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# Rail to Digital automated up to autonomous train operation

## D32.4 – ATO Human Factors Impact Assessment Analysis Report

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# EXECUTIVE SUMMARY

This deliverable presents a comprehensive assessment of the human factors implications of the system development and implementation of Automatic Train Operation (ATO) Grade of Automation (GoA) 2. It brings together findings from literature, expert input, task analysis, multi actor human-in-the-loop simulation, and a large European passenger acceptability survey. The result is a system-wide view of how automation affects passengers and operators, such as onboard personnel, train drivers, traffic controllers and network controllers.

A key contribution is the development of a Human Factors (HF) - Business Case (BuCa) interface model that links HF related risks to business impacts using the ISO 31000 risk management framework. It maps cognitive, behavioural, organisational, technological, and societal factors to operational risks such as vigilance loss, deskilling, over reliance, mode confusion, and acceptance barriers. By outlining risk treatments and their implications for cost, risks and benefits, the model offers a structured approach for integrating HF considerations into ATO business case development.

Desktop and empirical studies in later chapters analyse how tasks and processes shift from GoA1 to GoA2. Findings from the desktop analysis in the Swedish context show that train drivers' roles evolve toward supervisory monitoring, increasing exposure to underload, fatigue, boredom, and skill degradation. The findings from the multi-actor human-in-the-loop (HITL) simulation study in the Netherlands show that workload for traffic and network controllers increases due to misalignments between ATO information and current Traffic Management System (TMS) functionalities and procedures.

Adoption of automated operations is assessed from both passenger and different types of operator (i.e. train driver, traffic controller, network controller) perspectives. A large European passenger survey (N=519) shows strong acceptance for GoA2 and GoA3 but significantly lower acceptance for GoA4, driven by concerns about safety, staff absence, reliability, and cybersecurity. Clear communication and robust remote assistance are essential to maintaining public trust. For operators, successful transitions depend heavily on human and organisational factors such user involvement in the system design and system robustness. We strongly recommend to use frameworks on organizational readiness and human readiness level (HRLs) alongside the technical readiness levels (TRLs).

Overall, this work provides human factors frameworks, tools, evidence, and guidelines to support automation developments in the railways.

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| **ATC** | Automatic Train Control |
| **ATO** | Automatic Train Operation |
| **ATP** | Automatic Train Protection |
| **BuCa** | Business Case |
| **CBTC** | Communication-Based Train Control |
| **DMI** | Driver Machine Interface |
| **DR** | Train Driver |
| **EMU** | Electric Multiple Unit |
| **ERTMS** | European Rail Traffic Management System |
| **ETCS** | European Train Control System |
| **ETCS MB** | ETCS Moving Block (“MB” replace “level 3” in TSI-CCS) |
| **FP** | Flagship Project |
| **GoA** | Grade of Automation (GoA1 - GoA4) |
| **GSM-R** | Global System for Mobile Communications - Railway |
| **HITL** | Human-in-the-Loop |
| **HMI** | Human-Machine Interface |
| **HRL** | Human Readiness Level |
| **HTD** | Hybrid Train Detection |
| **IM** | Infrastructure Manager |
| **NC** | Network Controller |
| **OB** | On-board (e.g., ATO OB) |
| **RU** | Railway Undertaking |
| **SA** | Situation awareness |
| **SPAD** | Signal Passed at Danger |
| **TC** | Traffic Controller |
| **TCMS** | Train Control and Monitoring System |
| **TCS** | Traffic Control System |
| **TMS** | Traffic Management System |
| **TOC** | Train Operating Company |
| **TPE** | Train Path Envelope |
| **TRL** | Technology Readiness Level |

| | |
|---|---|
| **TS** | Trackside (e.g., ATO TS) |
| **UX** | User Experience |
| **WP** | Work Package |

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# 1 INTRODUCTION

The present document constitutes the Deliverable 32.4 “ATO Human Factors Impact Assessment Analysis Report” in FP2/WP32. This report addresses the critical role of human factors in the transition toward higher levels of railway automation, specifically Grade of Automation (GoA) 2 (see Figure 1 for its context and definition). This report synthesizes research, models, and empirical findings to guide safe, efficient, and socially accepted implementation of Automatic Train Operation (ATO) GoA2 within the Europe’s Rail framework.

| Grade of Automation | Type of train operation | Setting the train in motion | Stopping train | Door closure | Disruption events |
|---|---|---|---|---|---|
| GoA 1 | Driver with support (Automatic Train Protection) | Driver | Driver | Driver | Driver |
| GoA 2 | Semi-Automated Train Operation | Automatic | Automatic | Driver | Driver |
| GoA 3 | Driverless | Automatic | Automatic | Attendant | Attendant |
| GoA 4 | Fully automated trains | Automatic | Automatic | Automatic | Automatic |

**Figure 1: Grade of Automation (GoA) levels in Automatic Train Operations (ATO)**

Chapters 2 to 7 collectively explore the context, tools, and implications of automation on operational roles, organizational processes, and passenger acceptance.

- **Chapter 2** includes an extensive literature review on human factors and automation, which forms the basis for the Human Factors - Business Case (HF - BuCa) interface model, linking human factors risks to business impacts. It outlines cognitive, attitudinal, behavioral, organizational, technological, and societal dimensions, highlighting risks such as deskilling, mode confusion, and reduced vigilance, alongside risk treatment strategies like training and mitigating tools.

The literature review presented in Chapter 2 also serves as the basis for the human factors toolkit in Chapter 3 and the task analysis of drivers and onboard personnel in Chapter 4.

- **Chapter 3** introduces tools and guidelines for human factors research, including the Human Factors Toolkit developed for human-in-the-loop (HITL) simulations that can be used by human factors researchers and practictioners in rail. This toolkit identifies key constructs, such as situation awareness, workload, fatigue, attention, and trust in automation, which are essential for evaluating operator performance and system usability during automation transitions. Application of this toolkit is done as part of the human factors assessment in the human-in-the-loop simulation, see Section 5.2.

- **Chapter 4** provides task analyses and operational process descriptions in current GoA1 operations for the roles of train driver and onboard personnel on the Swedish Iron Ore Line.

Results on the (anticipated) of impact ATO GoA2 on operators are presented in Chapter 5.

- **Chapter 5** consists of three sections:
    - Section 5.1 firstly presents a task analysis of train drivers in GoA2 on the Swedish Iron Ore Line and discusses possible anticipated changes. These analyses reveal how automation reshapes the train driver role from an active control to supervisory tasks, introducing challenges related to workload distribution, situation awareness, and decision-making.
    - Section 5.2 focuses on the HF findings from a multi-actor HITL simulation study for TMS-ATO GoA2 between one train driver, two traffic controllers and one network controller in the Netherlands.
    - Section 5.3 presents a brief overview of other human factors tests, simulations, and demonstrations conducted in FP1, FP2 and FP5.

The acceptance and adoption of ATO is discussed in Chapter 6.

- **Chapter 6** consists of two sections:
    - Section 6.1 examines the adoption and acceptance of automated operations focusing on passenger expectations.
    - Section 6.2 focuses on the transition from an operational perspective.

  Both sections describe the findings from their systematic literature review, survey data, and consolidate these results in a set of guidelines.

Together, these chapters provide a comprehensive foundation for understanding the interplay between technology, human performance, and organizational readiness in the migration toward automated rail systems. The findings inform guidelines for operational transitions, risk mitigation, and stakeholder engagement, ensuring that automation enhances safety, efficiency, and user experience without compromising human oversight or societal trust.

# 2 HUMAN FACTORS – BUCA INTERFACE MODEL

The current section introduces an overview of a theoretical connection between HF and business case (BuCa) components through an interface model. The purpose of the interface model is to identify and relate relevant relations in the field of human factors in relation to the business case (BuCa) of a technological development. A team of five human factors experts conceptualized a two-part model regarding potential human factors-based risks in the implementation and operationalization of ATO in a GoA2 and GoA4 context in combination with HTD (Hybrid Train Detection). The HF-BuCa model in Section 2.1 uses a risk management framework and connects this to expected business impact factors. In the subsequent Section 2.2, an extended version of the HF-BuCa model is provided that summarizes all the relevant human factors aspects and their relations, informed by the literature review from D15.2 in FP1/WP15 and its related publication by by Kusumastuti et al (2025) as well as the work by Holmgren & Medina-Perreira (2023). The final model represented in Figures (3 and 4) is the result of multiple iterations with human factors experts, two iterations for review with a total of four business and organizational experts, and one review with two external human factors experts.

## 2.1 SUMMARIZED HF – BUCA INTERFACE MODEL

The HF-BuCa interface model uses the ISO 31000 risk management model (Figure 2) to visualise literature and expert-based analyses of potential risks (risk identification), risk evaluation from a human factors perspective (risk analysis) and potential solutions to mitigate or eliminate risks (risk treatment) that decision-makers can adopt. Additionally, the impacts that the treatment of the identified and analyses risks have on a business perspective are outlined. Overall, this visualization aims to summarize the key human factors issues and associated risks that must be considered in decision-making when investing on GoA 2 or GoA4 levels in combination with HTD.

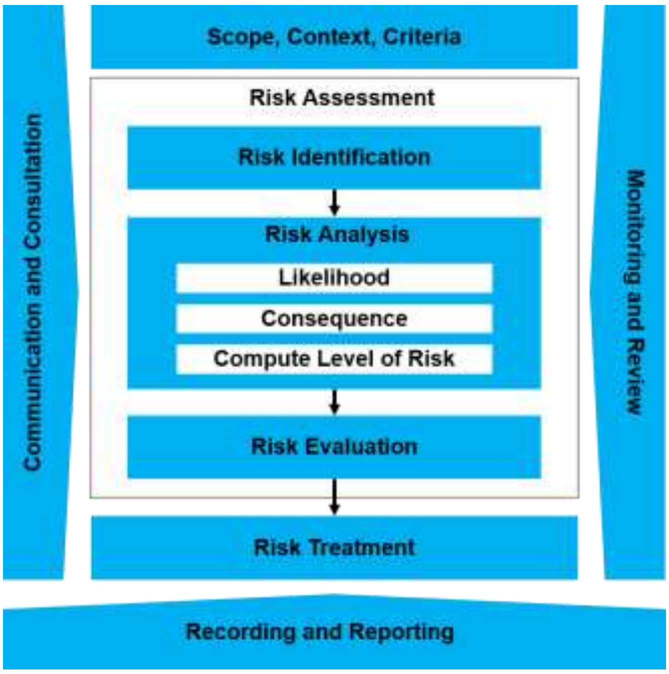


**Figure 2: ISO31000 risk management model**

This interface model (Figure 3) emerges as a component of the BuCA model outlining human factors aspects such as cognitive and attitudinal aspects, that were identified in academic literature (Kusumastuti et al. 2025) associated with potential risks for operators and passengers (risk identification). A set of risk treatments were developed through synthesising results from literature complemented with input by subject matter experts. Finally, this model predicts the expected Business Impact based on expert review. A condensed version of this model is featured in D32.1.

