Rail to Digital automated up to autonomous train operation

D38.9 – Analyses of all data collected during the tests, including expected benefits and contributions to KPIs

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EXECUTIVE SUMMARY

The insights gathered in this deliverable provide an analysis on the benefit and performance-related findings of the remote driving and ATO-GoA4 demonstrators performed in R2DATO WP38. It is divided into three components:

1) An analysis framework for remote driving technologies and WP38 evaluation
2) Analysis on ATO parameters
3) Input on how RTO can contribute to the staff productivity KPI's.

The first part of this deliverable proposes a methodology for evaluating the performance of a remote driving technical solution using criteria for normal, low performance and insufficient system performance. The measurements on system performance are extended with an evaluation framework for investigating the ability of a Remote Driver (RD) to perform specific tasks from a remote workplace compared to the onboard cabin. An analysis has been carried out on the work performed during the SBB and NS demonstrators, in which parts of the evaluation methods were applied, demonstrating the potential of the framework. Recommendations are made for the implementation of evaluation frameworks during future RTO projects, paving the way for future operational implementations.

The second part investigates the operational parameters of the Automatic Train Operation (ATO) system, focusing on the role these parameters play in balancing driving goals such as safety, punctuality, energy efficiency and comfort. Drawing from field studies conducted during ATO-GoA2 and subsequent GoA4-testing, this analysis highlights the importance of tailoring the ATO driving function to reflect both the physical characteristics of specific rolling stock and the dynamic operational conditions encountered during service. The analysis addresses challenges specific to low adhesion conditions, comfortable passing of switches and margins to the ETCS braking curves.

Finally, an investigation is done on how the RTO can affect the process time for an individual stabling procedure. It identifies the sub-tasks of a stabling procedure and describes how RTO will affect the duration of each sub-task, from which the time savings is extrapolated for four real-world scenarios. Results indicate that in some scenarios significant benefits can be achieved by eliminating the time required to reposition personnel. An estimation is done for the KPI “Staff Productivity”, but is based on a limited number of scenarios and several limitations. Benefits are not always collectable due to remote driving requiring additional staff or investments on infrastructure equipped with manual switches. Additional research is necessary to extrapolate these findings for specific operating contexts

ABBREVIATIONS AND ACRONYMS

ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATSM	Automatic Train Stopping Management
EOA	End of Authority
ETCS	European Train Control System
KPI	Key Performance Indicator
R2DATO	Rail to Digital automated up to autonomous train operation
RD	Remote Driver
ROC	Remote Operations Centre
RTO	Remote Train Operation
RU	Railway Undertaking
SMB	Stop Marker Board
SPC	System Performance Criteria
SSEM	Supervised Speed Envelope Management
TTSM	Time Table Speed Management

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1 INTRODUCTION

Deliverable D38.9 “Analyses of all data collected during the tests, including expected benefits and contributions to KPIs” is part of R2DATO WP38 titled “Automatic Stabling, Shunting, and Non-commercial runs Demonstrator”. The aim of this work package is to test the different technical enablers for automatic stabling, shunting and non-commercial runs of passenger trains.

The study described in this deliverable can best be described as a summary of the research that has been performed within WP38 on the topics of RTO and ATO-GoA4. It aims to analyze and combine input that was collected during the field trials, this input is then used to provide suggestions for improvement and make estimates towards the KPI's set out in the annual working programm.

The work in D38.9 utilizes data that was collected during the field trials of:

- Task 38.2: Stabling a train and bringing a train to the station by remote control.
- Task 38.4: GoA4 stabling and shunting, including non-commercial runs, with Remote Control Centre as backup
- Task 38.7: Results of remotely controlled shunting

Results contain both insights from the demonstrator performed by NS (38.2, 38.4), as well as the demonstrator performed by SBB (38.7), allowing for comparison and more diverse insights.

The deliverable will be split into three different parts:

1. **Data & Analysis:** Analysis on the behaviour of the train in various conditions, analysis on the collected data, suggestions for improvement and reports. (Chapter 2)
2. **Operational Parameter Insights:** Input related to the operational insights on the driving parameters of ATO-trains. (Chapter 3)
3. **KPI Estimations:** An estimation will be made towards the expected contribution to the KPIs set out in the Annual Working Program based on RTO simulations for four real-world shunting and stabling scenarios. (Chapter 4)

1.1 DELIVERABLE OUTPUT

The output of this deliverable provides valuable information for future work on the topics of RTO and ATO, specifically on the topics of KPI's, business cases and migration strategies. It is expected that the work will be applied for the purpose of:

- **KPI's:** A number of KPI's have been identified to indicate the potential benefits of the technologies that are researched within the R2DATO project. This deliverable will provide insights into the potential benefits of RTO and ATO-GoA4 for the KPI of “Staff Productivity”. The results for this KPI are described in this deliverable and will be supplied to the Joint Undertaking as part of Deliverable 2.2 “KPI Monitoring Report”.
- **Business Cases & Migration Plans:** This deliverable contains information on the potential benefits, but also challenges related to the future application of RTO and ATO-GoA4 in operational settings. The information provided in this deliverable can be utilized during the establishment of business cases and migration plans as part of future waves of R2DATO.
- **Second Wave:** Some of the technical restrictions and operational challenges described in this deliverable can form the basis for future progressions of the ATO and RTO technologies.

It is therefore expected to be used during the consolidation and specification in the Second and Third wave of R2DATO.

- **Capacity Simulations:** Inputs related to the driving behaviour of the ATO shunting movements is discussed in close consultation with ERJU Flagship Area 1, WP8/9. Some of the output may be applied during the future modelling of ATO shunting movements and passenger operations in capacity simulations.

2 DATA & ANALYSIS

During the RTO tests, a lot of data has been collected including both technical data evaluating **the performance of the technical solution**, as well as operational data evaluating **the ability of users (remote drivers) or autonomous systems (ATO) to perform operational tasks**. This chapter will investigate the data analysis that has been performed for both purposes but also investigates the limitations of the performed analysis and recommendations for future research projects.

2.1 EVALUATING RTO

When evaluating the performance of a RTO solution, it is possible to evaluate the performance from two different perspectives:

- **Technical Performance:** What is the availability of the technical RTO solution and the underlying systems?
- **Task Performance:** How well is the end-user able to perform the different operational use-cases using the RTO technical solution?

The technical performance will provide an indication of the reliability of the solution and the availability for the end user to use this technical solution. The technical performance can be considered at various levels, the most meaningful metrics evaluating the performance at a system level, but improved insights can be collected when also considering performance at a lower technical level such as the performance of the onboard solution or specific sensors.

From an operational perspective, it is also important to investigate the practical applicability of the developed solution. This will provide insights in the ability of the system to perform the operational use-cases that are important for the daily operations of RUs. Example metrics could for example investigate the ability of the driver to perform basic driving tasks (i.e. punctual driving), allowing for comparison between remotely and physically operated trains.

