Operational Concept associated with ATO over ERTMS, including the interaction between Traffic Management Systems, Train Path Envelope (TPE) generation, ETCS, ATO onboard systems, traffic controllers and train drivers.

The work presented in this deliverable is based on a combination of microscopic railway simulations, operational scenario analysis, Human-in-the-Loop demonstrations, technical validation activities and qualitative expert evaluation. The studies focus primarily on the SAAL corridor in the Netherlands and the Southern Main Line in Sweden, representing realistic high-density railway environments with heterogeneous traffic conditions.

The remainder of this deliverable is structured as follows. Chapter 2 presents the background, objectives, scope, and limitations of the mainline capacity assessment and Operational Concept testing activities. Chapter 3 describes the methodologies applied for the best practices resulting from the simulations and demonstrations in FP1 WP9 and FP1 WP16. Chapters 4 and 5 summarise the obtained results from the capacity assessment and Operational Concept testing, respectively. Chapters 6 and 7 define the identified best practices for mainline capacity assessment and the Operational Concept testing. In Chapter 8, several considerations for implementation strategies of the Operational Concept are presented. Finally, Chapter 9 presents the overall conclusions and recommendations for future research.

2 BACKGROUND AND CONTEXT

We present in this chapter the objectives of the mainline capacity assessment and Operational Concept testing, as well as their scope and limitations.

2.1 OBJECTIVES OF THE MAINLINE CAPACITY ASSESSMENT

The objective of the mainline ATO capacity assessment was to measure the capacity effects of ATO that can be recouped in timetable planning. The motive for this exercise was to gain insight in societal and sector-specific potential benefits, which can convince policymakers to initialize according deployment strategies. For example, capacity assessment results can show whether or not to roll out ATO, when to roll out ATO, and how to recoup the ATO benefits in timetable planning. The measurements described in this document provide input for economic and financial analysis, described at length in FP2 D32.5 [1] and used as input for an overall business case methodology for DATO in FP2 D32.1 [2].

2.2 OBJECTIVES OF TESTING THE OPERATIONAL CONCEPT

The Operational Concept testing primarily aimed to validate the interaction between Traffic Management Systems (TMS), Automatic Train Operation (ATO), and the Train Path Envelope (TPE) Generator within a realistic Human-In-The-Loop (HITL) railway simulation environment. More specifically, the objectives include:

- Validating the feasibility and operational behaviour of the ATO–TMS feedback loop under both nominal and disturbed operational conditions.
- Assessing whether the TPE Generator can generate feasible Train Path Envelopes (TPEs), detect blocking time conflicts, autonomously resolve conflicts through timing-point adjustments, and escalate unresolved conflicts to traffic management systems when necessary.
- Testing the operational feasibility of ATO-supported railway operations in realistic mainline conditions, including delay propagation, rerouting, infrastructure disturbances and conflict management.
- Assessing Human Factors aspects such as workload, situation awareness, trust in automation, communication and operational acceptance of GoA2 operations.
- Evaluating operational performance indicators like timetable adherence, energy consumption, braking interventions, conflict resolution capability and robustness of train operations.

2.3 SCOPE AND LIMITATIONS OF THE MAINLINE CAPACITY ASSESSMENT

The scope of the mainline capacity assessment is a study on ATO GoA2 and GoA4 in the Netherlands (SAAL corridor) and a study on ATO GoA2 in Sweden (multiple lines). The main limitation of the mainline capacity assessment is that, to test the real potential running time and headway benefit of ATO within a situation with network-level connectivity constraints, one would ideally require a new timetable that incorporates ATO-induced allowance benefits. Since this was beyond the scope of the associated FP1 WP9 Demonstrator, this was not done here, and any reported potential running time benefits are based on decreases in plannable running time between timetable points relative to the old timetable, not based on a network-level re-optimisation.

2.4 Scope and Limitations of Testing the Operational Concept

The scope of the testing focused on a Dutch mainline railway environment within the SAAL corridor and considered dense passenger traffic operations under ETCS Level 2 with ATO functionalities. The demonstrations covered both technical and operational aspects, including delay scenarios, rerouting, infrastructure disturbances, and traffic conflict management. Human-In-The-Loop simulations were used to assess collaboration between automated systems and operational staff, while validating the interaction between TMS, ATO Trackside (ATO-TS), ATO Onboard (ATO-OB), and the TPE Generator.

However, the Operational Concept testing also had several limitations. The demonstrations were performed in a simulation environment (Technology Readiness Level – TRL 5) and therefore do not fully represent real operational deployment conditions. The investigated scenarios mainly focused on Dutch railway operations and passenger services, limiting direct transferability to other operational contexts or freight applications which was excluded in the investigated scenarios. In addition, the number of participants involved in the Human-In-The-Loop tests was relatively limited, and some operators were not fully familiar with the simulation environment. Another limitation regarded the mismatch between second-based ATO operations and minute-based operational planning processes. The study also identified that further validation, larger-scale testing, harmonisation of procedures and additional development of TMS functionalities are still needed before large-scale operational implementation can be achieved.

3 METHODOLOGY

This deliverable aims at providing the best practices for the mainline capacity assessment simulated in FP1 WP9, and the best practices from the testing of the ATO Operational Concept demonstrated in FP1 WP16. The methodology for developing the best practices of each analysis is provided in Sections 3.1 and 3.2, respectively. In particular, the best practices are a result of the outcomes of the capacity simulations and the demonstrations of the DATO-TMS interface. These best practices build upon the test specification defined in [3].

3.1 METHODOLOGY FOR BEST PRACTICES OF MAINLINE CAPACITY ASSESSMENT

Deliverable 32.5 of FP2 [1] describes at length the methodology for mainline capacity assessment. This deliverable's direct counterpart is FP2 D39.1 [3]. Specifically, they state that ATO may lead to the following capacity effects.

First, they argue ATO may allow reductions in planned running time allowance and headway allowance due to the removal of driver variation. Second, they argue that ATO may allow reductions in planned running times due to, ceteris paribus (i.e., while being located on the same Pareto front of co-optimised capacity, comfort and safety), being able to brake later more consistently than the average driver. In parameter terms, this leads to a potentially higher planned "free", or comfort, braking rate. Third, they argue that ATO may eliminate driver reaction time to upgraded movement authorities, although these are only relevant in simulations with conflicts. Fourth, they argue that ATO may allow reductions in planned running times due to the potential to reduce the ETCS safety parameter T_driver, which shifts the permitted curve that constrains trains closer towards the service braking curve. Finally, they argue that ATO GoA4 may allow for a reduction in the planned stopping time allowance or planned stopping time, due to potential reductions in certain process times that take place around a train's stop and departure.

The question whether these are best practices relies on expert judgement while modelling and analysing results. In such, the methodology for *Best Practices of Mainline Capacity Assessment* is qualitative in nature.

3.2 METHODOLOGY FOR BEST PRACTICES OF TESTING THE OPERATIONAL CONCEPT

The methodology applied in Demonstrators 16.1 and 16.2 was based on a scenario-driven Human-in-the-Loop (HITL) simulation approach within a realistic railway operational environment representing the SAAL corridor in the Netherlands. The demonstrations were executed in an integrated simulation environment combining FRISO, Traffic controller (PRL), network controller (VOS), TMS, TPE, ETCS and ATO-OB components connected through real-time High-Level Architecture (HLA)-based interfacing. A structured set of operational scenarios was developed to evaluate both technical system behaviour and the interaction between automation and operational staff under normal and disturbed traffic conditions.

Demo 16.1 focused primarily on the technical TRL5 validation of the ATO-TMS feedback loop. The methodology evaluated the ability of the TPE Generator to process timetables, generate Journey Profiles, detect conflicts, resolve conflicts autonomously where possible, and escalate unresolved conflicts to operational systems and operators. Real-time updates from traffic management systems and train status reports were continuously processed to assess the dynamic behaviour and robustness of the integrated ATO-TMS environment.

Demo 16.2 extended the methodology towards operational and Human Factors validation. The scenarios included infrastructure failures, delay propagation, and operational recovery situations to analyse the interaction between ATO, TMS, signallers/dispatchers, network traffic controllers, and train drivers. The methodology combined real-time simulation, KPI-based performance assessment, operator observations, questionnaires, interviews, and qualitative analysis of workload, usability, communication, trust in automation, operational acceptance, and decision-making processes.

4 SUMMARY OF RESULTS ON MAINLINE CAPACITY ASSESSMENT

This chapter presents a summary of the results on the mainline capacity assessment, specifically applied to the case studies defined in [3], namely the SAAL corridor in the Netherlands (Section 4.1) and the Southern mainline in Sweden (Section 4.2).

4.1 SAAL CORRIDOR IN THE NETHERLANDS

For the Dutch case, Table 1 describes the assumed parameters. They follow the theory described in FP2 D32.5 [1].

Specifically, first, based on expert judgement and real life ATO tests in the Netherlands, we conservatively assume a potential increase in the comfort braking rate from -0.5 m/s^2 to -0.72 m/s^2. In reality, the -0.72 m/s^2 is an approximation of a comfort braking rate of -0.5 m/s^2 between 0 and 40 km/h, and -0.8 m/s^2 between 40 and 130 km/h, with 130 km/h being the usual maximum speed within the use case area. We extend this assumption of a higher comfort braking rate proportionally to freight trains. Second, we assume that driver reaction times to upgraded movement authorities decrease from 2 to 0 seconds. Third and fourth, for ATO GoA4, we assume that T_driver can decrease from 4 to 2 seconds for ATO GoA4 and that minimal stopping times can decrease by 10 seconds for InterCity (IC) trains and 4 seconds for Stopping trains. Most notable is the assumption on standard running time allowance and headway allowance. We assume a decrease of up to 3% in standard running time allowance and a decrease of 15 seconds in planned headway allowance due to removal of driver variation, based on knowledge exchanges with capacity performance analysis experts at ProRail's capacity management department.

Table 1: SAAL (NL) study parameters for ATO and NG Brake

Parameter	Reference (ETCS L2)	ATO (GoA2)	ATO (GoA4)
Comfort braking rate for passenger trains, and adhesion condition	-0.5 m/s^2	-0.72 m/s^2	-0.72 m/s^2
Comfort braking rate for trains	-0.2 m/s^2	-0.3 m/s^2	-0.3 m/s^2
Driver reaction	2 s	0 s	0 s
T_driver	4 s	4 s	2s
Standard running time allowance	7% IC 6% Stopping 0% Freight	4% IC 4% Stopping 0% Freight	4% IC 4% Stopping 0% Freight
Headway allowance	60 s IC 45 s Stopping	45 s IC 30 s Stopping	45 s IC 30 s Stopping
Minimal stopping time passenger trains	ref	ref	-10 s IC - 4 s Stopping

We note that freight trains do have driver variation, but the planning norm is to instead get running time buffer by freight trains not running as much as their paths are scheduled and running at a lighter weight than they are planned as in simulation, hence being able to run faster than planned. We postpone a proper test of the ATO running time buffer benefits for freight trains to future research.

As ATO decreases the standard running time allowance and decreases the technical minimal running time through harder braking, there exists a decision what to allocate this additional time benefit to: lower running time (and resulting potential economic and financial benefits),or improved operational stability (and resulting potential economic and financial benefits). Here, we assumed theoretical running time gains as accruing to running time. While we acknowledge that this is a shortcut, designing a new optimised timetable with ATO allowances and running times would take effort beyond the scope of the capacity simulation study. In addition, ATO does still have an operational stability benefit that we could and did not allocate to running time, which is the 15 seconds decrease in the headway allowance.

Table 2 shows the running time gains when going from the reference, which is a driver with C-DAS, towards ATO GoA2 and GoA4, respectively. We observe a potential reduction in running time of 1.97 seconds per kilometre for ATO GoA2. This benefit is slightly higher for stopping trains, reflecting the larger number of scheduled braking actions they carry out. The benefit is much lower for freight trains, reflecting both a lesser number of braking actions and the begrudging omission of running time allowance improvement through the assumption of zero allowances for freight trains in our reference timetable.

Table 2: Running time (s/km) and stopping time (s/km) benefits for ATO

Scenario	Train type	ATO GoA 2	ATO GoA 4
Running time	Intercity	-1.65	-1.90
	Stopping	-2.35	-2.67
	Freight	-0.12	-0.14
	All	-1.97	-2.26
Stopping time	Intercity	0	-0.66
	Stopping	0	-0.71
	Freight	0	0
	All	0	-0.67
Total		-1.97	-2.93

We can also represent the capacity benefit of ATO using UIC406 timetable compression including allowance times. Figure 1 shows the relative changes in capacity utilisation percentage including allowance times compared to the reference manual driver. Most of this effect is driven by the reduction in headway allowance. The additional effect for GoA4 comes from slight further running time improvements due to running closer to the emergency braking curves, as well as the assumed reduction in stopping time. Figure 2 adds context to the timetable abbreviations in Figure 1.