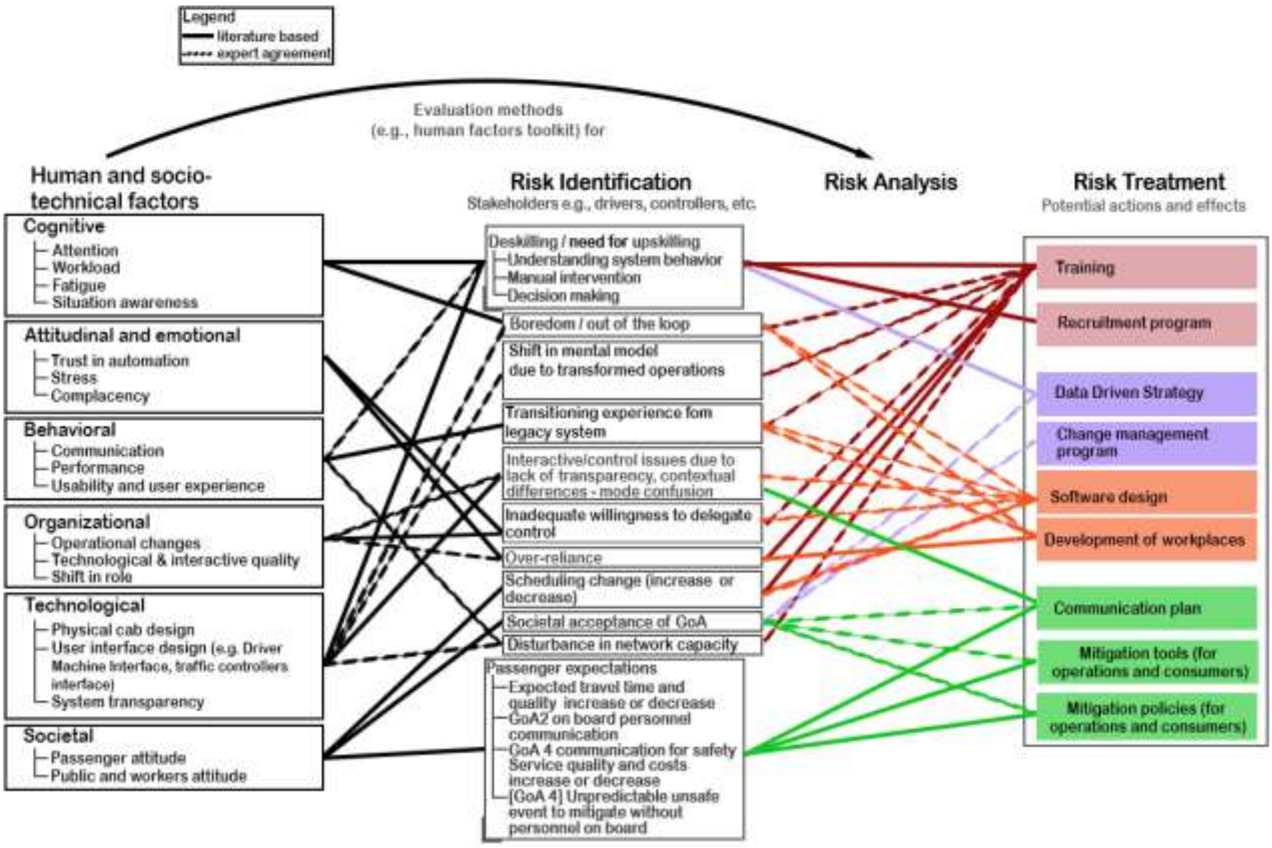


**Figure 3: BuCA interface model presents the mapping of human factors risks and mitigations in railway systems involving automation. The diagram illustrates the flow from human and socio-technical factors (cognitive, behavioural, attitudinal, organizational, and technological) through risk identification and analysis to treatment options and business impacts. Color-coded connection lines that correspond to the risk treatment distinguish between literature-based evidence (solid lines) and expert consensus (dotted lines), revealing relationships between specific human factors challenges - such as deskilling, operator disengagement, and transparency issues - and their corresponding mitigation strategies, including training, software development, and procedural interventions.**

## 2.2 Extended version of the HF-BuCA model

### 2.2.1 Human and socio-technical factors

This section details the potential human factors aspects associated with the identified risks in transitioning to a higher level of automation e.g., GoA2 and GoA4. A visual summary of the association between Human Factors aspects and Identified Risks is presented in Figure 4. This model is an extension of some of the component of the BuCa model in Section 2.1, particularly the relationship between human and socio technical factors (upper side of the model in Figure 3) and risk identification (most left column of the model in Figure 3).

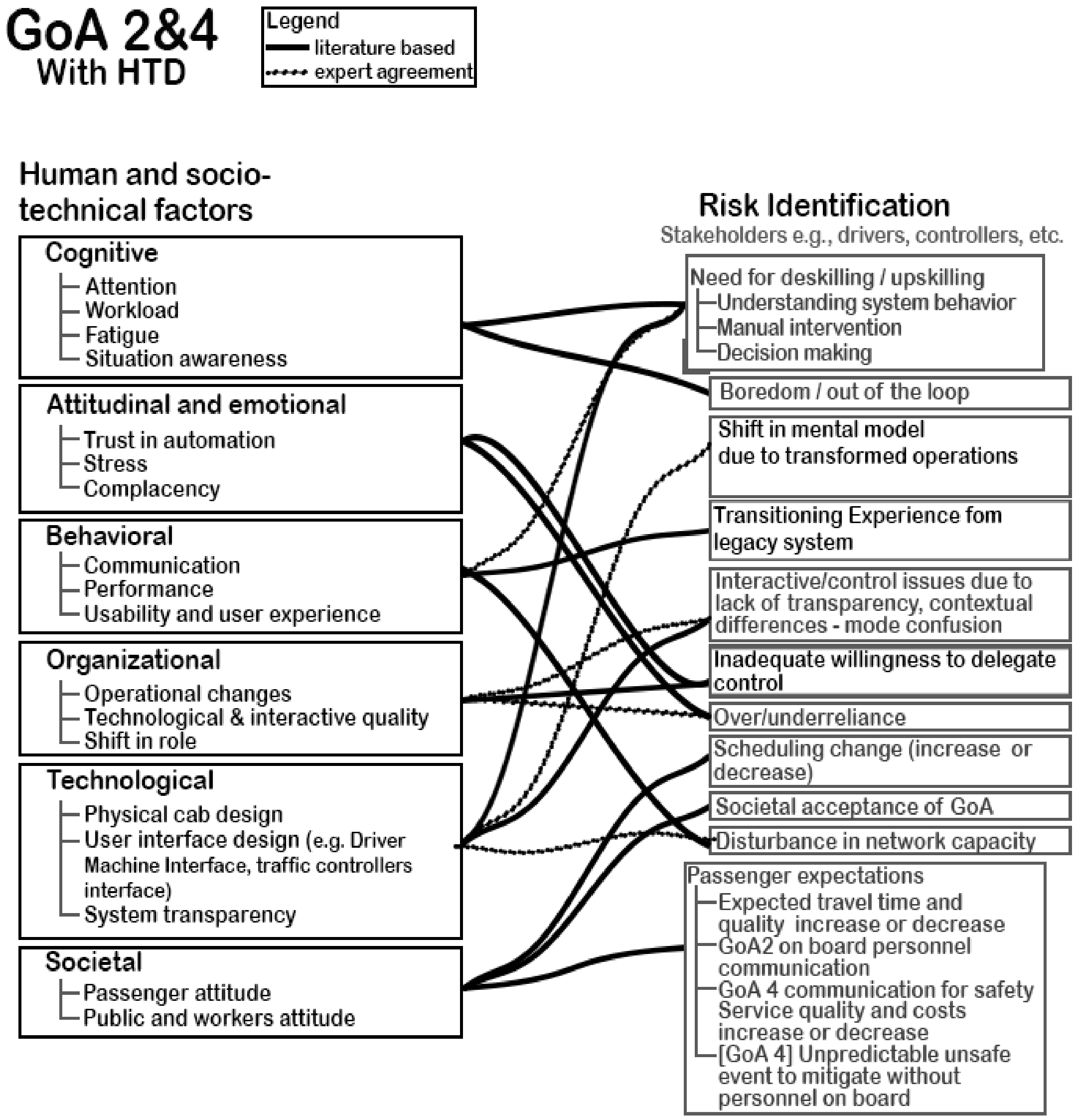


**Figure 4: Conceptual mapping illustrating the relationships between human and socio-technical factors (left) and identified risks (right) in railway automation transitions. Conceptual mapping illustrating the relationships between human and socio-technical factors (left) and identified risks (right) in railway automation transitions. The diagram categorizes human factors into six domains (*cognitive, attitudinal/emotional, behavioral, organizational, technological, and societal)* and connects them to specific operational risks. Solid lines represent evidence-based connections from literature while dotted lines indicate expert consensus, providing a structured framework for identifying which human factors contribute to critical risks in Grade of Automation levels 2 and 4. This model serves as a foundation for selecting appropriate assessment tools from the Human Factors Toolkit.**

Human factors issues span multiple dimensions, including those related to train operations, such as cognitive, attitudinal, and behavioral aspects of operators, as well as organizational factors, technological and design considerations, and broader societal aspects. These dimensions are by no means independent from each other, and the risks identified in this model is in practice often the result of interactions between multiple issues. There has been a sizeable body of literature regarding the effects of automation on railway operators (Kusumastuti et al., 2025), particularly examining the cognitive, attentional, and behavioural aspects of automation through various methods such as surveys, interviews, as well as human-in-the loop (HITL) simulations. Human factors issues in high levels of railway automation are addressed by Medina Pereira (2023), particularly examining critical challenges and opportunities for the railway industry as it adopts higher automation levels. Having awareness of the types of human and socio technical factors responsible for risk is key in identifying methods and tools to use for risk assessment (e.g. the Human Factors Toolkit – see Chapter 3). The description of components in this model is outlined below.

#### 2.2.1.1 Cognitive aspect

The effectiveness of rail operations depends on rail operators performing their key tasks, which are affected by their cognitive state during operations. Many errors and degraded performances can be traced to a suboptimal distribution of workload (Hunter & McDermid, 2022) where both underload and overload (Brandenburger & Naumann, 2019; Cogan & Milius, 2022) can be issues. Higher levels of automation tend to lead to underload (Hunter & McDermid, 2022), which in turn increases fatigue levels (Brandenburger et al., 2017; Brandenburger et al., 2021; Hassanzadeh-Rangi et al., 2023). Another cognitive aspect that affects operator performance is attention. This includes both the aspect of vigilance (Brandenburger & Naumann, 2019), which is the ability to sustain attention for a period, as well as the aspect of allocation of attention (Hassanzadeh-Rangi et al., 2023) towards different spaces of visual cues such as interfaces and outside cues (Jing et al., 2022; Schackmann & Bosch, 2024). Situation awareness has also been found to affect performance in both train drivers and traffic controllers (Fan et al., 2022). An improper management of workload could also lead to higher levels of stress (Hunter & McDermid, 2022)

#### 2.2.1.2 Attitudinal and emotional aspect

Rail operators' attitude and emotional aptitude is also a key human factor that should be considered in the implementation of automated systems. Trust in automation has been found to be a key differentiator in how operators react to the introduction of new automated technology (Hoff & Bashir, 2015). A lack of trust in automated systems may cause an operator to overthink and under-rely on the advice given by the system, which may lead to error (Hoff & Bashir, 2015; Jing et al., 2022; Fan et al., 2022). This is found more commonly in operators experienced in less automated systems (Hoff & Bashir, 2015). Complacency among train drivers is a risk that stems from reduced workload and increased automation of routine tasks (Ahmadi Rad et al., 2021; Merritt et al., 2019).