2.1.1 Evaluating Technical Performance

A remote driving solution is not a single technical application, the driving function is created by the combined performance of many interdependent systems, distributed between the train, communication network and the Remote Operations Centre (ROC). The RTO on board unit manages input of different cameras, sensors and interfaces with the train control interface and train protection. Between the train and the ROC sits the wireless network which is not just a "data pipe", but an active and variable part of the system, affected by radio coverage, cell handovers and network congestions. At the ROC level, another set of systems is involved such as the decoding and displaying of video streams and the establishment of command interfaces.

In order for a remote driver to safely operate a train remotely, the remote driving system should not just be available but must also be performing at a minimal performance level of the end-to-end functions that form the basis of the remote driving system. A base performance level needs to be determined for each of the end-to-end functions to assess when the remote driving system is working sufficiently, these criteria will be referred to as System Performance Criteria (SPC).

It is possible to define SPC for different types of operating modes:

- Safety-Critical SPC: Defining the minimal system performance for the RD to remotely operate the train.

- Operational SPC: Defining the regular system performance level for the RD to perform its day-to-day operations.

The SPC should preferably be linked to the technically implemented safeguards (i.e. automatic interventions). The defined conditions can be used for both technical measures (reaction to low performance scenarios) and evaluation.

This chapter describes different end-to-end functions that are important for driving a train remotely, the relevant metrics on measuring the performance of these functions, and an analysis on the relevant insights that were made during the WP38 demonstrators.

2.1.1.1 Network Quality

An important requirement for operating a train remotely is the availability of a sufficient connection between the RTO-solution on the train and the wayside systems. This connection is important for sending commands between the ROC to the Train (command stream), transmitting data from the Train to the ROC (data stream) and transmitting video livestreams from the onboard cameras to the ROC (video stream). While the ROC can be equipped with an ethernet connection, the connection between the train and the wayside systems is typically established using telecommunications on 5G networks, which are prone to varying coverage and bandwidth. Many factors can influence the quality of the network, not just in the design of the technical equipment in the train but also depending on the network coverage in the operating environment and the interference or saturation of the network. Analysis on the network quality of an ROC operation should therefore include several topics:

- Analysis on the overall performance of the network quality (providing insights in the capabilities of the network function over longer periods and operating environments)
- Analysis on the network quality and coverage of the operating environment
- Analysis on the network quality should be repeated in different operating conditions and locations that may interfere with the network quality. Examples of operating conditions that affected the network quality were shared by researchers involved in the NS study:
    - Severe cloud covers,
    - Passing of crowded double-decker trains during rush hour
    - A music festival close to the track with 17500 visitors.

  Repeating these tests in different operating contexts is required to identify additional factors that may influence the network quality. For example, at a large station, during rush hours with many passengers (and devices) being present.

Inspiration on what measures to use for evaluating the network quality of remote operations can be taken from a previous study evaluating the feasibility of teleoperated car driving on mobile networks [3]. This study evaluates the network quality using the metrics of latency, jitter and throughput (up- & downlink). Additionally, it proposes a minimal performance level for car teleoperation of:

- Latency: < 250ms
- Jitter: < 150ms
- Uplink speed (3 cameras): > 3 Mbit/s
- Downlink speed: > 0.25 Mbit/s

The combination of the selected metrics, as well as the proposed minimal values can serve as inspiration for future remote driving studies in the railway industry. This should consider the differences between railway operations (on a fixed track, with ATP-systems in train and infrastructure) compared to car operations that may result in different operational requirements from the network.

Within the scope of the NS study [1], simple evaluations on the network quality have been conducted investigating only the topic of latency. Latency is measured using two different methods: (1) continuous monitoring of the network latency by using timestamps on the communication from the train to the ROC, and (2) sample measurements of the glass-to-glass latency using atomic clock references in front of the cameras as well as the ROC. An example of the glass-to-glass measurement is shown in Figure 1. The used methodology is further described in [1].

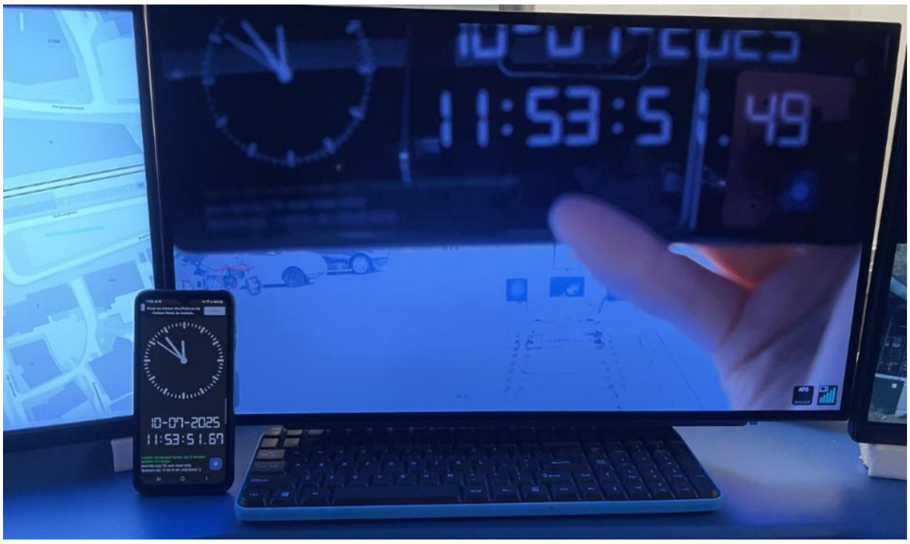

Figure 1: Measuring of glass-to-glass latency

The NS demonstrator [1] has applied one SPC on the maximum allowed latency of 2000ms on the video and command streams. When exceeding this value, the train would trigger a full service brake until standstill. The data related to the latency values and the consecutive braking interventions were analysed and logged during specific test runs, but this was not monitored continuously throughout the test campaign. The threshold of 2000ms was rarely exceeded during the duration of the study, except for a situation where the network was saturated due to a music festival with 17500 visitors located close to the test environment. In general, the measured glass-to-glass latency was on the range of 150ms – 200ms with sporadic peaks up to 1.2s due to network saturation.

In the remote driving study of SBB [2], the intended maximum latency is described as 500ms. However, the actual latency ranged between 500ms and 750ms. Several rules were programmed on handling connection losses or excessive latency; this includes traction cut-off (>1 sec of connection loss) and triggering of service brake (>3 sec of connection loss). The researchers report that continuous variations in latency are more problematic than increased latency, as these fluctuations make it more difficult for the remote driver to use the system. This should be further analysed in future studies.

2.1.1.2 Video Stream Quality

One of the important tools for the remote driver is the video stream shown in the ROC. The video stream is the primary situational awareness channel for the remote driver; it replaces the direct line of sight that an onboard driver would naturally have to observe the outside world. The performance of the video stream is affected by the entire end-to-end stream, ranging from the cameras and network to the driver display in the ROC. A sufficient quality level of the video stream is required for the driver to perform their tasks remotely.

The quality of the video stream partly relies on the quality of the network connection as described in chapter 2.1.1.1, but may also be affected by other circumstances. It can therefore be important to also have SPC in place on the quality of the video stream. Example metrics to evaluate the quality of the video stream connection were studied related to teleoperation of robots [4], it described metrics to evaluate degraded video image such as the minimal frame rate of the video, as well as the glass-to-glass latency.