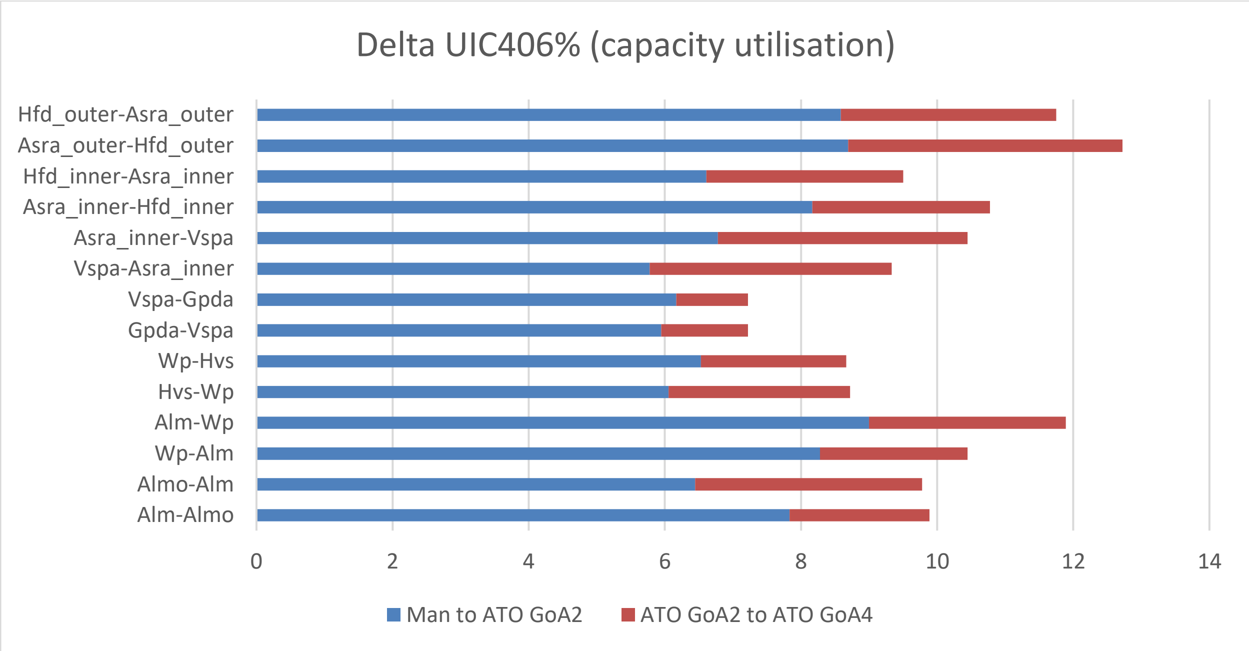

Figure 1: Capacity utilisation (including headway and running time allowances) - ATO GoA2 and GoA4 relative to manual driver

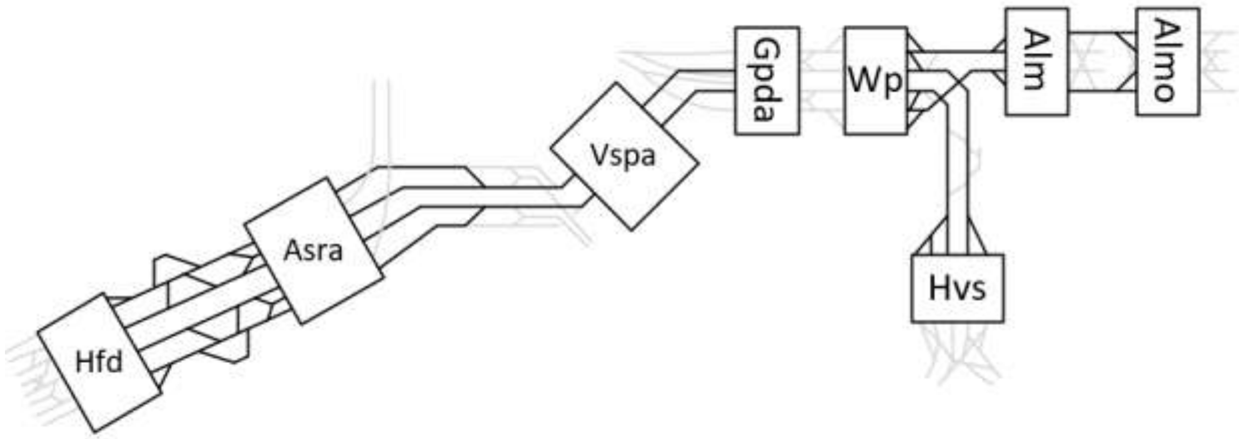

Figure 2: Schematic overview of UIC406 track segments for SAAL corridor (NL)

We observe very sizeable reductions in capacity utilisation, ranging from 6 to 12 percentage points. Note that 10 percentage points represent 10% of a full hour, so 6 minutes. This shows that ATO can easily add the timetable space to run one extra train per unit of time or enjoy a large operational stability improvement.

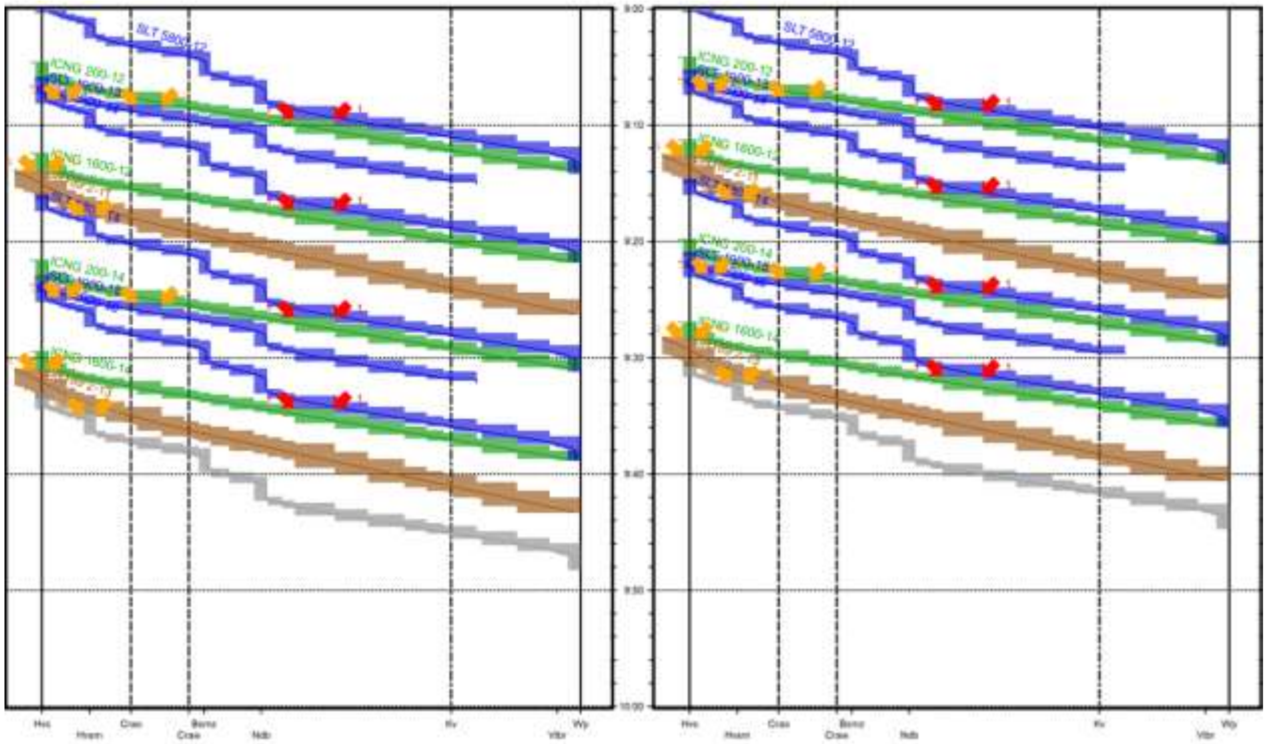

Figure 3: UIC406 compression for line segment Hvs-Wp, comparing human drivers to ATO GoA4

Figure 3 shows an example of the compression effect, comparing the situation with manual drivers on Hvs-Wp to the situation with ATO GoA4. Time-distance diagrams for each train are flatter, implying faster trains. Note that the difference in headway allowances is not pictured.

4.2 SOUTHERN MAIN LINE IN SWEDEN

For the Swedish case, Norrköping-Mjölby, the largest effects of GoA2 were for commuter trains with frequent stops (see Table 3). This is probably because of the braking behaviour where ATO has a largest benefit. If the effects of ATO are used to reduce running times, it varies from -1.28 s/km for commuter trains in urban areas to -0.83 s/km for long-distance trains. The capacity utilisation (UIC 406) decreases for all scenarios between -10.7 to -1.2 percentage points. If the ATO effects are used for delay recovery, the average delay decreases with -12 seconds per train.

Table 3: ATO GoA2 results for Norrköping-Mjölby

Running time (s)/km	Norrköping-Mjölby GoA2-Ref
Commuter	-1.28
Regional	-0.88
Long-distance	-0.83
Average delay (s)	-21

5 SUMMARY OF RESULTS ON OPERATIONAL CONCEPT TESTING

This chapter presents a summary of the results on the ATO Operational Concept testing based on the test specification defined in [3] for demonstrations 16.1 (Technical/Live demo) and 16.2 (human factors research), which are further detailed in Sections 5.1 and 5.2, respectively.

5.1 Demonstration 16.1: Technical/Live demo

5.1.1 Scenario 1: Baseline Conflict-Free Timetable Processing

Scenario 1 validated the static Train Path Envelope (TPE) generation functionality using a full timetable consisting of 38 trains operating within the SAAL corridor case study area. The objective was to verify whether the TPE generator could process the received Real-Time Traffic Plan (RTTP), compute train trajectories, construct train path slots, detect blocking time overlaps, and resolve potential conflicts by adjusting the generated TPEs, which serve as train trajectory generation constraints, without modifying the RTTP.

The simulation included 18 Intercity and 20 Sprinter services. For all trains, trajectories were calculated using the relevant driving strategies, including Minimum-Time Train Control (MTTC), Reduced Maximum Speed (RMS), and Energy-Efficient Train Control (EETC). The generated train path slots were subsequently analysed for blocking time overlaps. During the conflict detection process, one series of blocking time overlaps was identified between trains SPR4301 and ICA7001, with the largest overlap located at section Gpda.IAWISSELGEB.1208BT and having a duration of approximately 52 s. This conflict was resolved by introducing an additional control timing point for ICA7001 at the beginning of the critical block section. This adjustment allowed the conflict to be removed through an update of the generated TPE without requiring an RTTP modification.

In addition, the TPE generator adjusted departure tolerances for several train pairs where this was required to maintain conflict-free train path slots and improve robustness against possible dwell time extensions. All generated TPEs were feasible, and no unresolved conflicts remained after processing. In total, 185 timing points were generated across all 38 trains, including the additional control timing point for ICA7001. The resulting time-distance diagram is presented in Figure 4.

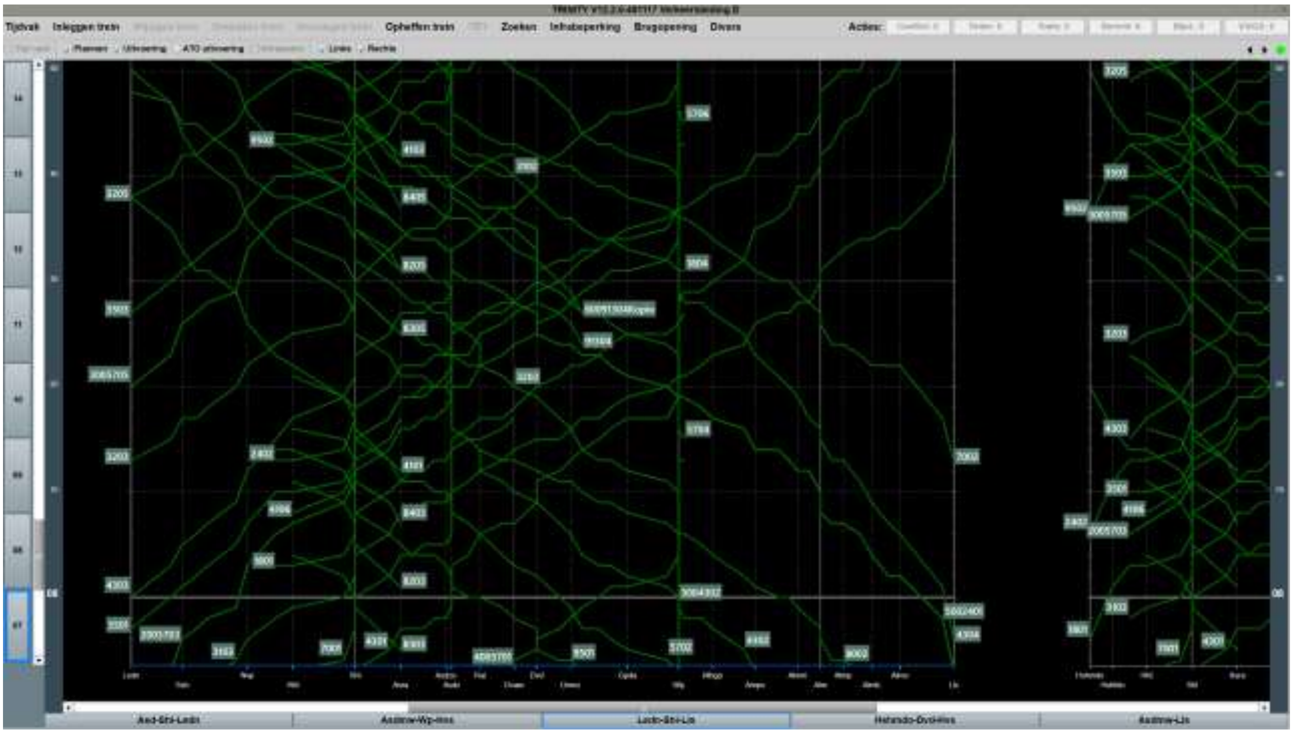

Figure 4: Time-distance diagram of Scenario 1 for the 38 trains in the conflict-free timetable

5.1.2 Scenario 2: Unresolvable Conflict and TPE Escalation

Scenario 2 validated the static TPE generation functionality under an intentionally conflicted timetable condition. The objective was to verify whether the TPE generator could process a received RTTP with predefined blocking time conflicts, compute train trajectories, construct train path slots, detect blocking time overlaps, resolve conflicts where possible by adjusting the generated TPEs, and report unresolved conflicts that require RTTP modification. The scenario included 38 trains operating within the SAAL corridor case study area. For all trains, trajectories were calculated using the relevant driving strategies, including MTTC, RMS and EETC. The generated train path slots were subsequently analysed for blocking time overlaps. During the conflict detection process, two series of blocking time conflicts were identified. The first was between ICA3501 and SPR2005703, with the largest overlap located at section Asra_Shl.IAVERBINDING.1714BT and having an overlap duration of approximately 108 s. The second was between SPR4301 and ICA7001, with the largest overlap located at section Gpda.IAWISSELGEB.1208BT and having an overlap duration of approximately 53 s.

The conflict between SPR4301 and ICA7001 was resolved by introducing an additional control timing point for ICA7001 at the beginning of the critical block section. This adjustment allowed the conflict to be removed through an update of the generated TPE without requiring an RTTP modification. The conflict between ICA3501 and SPR2005703 could not be resolved within the available headway and running time supplement. As a result, SPR2005703 was classified as infeasible and excluded from the final TPE generation. The unresolved conflict was reported to the Traffic Management System (TMS) for an RTTP modification to increase the headway between the involved trains.