By contrast, an excessively high trust in automated systems may cause overreliance of the operator towards automated system (Brandenburger & Naumann, 2019; Hunter & McDermid, 2022), which could be problematic in cases where emergency situations that require critical thinking, familiarity with the system, and decision-making skills may be required.

#### 2.2.1.3 Behavioural aspect

Other human factors issues that may be impacted by the introduction of higher levels of automation include communication. Automated processes may decrease the need for train drivers and/or traffic controllers to communicate (Kolkman, 2023; Naumann & Thomas-Friedrich, 2024). The changes in interfaces that follow the introduction of new technologies can also affect the user experience for the rail operators (Brandenburger & Naumann, 2018; Ma & Yao, 2025) which impacts its usability (Kolkman, 2023; Lindblom & Laaksoharju, 2022; Tschirner et al., 2013). ATO GoA 2 testing by Nederlandse Spoorwegen/NS (2023) points out design transparency is a key factor for human-machine interaction to be able to complete the tasks it was designed to aid, e.g. if a driver is able to understand when ATO onboard systems starts to brake.

#### 2.2.1.4 Organisational aspect

Addressing these individual level human factors issues for operators would also require an understanding of the changes happening on the organizational and technological level Morin et al. (2025 – see deliverable D32.1) with the introduction of higher levels of automation in rail (Keevill, 2017). This requires a reflection in how roles and operations are organised according to the current standard operating procedures, and anticipating changes to be made due to new technologies. In general, operators are expected to shift to a more supervisory role in GoA level 2 (Cogan & Milius, 2022; Cort, 2020; Keevill, 2017) given that some tasks will be delegated to automated systems. The initial impact of the shift in roles for existing operators may lead to higher levels of stress and fatigue as they attempt to adapt to the system (Brandenburger & Naumann, 2018; Rad et al., 2021). On the other hand, after successful familiarisation, fulfilling a mainly supervisory role in an automated system that runs well most of the time easily results in monotony and lack of holism of activities in the workplace, potentially entailing negative effects on performance, skills, work satisfaction, health and willingness to stay at the workplace (Dreßler, 2025; Naumann & Thomas-Friedrich, 2024; Thomas-Friedrich et al., 2024). Therefore, the prospective design of responsibilities, tasks and collaboration processes should take into account operator needs. Moreover, looking forward, a shift in role could also lead to a shift in required skills to become an operator, which should be reflected in future recruitment and training efforts for train drivers (Brandenburger & Naumann, 2018; Naumann & Thomas-Friedrich, 2024; Goerke et al., 2025).

#### 2.2.1.5 Technological aspect

On a technological level, various design choices in implementing automated rail technologies should be made in consideration of the cognitive factors previously outlined. Aspects such as physical cab design, as well as any user interfaces, can be used to address potential adverse effects during the implementation of automated systems. Various studies have outlined ways to incorporate human factors research to address potential negative effects during the implementation of automated systems. Other studies have also outlined ways to integrate human factors research into the development of rail technology design (de Egea et al., 2012; Dobson, 2015; Dreßler et al., 2025; Hammerl et al., 2009; Naumann & Adam, 2025a+b; Qiu et al., 2011), which can be used to address potential adverse effects during the implementation of automated systems. Involving operators in the design process is also a key factor in ensuring a smoother and more effective implementation of new technologies (Buksh et al., 2013; Crawford et al., 2014).

#### 2.2.1.6 Societal aspect

When discussing human factors issues in rail, beyond the issues related to rail operator performance, the external perspective of passengers should also be considered, particularly passenger attitudes towards automated vehicles and the changes they bring to society at large. The benefits of ATO on passenger rail would only be obtained when passengers choose to use rail over less sustainable transport options such as personal automobiles or airplanes (European Commission, 2020), thus any barriers to acceptance should be addressed.

Additionally, the attitudes of rail operators as well as the public's perception of their perspective should also be considered as a driving force for societal acceptance of automated rail. As with many technological transitions, the introduction of new systems is often met with scepticism about how they will improve workers' lives, alongside concerns about potential job losses (Włoch et al., 2025). This could potentially hinder the acceptance of automated rail technologies.

### 2.2.2 Risk identification

The next step after compiling human factors issues in rail is to identify relevant risks associated to them. The initial part of this analysis was generated by extracting human and socio-technical factors from the literature review and multiple brainstorming sessions by five experts in rail and human factors outlining the relationship between factors. Additional domain experts (six in total) in rail operations in both technical and operational aspects were also involved in the latter stages of review and feedback.

#### 2.2.2.1 Deskilling/need for upskilling

One of the key consequences of the shift in roles for train drivers is the potential loss of specific job skills, commonly referred to as deskilling. The lesser need for manual operations may cause operators to underutilise their knowledge for tasks that require, e.g. speed control or having route knowledge (Buksh, 2013; Cogan & Milius, 2022; Emery, 2017), thus putting themselves in danger of losing the skill completely, while it is still useful in the case of a required manual intervention. There is also the potential case of drivers mainly trained to operate ATO GoA2 trains but needing to drive manually most of the time due to limited availability of trains running ATO GoA2. These drivers are also at risk of deskilling on using automated systems due to lack of practical use even after training.

The increasing utilisation of automated operations and decision tools could also degrade operators' decision-making skills in critical situations (Brandenburger et al., 2016; Keevill, 2017; Naumann & Thomas-Friedrich, 2024). One crucial aspect of automation is that while it aims to reduce errors, it can increase the risk of rare but serious errors when human intervention is suddenly required after prolonged inactivity (Cogan & Milius, 2022; Hunter & McDermid, 2022).

#### 2.2.2.2 Boredom/ "out-of-the-loop"

Automation reduces the driver's active involvement and changes the work to a passive supervisory role (Vanderhaegen et al., 2021). This change can make the work mundane and routine, leading to boredom and understimulation (Cogan & Milius, 2022; Naumann & Thomas-Friedrich, 2024), also referred to being "out-of-the-loop" regarding the system state. Drivers must monitor automated systems and the internal and external environment continuously, but with less frequent needs for intervention (Bernheim, 2022). Long periods of low demand for intervention and monotonous monitoring can impair vigilance (Robinson et al., 2015). Drivers may experience a decrease in vigilance which reduces their ability to detect anomalies or respond quickly to critical events (Ahmadi Rad et al., 2021; Australian Transport Safety Bureau, 2024). Several incidents in the GoA2 systems, such as on the London Underground (at Notting Hill Gate, 2018) and the Bucharest Metro (in 2019), have highlighted how boredom and monotony can contribute to human error, including missed hazards, incorrect door operation and delayed emergency response (Hunter & McDermid, 2022). These incidents show that it is insufficient to blame the operator, as system design and training must address the human factors introduced by automation (Ahmadi Rad et al., 2021). A simulation study by a Dutch rail undertaking discovered cognitive limitations from drivers operating ATO, such that the risk of out-of-loop behaviour may lead operatos to restrict the usage of ATO to predefined time intervals (Nederlandse Spoorwegen 2024a), although further research is needed on the different driving phases such restrictions may need to apply to.

#### 2.2.2.3 Shift in mental model due to transformed operations

One of the potential technologies that will be introduced in the implementation of a higher grade of automation is the use of Hybrid Train Detection (HTD) on ERTMS level 3, which uses dynamic blocks to manage train traffic. This will require both traffic controllers and train drivers to adapt their approaches in terms of strategies to build situational awareness and to support decision-making. Previously, operators - whether traffic controllers or train drivers - relied on their contextual knowledge, such as familiarity with routes and environmental constraints, to develop mental models based on accumulated experiences.

The shift to dynamic blocks might entail that traffic controllers will transition from managing fixed blocks to operating within a framework dictated by real-time, contingent factors. At the same time, train drivers will need to adjust to a more data-driven, automated system that reduces reliance on manual interventions. This change will diminish the dependence on accumulated knowledge and preformed schemas developed through repeated exposure. Traditional route-based decision-making and manual distance adjustments will be enhanced by leveraging predictive systems and automated distance control. Instead of relying solely on their experience, operators will need to focus on interpreting real-time system feedback and interacting with advanced automation tools.

These changes will require the development of appropriate interfaces and systems to support operators and a reshaping of the training content regarding how to drive and control traffic with the potential introduction of HTD in the implementation of GoA level 2 or 4.

#### 2.2.2.4 Transitioning experience fom legacy system

Transitioning current staff to higher levels of automation requires them to forego their familiarity with legacy systems and adapt to new modes and interfaces. While this requires some learning curve, the knowledge gained from operating previous systems may transfer to the more general context of train operations (Grippenkoven, 2022), which can be either beneficial when the new system's workings are compatible with the previous knowledge, or harmful to performance, when the new system's workings differ from the expectations. However, the new system should be designed so that even newly trained operators without knowledge of previous systems can perform as well. fBrandenburger et al. (2021) emphasize involving both old and new operators in the development of new systems for a smooth and efficient transition

#### 2.2.2.5 Interactive/control issues due to lack of design transparency, contextual differences or mode confusion

Mode confusion occurs when train drivers misinterpret or lose awareness of the automation level, e.g. GoA1 to GoA2, leading to errors in role expectations, system monitoring, or interventions (Ahmadi Rad et al., 2021; Stene, 2018). This issue is critical in transitions between manual driving with ATP supervision (GoA1) and semi-automatic operation with driver monitoring the route (GoA2). Poorly defined or communicated mode transitions as well as poor display of the current mode may leave operators uncertain about their responsibilities and the required actions (Keevill, 2017). Mode confusion can be caused by lack of transparency and by contextual differences e.g., differences in terms of needs or interfaces. This may contribute to incidents, such as signals passed at danger (SPAD) or derailments, when operators misinterpret system states (Ahmadi Rad et al., 2021). Tests at a Dutch railway operator have also shown that the lack of information of what is happening inside of the system may lead drivers to intervene on ATO GoA level 2 (Nederlandse Spoorwegen, 2024a).

#### 2.2.2.6 Inadequate willingness to delegate control

Reliability of the ATO system is a critical factor, because it will influence the train driver's willingness to delegate control to the ATO system, especially in the GoA2 level of automation (Azevedo Sa, 2021). If the system consistently demonstrates a robust performance across various scenarios including adverse weather and operational disruptions, operators are more likely to trust and rely on the system (Hoff & Bashir, 2015). Furthermore, when the ATO system handles routine operations and recovers from malfunctions or disruptions, drivers adjust their mental models and become more comfortable delegating control (Azevedo Sa, 2021; Walker et al., 2023). Feedback on the system's intentions and actions is crucial. It needs accurate and timely feedback; trust is gained when automation explains its behaviour, and trust is maintained even if the system experiences occasional errors (Balfe et al., 2018). It is also essential to take a user-centred approach to the UX design to ensure the system is intuitive and therefore trusted by train drivers (Merlevede et al., 2024). However, underlying the issue with delegating control is to what extent is driving under ATO GoA systems is mandated in order to encourage a level of adoption of GoA2 that will realise its potential benefits.