Both the NS and SBB study have not set any SPC on the quality of the video stream. During the NS study, some occurrences were observed where the video stream was impacted by increased latency / packet loss due to network saturation, in this scenario, the increased latency was not severe enough to trigger the braking intervention. Depending on the severity of the quality loss of the video stream and the duration, this behaviour may be accepted temporarily. It would be recommended for future research projects to further quantify, measure and evaluate SPC related to the quality of the video stream. During the SBB study, several interruptions of the video stream were observed. After some improvements, the system became more stable and interruptions were almost eliminated. The camera quality was sufficient for the demonstrator and the test campaign. However, camera improvements would be required for a further system in operational use.

One of the research leaders of NS has also stated issues with the camera images being blocked by filth. Some of the cameras were placed behind the glass within range of the wipers, but the coupler camera and LIDAR installation were placed on the front of the train, with no dedicated cleaning mechanisms. They may therefore be prone to becoming obstructed and less usable. An example of a camera and sensor prone to filth is shown in Figure 2. This topic should be addressed during the design of camera and sensor placement in future projects, but that may not entirely solve the issue. It is therefore recommended to also include continuous monitoring of the soiling of cameras and establish relevant SPC.

Figure 2: Sensor positions on demo train

2.1.1.3 System Uptime

When the SPC of the remote driving solution is determined and measured, it becomes possible to evaluate the system in its entirety, evaluating both the availability of system as well as the practical applicability. An example definition for evaluating the operational uptime of the remote driving solution is proposed:

- **System status 'FULL**: All the SPC are met.
- **System status 'DOWN'**: One or more of the SPC are not met.

Using this definition, the operational uptime of the RTO-solution can be measured using the formula of:

$$Uptime = \frac{Time\ in\ system\ status: 'FULL'}{Total\ observed\ time}\ X\ 100\%$$

This measure will provide insight in the total uptime of the system, however, does not provide full insight in the practical applicability. Frequent, short outages may have high impact on the operational aspects of remote driving but may not be well reflected in above formula. It should therefore be extended with measures indicating the frequency of and interval between system interruptions.

There may also be occasions where the system performance is not performing at optimal conditions but may also not be severe enough to warrant interventions such as a full service brake. It would be possible to include an additional system status for such low performance conditions:

- **System status 'FULL**: All the SPC are met.
- **System status 'LOW PERFORMANCE**: All the safety-critical SPC are met. Some of the operational SPC are not met.
- **System status 'DOWN'**: One or more of the safety-critical SPC are not met.

Example set of SPC:

- Safety-critical SPC on latency: The maximum allowed latency is 1000ms. The latency may not exceed 500ms average for longer than 5 seconds.
- Operational SPC: The maximum allowed latency is 500ms.

In this scenario, the system status would be considered "FULL" when latency is less than 500ms, "LOW PERFORMANCE" when latency is between 500-1000ms, and "DOWN" when the latency exceeds 1000ms, or is above 500ms for longer than 5 seconds.

Measuring the system status allows to evaluate the availability of the system in both the perfect operating conditions ("FULL"), and the availability in the minimal operating conditions ("LOW PERFORMANCE + FULL").

$$Uptime\ full\ system = \frac{Time\ in\ system\ status: 'FULL'}{Total\ observed\ time}\ X\ 100\%$$

$$Uptime\ operational = \frac{Time\ in\ system\ status:\ 'FULL' \ +\ time\ in\ 'LOW\ PERFORMANCE'}{Total\ observed\ time} X\ 100\%$$

When the system is able to detect between the status of "FULL", "LOW PERFORMANCE" or "DOWN" it also becomes possible to inform the remote driver of this status. This can be an important feature to inform the driver on any underlying technical issues.

No such measurements have been performed during the WP38 demonstrators, thus making it difficult to quantify the operational uptime of the prototype solutions in the test environment. It is recommended to include such measures for future research projects to gain better insight into the operational feasibility and the current status of the prototype technologies.

2.1.2 Evaluating Task Performance

Operating a train from a ROC is different compared to operating a train from the cab. There are differences in the field of view to the outside world, the sensory cues (i.e. sounds, vibration) that are available and the tactile and kinesthetic feedback when operating controls. Even with a fully functioning system, performing specific tasks is different when performed remotely compared to onboard of the train. This may affect the ability of the driver to perform the day-to-day driving operations with the same level of precision and quality. Some tasks may be aided by new functionalities, sensors and cameras, whereas other tasks become more difficult to perform.

A method to evaluate the ability of the RD to perform specific driving functions with the RTO-solution consists of using measurable tasks. This methodology was applied during the SBB tests [2] where in collaboration with DLR [5] a number of scenarios were identified that are relevant in real SBB shunting operations, including situations that are associated with risks for safety and operation. For each of the scenarios, criterion for successful execution were determined (either pass or fail). The participating RDs were then asked to execute the specific tasks while under observation of the researchers. The outcome was then also compared in daytime and nighttime conditions.

This chapter aims to identify how tasks can be implemented to evaluate how effectively a train driver can perform key operational tasks from a remote location compared to the conventional in-cab situation. The assessment looks at whether the driver can execute required actions with the same level of accuracy, timeliness, situational awareness and safety as in the traditional setup. The chapter is divided into tasks relevant to performance and tasks relevant for safe operation of trains. It is assumed that the tasks are tested as part of a complete solution and therefore does not investigate the feasibility of performing specific functions and tasks but rather looks at the performance of tasks.

2.1.2.1 Driving Performance

The evaluation of tasks related to driving the train primarily focuses on the operational performance and quality of the driving. This should not investigate the performance of the driver, but rather the ability of the driver to perform specific tasks from the ROC, compared to being onboard of the train. Measurements on the performance and quality of the driving can include the topics of:

Measurement	Description	Potential Applications
Task Duration	The duration that it takes to perform a specific task.	Shunting Movement, Coupling, Train Preparations
Punctuality	The punctuality of a given movement	Mainline Operations
Stopping Accuracy	The accuracy of stopping at a certain target location.	Shunting, Coupling, Halting
Energy Consumption	The energy that is consumed during the performing of a certain task.	Mainline Operations, Shunting
Passenger comfort	The perceived comfort of onboard passengers during an operation.	Mainline Operations, Fallback

Table 1: Overview of tasks that can be evaluated to measure driving performance

2.1.2.2 Safety Performance

A key factor in European train operations is the compliance with strict safety standards when operating a train. This includes both driving in compliance with the local ATP, signage and regulations as well as responding to hazardous situations and irregularities. Several measurements can be used to evaluate the ability of the driver to perform specific tasks in a safe manner and respond to hazardous conditions while operating from the ROC compared to being onboard of the train. Measurements related to safety include the topics of:

Measurement	Description	Potential Applications
Obstacle Detection	The ability of drivers to recognize potential obstacles in front of the train. (i.e. recognition distance, reaction time or is it detected at all?)	Mainline, Shunting
Signal Compliance	The ability of drivers to recognize and comply with railway signals.	Mainline, Shunting

Safety Driver Interventions	In test environments, safety drivers may intervene if (deemed) necessary. This should be measured to gain insight in safety issues.	Mainline, Shunting
Response Time	The time required to respond after a hazardous situation is presented.	Mainline, Shunting

Table 2: Overview of tasks that can be evaluated to measure safety performance

By analysing the different measurements related to safety and driving performance it will provide insights into the operational readiness of a remote driving solution compared to the onboard situation. Thus providing valuable insights for future operational concepts and the design of technical solutions of the ROC and RTO-OB.