In addition, the TPE generator adjusted departure tolerances for selected train pairs where this was necessary. Conflicts involving SPR2005703 were not further resolved through departure tolerance adjustment because the TPE of this train had already been classified as infeasible. Feasible TPEs were generated for 37 out of the 38 trains. In total, 177 timing points were generated across the feasible trains, including the additional control timing point for ICA7001. The resulting time-distance diagram is shown in Figure 5, and the unresolved conflict reported to the TMS is shown in Figure 6.

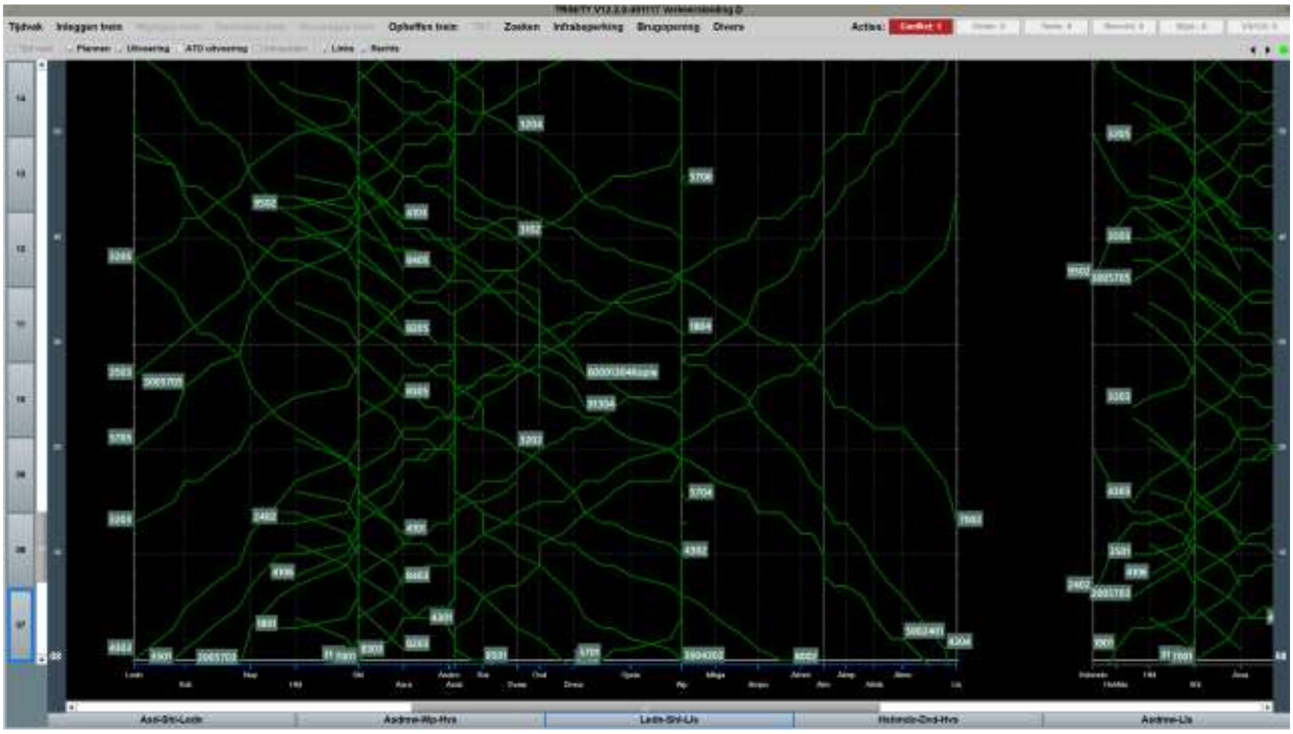

Figure 5: Time-distance diagram of Scenario 2 for the 37 feasible trains after excluding the infeasible train

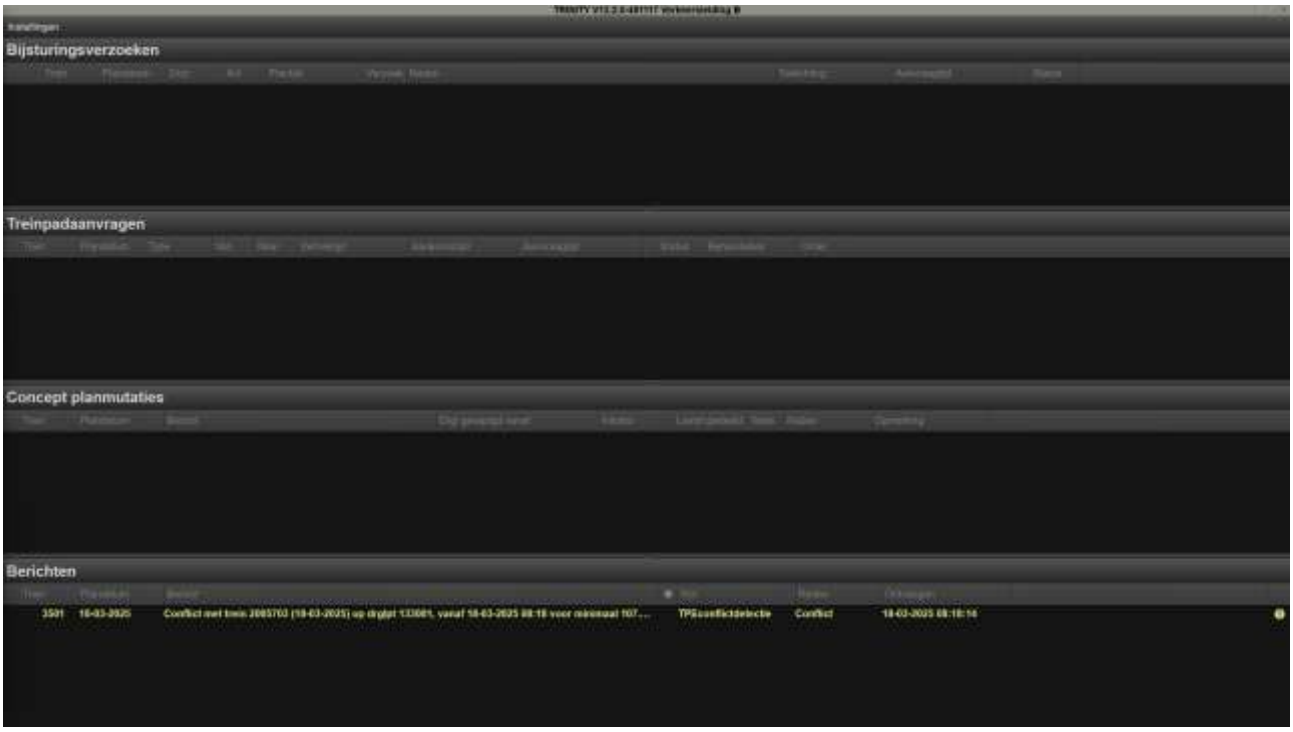

Figure 6: Traffic controller interface in Scenario 2, showing the reported blocking time conflict between ICA3501 and SPR2005703

5.1.3 Scenario 3: Headway Conflict Resolution by TPE

Scenario 3 validated the dynamic TPE generation functionality after an RTTP update. The objective was to verify whether the TPE generator could process an updated RTTP, recalculate train trajectories and train path slots, detect a dynamically introduced headway conflict, and resolve it by adjusting the generated TPE without requiring a further RTTP modification.

The scenario included two trains, ICA4002401 and ICA91304, which were initially scheduled without blocking time conflicts. For both trains, trajectories were calculated using the relevant driving strategies, including MTTC, RMS and EETC. The generated train path slots were subsequently analysed for blocking time overlaps. In the initial RTTP, no blocking time conflict was detected, and TPEs were successfully generated for both trains, as shown in Figure 7.

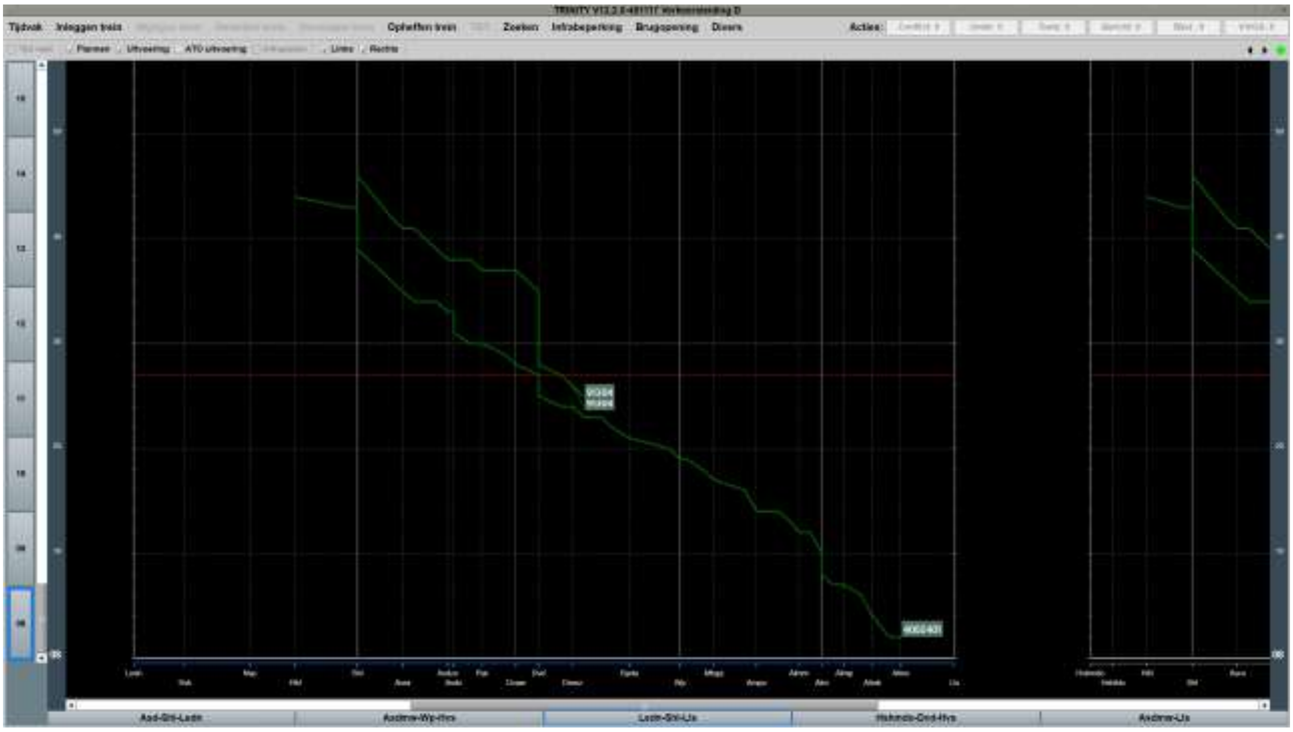

Figure 7: Time-distance diagram of Scenario 3 before the RTTP update

During the simulation, the traffic controller extended the dwell time of ICA4002401 at Amsterdam Zuid by 4 min, as shown in Figure 8. This RTTP update reduced the available headway between ICA4002401 and the following train ICA91304 after Amsterdam Zuid. After receiving the updated RTTP, the TPE generator recalculated the trajectories and train path slots for both trains. During the conflict detection process, one series of blocking time overlaps was identified between ICA4002401 and ICA91304, with the largest overlap located at section Asdzo.IAWISSELGEB.736T and having an overlap duration of approximately 8 s.

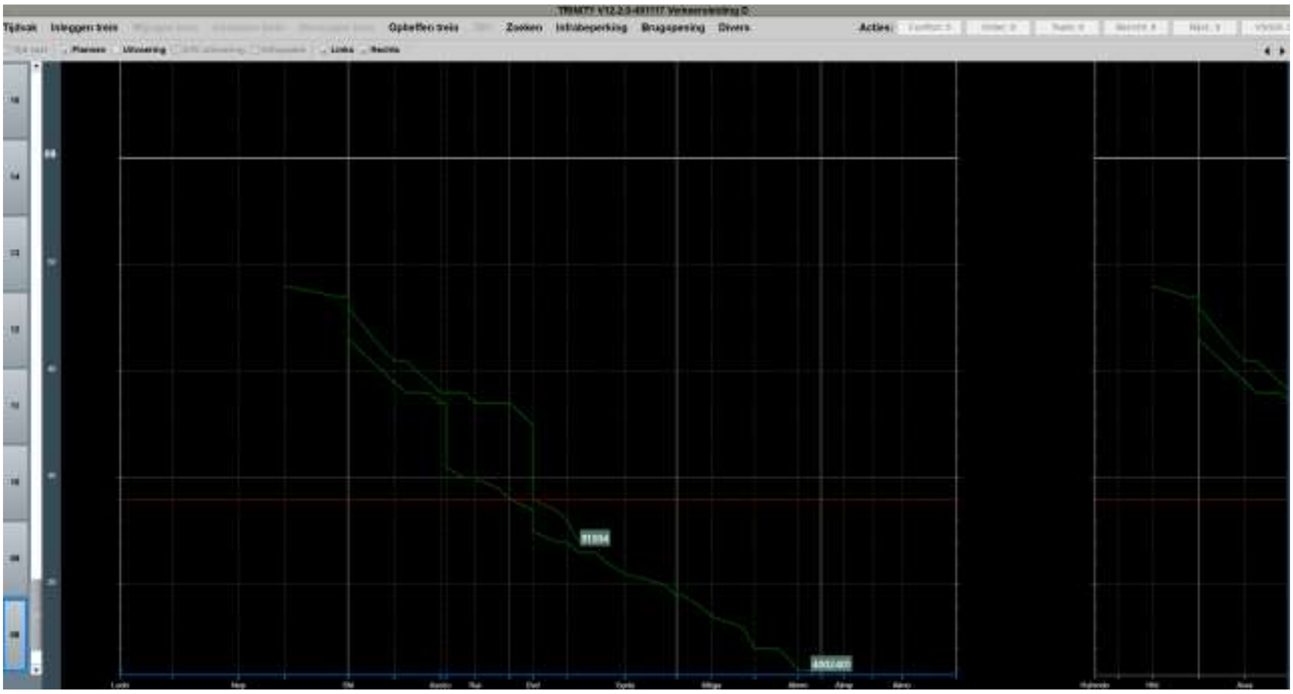

Figure 8: Time-distance diagram of Scenario 3 after the RTTP update

The conflict was resolved by introducing an additional control timing point for ICA91304 at the beginning of the critical block section. The generated TPE of ICA91304 included an earliest passing time of 5995.38 s at this location, with an associated time window of approximately 122 s. This adjustment allowed the conflict to be removed through an update of the generated TPE without requiring a further RTTP modification.