#### 2.2.2.7 Over-reliance

As drivers observe the automated system performing reliably, they may become complacent and develop automation bias, overestimating the system's capabilities and failing to monitor it critically (Hunter & McDermid, 2022). This can lead to "out-of-the-loop" performance issues, where driver skills and situational awareness deteriorate due to a lack of active engagement (Grippenkoven, 2022). The Bucharest Metro Line 2019 incident highlighted how software limitations and inadequate driver intervention contributed to a derailment due to overtrusting the automation (Hunter & McDermid, 2022).

#### 2.2.2.8 Scheduling changes (increase or decrease)

The advantage of automated rail technology allows increased availability of trains through increased frequency, longer service hours, and less dependency on human labour availability. Prospective passengers are generally aware of these advantages, where increased frequency and reliability being drivers for acceptance towards automated rail, however, safety issues take priority above advantages from automated rail, particularly for GoA level 4 (Arzer et al., 2024; Lemmonier et al., 2023; Cogan et al., 2022, Fraszczyzk et al., 2015).

#### 2.2.2.9 Lack of social acceptance of GoA

Social acceptance of automation is a key enabler of innovation deployment. Literature (Hancock, 2023) suggests that workers and society are uncertain about the benefits and disadvantages of automation. Recent survey data indicate that one out of six European workers fear automation will reduce job opportunities (Włoch et al., 2025). In the context of railways, there are certainly concerns about potential job loss and function reallocation that should be mitigated (Lemonnier et al., 2023). In this sense, operationalizing appropriate mitigation strategies to minimize unacceptable consequences for workers and society is essential to social acceptance. Concurrently, it is important to develop an appropriate plan for communicating the realistic implementation of autonomy in railways. This will contrast the "imagined" automation of train operations, which, as Lemonnier et al. (2023) suggest, is often built upon inappropriate narratives and the individual fear of the dehumanization of services. Additionally, the train riding experience itself may be possibly be negatively affected under ATO due to braking and accelerating actions triggered by automated systems when not properly optimised. In an evaluation of brake comfort in an early prototype of ATO driving algorithms, the braking was perceived to be more abrupt and uncomfortable compared to manually driven trains (Nederlandse Spoorwegen, 2024b). A further examination of passenger acceptance towards automated rail systems is included in our passenger acceptane study in chapter 6.1 of this deliverable.

#### 2.2.2.10 Disturbance in network capacity

All types of operators can (in)directly influence the availability of the infrastructure (i.e. capacity) in GoA1, e.g. train drivers can vary in their driving styles via e.g. headway, platform occupation time (see D32.5). Similary dispatchers/ traffic controllers can influence network capacity via e.g. routing, recovery time of incidents. The level of influence might differ amongst different GoA levels, in which the driving style of train drivers is minimalized with ATO.

#### 2.2.2.11 Passenger expectations issues

Ultimately, adopting ATO is done to increase train ridership and encourage the railway as a primary choice of transport. Beyond communicating the added value of these new technologies to potential passengers, any concerns and potential barriers should also be addressed. While the intention to use higher GoA trains is relatively high, particularly for regular train users (77.6%, Pakusch et al 2017) and people with experience using autonomous vehicles (88%, Pakusch et al 2017), the influence on passengers' trust towards automated trains should be addressed.

In particular, potential users are still cautious about the robustness of driverless train operations (GoA levels 3 and 4). While the advantages of these systems such as reduction in prices and better availability are apparent to the passengers, some surveys suggested that passengers would only find it acceptable if it did not compromise safety (Cogan, 2022; Fraszczyk, 2015)

Research indicates that train drivers are essential in addressing unplanned events, such as track obstructions, equipment failures, and emergencies (Jansson, 2023). Quantitative research shows that these situations occur frequently and often require human judgment and intervention (Karvonen et al., 2011). Respondents of surveys also point out concerns on passenger onboard safety and the lack of guidance on how to behave during disruptions without the presence of train staff (Arzer, 2024). These are examples of concerns that should be addressed regarding the elimination or reduction of onboard train drivers or train attendants with additional operational training (cf. Naumann & Adam, 2025a+b).

Literature on passenger expectations and acceptance of automated rail provides several communication strategies to address these concerns. Arzer (2024) emphasises the need for visible safety features, information transparency, and human-like communication (e.g., "humanising" autonomous systems). Detjen (2021) suggests targeted communication based on user attitudes (e.g., addressing detractors with safety data). At the same time, Wang (2016) posits that trust is built with advanced and perceivable/communicated safety technologies e.g., intrusion detection systems, platform screen doors etc.

A more thorough summary of the current landscape and discussion on the factors affecting passenger acceptance towards automated rail is presented in section 6.1. This section also presents additional data and insights collected from a survey study conducted for this Europe's Rail project.

### 2.2.3 Risk treatment

As part of the larger analysis conducted for the interface model, risk treatments were identified by analysing risk factors identified in the previous section. This section of the analysis expands the expertise of participants involved in the discussion beyond human factors experts. Experts from the business, management, organisational, and technical side of rail operations were involved in reviewing identified risks and provide feedback on possible treatments and solutions.

In line with Figure 3 we will focus on expected treatment of the identified risks. Figure 5 represent these risk treatments using a tree of indicators that encompasses different targets of risk treatments. Expected relevant stakeholders are noted for each 'risk treatment'.

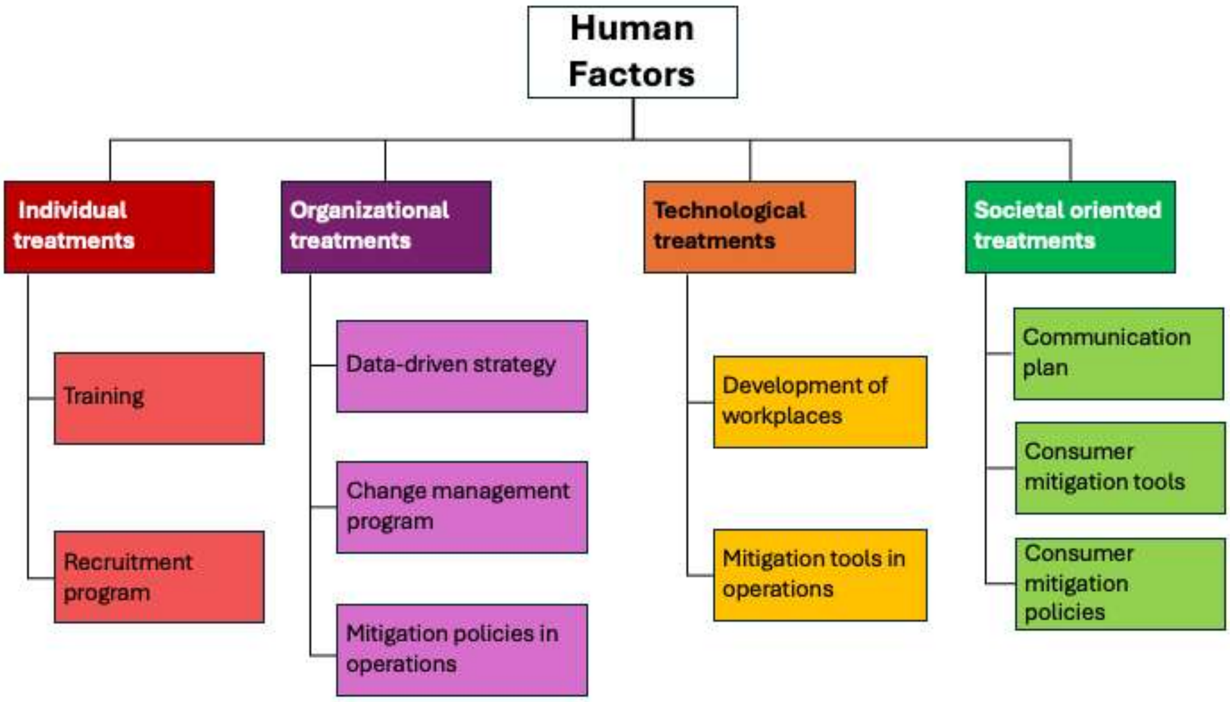


**Figure 5: Human factors risk treatment organised as tree of indicators**

#### 2.2.3.1 Individual treatments

Individual treatments deal with the risk aspects related to the effects of system changes on train drivers. As previously outlined, implementing new systems with automated components will most likely result in a shift in roles and changes in job description. This would in turn require a retraining of current employers to fit the new job requirements and an adjustment of what competencies are needed future employees. Addressing these issues fall within the domain of the direct employers of train drivers, such as infrastructure managers and train operating companies, particularly the human resources departments. The development of such programs should also involve regulation bodies and worker's unions to ensure equitable processes where all involved parties can cooperate.

#### *2.2.3.1.1 Training*

*Involved stakeholders: RU/IM training department*

Training of operators is often used to mitigate in probable issues in GoA2, e.g. training and interface design might mitigate lower situational awareness (SA), suboptimal workload, and fatigue induced by higher levels of automation (Brandenburger & Naumann, 2019). Training can also potentially increase operators' acceptance and awareness regarding the interaction with automated systems (Papadimitriou, et al., 2020).

#### *2.2.3.1.2 Recruitment program*

*Involved stakeholders: RU/IM HR*

The changed operational competences should be in line with new recruitment strategies. For GoA2 it has been identified that the delegation of part of the current tasks to automated systems will likely transform the duties of these jobs and potentially the way of recruiting and training operators (Brandenburger & Naumann, 2018).

### 2.2.3.2 Organizational treatments

Organisational level treatments involve strategizing change within organisations responsible for conducting train drivers. This falls mostly to the leadership of infrastructure managers and railway undertaking with regulatory oversight by train drivers and governmental bodies.

#### *2.2.3.2.1 Data-driven strategy*

*Involved stakeholders: government/infrastructure manager*

Societal value shifts (e.g., environmental concerns, accessibility expectations, digitalization preferences) and technological advances (e.g., ERTMS, predictive maintenance, autonomous systems) require railway organizations to adapt their structures, processes, and performance measures to maintain safety, quality, and regulatory compliance in line with contemporary standards and stakeholder expectations. The digitalisation of the railway sector is transformative in establishing rail operations as a sociotechnical system (Morin, 2025). The vast and rapid availability of infrastructure and operational data allows stakeholders to gain valuable insight on the status of infrastructure (Antonowicz, 2022). On the operational level, digitalisation has also been increasingly used to inform important aspects such as timetabling, traffic control and route setting, (Tschirner et al., 2014). Thus, the wealth of information available should be utilised. However, this should also be accompanied by a more increase of digital literacy in railway organisations (Tretten et al., 2021).

#### *2.2.3.2.2 Change management program*

*Involved stakeholders: RU/IM implementation program*

An implementation program as can be identified with the roll-out of ERTMS is needed as a change management program is necessary to address various challenges in the development of technology. A study by Morin et al., (2025) analyses cases studies in the implementation of Automatic Train Operation (ATO) and Remote Train Control (RTC) and conclude that collaborative approaches, stakeholder engagement, and incremental deployment is critical to mitigate risks and maximize the impact of automation technologies. Implementation programs should be preceded by a preparation phase that ensures the alignment between and readiness of the different stakeholders involved (Morin et al., 2024). A more thorough discussion of change management programs by these works is available in deliverable D32.1 of this work package.