2.1.2.3 Task Evaluation in WP38 Demonstrators

The methodology of task evaluation to measure the operational applicability of the remote driving concept has successfully been applied within both the SBB demonstrator and the NS demonstrator. In both cases, only the performance of the RD has been observed, and no reference performance was measured of onboard train driving. The SBB demonstrator has compared the performance of tasks during different operating conditions, evaluating the difference between day- and nighttime. An example set of scenarios and measurement criteria can be found in [5].

This methodology can be repeated – including reference measurements – during follow-up studies into the concept of remote driving (standalone) and remote fallback to further investigate the operational applicability of remote driving.

2.1.2.4 Human Factors

Working from a remote workplace is a different type of work environment compared to being on a physical train and shunting yard. This impacts the way of working for train drivers as seen in the human factors related lessons learned in D38.1, D38.2 and D38.7. Specific analysis must take place on the operational concept and worker conditions for the ROC, which may not be caught with the aforementioned system and task evaluation methods. For this purpose, it is recommended to organize human factor studies that are specific for the intended operational concept in which the RTO solution will be applied. Example topics to investigate include the shift from physical operation to screen work, situational awareness, motion sickness, workload, etc.

2.1.3 Evaluating ATO

The methods that are described for evaluating the RTO solution may also be applicable for evaluating the performance of ATO-up-to-GoA4 solutions, both for system and task performance. To apply the evaluation methods for ATO, the evaluation should be comparing the performance of an ATO-system to the performance of drivers. No such comparisons were made yet during the WP38 ATO-GoA4 demonstrator due to the early nature of the technical solution, but measurements were done on task performance. These measurements include evaluation on the stopping accuracy of the solution as well as the correct recognition of railways signal aspects. The approach of using task evaluation, performance measurements and comparing them to regular driver performance may be promising for future research projects on ATO-GoA4 solutions.

2.1.4 Operating conditions

The tasks described in this chapter should be repeated under a wide range of operating conditions to ensure that the technical solution is evaluated realistically and robustly. This includes different times of day – such as daytime, nighttime, and sunset – where visibility, lighting conditions, and contrast may affect the driver's perception through remote sensors and displays. It should also be repeated by a representative set of remote drivers, featuring various levels of experience, backgrounds and cultures.

In addition, testing should take place in different operational environments, for example open track, shunting yards and station areas. Each environment presents unique visual and operational characteristics that may influence the performance of the RD.

The system must also be assessed under varying weather conditions such as rain, fog, snow and slippery tracks. Adverse weather conditions may degrade camera visibility, sensor performance, braking behaviour and situational awareness in a different manner from the ROC compared to onboard. Evaluating performance across these scenarios helps to identify limitations, safety risks, and necessary mitigations for reliable remote operations.

3 OPERATIONAL PARAMETER INSIGHTS

When driving a train from A to B, not a single trip is the same. While a lot of the route characteristics (i.e. infrastructure) are static, operational conditions (i.e. weather) are dynamic. The combination of the timetable, static and dynamic conditions form the basis for the driving strategy that a driver adopts. While a driver determines his driving strategy based on his experience, training and workmanship, this intelligence must be made specific for an ATO-system. This chapter addresses the topics related to the driving strategy and the configurable parameters of ATO-systems for EMUs/DMUs.

Customization of the driving strategy parameters by the RU may be necessary to implement restrictions for safety, human factors or comfort related purposes (i.e. introducing a max operating speed for passing switches), but can also be value priorities such as the trade-off between punctual driving and energy efficient driving. While human actors are familiar with making such decisions based on their training, experience and workmanship, determination of the right driving style operational parameters is crucial for implementing ATO-systems and necessary to optimize ATO's operational benefits for all grades of automation.

One of the key functions of the ATO system is the Driving Function, which consists of the features TimeTable Speed Management (TTSM), Supervised Speed Envelope Management (SSEM), Automatic Train Stopping Management (ATSM) and ATO Traction/Brake Control. This Driving Function employs an algorithm that generates traction and braking commands to ensure the train follows the speed profile calculated by ATO for its trajectory.

This driving algorithm relies on a **behavioural model** and requires several **operational parameters** related to traction and brake modelling, passenger comfort, adherence to ETCS braking curves, low adhesion management, stopping behaviour, and more. Throughout the ATO testing phase, valuable insights have been gained concerning the modelling and operational parameters of the ATO Driving Function.

It is important to emphasize that parameters are supplier-specific, reflecting differences in ATO modeling and parameterization between train types (and even train compositions) that exhibit distinct driving characteristics.

The insights presented in this chapter are based on field studies that were performed during the early technical maturity stage of the ATO-GoA2 functionality (that was later applied during the RTO-GoA2 tests of D38.3 and the ATO-GoA4 tests of D38.4). The results are based on the outcome of these field tests, combined with input from experts that have been involved in different ATO research programs including the WP38 ATO stabling/shunting demonstrator of NS.

3.1 Operational Relevance

The output commands from the ATO Driving Function directly influence the driving behavior of the train, and therefore directly impacts the overall operational performance-related to driving. To fully realize the benefits of ATO, optimizing the behavioural model and corresponding operational parameters is crucial.

3.1.1 Balancing driving goals

During each trip, six main driving goals must be balanced:

- Maximize safety (while never compromising a minimum level of safety)

- Maximize punctuality
- Minimize energy consumption
- Maximize comfort
- Minimize wear on train and rail assets
- Maximize accurate stopping

Like a human train driver, the ATO system must prioritize these goals dynamically based on the operational context. While drivers balance these goals intuitively, ATO requires explicit instructions for driving behavior and to avoid unintended behavior. This is not always easy, since some goals are subjective and hard to parameterize. It is also possible that ATO does not have the data available to support certain logic. Insufficient behavior logic or poorly tuned operational parameters can lead to suboptimal performance.

Note that the prioritization of goals may also vary depending on the operational context:

- When passengers (or train personnel) are aboard, driving comfort becomes more important.
- Under GoA2 (Grade of Automation level 2), driver acceptance of ATO driving behavior becomes a critical aspect for operational performance. Frequent manual take-overs by drivers reduce ATO's effectiveness. Uncovering the relevant aspects that lead to manual take-overs and adjusting the ATO driving model and/or parameters to prevent them is key. This aspect is not relevant in GoA3/4.