Feasible TPEs were generated for both trains after the RTTP update. ICA4002401 received four timing points, while ICA91304 received three timing points, including the additional control timing point. The realised operation in the FRISO simulation showed that ICA91304 adapted its trajectory by cruising at a lower speed before the control timing point and then accelerating afterwards to comply with the arrival constraint. ICA91304 arrived at Schiphol 1 s earlier than the scheduled arrival time, which remained within the tolerance. The realised speed profile of ICA91304 is shown in Figure 9.

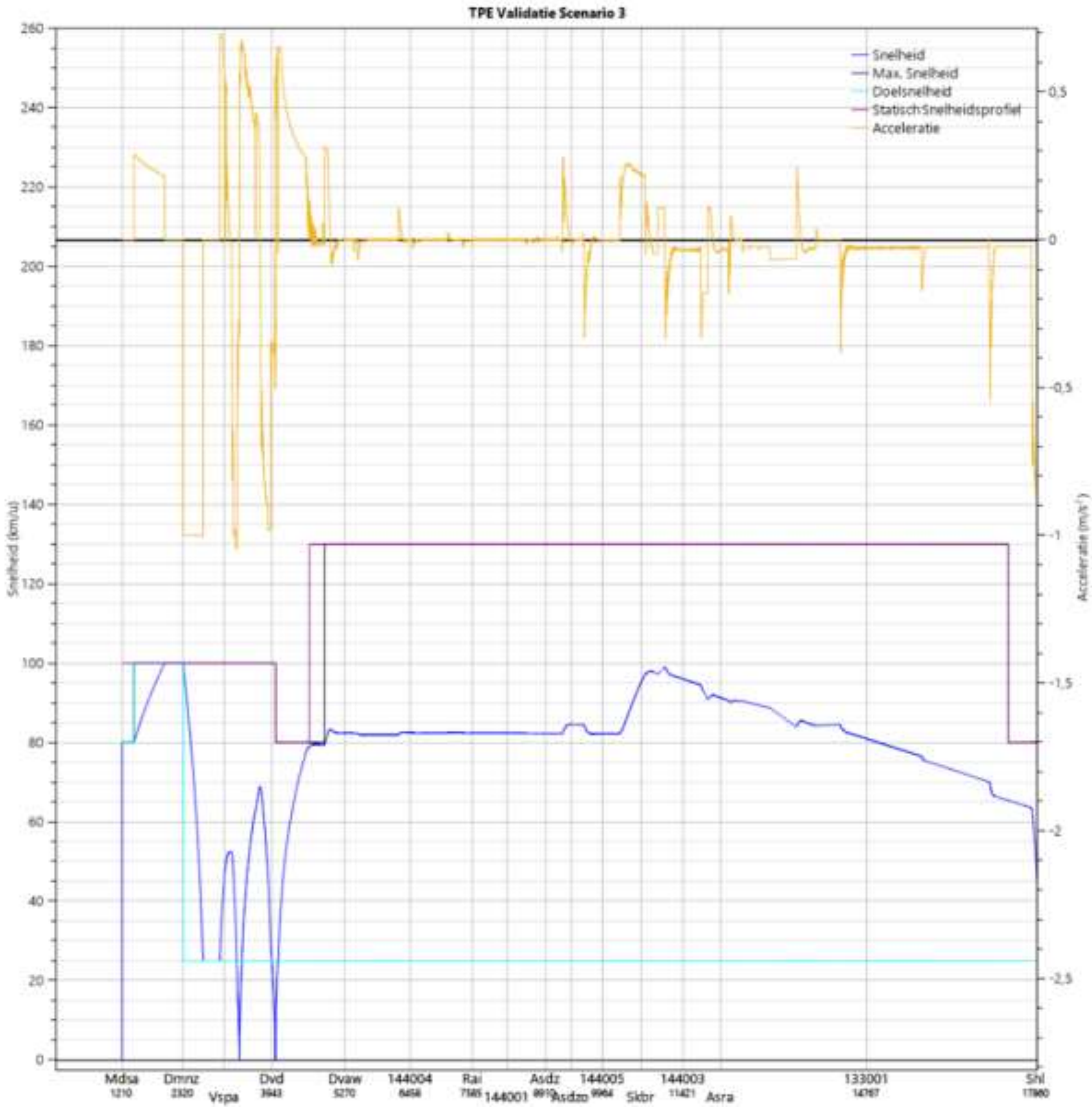

Figure 9: Realised speed profile of ICA91304 in Scenario 3, showing the trajectory adaptation after the added control timing point

5.1.4 Scenario 4: Manual Conflict Resolution following TPE Escalation

Scenario 4 validated the dynamic TPE generation functionality in a situation where the detected conflict could not be resolved through an update of the generated TPE alone. The objective was to verify whether the TPE generator could process train status updates, recalculate train trajectories and train path slots, detect unresolved blocking time conflicts, report the infeasible TPE to the TMS, and confirm conflict-free operation after a subsequent RTTP modification.

The scenario included two trains, ICA5002401 and ICA50091304, both operating from Weesp towards Schiphol. In the initial RTTP, both trains were planned to arrive at Schiphol on platform track 105. For both trains, trajectories were calculated using the relevant driving strategies, including

MTTC, RMS and EETC. The generated train path slots were subsequently analysed for blocking time overlaps. In the initial RTTP, no blocking time conflict was detected, and TPEs were successfully generated for both trains.

During the simulation, ICA5002401 experienced a delay of 5 min at Amsterdam Zuid. This delay propagated towards Schiphol and created blocking time overlaps with the following train ICA50091304, which was planned to use the same arrival track at Schiphol. Based on the train status reports received from ATO-OB, the TPE generator recalculated the trajectory and blocking times of the delayed train. During the conflict detection process, one series of blocking time overlaps was identified between ICA5002401 and ICA50091304, with the largest overlap located at section Shl.IAWISSELGEB.1063BT and having an overlap duration of approximately 18 s.

Unlike previous scenarios, this conflict could not be resolved by introducing an additional control timing point or by updating the generated TPE within the available operational margin. As a result, the TPE of ICA50091304 was classified as infeasible, and the unresolved conflict was reported to the TMS. The corresponding conflict notification is shown in Figure 10.

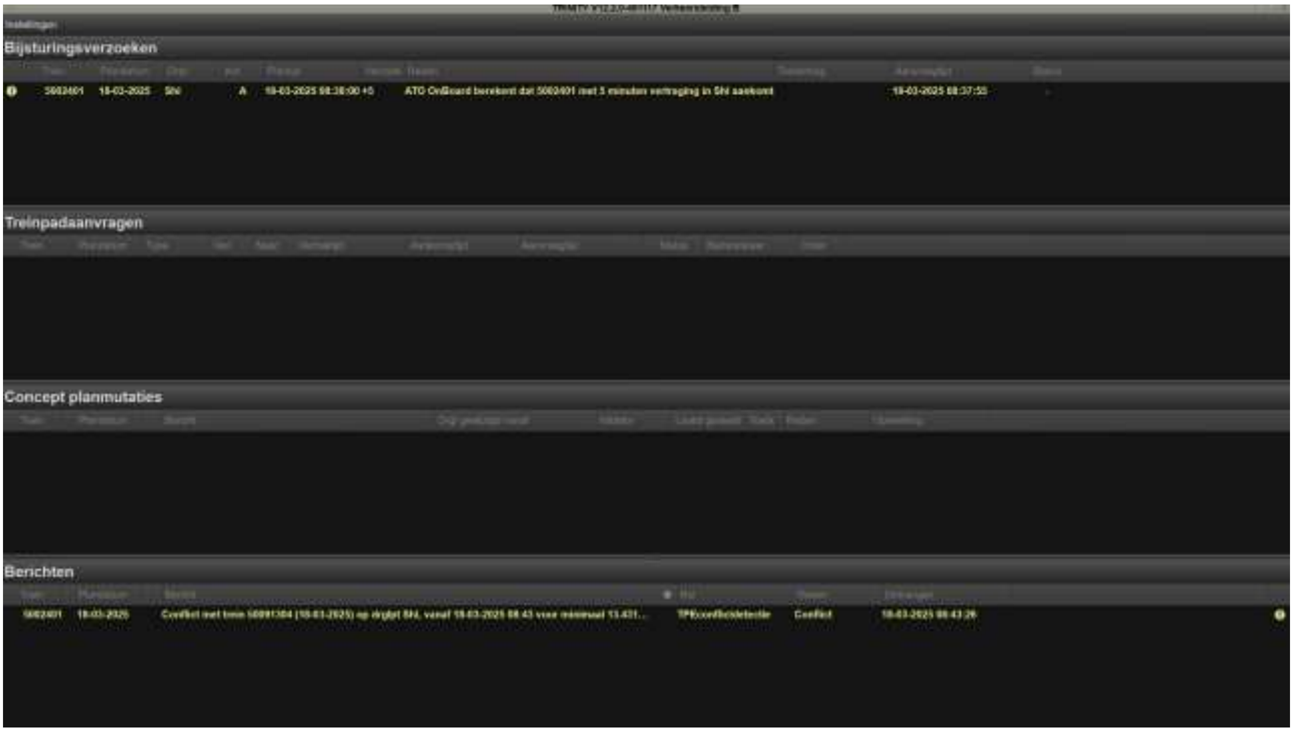

Figure 10: Conflict notification in Scenario 4, showing the unresolved blocking time conflict between ICA5002401 and ICA50091304 around Schiphol

Following the conflict notification, the signaller resolved the conflict by reassigning the arrival track of ICA50091304 from platform track 105 to platform track 106 at Schiphol. After receiving the updated RTTP, the TPE generator recalculated the TPEs for both trains and confirmed that no blocking time conflicts remained. The conflict-resolved information after rerouting is shown in Figure 11.

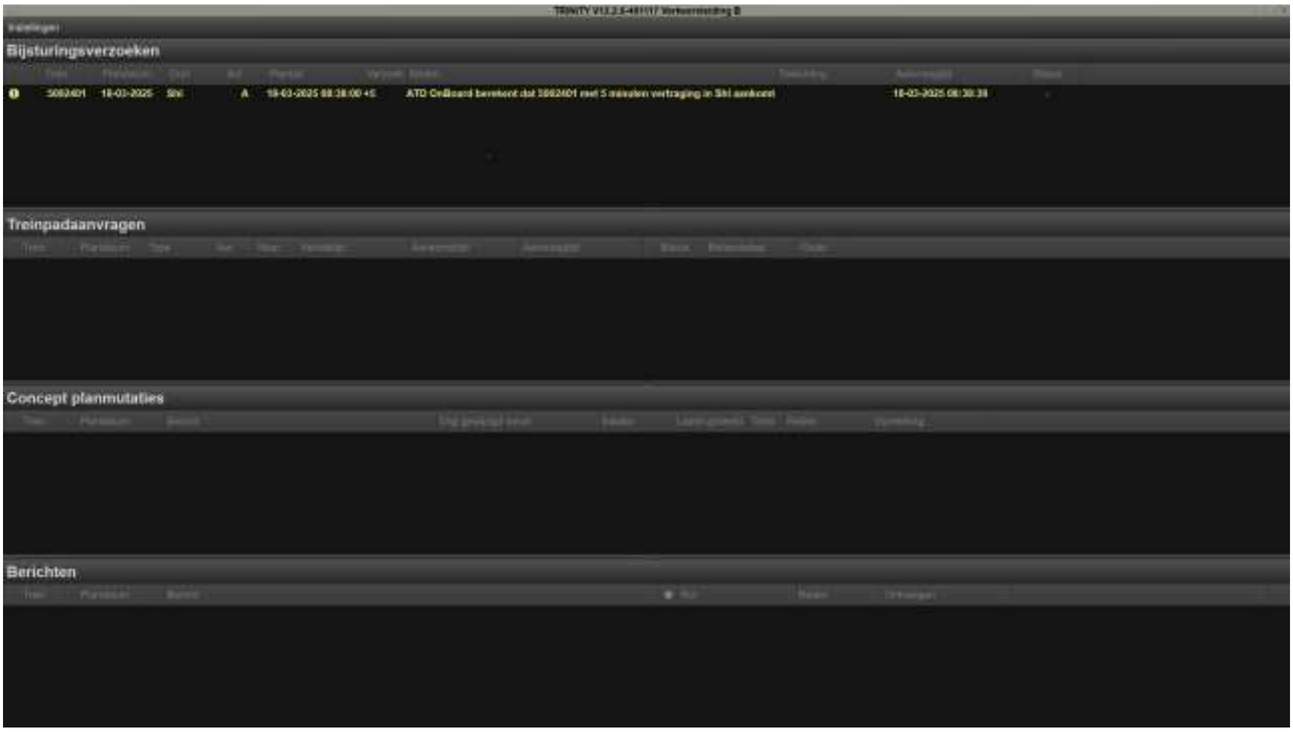

Figure 11: Conflict-resolved information after rerouting in Scenario 4, showing that no further blocking time conflicts were detected after reassigning the arrival track of ICA50091304

The realised operation in the FRISO simulation showed that the delay of ICA5002401 propagated from Amsterdam Zuid towards Schiphol and affected the following train ICA50091304. ICA5002401 arrived at Schiphol with a delay of 322 s, while ICA50091304 arrived at Schiphol with a delay of 197 s. Although both trains were delayed, the rerouting intervention removed the blocking time conflict at Schiphol. The realised speed profiles further indicated that the rerouting intervention and updated TPE generation helped ICA50091304 avoid a repeated speed reduction and re-acceleration pattern near Schiphol, which could otherwise occur when the ATO-OB system reacts to successive signalling constraints without intermediate timing points that anticipate the upcoming conflict.