#### *2.2.3.2.3. Mitigation policies in operations*

*Involved stakeholders: RU/IM*

Similarly to mitigation tools, additional procedures may be needed to mitigate a gap between the designed and implemented ATO system in countries. For instance, countries may deal differently with disruption mitigation procedures, which may result in additional use cases and user processes for certain countries.

### 2.2.3.3 Technological treatments

As with any technological advancement, risk should also be addressed on the technical side. Here responsibilities lie with parties responsible for software development and implementation, in this case technology suppliers, infrastructure managers, and railway undertaking. It is also important for regulators to provide oversight.

#### *2.2.3.3.1 Software design*

*Involved stakeholders: suppliers*

Human-centred design of the new workplaces (for staff) and human-technology interfaces (for passengers) involved in higher GoAs should support system performance and safety. This concerns design decisions regarding aspects such as the work environment, hard- and software, information content and display, control elements provided and operator tasks. Co-design with users can ensure better aligned requirements and facilitate positive HF impact such as improved usability, situation awareness etc. This can be facilitated through the systematic integration of human factors considerations and experts in the technology development and steady development of Human Readiness Levels in alignment with Technology Readiness Levels as discussion in deliverable D15.1 in FP1-MOTIONAL

#### *2.2.3.3.2 Development of workplaces*

*Involved stakeholders: suppliers*

Moreover, it is not sufficient to concentrate on HMI alone. The design of workplaces should also include considerations of and adequate solutions for the operational and collaboration processes that the work will involve. Workplace development should also support deviation management. When systems, subsystems, infrastructure or vehicles fail, there must be well-designed auxiliary solutions that contribute to good problem-solving ability for personnel who take over operations from the automated systems.Therefore, stakeholders such as railway operators and infrastructure managers need to be involved as well.

#### *2.2.3.3.3 Mitigation tools in operations*

*Involved stakeholders: RU/IM/ implementation program*

Mitigation tools can be hardware as well as software tools that are needed to support the core ATO system that is developed by suppliers. Mitigation tools can be developed by other parties and these tools may vary per country due to country specific procedures, e.g. a mitigation tool might be a solution to mitigate the boredom/ out-of-the-loop risks that train drivers when driving longer than 10 minutes with ATO GoA2 (see section 2.2.2.2).

### 2.2.3.4 Societal oriented treatments

In order to ensure a smooth adoption of automated train systems, it is also important to examine risk aspects related to end users, i.e. passengers, as well as the societal perception of automated train operations of the general public. Communication plans should be co-designed between all stakeholders. The communication plans could be developed to target certain demographic or address specific concerns. In addition, there are also mitigation tools and policies as it relates to the experience of passengers, with a particular emphasis in addressing safety concerns.

#### *2.2.3.4.1 Communication plan*

*Involved stakeholders: government/suppliers/RU/IM)*

Targeted communication by the sector to support public acceptance can be applied based on user attitudes (e.g. addressing detractors with safety data) (Detjen et al., 2021). Arzer et al. (2024) identified communication quality as a key factor influencing passenger experience with autonomous trains.

#### *2.2.3.4.2 Consumer mitigation tools*

*Involved stakeholders: RU/IM*

Additional tools can support in the public acceptance of ATO GoA2, e.g. Arzer (2024) emphasizes the need for visible safety features, information transparency, and human-like communication (e.g., "humanizing" autonomous systems). Additionally, trust is built with advanced and perceivable/communicated safety technologies e.g., intrusion detection systems, platform screen doors, etc. (Wang, 2016). Other solutions in development that could address this problem include AI-based crowd detection technology.

#### *2.2.3.4.3 Consumer mitigation policies*

*Involved stakeholders: RU/IM*

Complementary to the mitigation tools, policies should also be developed to build passenger trust. It is particularly critical to address safety concerns through policies, such as emergency protocols in the case of disruptions or even calamities.

## 2.2.4 Business impact

The decision to deal with the potential risks, and on how to treat these is based on priorities and strategic processes of decision-making. Human factors is only one component in assessing overall business impact. A more holistic view is required to properly assess a comprehensive business impact by integrating analysis from other factors, such as technical specifications or from a policy perspective. Figure 6 illustrates how business impacts relate to human factors risks in the model.

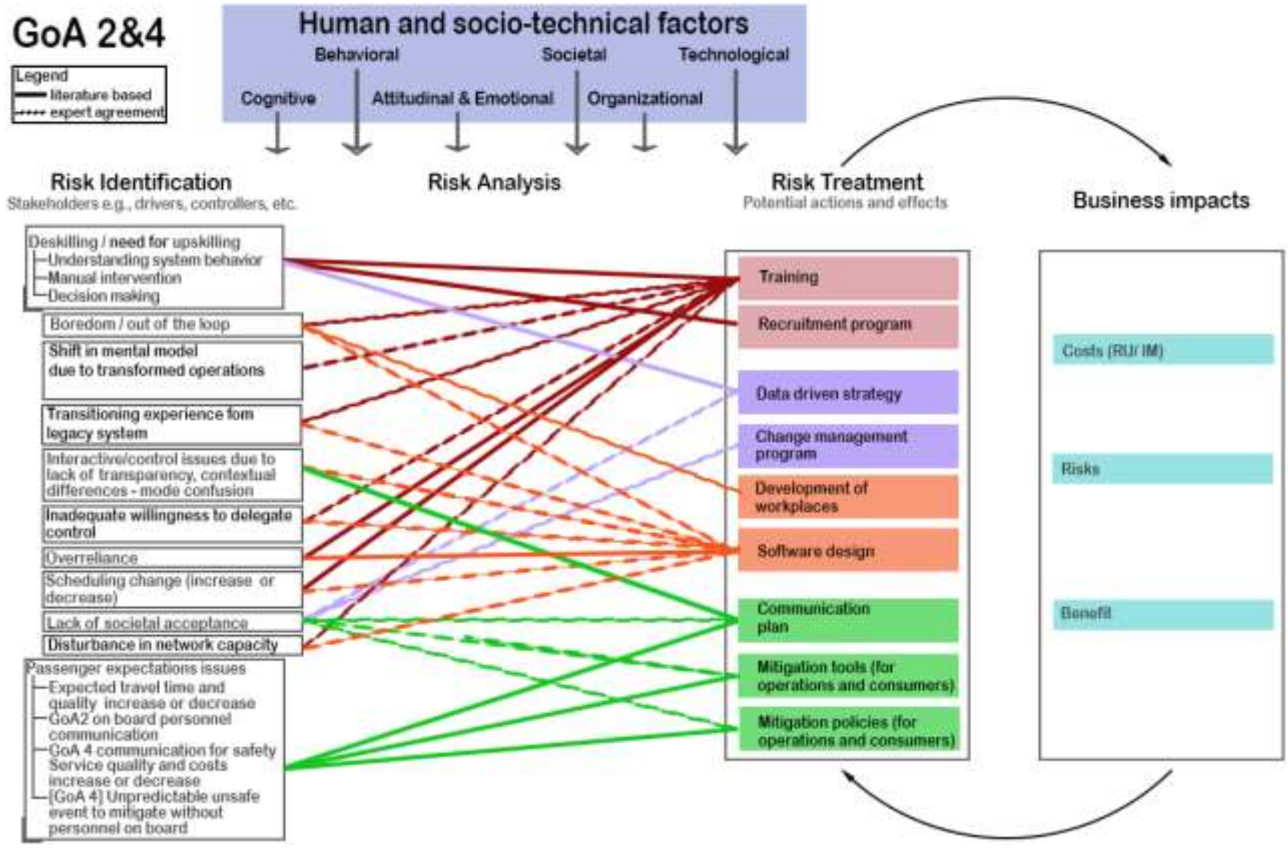


**Figure 6: Relationship between human factors risk model with business impacts**

A more condensed representation of the human factors component of the business case can also be seen in Figure 7. Here we can see costs as 'treatments costs' outlined in section 2.2.4.1, and the components of risk and benefit. This model should be treated more as a starting point of mapping possible human factors components that can contribute to a business case, and should not be treated as a complete and comprehensive list of human factors issues and further analysis may enrich the model.

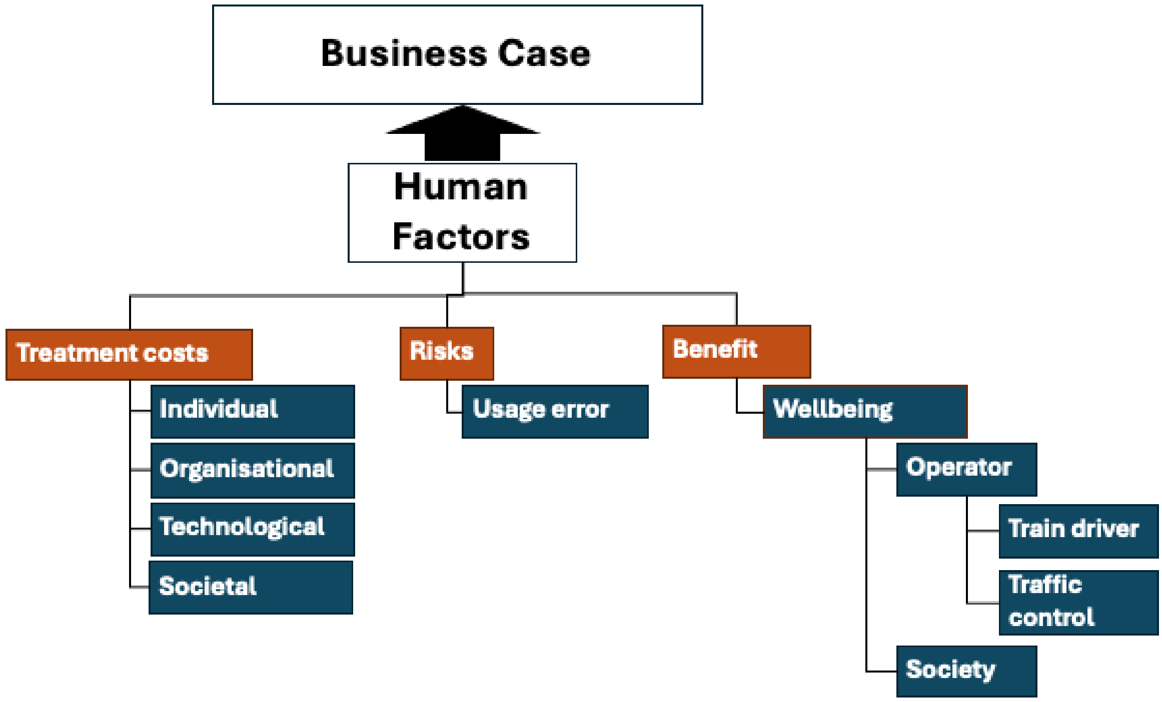


**Figure 7: Human factors components in the business case**

#### 2.2.4.1 Cost

Costs in the business case element generally refers to resources allocated to implement different risk treatment costs (see section 2.2.3). Essentially, in accompanying upgrades in technical systems, investment in financial capital is necessary in addressing human factors risk through risk treatment, both through CAPEX and OPEX. Ensuring that systems comply with human factors requirement could require implementation of additional software and hardware, as well as associated maintenance costs.