3.1.2 Validation

Another critical factor for operational performance is ensuring that the ATO behaviour model and operational parameters accurately represent the physical characteristics of the rolling stock. Mismatches between input parameters and the realization of the train dynamics while driving can cause the ATO algorithm to constantly adjust speed profiles and make excessive amounts of traction and braking corrections, resulting in a degraded performance and undesirable behaviour.

3.2 EVALUATING OPERATIONAL PARAMETERS

In theory, operational parameter values can be initially determined by consulting experts from various knowledge domains. However, before deploying ATO on any rolling stock type, it is strongly recommended to evaluate its driving behavior during dynamic tests with drivers and passengers. This practical evaluation is necessary because parameters based solely on theoretical knowledge can lead to undesired driving behavior in practice and unrealistic benefit expectations. Furthermore, fine-tuning these parameters is always required to achieve a balanced performance across the multiple operational objectives.

A potential way to assess the ATO driving style is to analyze the number of traction and brake corrections the algorithm makes to follow the calculated speed profile. A higher number of corrections indicates that the model is less representative of real-world conditions and results in suboptimal performance. Another valuable assessment involves reviewing the execution of driving regimes – specifically, when ATO is braking, accelerating, cruising, or coasting – and verifying whether these behaviors are reasonable in the given context.

Experience shows that most issues do not stem from punctuality but rather from the 'soft' goals, such as comfort and (perceived) safety. These aspects require dedicated attention to meet acceptable standards.

3.2.1 Comfort

Comfort is particularly challenging to quantify and optimize because it is a subjective experience and difficult to express through explicit parameter values.

During ATO tests, it was observed that operational parameters heavily influence the perceived comfort of both passengers and drivers, where standing comfort is more affected than sitting comfort. Poorly optimized settings can lead to uncomfortable ride experiences, which should be avoided.

A notable example relates to driving through switches, where comfort tends to be affected when passing at the maximum allowed speed level. While this speed is accepted from a safety perspective, human drivers typically apply a speed margin to smooth the ride in these situations. Current ATO systems, however, do not (yet) have the necessary data or logic to replicate this behavior, which can result in diminished comfort.

Another important comfort aspect involves how traction and braking forces are applied. Instead of sudden changes, gradual build-up of traction and braking is preferred, as abrupt changes increase jerk (the rate of change of acceleration) which detracts from comfort.

3.2.2 Driver Acceptance (GoA2)

An important topic to consider for ATO-operations, - especially GoA2- is driver acceptance and the interaction between the automatic system and the driver. During GoA2 operations, the driver is still responsible and remains actively involved in monitoring and intervening if necessary.

During a study with ATO-GoA2 on ETCS-trajectories, questionnaires and driver interviews showed that the safety perception of drivers in a GoA2-operation often relates to how closely ATO follows the ETCS braking curve, or the braking behavior towards a halting position at a platform or an End of Authority. Feedback on this point is mixed, reflecting a trade-off between driver acceptance (minimizing take-overs) and the potential capacity gains from braking later. Starting the braking process earlier and adding ATO brake information to the ETCS DMI helps improve driver anticipation and increases acceptance, knowing that ATO is planning on braking. An operational parameter that makes it possible to value the margin before reaching the ETCS braking curve is valuable to reflect the reaction time of a driver.

Some differences in decision making between ATO and human drivers can also lead to takeovers. When approaching an unplanned EoA, drivers will naturally decrease speed and drive slowly towards the Stop Marker Board (SMB), prioritizing safety and anticipating on a possible MA-improvement. ATO will, if not told differently, drive maximum speed and brake maximally from a punctuality standpoint. Especially when arriving at a station platform, while delayed, located immediately before the SMB.

When approaching a station, ATO may also accelerate before braking towards the halting position to make up for a few seconds of delay, while a human driver would never do that from a comfort and energy-efficiency perspective.

Using maximal acceleration to gain speed does not really affect acceptance, except when coming out of standstill. Drivers use a smooth build-up when coming out of standstill to prevent a sudden jerk (or slip), but after gaining a bit of speed it is acceptable to use maximum acceleration.

Additionally, minimizing unnecessary braking corrections is key, as drivers generally dislike frequent braking from a comfort and energy efficiency standpoint. Instead, coasting down to a lower speed is preferred to maintain smoothness.

One of the train drivers involved in the field study also stated the importance of early involvement of drivers, clear distinguishing of responsibilities between the driver and GoA2-system, and systematic training to understand the systems behavior.

3.2.3 Low adhesion

Operational parameters related to driving under low adhesion conditions are critical as they help prevent slip and slide incidents and can reduce ETCS interventions. When a driver observes indications of low adhesion, such as weather conditions, slippery tracks, reduced braking response or wheel slip/slide behavior, the driving style is typically adapted in several ways:

- Traction is applied more gradually, especially when departing from standstill;
- Acceleration levels are reduced to avoid wheel slip;
- Braking is initiated earlier and with a lower braking percentage to prevent wheel slide;
- Additional margins are applied towards stopping locations, End of Authority or ETCS braking curves;
- And unnecessary traction/brake corrections are avoided in favor of smoother coasting or more defensive speed control.

These adaptations are context-dependent and based on the driver's experience, training and workmanship. For ATO, this behavior must therefore be translated into explicit operational parameters, including reduced traction and braking limits for different adhesion levels and logic for smoothly transitioning between adhesion regimes based on real-time train behavior.

3.3 Capacity Simulations

Input that was collected related to parameters, driving behavior and observations from ATO and dedicated parameter tests have been shared with FA's SG1 WP8/9 during a verbal presentation by NS and was discussed during interactive group sessions. This information may be used for the future modelling of ATO operations.

4 KPI ESTIMATIONS

A number of KPI's have been identified within R2DATO to indicate the potential benefits of the technologies that are researched. For the stabling/shunting demonstrator the applicable KPI is "Staff Productivity", providing insights in the improved utilization of staff. The goal of FP2-R2DATO defined in the Annual Working Program is to achieve:

- **[Staff Productivity]** 30% increase in productive hours

This chapter will provide insights into the potential benefits of RTO and ATO-GoA4 based on the demonstrator results and theoretical analysis.

4.1.1 Context

Stabling and shunting operations form an essential part of train operations within the railway industry, allowing the transition from parked trains at the shunting yard from and to the railway station, but also bringing the train to maintenance and cleaning facilities. Transferring trains between shunting yard and station is mostly an asymmetrical process; in the morning the majority of trains need to go into service towards the station, and in the evening (or in between morning and evening rush hours) they need to be brought back to the shunting yard.

Shunting yards are often located far from a station, requiring the driver to physically travel between stations and the shunting yards. Depending on the operating context, it may mean that after parking a train, the driver returns on foot, by bicycle, or by taxi to the station or shunting yard. These movements, especially, make the shunting process labour-intensive and less productive. The characteristics of the shunting yard can differ; some shunting yards have automatically operated switches whereas other shunting yards are locally controlled using manual switches.