5.2 Demonstration 16.2: Human factors research

Results of the simulation experiments performed to test the ATO Operational Concept are provided in the following sections for the described delay scenarios and operational situations. Further details on the test specification can be found in [3].

5.2.1 Participants

In total, seven simulations took place with 26 participants consisting of seven train drivers, thirteen traffic controllers and six network controllers. One simulation day was cancelled due to extreme weather conditions in the Netherlands. Two participants could not participate due to illness.

On average, the work experience of all participants in the rail sector was 13.72 years (SD = 10.03). When split out, the average work experience per role was train drivers (M = 19.37 SD = 6.38), traffic controllers (M = 8.5, SD = 6.59) and network controllers (M = 12, SD = 11.02).

All train drivers were familiar with the trajectory. Five out of 13 traffic controllers were familiar, and no network controllers were familiar with the geographical area.

Mental model development

- *Geographical area and timetable*

Limited learning of the (new) geographical area and the timetable occurred in the 'ATO situation' as train drivers indicated that they were sufficiently used to the area and timetable after session 3 and 4, both: M = 4.3, SD = 0.6 (from a maximum score of 5).

Likewise, traffic controllers indicated that they were sufficiently used to the area and timetable after session 3: M = 4, SD = 0.9, and slightly more after session 4: M = 4.3, SD = 0.8. As such there was still but little mental model development occurring.

The mental models of network controllers regarding the geographical area and timetable were slightly above neutral, which indicated that after the third session, network controllers were neutral to being used to the area and timetable (M = 3.3, SD = 1.3) and after session 4 (M = 3.3, SD = 1).

- *Scenarios*

Learning effects regarding the scenario could be found for all participants: all operators indicated that they experienced the scenarios in the 'ATO situation' to be easier because they already knew them from the 'current situation' condition (train drivers - M = 4, SD =1; traffic controllers - M = 4.2, SD =1; network controllers M = 3.7, SD =0.6).

5.2.2 Simulator validity

The average simulation validity score across all participants is 31.7 with a standard deviation of 5.5 from a max score of 45. Figure 12 shows the distribution of simulation validity scores for each role in a boxplot. Pairwise nonparametric testing with the Wilcox test discovers that the scores for traffic controllers (M = 34.6, SD = 4.7) are significantly higher than those of train drivers (M = 27.8, SD = 5.1) (p-value = 0.04) but not with network controller (M = 30.2, SD = 4.8) (p-value = 0.4). There is also no statistically significant difference between train driver and network controller (p-value = 1).

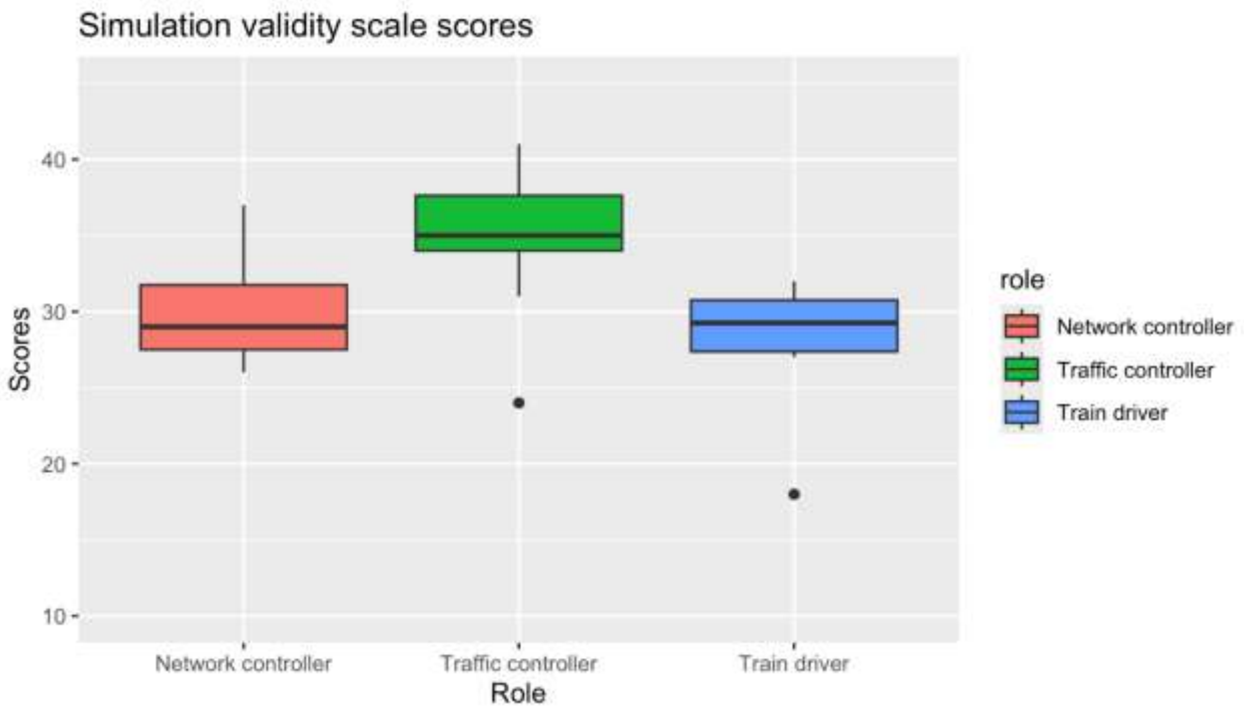

Figure 12: Boxplot of simulation validity scores by role

5.2.3 Human operator workload

Workload was analysed as repeated measures linear mixed model with participant ID as a random effect to account for missing data collection across different sessions. The distribution of workload values across all sessions is shown in a boxplot in Figure 13.

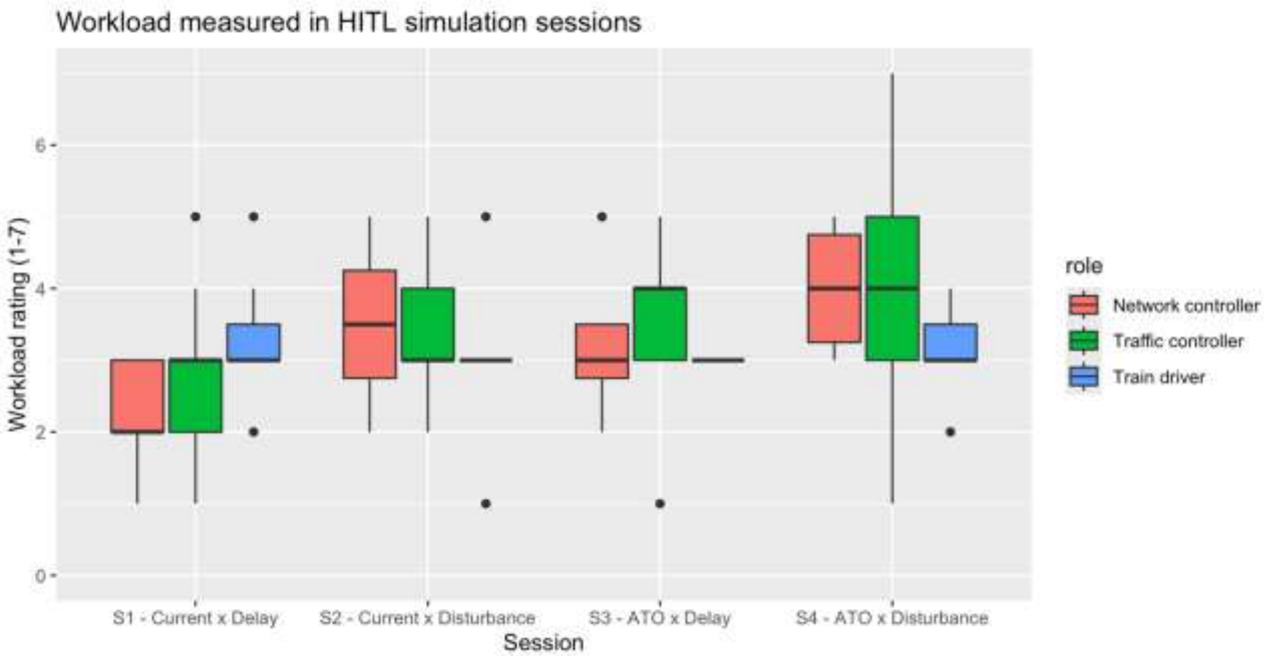

Figure 13. Boxplot of workload rating by session and role

Overall, there are no statistically significant differences found in workload between roles (p-value = 0.59). As shown in the boxplot, driver workload remains relatively stable, and previous literature ([4], [5]) have indicated that driver workload during ATO sessions tend to be underloaded. Therefore, the analysis will focus on the workload of traffic controllers and network controllers.

The workload overall in the ATO situation is higher than the current situation for traffic controllers and network controllers (p-value = 0.01). Comparison between current situation and ATO in equivalent conditions:

- Delay scenario (S1 vs S3): workload is statistically significantly higher in ATO situation during the delay scenario (p-value = 0.02)
- Disturbed scenario (S2 vs S4): there is no statistically significant difference found in the workload of participants during the disturbance scenario.

The means for workload for each role and the aggregated values across all scenarios is shown in Table 4.

Table 4. Mean values of workload rating by role across sessions

Scenario	**Role**	**Situation**					
		Current (with ETCS)			ATO (with ETCS)		
		n	Mean	SD	n	Mean	SD
Workload delay scenario	Train driver	6	3.3	1	3	3.0	0
	Traffic controller	13	2.8	1.1	9	3.6	1.2
	Network controller	5	2.2	0.8	4	3.3	1.3
	Everyone	24	2.8	1	16	3.4	1.1
Workload disturbance scenario	Train driver	5	3.0	1.4	6	3.2	0.8
	Traffic controller	9	3.6	1	13	4	1.6
	Network controller	4	3.5	1.3	6	4	0.9
	Everyone	18	3.4	1.1	25	3.8	1.3
Overall for situation		42	3.0	1.1	41	3.6	1.2

5.2.4 Trust in automation

Trust in automation was collected prior to the first session and after the last session. The breakdown of the means and standard deviation is indicated in Table 5, the maximum value for the scale is 25. Figure 14 shows the distribution of trust in automation scores for each role in a boxplot. Nonparametric testing with Wilcox test indicates that the score after the experiment is significantly lower than before the experiment (p-value = 0.045). There are no significant differences detected between the different roles (p-value = 0.79).

Table 5. Pre and post-test means of trust in automation scores by role and aggregated for everyone

Role	Trust in Automation Score					
	Before experiment			After experiment		
	n	Mean	SD	n	Mean	SD
Train driver	7	17.3	3.9	6	16.6	3
Traffic controller	12	17.4	1.5	12	15.7	2.6
Network controller	5	18.4	3.7	6	15.7	4.1
Everyone	24	17.5	2.7	24	15.9	3

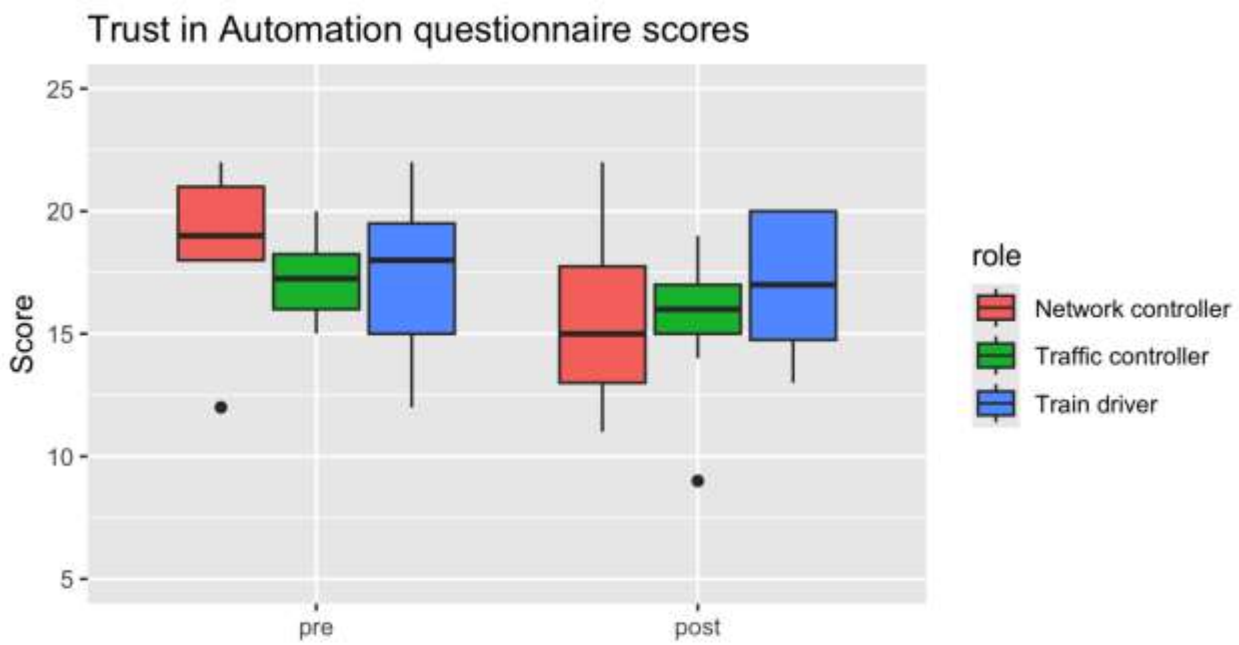

Figure 14. Boxplot of trust in automation scores by role

During the debriefing, few train drivers highlighted two critical requirements: the reliability of the journey and segment profile data, and the assurance that the ATO algorithm operates as intended.

5.2.5 Interface design

All operators indicated that they quickly got used to the new user interfaces after session 3 (ATO situation), i.e., ATO/ETCS DMI for train drivers (from a maximum score of 5): M = 4, SD = 1; traffic controllers: M = 4.1, SD = 0.7; network controllers: M = 4.3, SD = 0.6.

Additionally, in the debriefing session, few train drivers indicated the need for additional information in their DMI to understand what the progress or intention of the ATO algorithm, e.g., when ATO is planning to start braking. Train drivers reasoned that they still would be responsible for the train operations and could be blamed for ATO errors. Also, few train drivers mentioned the use of supporting tools to balance the divided attention between the outside environment and in-cab information across interfaces, e.g., through the use of a head-up display in cabins.