In addition to capital costs, the implementation of software and change management programs, training and shift in recruitment materials, development of mitigation tools and procedures, etc. will also require human resource investment. Proper implementation of risk treatments will require involving experts with specialised knowledge and training, who may also need to facilitate knowledge transfer for management and operators.

#### 2.2.4.2 Risks

One of the ways to frame the concept of human factors in rail operations is to conceptualise it as a risk, particularly safety risk. One of the key goals of identifying human factors risk and developing risk treatments is to address potential safety issues. Not accounting for human factors risks and appropriately applying risk treatments could lead to avoidable errors and incidents that may be financially costly and/or endanger the safety of train drivers/passengers. Safety failure incurs massive economic consequences not only in financial loss but also reputational damage and loss in trust. Errors in a human factors sense is often conceptualised as “human error.” However, the term human error is often interpreted as an error that is caused by a mistake of an operator interacting with the system, attributing fault to the human. Human factors error can also arise from the system not properly accommodating user needs and way of working. Thus, we encourage the use of the term “usage error” as the potential consequence of human factors risk.

#### 2.2.4.3 Benefit

Attending to human factors issues may also provide a benefit of improving the well-being of rail workers, as well as society at large by the implementation of ATO. A survey of train drivers determined that major issues in their work include work hour and schedule, work-life balance, driving on the similar route in the same locomotives, behaviours of passengers and fallback strategies of the automatic systems (Qiu et al., 2011). Even in higher levels of automation, there is still some level of human-in-the-loop in rail operations, such as remote train drivers and train traffic controllers to supervise automated train traffic. Adjusting job descriptions and balancing employee workload would lead to more effective and satisfied workers and lower retention rates.

Additionally, well-being of society, particularly train passengers, is also an important component. When society is able to trust automated technologies in rail and feel safe using it, then the potential benefits in ATO usage can be reached. This is relevant as well to society as large, as public sentiment, which includes non-rail users, also shape automated rail’s acceptance in society.

While this model was initially developed for the context of GoA level 2, the concepts and relations outlined in this model also applies to transition to GoA level 4. The main difference being that the presence of onboard staff is no longer essential for operations. Aspects related to in cab performance of train drivers are no longer significant, but remote driving may still be needed on occasion, so competencies regarding driving performance will still be relevant in emergency contexts.

### 2.2.5 GoA4 in the HF-BuCa model

The GoA4 model introduces relatively little change for traffic control room operators compared to GoA2. Meanwhile, remote driving will necessitate significant advancements in software solutions, operator training, and system reshaping compared to GoA2. In GoA4, while the driver does not need to always directly control the train cab, responsibility still falls to them in the case of needing manual takeover due to emergencies. In some cases, drivers are also responsible for monitoring trains leaving the station (Niu, et al., 2018). In other cases, this falls to the domain of the train traffic controller. Richard, et al. (2021) examined an incident involving autonomous train operations and concluded that managed safety should be developed based on the distribution of shared tasks and/or supervision process between operators and autonomous systems.

One of the primary areas requiring investment will be communication systems to ensure safety in the absence of onboard personnel. This is particularly important given that most passengers, when surveyed (Lemonnier et al., 2023), expressed a preference for having personnel onboard to address safety concerns, especially in cases of unexpected incidents, malfunctions, or other emergencies. To address these concerns, the development of advanced communication applications, as well as digital and robotic solutions, could help mitigate public apprehension by providing effective responses to such situations.

Despite these potential technological mitigations, strategies for fostering public acceptance of completely unattended trains remain unclear. Ensuring trust and confidence in fully autonomous systems will require not only technical innovation but also comprehensive public engagement and education.

### 2.2.6 Conclusion

This section started with an extensive literature review on focus on human factors and automation. Based on these insights, the HF-BuCa interface model was built, providing a structured and evidence-informed foundation for understanding how human and socio-technical factors shape the risks, opportunities, and business implications of transitioning to higher Grades of Automation (GoA2 and GoA4), and when combined with HTD. Through multiple iterations with human factors and business case experts, the model integrates academic knowledge with expert judgement to map how cognitive, attitudinal, behavioural, organisational, technological, and societal dimensions contribute to specific operational risks. These insights form the basis for identifying effective risk treatments at individual, organisational, technological, and societal levels.

By embedding human factors considerations into risk identification, analysis, and treatment, the model highlights the central role of human-system interaction in ensuring safe, efficient, and accepted automated railway operations. It also illustrates how investments in training, workplace and software design, change management, communication strategies, and mitigation tools may influence both costs and benefits within the wider business case.

All in all, the HF-BuCa model demonstrates that addressing operational actors/ operators are not only essential for safety and operational performance, but that a focus on passengers is also needed for long-term societal acceptance. Future work should further develop this interface model for GoA4 and HTD, and also focus on potential benefits.

# 3 HUMAN FACTORS TOOLKIT FOR RESEARCH

This section describes a summary of the development and use of the HF toolkit 1.0 from FP1/WP15 which is also reported in FP1/D15.2 and applied in FP1/D16.1.

We synthesised information from academic literature on human factors research in railway and developed a toolkit that identifies a set of human factors constructs that were commonly measured by practitioners in the railway domain, particularly in human-in-the-loop (HITL) simulations, and methods used to measure them. We then conducted 3 rounds of feedback consisting in total of 20 responses rail human factors experts to review and validate information from the literature and contribute to the list of tools and measurements. We identified 8 main constructs that are commonly measured in rail HITL studies (Figure 8).

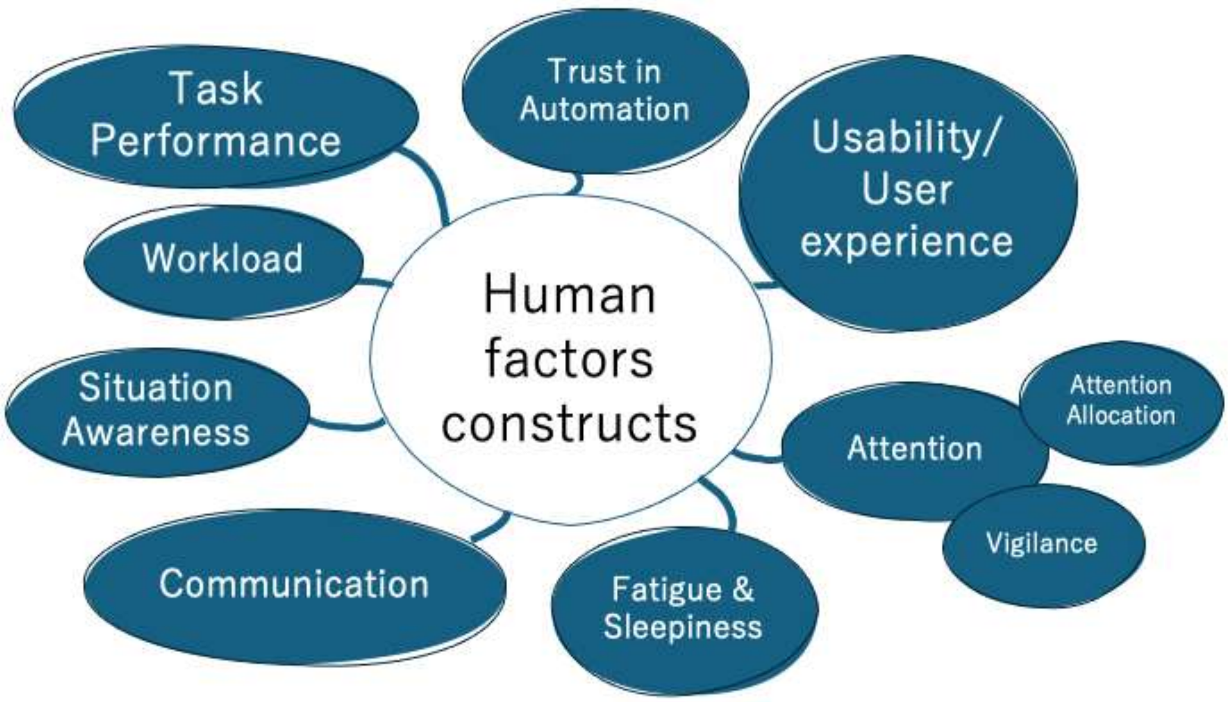


**Figure 8: Diagram of eight human factors constructs included in the HITL toolkit**

The constructs and the numbers of measures compiled are as follows:

1. Task Performance: Performance as a construct generally refers to how well an operator executes a specific task or duty in a simulation. This is connected with the concept of human reliability and safety (Ciani, et al., 2022). Measuring performance serves the purpose of identifying the direct impact of certain experimental scenarios and conditions in the simulation. Skill degradation is a specific performance aspect to investigate. The way performance is measured is very dependent on the goals, specifications, and the capability of the simulation, but in general it should be as close as possible to how the performance would be measured in practice.
2. User experience and usability: User Experience and usability is a construct that is oriented towards how operators judge their impressions of the systems they encounter in the

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

3. Workload: Workload may be defined as the relationship between the resources required to carry out a task and the resources available to, and hence supplied by, an operator[1]. These resources include, but are not limited to, time, mental and physical resources.
4. Fatigue and Sleepiness: Fatigue is a complex state manifested by a lack of mental alertness, reduced physiological functions, and drowsiness (Fan, et al., 2022). Researchers generally classify driving fatigue as central nervous fatigue, psychological fatigue, and physical fatigue according to the causes of its generation.
5. Communication: Communication in railways is the ability to clearly and effectively exchange and transmit information between operators and/or passengers. It is often cited by operators to be one of the key non-technical skills that should be possessed by both train drivers and traffic controllers (Brandenburger, et al., 2017; Du, Fang & Niu, 2018). Communication between train drivers is critical from a safety perspective and is often regulated through strict operational communication procedures. On the other hand, communication with passengers focuses on providing clear, timely, and understandable information to ensure a safe and smooth travel experience, especially during disruptions or emergencies.
6. Situation Awareness: Situation awareness (SA) is defined as (1) the perception of elements in the environment, (2) the comprehension of these elements, and (3) the projection of these elements in the near future (Endsley, 1988). SA is one of the most studied human factors construct, including studies concerning human factors in railway contexts. SA is also commonly identified by end users to be a critical aspect to be aware of while performing their duties (Buksh, et al., 2013; Brandenburger & Naumann, 2019; Brandenburger, et al., 2017; Du, Fang & Niu, 2018; Lo, et al., 2016).
7. Attention: There are two subconstructs related to attention covered: attention allocation and vigilance. Attention allocation refers to the division of an operator's attention during operations. Attention allocation may be used to test the effectiveness and efficiency of information gathering from a new interface. Vigilance, also termed sustained attention or concentration, is defined as the ability to maintain concentrated attention over prolonged periods (Fan, et al., 2022; Spring, et al., 2012). During this time, operators attempt to detect critical stimuli in their respective workstations.
8. Trust in Automation: Trust can be defined as "the attitude that an agent will help achieve an individual's goal in a situation characterized by uncertainty and vulnerability" (Papadimitriou, et al., 2020). Trust in automation impacts the extent to which operators utilize the affordances provided by automated systems. Both over and under-reliance on automated systems may lead to safety violations and incidents (Pacaux-Lemoine, Gadmer & Richard 2020; Rad, et al., 2021).