With the advent of remote driving technology, it has become possible to control these operations remotely, allowing drivers to save minutes of walking and waiting time. With ATO-GoA4, the necessity of having a driver on the train during a shunting movement can be removed. This report provides insight into the current situation and examines how the introduction of these technologies affects the required duration of different shunting tasks. Within the scope of WP38 several demonstrators have been performed in which the technologies of RTO and ATO-GoA4 were applied in real-world operational environments, providing tangible insights into the potential staff productivity improvements that these technologies may enable. The results of these field demonstrators, combined with an analysis of some example application areas is used to estimate a KPI-score of the potential benefits for RTO in the shunting / stabling process.

4.1.2 Research framework and objectives

The objective is to define a simple, clear, time-based measurement that indicates the benefits on the KPI "Staff Productivity" between the current situation and after the introduction of remote driving. This is done by measuring the KPI:

- **Average staff time required to perform a single stabling operation.**

A single stabling operation consists of several steps that the driver normally performs, some of them are affected by the introduction of RTO. An overview of the different steps and how they are affected by RTO is shown in Table 3.

Steps	How does RTO affect the steps?
Movement from starting point to the vehicle	No longer required to reposition towards the train.
Preparing the train	Remains unchanged
Executing the shunting/stabling movement	Remains unchanged
***Optional*: Changing driving direction**	If it is necessary to switch the driving direction during the movement (i.e. when relocating to a parallel track), the driver no longer needs to reposition to the other cabin.
Switch Operation	Local switch operation requires someone to physically operate the switch. This task – normally performed by the onboard driver – cannot be done remotely. For the full benefit of RTO, local switch operation needs to be addressed.
Switching off the cabin	Remains unchanged
Moving to the next task or to the starting point	No longer required to reposition after performing the shunting movement.

Table 3: RTO impact on different stabling/shunting steps

The duration of the different steps depends on the operating context (i.e. distance from the station to the shunting yard), but also the design of the physical train asset. To account for these differences and achieve a more realistic KPI score, this study has estimated the potential improvements that RTO may bring in different operating environments.

A number of example shunting movements were investigated on different shunting yards in the Netherlands, including the shunting yard from the WP38 demonstrator environment (Enschede):

1. Stabling a train from the Enschede train station to the (parallel) Enschede shunting yard, including changing of driving directions.
2. Stabling a train from the Groningen train station to the Groningen de Vork shunting yard, including the return cab ride.
3. Shunting a train from Utrecht Cartesiusweg from a maintenance track to a shunting track. (Manually operated shunting yard.)
4. Stabling a train from Lelystad shunting yard to the Lelystad station, including the cab ride. (Manually operated shunting yard.)

For each of the scenarios, the required time for each of the steps is estimated for both the current situation and a future scenario where RTO is applied. This estimate is based on:

Preparation Time: A static time of 246 seconds is applied in all scenarios. This is based on a one-sample measurement.

Driving Time: The required driving time is calculated based on the distance (measured on Google Maps) and the local driving speed (20km/h for shunting yards, segment speed for mainline).

Walking Time: The time required to move from/towards the train is based on the distance from the employee breakroom towards the target track on the station/shunting yard, assuming an average walking speed of 4km/h.

Taxi Time: The time required for a taxi assumes the estimated duration of the journey from Google Maps estimates, with an added 15-minute margin to account for potential delays in the taxi's arrival, as well as potential traffic during the journey. This is important due to the station often being in the city centre.

Manual switch time: A duration of 60 seconds is assumed for operating manual switches with a local switch operator, a duration of 120 seconds per switch is assumed for train drivers that need to physically leave and enter the train.

4.1.2.1 Switch Operation

There are currently many shunting yards in Europe that are equipped with manually operated switches that require someone physically on the shunting yard to operate the switch. This task is normally performed by the onboard driver but will not be possible when the driver is not physically present in the cabin during remote or autonomous driving.

Several solutions can be identified to accommodate remote or autonomous driving systems on shunting yards equipped with manual switches, such as:

- Physical modifications to the infrastructure (i.e. making switches (semi-)automatic).
- Having dedicated people on the shunting yard for operating the switches. This could be filled by a less-skilled operator compared to a train driver.

To ensure that the potential of remote driving in non-automated shunting yards is also considered, two scenarios (3 & 4) were included in which the time required for a local driver to perform a shunting/stabling operation is compared to the time required for a remote driver to perform the operation, while being assisted by an on-site switch operator. This scenario can still lead to a reduction of overall productive time, and especially high-skilled train driver productive time which can be important in time of scarcity.

4.2 ENSCHEDE STABLING

Stabling a train from the Enschede train station to the (parallel) Enschede shunting yard, including changing of driving directions. This scenario has been visualized in Figure 3.

Figure 3: Enschede stabling scenario (©Google Maps)

Steps	Current Situation	RTO Situation
Movement from starting point to the vehicle	181 seconds	0 seconds
Preparing the train	246 seconds	246 seconds
Executing the shunting/stabling movement: (1) Station Platform to (2) Turnaround Track	180 seconds	180 seconds
Changing driving direction (cabin deactivation + activation)	96 seconds	96 seconds
Walking towards the other cabin	54 seconds	0 seconds
Executing the shunting/stabling movement: (2) Turnaround Track to (3) Shunting Track.	180 seconds	180 seconds
Switching off the cabin	20 seconds	20 seconds
Moving to the next task or to the starting point	211 seconds	0 seconds
Total Duration	1.168 seconds (19,5 min)	722 seconds (12,0 min)
RTO Savings		Reduction: **38,5%**

Table 4: RTO benefit estimates: Enschede Stabling

4.3 Groningen Stabling

Stabling a train from the Groningen train station (1) to the Groningen de Vork shunting yard (2), including the return cab ride. This scenario has been visualized in Figure 4.