5.2.6 ATO GoA2 risks and benefits

In the debriefing, participants mentioned the following benefits and risks, outlined in Table 6. An overall mentioned risk was cyber security.

Table 6. Debriefing results

	Benefits	**Risks**
Train driver	Consistency in driving	Lower workload
	Cruise control support	Attention reduction
	Optimal driving combined with monitoring of train driver	Boredom
		Skill degradation
		Passenger comfort (e.g., braking with a full train and elderly on board)
Traffic controller	Predictability (guarantee that ATO train catches up on a delay)	
	More accurate estimated time of arrival (ETA) of the ATO train	

5.2.7 Communication and collaboration among railway operators

- *Interaction Train driver – Traffic controller*

Results from the observations and debriefing indicate that there is no change in communication and collaboration between train driver and traffic controller in the simulation. However, participants expect that in general the communication goes down as train drivers now occasionally call traffic controllers if they think they can catch up a delay or if train drivers want to obtain more information about the situation.

In one of the debriefings, a point was raised where operators indicated that there is a misalignment in the application of time: a train driver drives on second while the planning (in NL) is still done in minutes.

- *Interaction Traffic controller – Network controller*

Traffic controllers and network controllers experienced a shift in their tasks and procedures: network controllers will replan train paths whilst this is currently not done, while traffic controllers will not need to change the planned route setting trigger time anymore. This shift in responsibilities impact their collaboration. The mismatch in procedures that is caused by the replanning of ATO trains shows that Dutch traffic operations is in the current state not ready for implementation of ATO GoA2 and further system design of the TMS and procedures is needed. A more extensive description is provided in FP1 D16.1 [6].

5.2.8 Designed versus operational plan

In one of the debriefings, traffic controllers indicated that in practice they occasionally identify a mismatch in the designed planning and the planning as is done in operations. This is not directly observed in the ATO study; however, operators wonder how ATO will deal with these types of issues in practice. Traffic operators experience that in practice:

- errors in the planning are found, e.g., trains who are planned and allowed to drive 100 km/h on a trajectory, but are restricted due to planned rolling stock to drive only 80 km/h.
- there are certain uncertainties affecting the planning – such as the inconsistency in the duration of the opening of bridges.
- negative delays of trains occur.

Another noted discussion point that was raised was the planning resolution that was used by the railway undertaking and infrastructure manager. In the Netherlands and with ATO, train drivers are driving on a time resolution of seconds, while currently the operational plan is executed on a time resolution of minutes by the traffic control.

5.2.9 ATO acceptance

Five out of seven train drivers accepted that ATO may need to become mandatory (at least in some areas) to support the business value. Despite understanding the business value rationale, some drivers may leave the profession when they have to use ATO at all times.

Traffic controllers and network controllers experienced that the current ATO information integration in the TMS caused an increased number of actions and therefore a higher workload (see above workload Section 5.2.3). Additionally, misalignment in current procedures were identified: traffic controllers resolve delays locally to preserve planned passenger-train times. Under ATO planning, times become leading, requiring network controllers to resolve delays by adjusting train paths within TMS. This misalignment in procedures together with the need for more decision support for several types of planning conflicts led to the overall statement that traffic and network controllers did not find the use of the current ATO integration acceptable for operational use.

6 BEST PRACTICES OF MAINLINE CAPACITY ASSESSMENT

This chapter reflects on the mainline capacity assessment we carried out as elaborated in Chapter 3 with the described results in Chapter 4. We interpret our method qualitatively, judging whether our capacity indicators made sense and/or can be further improved, our data collection and analysis techniques made sense and/or can be further improved, and whether our modelling strategy made sense and/or can be further improved. In FP1 Motional WP8/9, ATO GoA2 and GoA4 have been simulated with Dutch and Swedish case studies. A detailed report on the simulation results can be found in D8.3 [7] and D9.2 [8]. Here follows a summary of the results and input on the evaluation from D32.5 in R2DATO (Koopman van Welij et al., 2026).

6.1 Mainline Capacity Metrics / Test Success Criteria / KPIs

Deliverable 32.5 [1] justifies to a strong extent the capacity metrics used (no. of trains per unit of time through UIC406 compression including allowances; the operational stability through UIC406 compression including allowances and an assumption on the punctuality curve and rate of hindrances (deterministic), or through stochastic measurements of delay time and delay recovery (stochastic); the running time through changes in plannable minimal running times).

Specifically, they justify them both through capacity literature, economic and financial appraisal literature, and technical changes as a result of ATO. In addition, we observed that the resulting effects were easy to process onwards into economic and financial KPIs. In such, we have strong confidence that the tested metrics make sense, and we recommend the usage of these metrics as a best practice for mainline capacity assessment of ATO going forwards.

ATO GoA2 would have an effect headway and running time including buffers. Based on the interface matrix from D32.5, this would have an effect on the number of train per unit of time, operational stability and running times, see Figure 15. The general expectation is that ATO may allow faster deceleration than manual driving given the same set of context-dependent optimisation criteria (such as safety, capacity, energy efficiency and comfort). Hence, ATO affects the capacity building blocks Running time and Headway. It allows trains to be planned faster from origin to destination due to higher planned braking rates, and it allows trains to be planned closer together because the braking distance towards the start of the next block decreases.

In addition, ATO allows a reduction in running time buffer and headway buffer. The variance of running times will decrease as the ATO onboard removes the need for Driver allowance, insofar drivers actually use the ATO GoA2 most of the time. Moreover, tests suggest that ATO algorithms will be able to run close to the shortest running time and close or equal to the best performing drivers.

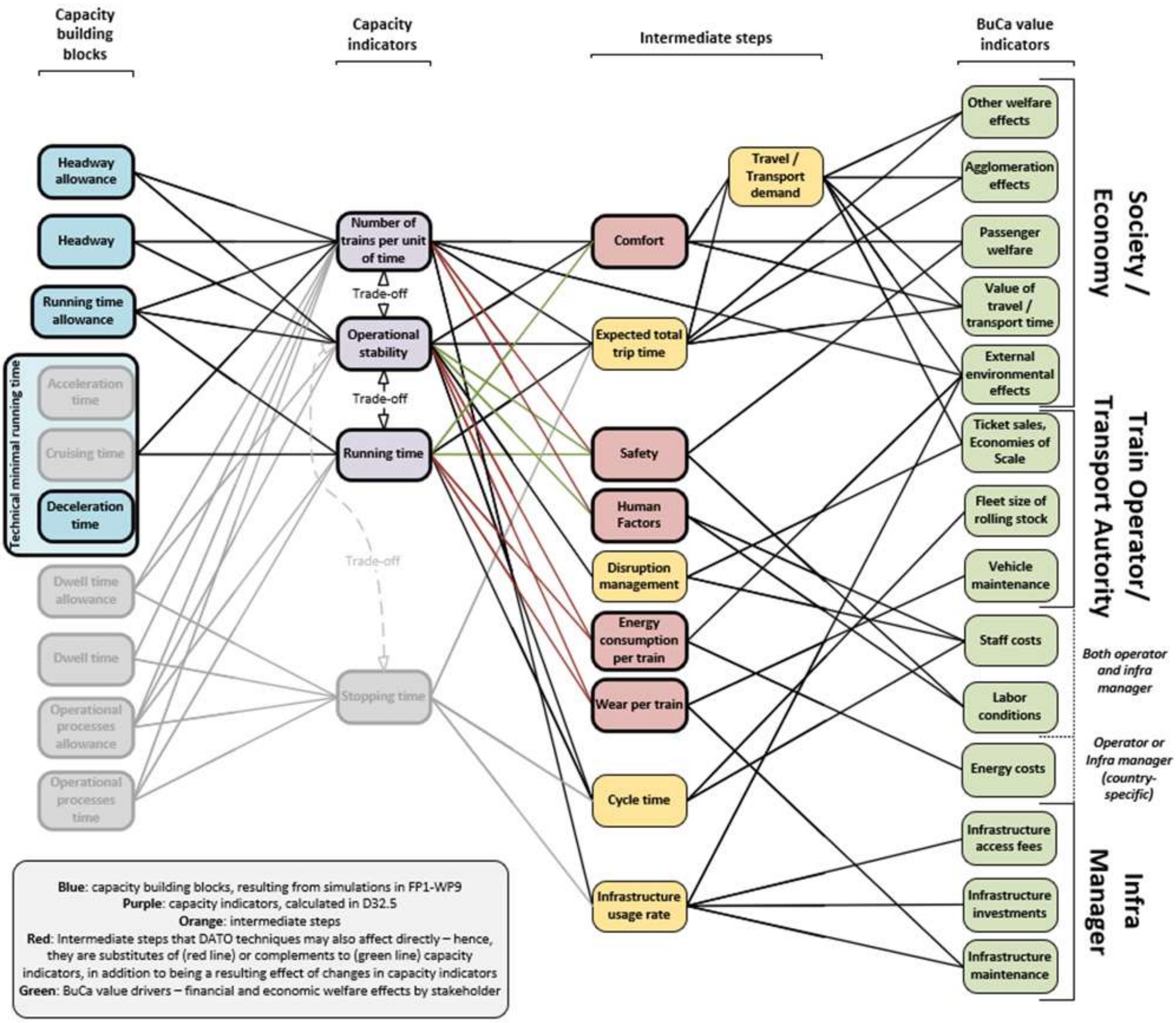

Figure 15: Interface matrix for ATO GoA2

In contrast to ATO GoA2, ATO GoA4 operates without a train driver present in the train cab and no drive-capable personnel on board the train. The most significant difference is that ATO GoA4 must fulfil additional functions, requiring the incorporation of extra systems. These functions include monitoring and responding to hazards on and around the track. Specifically, ATO GoA4 requires an obstacle detection system comprising sensors on the train (such as camera or lidar) and an image recognition model to detect and respond to obstacles. In the event of disrupted situations, the system must be capable of handling them autonomously. Accordingly, trains running with GoA4 require a high degree of reliability in the on-board systems. Mobile maintenance teams or remote control centres may alleviate some of this requirement and be able to manage larger disruptions.

For ATO GoA4, all building blocks affected for GoA2 are still present for the same reasons as previously mentioned for GoA2, see Figure 16. In addition, the boarding and alighting process will be shorter due to elimination of human check and reaction times. Therefore, the dwell time and dwell time buffer may be decreased. Also, with GoA4, some operational processes and their buffer can be shortened, such as elimination of the operational process of a driver walking between cabins or at the yard. Therefore, ATO GoA4 may decrease turnaround or shunting, and stabling times can be decreased.

x

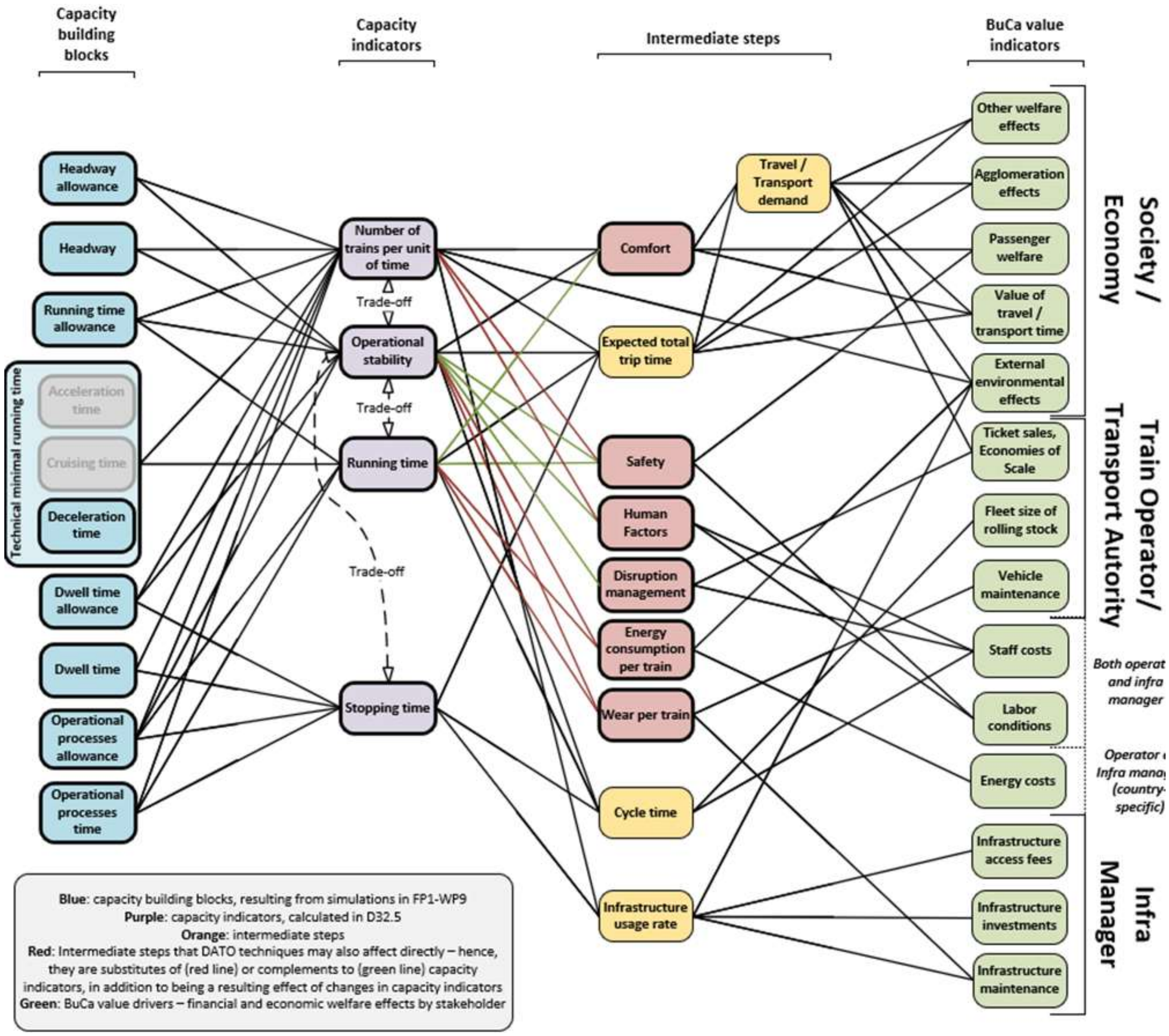

Figure 16: Interface matrix for ATO GoA4

6.2 Data Collection and Analysis Techniques

Ideally, already validated simulation software should be used for the analysis. With such a software or model, the parameter should be setup. In Motional FP1 WP9, the following parameters were changed in RailSys:

- Standard allowance – An additional buffer time that should not be used for delay recovery.