The content of this toolkit is then utilised to develop an initial section of the human factors section of the interface model (see chapter 2) by using it to identify individual human factors risks related to technology shift in rail operations. A summary of the measurement techniques that can be used to measure the above human factors constructs can be found in Appendix A. The full toolkit document is available as an open-source file at this URL: [https://osf.io/5rw24](https://osf.io/5rw24)

# 4 TASK ANALYSIS AND OPERATIONAL PROCESS FOR TRAIN DRIVER AND ONBOARD PERSONNEL IN CURRENT OPERATIONS (GOA1)

This chapter presents results from the Swedish context (Iron Ore Line) for the train driver and onboard personnel in the current operational situation (GoA1 with ATP). A method such as a task analysis is used to structure the work (tasks) of operators. The task analysis uses the literature review from Chapter 2 as input. In Section 4.1 the operational process descriptions for current operations are outlined. Sections 4.2.1 and 4.2.2 present the task analysis of the train driver and onboard personnel in the current operations (GoA1).

## 4.1 OPERATIONAL PROCESS

The operational process is based on the X52 Regina, a Swedish electric multiple unit (EMU) passenger train operating on the Iron Ore Line in Northern Sweden. Participant observation was used when developing the operating process. The researcher joined the operator during regular train operations and observed routine tasks and actions onboard. The process was validated by the train drivers.

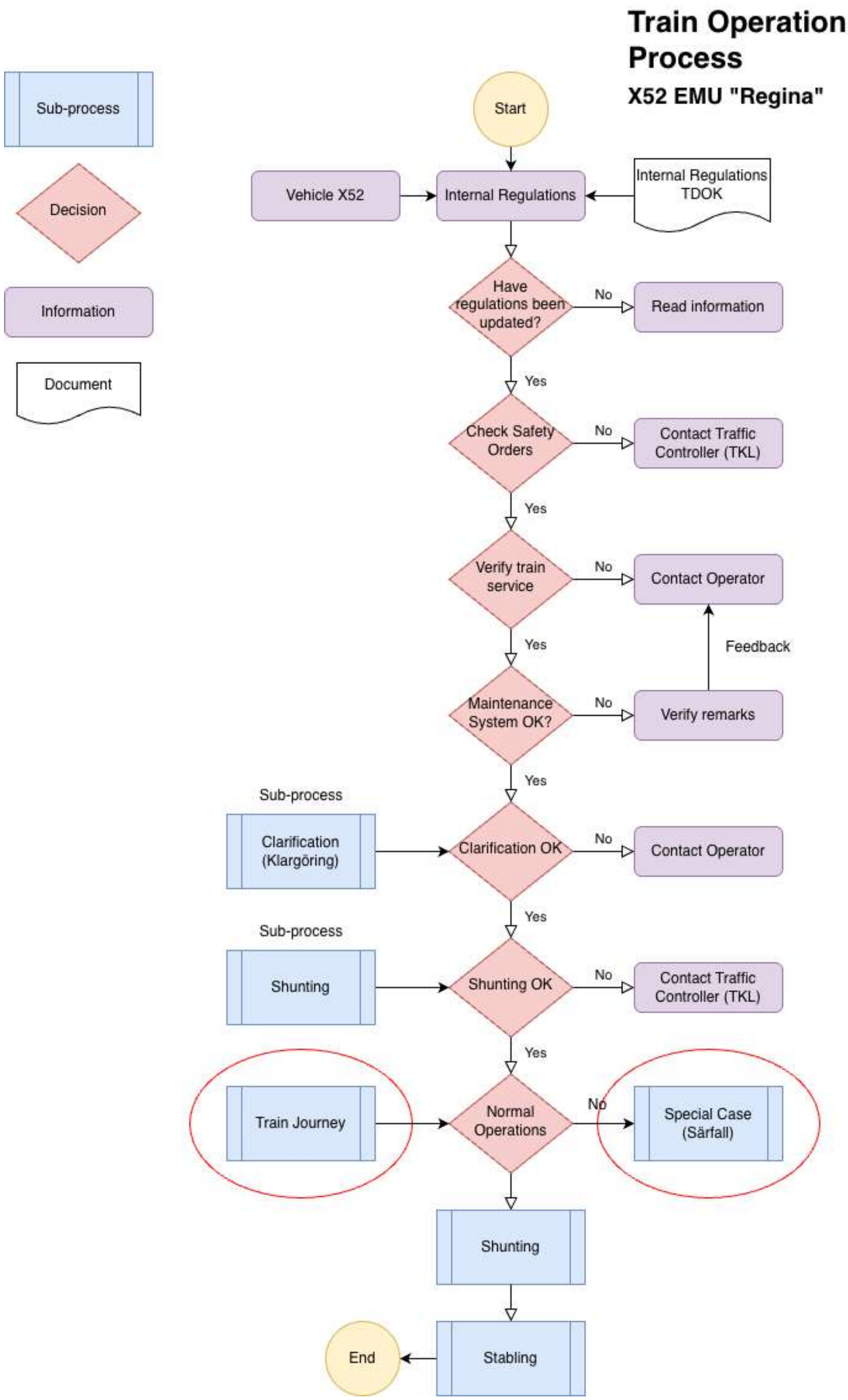


**Figure 9: Train operation process in GoA1 operation at the Swedish Iron Ore Line**

### 4.1.1 Start

#### 4.1.1.1 Vehicle

The driver powers up the train, activates all technical systems (such as control panels, displays, signalling systems), and ensures the train is ready for operation. When the X52 starts up, technical and operational vehicle information is displayed on the driver's monitor and control panel. This information is designed to give the driver full oversight and control of the train's status before departure.

1. Vehicle identity: train unit number, train number, and configuration (number of cars, designation)
2. System status: overview indicators for key systems include door status (all doors closed/open), brake status (ready/not ready), and the main power supply. Specific safety system status, such as ATC or ERTMS, includes activation status and system faults.
3. Diagnostics and error codes: error messages or warnings for deviations, for example, door faults, emergency brake events, fire protection alerts, low central line air pressure, or traction system problems
4. Power supply: display the actual overhead line voltage, pantograph position (up/down), and status of the main circuit breaker and power contactor.
5. Train: current length (number of modules), weight, and available tractive effort.

### 4.1.2 Internal regulations

The train driver provides updates based on the latest TDOK (Trafikverket Documents), such as TDOK 2015:0309, issued by the Swedish Transport Administration that outlines the procedures for its operations.

### 4.1.3 Safety orders

A safety order is an instruction from the train dispatcher to the driver or shunting supervisor, stating deviations from the standard timetable or normal safety procedures. Orders are issued in writing or electronically and must be retained until the journey is completed or the order is revoked. Driver must confirm receipt and understanding of the safety order before the train may move according to it.

Typical contents include substitute signals, reduced speeds, designated routes during signal failures, technical limitations, or other safety deviations from normal operation.

The X52 is certified for both ATC and ERTMS systems, so safety orders must specify which signalling system applies and the relevant shunting regulations.

Any issues with brakes, door systems, or traction technology must always be described in the safety order and observed with extra caution. A safety order always takes precedence over local safety routines and regular schedules and must be strictly followed.

### 4.1.4 Train service

The driver reviews the latest route and safety information, covering any temporary speed restrictions, work zones, or known issues along the route. This information is sometimes relayed to other crew members as needed.

### 4.1.5 Maintenance systems

The driver verifies remarks, checks if there are any open remarks in the system and whether other remarks is marked as resolved.

### 4.1.6 Documentation

All pre-departure checks and findings must be documented according to regulations and the train company's procedures. Defects or deviations are reported immediately to traffic control or technical staff.

### 4.1.7 Sub-process: Clarification (Klargöring)

1. Cab Entry and Setup: driver enters the cab, secures the door, and takes a seat at the control desk.
2. Main Power-Up: driver activates the master switch or main power, bringing onboard computers, control panels, and diagnostic systems online. Raises the pantograph (for electric units) to connect to overhead power or prepare power sources. The driver also turns on headlights, marker lights, cab lighting, and climate control systems as needed.
3. System Initialisation: boots' safety systems, such as Automatic Train Protection (ATP), ATC or ERTMS. Waits for these to finish diagnostic self-tests and confirms that all are in a ready state. Monitors automatic diagnostic checks on traction, brake, door, and communication systems, reviewing any alerts or error codes.
4. Train Composition and Communication Check: verifies trainset configuration: car number/order, that all coaches and onboard bus systems communicate, and that nothing is missing.
5. Braking System Setup: initiates and tests service brakes, emergency brakes, and parking brakes. If required, conduct brake tests locally from the cab and across the fleet. Applies and releases brakes to verify proper and complete functioning.
6. Door and Passenger System Check: cycles all external passenger doors, checks their proper operation, and confirms that the interlock prevents train movement when doors are open. Verifies the Passenger Information System is working, including audio and visual announcements.
7. Radio and Communication Test: powers up and tests the train radio (GSM-R network), PA system, and intercom, ensuring communication with train dispatcher and crew.
8. Safety and Emergency Equipment Check: verifies the presence and readiness of fire extinguishers, first aid kits and emergency tools. Check that all alarms are functioning.
9. Exterior and Visual Walkaround ("Rundgång"): walk the length of the train, inspecting underneath and along both sides. Look for leaks, loose or hanging equipment, wheel and

brake wear, and coupler or pantograph condition. Ensure that all hatches and covers are secure and that no foreign objects obstruct the train.

10. Documentation: records all checks, whether paper or digital logbook, marks off each task, and reports any faults immediately. The train is only declared "ready for departure" when all systems and checks pass.

### 4.1.8 Sub-process: Shunting

Shunting involves moving the train or its cars within a yard or station area, often to reassemble train sets, move them between tracks, or prepare for departure.

Shunting operations: driver waits for permission to start from the shunting supervisor, which can be given via a shunting signal or verbally. Shunting starts with a brake test and verification that doors are secure. The driver uncouples any necessary couplers and manoeuvres the train onto the desired track with regulated speed and vigilance over the surroundings. When shunting is complete, confirmation is given to the shunting supervisor, and the train or cars can be used as a new train formation or parked.

### 4.1.9 Sub-process: Train Journey

The Train Journey is described in Section 5.2.1.

### 4.1.10 Sub-process: Special Case

Special cases (särfall) in train driving are situations that deviate from normal operations and require specific actions from the train driver. Some examples include passing a main signal showing (stop) with authorisation, handling the train after an emergency stop mode, and moving past switches under special instruction. In each scenario, the train driver must communicate with the traffic controller, follow written or verbal clearances.

### 4.1.11 Sub-process: Stabling

1. Arrival and shutdown: after arrival, the driver ensures the train is positioned on the designated shunting track, applies the main brake, switches off traction, and confirms that all passenger areas, including interior and exterior lights, are secured if the train is stationary for an extended period. Verify that all passengers have disembarked and perform a general train check.
2. Preparation for shunting: release any on-train brake or parking brake and prepare controls for manoeuvring. Set the control panels to neutral and disengage any drawgear or coupling systems according to the vehicle's manual.

## 4.2 Task analysis of train driver and onboard personnel

This section contains the tasks analysis for the train driver and the onboard personnel at the Swedish Iron Ore Line in GoA1 operation, with ATP, based on activities performed on the X52 Regina. These activities are then evaluated in terms of how their performance and relevance change under GoA2 operation, with support of relevant literature.