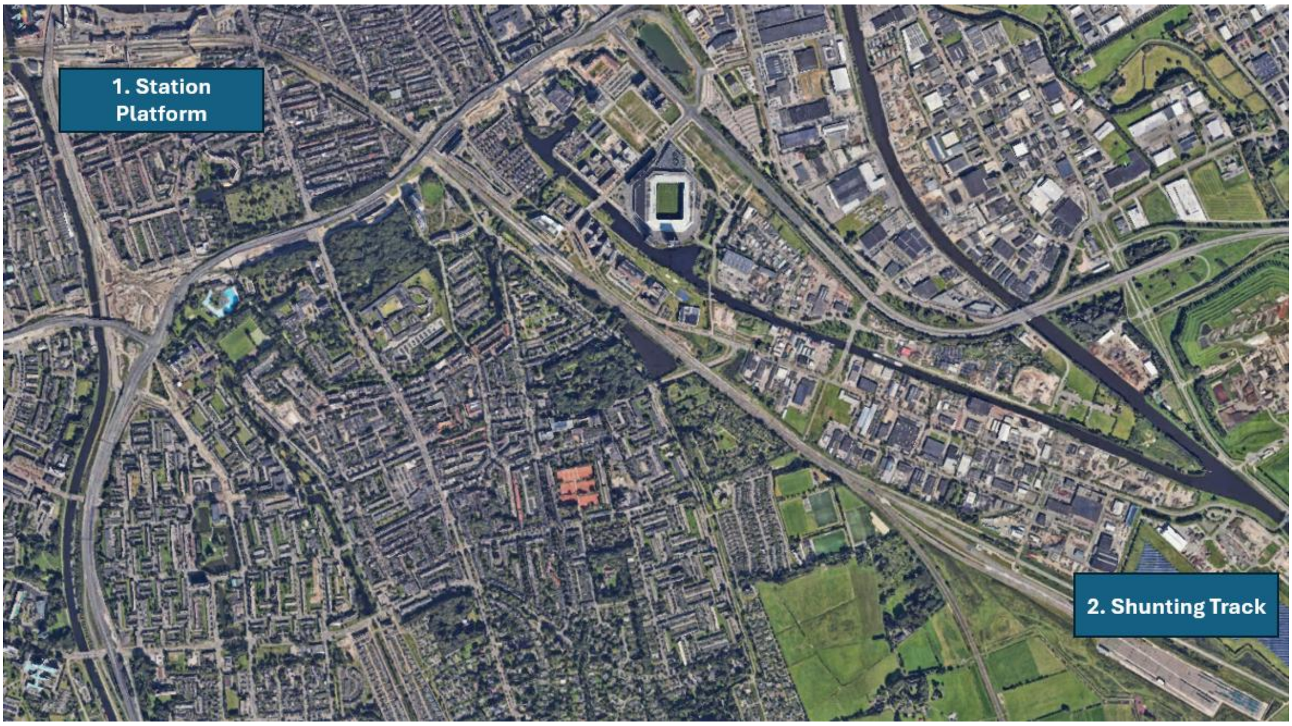

Figure 4: Groningen stabling scenario (©Google Maps)

Steps	Current Situation	RTO Situation
Movement from starting point to the vehicle	180 seconds	0 seconds
Preparing the train	246 seconds	246 seconds
Executing the stabling movement: (1) Station Platform to (2) Shunting Track	480 seconds	480 seconds
Switching off the cabin	20 seconds	20 seconds
Returning to the station	1830 seconds (taxi)	0 seconds
Total Duration	2756 seconds (45,9 min)	746 seconds (12,4 min)
RTO Savings		Reduction: **72,9%**

Table 5: RTO benefit estimates: Groningen Stabling

4.4 UTRECHT CARTESIUSWEG SHUNTING

Shunting a train from Utrecht Cartesiusweg from a maintenance track (1) to a shunting track (3) on a manually operated shunting yard. This scenario has been visualized in Figure 5. This scenario considers a remote driver in the ROC, and a switch operator physically present on the shunting yard.

Figure 5: Cartesiusweg maintenance shunting scenario (©Google Maps)

Steps	Current Situation	RTO Situation (Time for RD)	RTO Situation (Time for Switch operator)
Movement from starting point to the vehicle	450 seconds (walking)	0 seconds	60 seconds (walking)
Preparing the train	246 seconds	246 seconds	0 seconds
Executing the shunting/stabling movement: (1) Maintenance Facility to (2) Turnaround Track	55 seconds	55 seconds	55 seconds (available time)
Operate Switch	120 seconds (1 switch)	120 seconds (1 switch)	120 seconds (switch time)
Changing driving direction (cabin deactivation + activation)	96 seconds	96 seconds	96 seconds
Walking towards the other cabin	54 seconds	0 seconds	0 seconds
Executing the shunting/stabling movement: (2) Turnaround Track to (3) Shunting Track	120 seconds	120 seconds	120 seconds

Operate Switches (including towards walking next switches)	360 seconds (3 switches)	180 seconds	180 seconds
Switching off the cabin	20 seconds	20 seconds	0 seconds
Moving to the next task or to the starting point	60 seconds	0 seconds	60 seconds (walking)
Total Duration	1.581 seconds (26,4 min)	837 second (14 min)	691 seconds (11,5 min)
RTO Savings	Total reduction in productive staff time for remote driver + switch operator compared to onboard driver		**3,4%**

Table 6: RTO benefit estimates: Utrecht Cartesiusweg shunting

4.5 Lelystad Stabling

Stabling a train from Lelystad shunting yard (1) to the Lelystad station (2), including the cab ride. This scenario has been visualized in Figure 6. This scenario considers a remote driver in the ROC, and a switch operator physically present on the shunting yard.

Figure 6: Lelystad stabling scenario (©Google Maps)

Steps	Current Situation	RTO Situation (Time for RD)	RTO Situation (Time for Switch operator)
Movement from starting point to the vehicle	1380 seconds (taxi)	0 seconds	60 seconds (walking)
Preparing the train	246 seconds	246 seconds	0 seconds
Executing the shunting movement from	360 seconds	360 seconds	360 seconds

shunting yard to public tracks.			
Operating Switch	240 seconds	120 seconds	120 seconds
Executing the stabling movement	420 seconds	420 seconds	0 seconds
Switching off the cabin	20 seconds	20 seconds	0 seconds
Moving to the next task or to the starting point	60 seconds	0 seconds	60 seconds (walking)
Total Duration	2.726 seconds (45.4 min)	1.166 seconds (19.4 min)	600 seconds (10 min)
RTO Savings	Total reduction in productive staff time for remote driver + switch operator compared to onboard driver		**35.0%**

Table 7: RTO benefit estimates: Lelystad Opstel stabling

4.5.1 Analysis of RTO scenarios

Within this chapter, a total of four different scenarios have been investigated to study the potential benefits that RTO may bring for a single shunting scenario. The results indicate that using RTO to eliminate the process times for repositioning (taxi/walking) may bring serious benefits, as seen in the Groningen scenario [5]. Other scenarios such as Lelystad may have lower benefits due to the need for an additional on-site worker to operate the switches.

Location	Baseline (min)	Remote Driving including switch operator (min)	Saving (min)	Saving %
Enschede	19.5	12	7.5	38.5%
Groningen de Vork	45.9	12.4	33.5	72.9%
Utrecht Cartesiusweg	26.4	25.5	0.9	3,4%
Lelystad	45,4	29,4	16	35,0%
Average				**37.5%**

Table 8: Overview of estimated savings in four example scenarios

The results from the different RTO scenarios are shown in Table 8. In two of the scenarios, benefits can be achieved by introducing the technology of RTO. The other two scenarios cannot be achieved by the remote driver themselves, but requires the combination of a remote driver and a switch operator. Regardless, the overall productive staff time required to perform the task is still lower compared to the time it would require from an onboard driver. The average percentage of time saved by introducing RTO in these four scenarios is 37,5%.