- Driver reaction time – A time before the driver reacts to a new signalling message during disruptions.
- Braking rate – The braking rate at which the train should brake.
- T_driver – Determines the time distance from the permitted curve in ETCS L2 to the indication curve.
- Headway buffer – Determines the headway buffer.

Delay distributions – The delays with ATO could change and in Sweden the assumption is that they will be the same in GoA2 while they will change in GoA4. This is based on the role of train drivers and onboard staff and how they affect delays.

As FP1 D8.3 [7] emphasize, for ATO, one requires microscopic simulation software with fully integrated ETCS braking curves and options for timetable allowances. Namely, one requires these functions to model ATO induced parameter changes accurately. Ideally, such software also includes a native timetable compression tool, a simulation tool that allows for accurate and easy measurement of capacity indicators resulting from stochastic or deterministic delays, and an export format that is able to show planned running times per train between timetable points.

Since we applied a tool that satisfies all of the above criteria and used data that satisfied all of the above criteria, we experienced that these proposed practices work very well. In such, we may conclude that the above paragraph describes best practices for data collection and analysis techniques.

6.3 Factors affecting Mainline Capacity

The challenge regarding factors affecting mainline capacity is how to set them realistically. The used parameters for the Dutch case study pull from expert judgement and real life field tests, but there have not been any ATO demonstrations yet to feed parameter assumptions into the Swedish model. Conversely, the Swedish model was able to formulate a stochastic delay curve for ATO relative to the reference, but the Dutch case was not able to. Consequently, we formulate the best practices for factors affecting mainline capacity as a call for further research where necessary into a country- or even line-specific set of assumptions on size and scope of parameter changes and delay distributions resulting from ATO implementation.

6.4 Modelling and Simulation Approaches

The first step is to use a valid infrastructure model with valid train formations. One shall pick a software tool whose measurements can easily be translated into our suggested performance indicators for *number of trains per unit of time*, *operational stability* and *running time*. One shall also pick a software tool that is able to represent the ATO parameter changes accurately at a microscopic level. Within the modelling and simulation, the biggest limitation of the current research was the lack of a renewed ATO-optimised timetable to accurately measure network effects given its wider constraints. Hence, a best practice here is to design an alternative ATO timetable in future research.

In addition, we note that in our results, we assumed that capacity benefits accrue mostly to decreased running times, rather than increased trains per unit of time or improved operational stability (and according to energy efficiency). These are fundamental trade-offs described by the capacity interface model in FP2 D32.5 [1]. A best practice for the modeller is to be aware of these trade-offs and potentially allocate the extra capacity towards any set of the three objectives, in order to measure which allocation is most optimal from a total welfare point of view. Alternatively, integration of ATO with an optimised TMS may allow for the TMS to dynamically optimise across these trade-offs depending on the current situation. If a TMS gets developed enough to make reasonable assumptions on how this would work, then future capacity simulation studies should also aim to implement this TMS functionality.

7 BEST PRACTICES OF OPERATIONAL CONCEPT TESTING

In this chapter, the best practices of the testing of the Operational Concept for both Demonstrations 16.1 and 16.2 performed in FP1 WP16 are described in Sections 7.1 and 7.2, respectively. The study focuses on the research question: what is the impact of driving with ATO GoA2 on operational actors and on the network system performances? Testing this ATO Operational Concept is hence important to assess changes in human factors of both traffic controllers and train drivers as well as in train service performances when partial automated driving enabled by a direct TMS-ATO link will be implemented on mainline railways.

7.1 Demonstration 16.1: Technical/Live demo (TPE)

Building on the development and application of TPEs in Demonstration 16.1, a set of best practices is identified to support the effective interaction between traffic management and ATO in mainline railway operations. These best practices position the TPE as a structured interface between the discrete-event-based real-time traffic plan and continuous trajectory-based train operation. They focus on alignment between TMS and ATO, the generation of feasible and flexible trajectory constraints, operational decision support, TPE-based assessment of ATO capacity effects and data quality for reliable TPE generation.

7.1.1 Alignment between TMS and ATO via TPE

To ensure alignment between traffic management and train operation, infrastructure managers shall use TPEs to translate discrete planning decisions into feasible trajectory constraints for ATO onboard operation. The TPE translates the RTTP, including train order, event times and routes, into conflict-free trajectory generation constraints that can be interpreted by the ATO onboard subsystem. Within these constraints, ATO can generate punctual and energy-efficient trajectories while respecting the operational targets set by traffic management.

The use of TPEs also supports time resolution harmonisation. Traffic management commonly works with coarser temporal resolutions in minutes, while onboard trajectory generation and execution require a finer time resolution in seconds. By formulating constraints at a level compatible with onboard control, TPEs reduce mismatches between (re)scheduled event times and realised train movements.

TPEs further clarify the distinction between centralised traffic management and onboard trajectory optimisation. The TMS remains responsible for network-level decisions, including train order, routes, event times and rescheduling, while the ATO onboard subsystem remains responsible for trajectory optimisation and execution within the received TPE.

It is worth noting that the information exchange between the ATO trackside and the ATO onboard subsystem is standardised [9], [10], whereas the interaction between the TMS and the ATO trackside subsystem is not yet fully specified [11]. This leaves two possible positions for TPE generation: either at the TMS or at the ATO trackside subsystem [12]. TMS-based TPE generation is recommended when network-level coherence and coordinated rescheduling are required, as RTTP updates such as retiming, reordering and rerouting can be directly translated into updated TPEs for the affected trains. ATO-trackside-based TPE generation is recommended for responsive corridor-level speed regulation, as status reports from ATO onboard subsystems can be used to update TPEs locally and transmit them through updated Journey Profiles.

Several points warrant attention when applying this allocation of responsibilities between the TMS, the ATO trackside subsystem and the ATO onboard subsystem. First, to support finer-resolution conflict detection and resolution, it is recommended to use an automated or decision-support-enabled TMS, at least where rescheduling decisions are presented as recommendations to dispatchers and signallers. This supports a coherent network-level RTTP while leaving local fine-tuning to TPE generation. Second, TPE generation should not be expected to make every RTTP with unresolved conflicts executable without further intervention. A conflict-free RTTP remains the overarching basis for conflict-free traffic evolution and execution. If TPE generation identifies that feasible trajectory constraints cannot be produced, this should be used as feedback that the RTTP needs to be refined.

7.1.2 Generation of feasible and flexible TPE constraints

To support effective ATO operation, infrastructure managers and system developers shall ensure that TPEs are generated as feasible and flexible trajectory constraints, rather than as direct extensions of scheduled timetable events or as an overly restrictive set of intermediate timing points between two scheduled stops.

The generation of TPEs should be based on a set of feasible train trajectories and realistic blocking times. This allows potential blocking time overlaps to be detected and additional intermediate timing points to be introduced only where they are operationally needed. In Demo 16.1, three theoretically sound driving strategies were used, namely minimum-time train control, reduced maximum speed and energy-efficient train control. These strategies result in a range of possible passing times at block section entries between two scheduled stops. Other feasible driving strategies, such as maximal coasting, could also be considered and would change the resulting bounds of the passing times.

Additional timing points beyond scheduled event times should be introduced only at critical blocks ([13], [14]), such as the blocks where the maximum overlap occurs. This avoids unnecessary constraint density in train trajectory generation and preserves the ability of the ATO onboard subsystem to optimise the trajectory.

Infrastructure managers and railway undertakings should also communicate their preferred driving strategies when TPEs are generated. The TPE generator can support different operator-specific ATO algorithms, which is relevant for commercial and contractual reasons. Nevertheless, better alignment of driving strategy assumptions between planning and operation can improve the consistency between generated TPEs and realised train behaviour.

In Demo 16.1, timing points are assumed to be located at scheduled stops or block section entries. Future development should further investigate whether other locations can be used for timing point placement, particularly when these locations can be determined dynamically based on real-time train status. This may provide additional flexibility in resolving conflicts while avoiding unnecessary constraints on onboard trajectory optimisation.

7.1.3 Use of TPE generation for operational decision support

TPE generation can support operational decision-making by indicating whether a situation can still be handled through TPE-level trajectory constraints or whether TMS-level rescheduling is required.

First, when a train delay exceeds the available departure tolerance in the current TPE, the existing TPE is no longer sufficient to represent the updated traffic situation, for example due to dwell time extensions. In this case, TMS-level intervention is required to update the RTTP, after which the TPEs for the affected trains should be recomputed based on the revised RTTP.

Second, when a potential blocking time overlap is detected between neighbouring trains, the TPE generator can determine whether an additional control timing point can be introduced between two successively scheduled stops. Such an added timing point can constrain the following train at an intermediate block entry location and remove the overlap without changing the RTTP. If the overlap cannot be resolved by introducing an intermediate timing point, TMS-level rescheduling is required, after which the TPEs should again be recomputed based on the updated RTTP. TPE generation should therefore be used not only to produce trajectory generation constraints, but also to provide feedback on the operational feasibility of the RTTP. In Demo 16.1, this feedback includes information on conflicting train pairs, as well as the start, end and size of the blocking time overlap.

Infrastructure managers and system developers are recommended to consider pre-computing headway boundary conditions based on TPEs for representative traffic patterns and corridors. These boundary conditions can identify where departure tolerances are sufficient, where additional control timing points are required, and where TMS-level rescheduling is needed. Such pre-assessment is particularly relevant for highly utilised corridors, where small changes in train trajectories may quickly affect neighbouring trains. In addition, during the planning phase, sensitivity analysis can be used to evaluate the responsiveness of TPEs under different operational conditions. This can help identify situations in which TPEs may become less robust, for example under short headways, limited running time supplements, or delayed status updates. These situations may require closer supervision by the TMS and, where necessary, intervention from traffic controllers or signallers.

In relation to the human factors' findings, further research is also needed to determine how TPE-based decision support should interact with traffic controllers and signallers during operation. In particular, the update frequency of TPE-related advice should be carefully designed. Too frequent updates may increase workload and reduce acceptance, while insufficient updates may limit the operational benefit of the TPE generator. An appropriate balance is therefore needed between responsiveness, operational stability and human workload.

7.1.4 TPE-based assessment of ATO capacity effects

TPE generation can be used to support a microscopic, block-section-level and trajectory-based assessment of capacity effects in ATO-equipped railway corridors. ATO may reduce reaction times and variability in driving behaviour, thus contributing to increased capacity on railway networks. However, these effects should not only be represented by reducing timetable buffer times or running time supplements. They should be assessed through feasible train trajectories and corresponding blocking times, so that the resulting capacity assumptions and timetables remain conflict-free. The TPE generator can support this assessment by evaluating whether reduced buffer times, reduced running time supplements, or shorter headways between trains can be realised without creating conflicts.

Infrastructure managers, railway undertakings and system developers shall ensure that ATO-related parameter changes are aligned and communicated. These include assumptions on train parameters, ETCS brake curve configuration, timetable norms and blocking time components. Where these parameters are uncertain, they should be calibrated and validated using field tests, validated simulation models or expert judgement.

At the same time, the objectives of different actors are not always fully aligned, and the allocation of flexibility within TPEs has direct implications for capacity. Wider time windows and larger buffers reserve more time-distance capacity for each train and may limit the number of trains that can be accommodated on a corridor. Infrastructure managers, railway undertakings and system developers should therefore jointly assess how much flexibility is needed and how it should be allocated. This assessment should consider capacity utilisation, operational stability, punctuality and energy-efficient driving, without assuming that one objective is always dominant. Structured discussions among stakeholders are therefore recommended when defining TPEs and related timetable parameters.

7.1.5 Data quality and modelling fidelity for TPE generation

Since TPEs are used to translate the RTTP into trajectory generation constraints, errors in infrastructure, timetable, train or signalling data can directly affect the feasibility of the generated constraints. Infrastructure managers and system developers shall therefore ensure that the data used for TPE generation are complete and consistent.

Infrastructure data should include the relevant stations, block sections, signal locations, switches, gradients and speed limits. Train data should include train parameters that are consistent with manufacturer specifications. Timetable and RTTP data should include event times, train order, routes and sufficient running time supplements. Signalling and blocking time parameters, including blocking time norms and ETCS brake curve configuration, should also be modelled consistently.

In addition to data quality, the computational performance of TPE generation should be further improved to support real-life implementation. This requires methods to select the relevant trains and corridor sections efficiently and to update train trajectory calculations dynamically when operational conditions change. Since TPE generation is performed at corridor level, applying it to a larger network requires appropriate partitioning of the network into corridors and clear definition of the connection points between them. In particular, when TPEs are generated for a large set of trains, the number of possible train-pair combinations can increase the computational time needed to examine blocking time overlaps. Further software enhancements are therefore required to ensure that TPE generation remains efficient for real-life use.

7.2 Demonstration 16.2: Human factors research

Based on the findings from the Human Factors Analysis report produced in FP1 Task 16.4, a set of best practices for implementing ATO GoA2 in real rail traffic operations are derived in this section to bridge the gap between technological capability and human readiness. In detail the provided best-practices relate to: i) alignment of ATO with operational rules, ii) design of driver interface and information support, iii) human factors and staff wellbeing, iv) ATO system and data reliability as well as v) ATO system validation for gradual implementation.

7.2.1 Operational alignment and role definition

To avoid the procedural friction observed in the study, infrastructure managers and railway undertakings should:

- **Synchronize planning resolutions:** Align the time resolution used by drivers (seconds) with the operational plan executed by traffic control (currently minutes) to ensure consistency.
- **Clarify delay management:** Formally redefine task allocation between Traffic Controllers and Network Controllers, as ATO shifts the responsibility of resolving delays from local adjustments to centralized train path adaptations.
- **Update system philosophy:** Ensure the Traffic Management System (TMS) architecture is congruent with either existing operational roles or a redefined European system philosophy to avoid increased workload.