The value of 37,5% time savings provides first indication of the potential benefits that RTO may bring for increased staff productivity in these specific scenarios, but cannot one-on-one be extrapolated for other operational concepts. Several limitations, open topics and context information must be considered when interpreting this value:

- The example scenarios consist of only four locations with one shunting and three stabling situations, making it a small sample size. The benefits of RTO are very dependent on the characteristics of the application area, such as the presence of manual switches, the distance from station to shunting yard but also the layout of the shunting yard. It is unlikely that the benefits from the four example locations can be copied for other application areas.
- Even when considering the benefits for a specific application area, the characteristics of the shunting movement also affect the potential benefits. Certain tracks or routes may have more benefits (i.e. longer walking times) compared to others. Only one type of shunting movement was investigated for each of the example scenarios from this study.
- The time savings that can be achieved for a **single shunting movement** cannot easily be extrapolated to the effect on required staff capacity or collectable productivity gain for a given shunting yard. (i.e. a staff member may have 4 hours of productive work in the current situation, introducing RTO could then result into the staff member having 3 hours of productive work instead).
- During migration phases, or when operating in a mixed shunting yard of RTO and non-RTO trains, there may be need for both physical drivers and remote drivers. While the required time to perform a single shunting operation can decrease for the remotely performed runs, it could still lead to a net increase of the required staff capacity.
- The example scenarios with manual switches consider the total required time for the remote driver and the switch operator. While the net productive time is less compared to the onboard driver, this role is now split into two different persons that need to be attending. The results will need to be extrapolated on a full shift / shunting yard to investigate how this affects the total number of required staff.
- While the option for manual switch operators is considered in this example, it is also possible to make investments in the infrastructure (i.e. automating switches) or handing over the train to a local driver at the entry point of a shunting yard. These scenarios are not investigated in this study and may also introduce benefits.
- The example scenarios investigate happy flow scenarios, it does not consider additional capacity or margins required for new unhappy flow situations that are introduced by RTO such as stranded remote trains, a defective coupler, or similar.
- Developments related to automatically or remotely preparing the train are not considered in this study. This could lead to additional improvements on process times compared to the current situation.
- The example scenarios do not consider additional time that might be necessary for tasks when operating them remotely compared to the onboard situation. While some indicators are available on this topic from the D38.2 human factors study, it is not yet clear how these topics will be addressed in future technological solutions and operational concepts. Based on the current knowledge, additional time may be required for:

  - The RD to identify the position of the train on the shunting yard, compared to an onboard driver that has just physically approached the train.
  - A RD might apply a more defensive driving strategy and therefore require more time for shunting operations.
  - Additional breaks may be necessary due to the nature of computer work and ergonomic requirements.

While these findings provide an initial quantitative indication of RTO’s potential to improve staff productivity, the results **cannot yet be generalized** due to the limited scope, context dependencies, and unaddressed operational complexities.

Given these limitations, the authors **strongly advise against** drawing definitive conclusions from the current data. Instead, the scenarios should be viewed as a proof of concept, demonstrating:

- Where RTO **can** deliver productivity gains (e.g. in yards with long walking distances).
- Which **challenges** must be addressed to unlock its full potential.
- The **need for tailored business cases,** as benefits are highly dependent on local conditions.

Future work should prioritize larger-scale pilots, cost-benefit analyses, and cross-functional collaboration (e.g. with infrastructure managers) to refine the business case for RTO deployments.

5 CONCLUSIONS

This deliverable consolidates the main technical and operational insights obtained from the R2DATO WP38 demonstrators on Remote Train Operation (RTO) and ATO up to GoA4, and links them to the KPI contribution on Staff Productivity.

First, a structured evaluation approach for RTO has been developed, distinguishing between (1) system performance and (2) task performance. On the system side, the work underlines the importance of defining System Performance Criteria (SPC) for key end-to-end functions such as network connectivity, latency, video quality and system uptime. The demonstrators by NS and SBB show that remote driving over public mobile networks is technically feasible, with generally acceptable levels of latency, but also reveal sensitivity to network saturation and the absence of systematic monitoring of degraded modes. The report therefore concludes that future RTO projects should implement more complete measurement concepts (including differentiated FULL/LOW PERFORMANCE/DOWN statuses) and explicit SPC for both safety-critical and operational-related parameters, including the condition of camera images. The proposed evaluation methods are not only based on system performance, but also introduces tasks that assess how well remote drivers can perform operational and safety-critical activities compared to in-cab driving. The methodology, applied in both NS and SBB tests, uses measurable tasks (e.g. stopping accuracy, punctuality, obstacle detection, signal compliance, response times) and can be extended with reference runs by onboard drivers. The results confirm that remote operation is operationally viable, but that differences in field of view, sensory feedback and workplace ergonomics require dedicated human-factors analysis and design. The report recommends that future projects combine technical KPIs with systematic human-factors studies tailored to the intended operating concept.

Second, the deliverable provides insights into the configuration and operational relevance of ATO driving parameters. Field experience with ATO-GoA2/4 shows that the ATO Driving Function must explicitly balance multiple, sometimes conflicting, objectives: safety, punctuality, energy efficiency, comfort and asset wear. The tests highlight that many issues arise not from timetable adherence but from “soft” aspects such as comfort and perceived safety. Examples include the way ATO passes switches, the aggressiveness of braking near ETCS braking curves or End of Authority, and the handling of low-adhesion conditions. The findings underline the need for careful parameter tuning per rolling-stock type, validation of the behavioural model against real train dynamics, and explicit logic to reflect human driving practices (e.g. margins to braking curves, smooth build-up of traction/braking). For GoA2, driver acceptance is identified as a critical factor: if ATO behaviour is perceived as uncomfortable or unsafe, drivers will frequently take over, reducing the achievable benefits.

Third, the deliverable presents initial estimates of the impact of RTO on the KPI “Staff Productivity” for stabling and shunting operations. Four real-world scenarios (Enschede, Groningen, Utrecht, Lelystad) are analysed by decomposing a stabling/shunting process into discrete steps and comparing the time required with and without RTO. The results show that in environments where trains can be fully controlled remotely and no manual switch operation is required, significant savings can be achieved by eliminating walking and taxi times for drivers. In the example scenarios, time reductions of approximately 38.5% (Enschede) and 73% (Groningen) are calculated for a single movement. In the scenarios of Utrecht and Lelystad, manually operated switches limit the benefits for remote driving as a physical operator is required to move the switches in addition to the remote driver on the train. Benefits were still realized with a reduction of the totally required staff time of 3.5% (Utrecht) and 35% (Lelystad). However, this new situation requires two different people to perform this task that was traditionally performed by a single person. Averaging across the four illustrative scenarios yields an indicative time saving of 37.5%. At the same time, the deliverable stresses that **these figures must be interpreted with caution**. The analysis covers only a small number of scenario types and locations, focuses on “happy flow” operations, and assumes that remote execution of driving tasks is not slower than onboard operation. It does not yet translate time savings at movement level into collectable capacity reductions at yard, fleet, or network level, nor does it account for mixed operations with both remote and onboard drivers, or for additional breaks and workload constraints in ROC operations. Furthermore, additional infrastructure or organisational measures (e.g. local staff to operate manual switches, or handover concepts at yard entries) may be needed to unlock RTO benefits in certain environments, which are not all considered in the scope of the current calculation. Taking these topics into account, the deliverable concludes that RTO and ATO-GoA4 can make a meaningful contribution to the Staff Productivity KPI and to broader business cases and migration strategies within R2DATO, provided that further work is carried out. This includes expanding the empirical basis across more yards and use cases, refining technical and human-factors evaluation frameworks, considering infrastructural and organisational adaptations, and integrating the resulting insights into capacity simulations and future waves of the R2DATO programme.

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