7.2.2 Driver Interface and information support

Effective ATO GoA2 use requires providing drivers with enough context to maintain safe supervision and human engagement:

- **Enhance DMI transparency**: Include additional information on the Driver Machine Interface (DMI), such as the ATO's intended braking points, so drivers can verify if the system is operating correctly.
- **Implement attention support**: Consider supporting tools like Head-Up Displays (HUD) to help drivers balance attention between the outside environment and in-cab interfaces.
- **Configurable data**: Allow for country-specific DMI configurations to meet local operational requirements while adhering to European specifications.

7.2.3 Human Factors and staff wellbeing

The transition to ATO involves significant psychological and workload shifts that shall be managed by considering the following aspects:

- **Mitigate underload and boredom**: Address the risks of reduced attention and boredom for drivers by developing strategies to keep them engaged in the monitoring task.
- **Manage resistance to change**: Acknowledge and address driver concerns regarding skill degradation and job satisfaction to prevent staff turnover.
- **Monitor operators' workload**: Ensure that ATO information integration within the TMS does not result in a net increase in manual actions for traffic and network controllers, which currently leads to higher perceived workload.

7.2.4 System reliability and data quality

To increase trust in the ATO Operational Concept, technical consistency of data and functionalities is essential and shall specifically meet the following requirements:

- **Guarantee data integrity**: Ensure high reliability of journey and segment profile data, as drivers identify this as a critical requirement for accepting the technology.

- **Predictable ETA feedback**: Leverage ATO's ability to provide more accurate Estimated Times of Arrival (ETA) to improve network-wide predictability.
- **Cyber security**: Maintain robust cyber security protocols as a foundational safety requirement for automated operations.

7.2.5 Gradual implementation and validation

The ATO Operational Concept is considered not sufficiently mature to support real-life train operations, hence requiring a gradual validation and implementation to foster trust and final acceptance. The best practices to facilitate such a gradual implementation are:

- **Increase Human Readiness Level**: Before full rollout, move beyond technological testing to validate human roles and procedures in high-fidelity environments (aiming for TRL 8).
- **Mandatory use policy**: If ATO is necessary for business value, communicate the rationale clearly to staff while acknowledging its impact on their professional roles.

8 CONSIDERATIONS FOR IMPLEMENTATION STRATEGIES OF THE OPERATIONAL CONCEPT

In this section, we provide the considerations for implementation strategies of the Operational Concept for both Demonstrations 16.1 (Section 8.1) and 16.2 (Section 8.2).

8.1 Demonstration 16.1: TPE in ATO-TMS Feedback loop

The performed simulation scenarios demonstrated that the Train Path Envelope (TPE) functionality can play an important role within the ATO-TMS feedback loop for managing dense and heterogeneous railway traffic on mainline corridors. The results showed that the TPE generator is capable of dynamically translating timetable constraints, infrastructure capacity and train performance characteristics into operationally feasible trajectories that support both traffic management and automated train operation.

The scenarios further demonstrated that the TPE generator can autonomously detect and resolve a large proportion of operational conflicts through trajectory optimisation, control timing point generation and dynamic speed adaptation without requiring direct intervention from network controllers. This was particularly visible in scenarios involving dynamically introduced delays and reduced headways, where following trains were able to adapt their trajectories while maintaining operational stability and timetable adherence. At the same time, the simulations confirmed that not all operational conflicts can be resolved automatically. In situations where infrastructure limitations or platform occupation conflicts exceeded the available operational margins, escalation to the Traffic Management System (TMS) and human operators remained necessary.

From an operational perspective, the TPE-based feedback loop demonstrated several important benefits, including improved predictability of train behaviour through continuously updated trajectories, dynamic conflict detection, reduction of unnecessary stop-and-go behaviour, improved operational stability, and support for energy-efficient driving strategies through controlled cruising and coasting behaviour. In addition, the generated TPE information provided better insight into expected arrival and passing times for traffic management purposes.

The simulations also highlighted several implementation challenges. The effectiveness of the TPE-based feedback loop strongly depends on accurate infrastructure data, reliable train status information, and high-quality Journey Profile (JP) and Segment Profile (SP) generation. Furthermore, operators require clear conflict visualisation and understandable system behaviour in order to trust and effectively use the generated TPE advice.

Overall, the scenarios confirmed that TPE functionality can form a key enabling mechanism within future ATO over ERTMS implementations by connecting timetable planning, traffic management and automated train operation into a continuous operational feedback loop capable of improving capacity utilisation, operational robustness and energy-efficient railway operations.

8.2 Demonstration 16.2: Human factors impact

The study involved the feedback loop between a passive TMS, passive ATO-TS and an active ATO-OB in two scenarios, which respectively focused on train delays and a disturbance. Based on these conditions the impact on human operators (i.e., train drivers, traffic controllers and network controllers) was investigated. A summary of the important main findings is provided in the next sections. A more detailed reflection is provided in FP1 D16.1.

8.2.1 Traffic control

This was the first human-in-the-loop simulation of ATO-TMS interaction conducted for traffic control in the Netherlands. The simulation environment represented a TRL 5 in terms of maturity level. However, as no operators previously have been involved, this can be categorized at a low Human Readiness Level (HRL) (our educated guess is about HRL 3), where human roles, procedures and operational integration are still in early development and not yet tested with the technological capabilities (see FP1 D16.1).

A key perception identified during the study is that GoA2 is very limitedly experienced as beneficial for traffic control. In fact, controllers report more actions to perform, higher workload and inconsistencies with existing procedures. ATO benefits would entail the guarantee a train tries to catch up a delay (i.e., predictable) and ATO information (estimated time of arrival) is fed back into the TMS (i.e., more accurate arrival time of the train).

The inconsistencies with existing procedures may be explained by the mismatch between the TMS architecture and the currently implemented operational roles and procedures in the Netherlands. For example, the current set-up delays are typically processed locally by traffic controllers in order to adjust the time the routes will be set. This way the planning times of passenger trains remain intact. The travel information will show the planning times with actual delays. In contrast, under ATO operations where planning times are leading, network controllers are now required to process and resolve these delays by adapting the train path within their TMS. The findings indicate that ATO operational procedures, both within traffic control and in the interaction between decision support and automation of the TMS, require significant development and adaptions to be acceptable and useful for operators. The main cause of this need is the misalignment between operational roles and operational systems. Two potential development paths for TMS are identified:

- TMS development aligned with current Dutch operational roles: further develop TMS in a way that remains congruent with existing traffic control roles and procedures.
- Alignment of operational roles in accordance with the European TCS/TMS system philosophy: redefinition of task allocation and procedures of operational roles in the Netherlands to ensure consistency between the system, the roles and the procedures.

8.2.2 Train drivers

Although participants recognize that ATO negatively affect their role as train drivers (increased boredom, reduced attention and skill degradation), most understand that if the Railway Undertaking relies on the business value of ATO, it is necessary to make ATO mandatory. In terms of benefits, only a small number of train drivers perceive ATO as advantageous - mainly as a form of cruise control and for its ability to operate more consistently. A key requirement is that the data quality (of the journey and segment profile) and ATO algorithm work as intended. Despite this understanding, train drivers are verbalizing and reporting strong resistance to change, declaring that they might think on leaving the profession due to the foreseeable implementation ATO.

There is a mismatch between the European ATO DMI specification and the Dutch operational context. More information is required when the driver is responsible for the train operations (as in the Netherlands). The driver needs sufficient information to observe if ATO is following the right instructions, as the driver can be blamed for ATO errors. Possible solutions are:

- Include more information in other driver applications.
- Include additional information options in the ATO DMI which can be configured per country.

8.2.3 Passengers

The HITL simulation results reveal that changes in planning times affect passenger travel information under the current way of working, i.e., more dynamic information. Further analysis is needed to investigate the exact implications of these planning time changes on passenger needs and acceptance. In general, concerns of passengers are not much about time improvement but on a larger set of aspects.

8.2.4 Implications for the BuCa

The human factors data collected is not yet sufficiently representative of the operational activities of traffic control and should be regarded as an intermediate result in the ongoing development of ATO GoA2. Nevertheless, the findings are valuable for guiding further system development. The emphasis at this stage lies on procedural adjustments and TMS enhancements, particularly in the areas of conflict detection and resolution.

Given the current maturity level of the system (TRL 5) and low Human Readiness level (HRL 3) for traffic operators, the results are not yet suitable as a foundation for a business case. We recommend that any transfer of insights into the business case (as in D32.1) be used solely for illustrative purposes at this stage.

For a more accurate projection, future HF data from a TRL 7 ATO-TMS system development state should be used in line with the method that is currently investigated in D32.1. Ultimately, a TRL 8 ATO-TMS system development state is required to validate and confirm business case projections.

8.2.5 Limitations of the study

In many debriefing sessions traffic/network controllers indicated that they needed to get used to the unfamiliarity with the workstation, which was mainly related to the geographical area and the timetable. This unfamiliarity, together with simulation bugs could have influenced the perceived workload. Few train drivers indicated that they experienced a higher workload due to missing information in the simulation environment (e.g., no location signs on the track), while in general ATO GoA2 leads to underload.

Another point that should be mentioned is that all train drivers have had previous experiences with ATO GoA2 tests. There have been multiple previous tests based on different ATO software versions. Next to different ATO software versions of different suppliers it should be noted that there are also various parameters that influence the ATO driving behaviour that may be present during the previous tests. As such, this mix of previous experiences may have influenced the current results of the study as drivers in essence only experienced one hour of driving with an ATO GoA2 train.

Building on the results provided by the Human Factor Analysis Report in FP1 Task 16.4 and the best practices identified in the previous section, a set of considerations are here made to support the definition of effective implementation strategies of the ATO Operational Concept. The provided considerations specifically cover essential ATO implementation aspects which include: i) ATO technological validation and maturity level, ii) strategic staff reskilling and task redefinition, iii) design of the human-machine interface, as well as enabling technical and operational requirements of the ATO and TMS systems. In particular:

1) Phased Maturity and Validation

- **Align HRL with TRL**: Future implementation strategies should focus on raising the Human Readiness Level (HRL), which is currently estimated at a low HRL 3, to match the technical TRL 5 maturity level reached in FP1 Demonstrator D16.2.
- **Validate Business Cases at Higher TRLs**: Business case projections should only be finalized once the system reaches TRL 8 to ensure that human factors and operational data are sufficiently representative.
- **Iterative Testing**: Conduct further simulations to investigate the implications of planning time changes on passenger needs and travel information.

2) Strategic Role and Task Redefinition

- **Address Procedural Misalignment**: Develop a clear path for TMS development, choosing between maintaining current Dutch operational roles or redefining them according to European philosophy.
- **Shift in Responsibility**: Strategy must account for the shift where Network Controllers resolve delays via train path adjustments, rather than Traffic Controllers resolving them locally.
- **Time Resolution Synchronization**: Implement a strategy to synchronize the time resolution between drivers (who drive in seconds) and traffic control (which currently plans in minutes).

3) Human-Centric Design and Acceptance

- **Enhance Information Transparency**: Update the ATO DMI (Driver Machine Interface) to include more information about the ATO algorithm's intentions, such as planned braking, to ensure drivers can effectively monitor the system.
- **Mitigate Driver Resistance**: Address potential staff turnover by developing strategies to counter boredom, reduced attention and skill degradation associated with ATO GoA2.
- **Reduce Controller Workload**: Optimise the integration of ATO information within the TMS to prevent an increase in the number of manual actions required by operators.

4) Technical and Operational Prerequisites

- **High data Quality**: Establish high standards for journey and segment profile data, as operators view the reliability of this data as a critical requirement for trust.
- **Develop TMS conflict detection and resolution**: Enhance TMS capabilities in automated and optimised conflict detection and resolution to support traffic controllers during disturbed traffic scenarios.
- **Ensure cyber security:** Robust cyber security measures shall be adopted and implemented to mitigate any risk connected to external and/or non-authorised intrusion in data exchange processes underpinning automated train operations.

9 CONCLUSIONS

This deliverable presented the best practices identified from the mainline capacity assessment and the Operational Concept testing activities performed together with FP1 WP9 and FP1 WP16, respectively. The work combined simulation-based capacity studies, technical demonstrations and Human-in-the-Loop operational validation to assess the potential benefits and implementation challenges of ATO over ERTMS for mainline railway operations.

The performed capacity assessments demonstrated that ATO GoA2 and GoA4 can provide significant operational benefits for high-density railway corridors. The results indicate reductions in running times, headway allowances and capacity utilisation, together contributing to increased timetable flexibility, improved operational stability and the potential to accommodate additional train services. The studies further confirmed that the operational benefits are particularly relevant for commuter and stopping services operating in dense traffic conditions where braking behaviour and timetable margins strongly influence overall capacity performance.

The demonstrations of the Operational Concept validated the capability of the Train Path Envelope (TPE) functionality to support the interaction between Traffic Management Systems and ATO trackside and onboard systems. The performed scenarios showed that dynamic TPE generation can support conflict detection, trajectory adaptation, operational robustness and energy-efficient train operation while maintaining compatibility with real-time traffic management processes. At the same time, the demonstrations confirmed that certain operational conflicts still require intervention at the traffic management level and that fully automated conflict resolution remains dependent on infrastructure constraints, operational margins and system maturity.

The Human Factors evaluation highlighted the critical importance of operational procedures, interface design, organisational alignment and trust in automation for successful ATO deployment. While operators recognised the potential benefits of ATO regarding consistency, predictability and operational support, the demonstrations also identified concerns related to workload distribution, transparency of automation behaviour and changes in operational responsibilities. These findings confirm that future ATO deployment strategies must consider not only technical performance but also the operational readiness and acceptance of railway staff.

Based on the obtained results, this deliverable defined best practices for microscopic capacity simulation, operational scenario design, TPE generation, data quality management, conflict handling, Human-in-the-Loop validation and operational implementation strategies. The work further emphasised the importance of realistic operational assumptions, integrated ETCS-based simulation environments and iterative validation processes involving infrastructure managers, railway undertakings and operational personnel.

Although the presented work demonstrates important progress towards automated and digitally supported railway operations, further research and large-scale demonstrations remain necessary. In particular, future work should focus on integrated ATO-optimised timetable design, stochastic operational modelling, harmonisation of operational procedures, improved decision-support functionality, interoperability between TMS and ATO systems, and the continued validation of human factors impacts in real operational environments.

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