## 4.2.1 Task analysis of the train driver, GoA1

Tasks performed by the train driver in GoA1 operation at the Swedish Iron Ore Line.

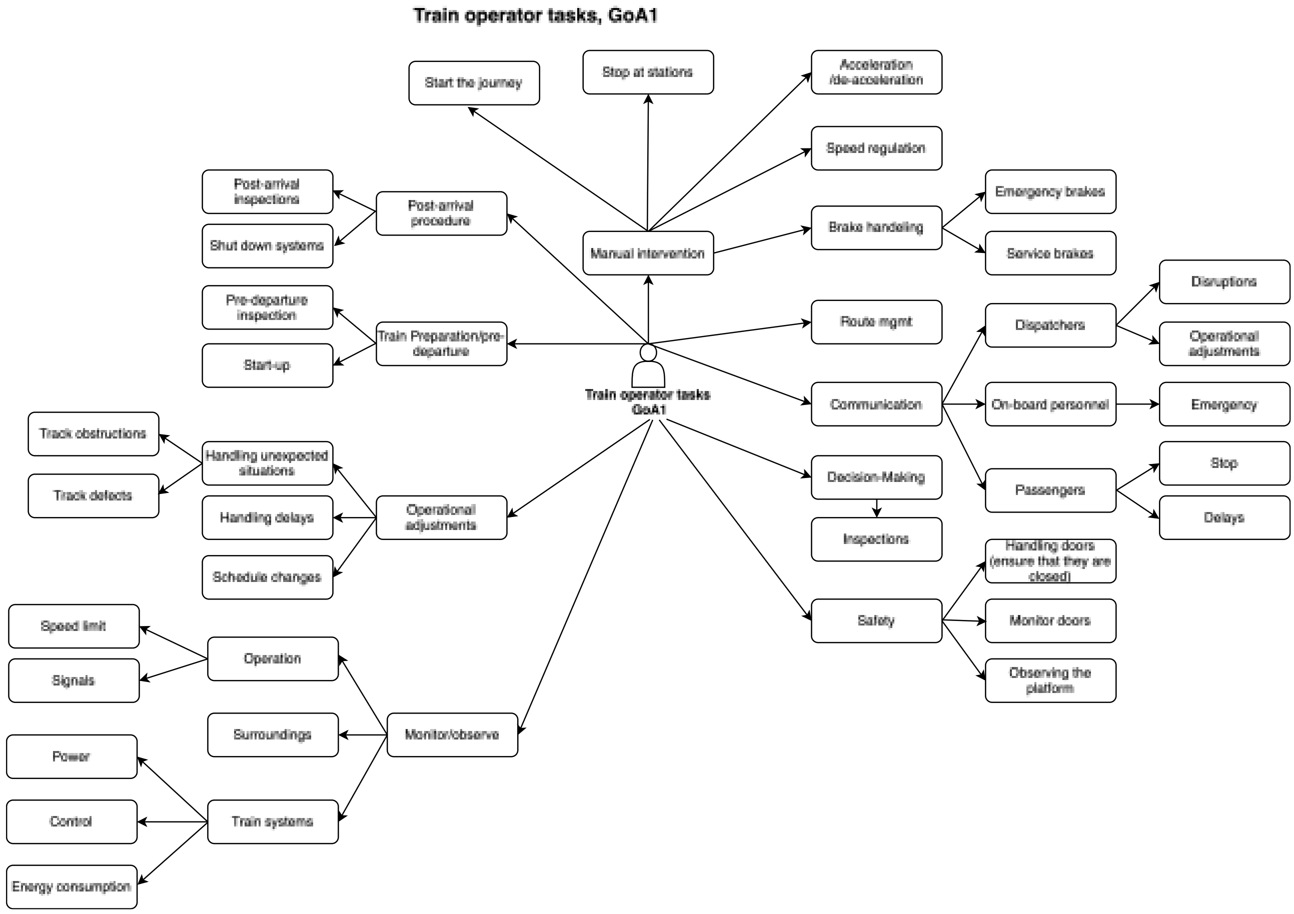


**Figure 10: Tasks performed by the train driver in GoA1 operation at the Swedish Iron Ore Line**

### 4.2.1.1 Start the journey / Acceleration/de-acceleration

When route clearance has been granted, the driver announces departure to the passengers and ensures all doors are locked. The driver accelerates smoothly to reach cruising speed in accordance with speed restrictions and signal indications. During the journey, the driver continuously monitors the onboard systems and external signals and surroundings.

### 4.2.1.2 Stop at stations

During the stop, the driver manually releases the doors for opening (at the correct side of the train according to the station platform). The doors remain open during the scheduled dwell time. Toward the end of the stop, the driver commands the doors to close, and the door locking systems verify it is safe to depart. The driver then confirms with traffic control that the route ahead is clear and prepares to accelerate smoothly when the departure signal is given.

#### 4.2.1.3 Speed regulation / Acceleration/de-acceleration

The driver maintains the train's speed within upper and lower threshold values around the nominal speed permitted by the automatic train control system (ATC). When the upper limit is reached, the driver reduces traction and allows the train to coast until the speed drops to the lower limit, then accelerates again. This optimises energy consumption and reduces wear. Both acceleration and deceleration are controlled to avoid sudden changes in speed, ensuring passenger comfort and minimising wasted energy.

#### 4.2.1.4 Brake handling, emergency and service brakes

The train uses a combination of regenerative electric braking (which feeds energy back to the catenary line), pneumatic disc brakes, and magnetic track brakes. Regenerative braking is prioritised to increase efficiency and reduce mechanical wear. This system monitors the maximum allowed speeds on each track section. Automatic Train Control generates a warning to the driver and will eventually activate automatic braking if the train exceeds the speed slightly above the maximum allowed line speed. The emergency brakes can be triggered manually by the driver or automatically by safety systems such as ATC when critical conditions occur, such as overspeed, passing a signal at danger, or obstacles on the track. When the emergency brakes are activated, the train's systems prioritise maximum deceleration.

#### 4.2.1.5 Route management / Communication: Dispatchers

Route management begins when the driver communicates with the railway traffic control and receives operating documents — including the current timetable, route maps, and safety notices — typically from the control system or printed documentation. These indicate the designated line sections, permitted traction modes, and communication channels for the operated route. The driver then aligns the onboard train control system to the specific route and sets the direction of travel. When all is secured and safe, the route sets remotely, and the driver receives confirmation via signals on the cab's display or trackside signals changing to green. The driver confirms signal aspects visually before train movement.

#### 4.2.1.6 Communication: Dispatchers, Onboard personnel, Passengers

The primary method of communication is dedicated railway radio systems (GSM-R). This allows direct, instant voice communication between the driver, dispatcher, and onboard personnel regardless of location. The driver has onboard communication equipment integrated into the driver's cab, which shows messages from traffic control and enables calls or announcements. The driver or onboard staff use intercom systems to announce passenger information, such as communication during delays, stops, or disruptions.

#### 4.2.1.7 Communication: Dispatchers

About disruptions and operational adjustments.

#### 4.2.1.8 Communication: Onboard personnel

About emergency or disruptions.

#### 4.2.1.9 Communication: Passengers

The next stop (if not handled by onboard displays) and delay information are sometimes handled by the train driver (or train host/onboard personnel).

#### 4.2.1.10 Decision-making: Inspections, Safety-related decisions

A pre-departure safety check is performed before each departure, including inspection of brakes, train control systems, passenger emergency systems, doors, lighting, and signalling equipment. All passenger doors, emergency release mechanisms, and interlocks are tested for correct operation. Fire extinguishers, alarms, intercoms, and evacuation tools are checked for availability and full function.

Inspection and functionality check of service brakes (disc and magnetic track brakes). Bogies, suspension, and coupling components checked for structural integrity and proper function. Driver ensures that all critical control and safety systems (ATC/ERTMS) are operational.

#### 4.2.1.11 Safety: Handling doors

The driver controls the door operation, using an interface in the driver's cab or from onboard control panels. Before departure, the driver ensures all doors are properly closed and locked, verified by onboard sensors. The driver or in cooperation with the train host handles door closure. Doors open only when the train stops at a station. After the doors are closed, safety system checks occur automatically. Emergency door release mechanisms are available for passengers and onboard staff in case of evacuation.

#### 4.2.1.12 Safety: Observing the platform

The driver looks out from the cab, typically through windows at the front and side of the train, to ensure the platform is clear of passengers before door opening and departure. Some trains may be equipped with platform-facing cameras that provide additional views to the driver and help monitor blind spots along the full length of the train. The driver maintains contact with onboard personnel who can monitor platform conditions and passenger flow.

#### 4.2.1.13 Monitor/observe: Operation

Signals, switch positions, instruments, and obstacles. The driver's attention is divided between monitoring the outside environment and the instruments inside the train cab.

#### 4.2.1.14 Monitor/observe: Surroundings

The train driver must constantly assess the track ahead for Signals and switch positions along the line. Possible obstacles include vehicles, animals, or people near or on the track. Level crossings, especially in poor visibility, road users may have ignored the warnings and are on the track. At the station, the driver observes crossovers and platforms at stations where passengers might be close to the train.

#### 4.2.1.15 Monitor/observe: Train systems

Inside the cab, the driver continuously checks several displays and controls, including the speedometer and traction (brake) controller position. The ATC or ERTMS display shows the current permitted speed, signal indications, braking curves, and any warnings. Pressure gauges for the main air line and brake system. Electrical systems such as power draw and regenerative braking feedback.

The driver monitors the diagnostic and status screens in the train's TCMS (Train Control and Monitoring System), which display door states, performance, and bogie brake conditions.

#### 4.2.1.16 Operational adjustments: Handling unexpected situations

Unexpected situations are generally divided into physical obstacles on the line, environmental causes, and technical track defects. According to safety regulations, each type requires different procedures.

**Physical obstacles**: include objects on the track, such as branches, stones, or large debris; animals or people on the line, which are common causes of emergency stops; and vandalism, for example, placing objects on the rails, which can cause derailment or wheel/track damage. The driver must immediately brake, contact the traffic controller, and report the obstacle's position. The control centre stops traffic, cuts traction power (if required), and confirms when it's safe to proceed. If the obstacle is visible in time and poses no danger, the driver should note it and report it after arrival.

**Environmental**: leaf contamination in autumn and crushed leaves create a slippery film on the rails, reducing adhesion and making it difficult to accelerate or brake. Drivers compensate with smoother acceleration and earlier braking. Track buckling in hot weather, rails can expand and bend outward, increasing derailment risk. Affected sections are closed until repaired. Snow and ice can block switches or reduce electrical contact between wheels and rails, especially when the train is stationary. Switches are heated electrically, and the driver may need to report disruptions to the control centre. The driver goes out and tries to remove snow and ice.

**Technical track defects:** Cracked rails or damaged switches may cause strong jolts or vibrations in the train. catenary line faults are detected through loss of power or sparking. Damaged ballast (track foundation) can cause instability in track geometry. If the defect is a safety risk, the driver stops the train and contacts the dispatcher. The dispatcher then decides whether the track should be closed until repair.

#### 4.2.1.17 Operational adjustments: Handling delays & Schedule changes

When delays occur, the driver communicates continuously with the traffic controller, which prioritises train movements and aims to prevent further delays. If the cause is technical (vehicle fault, signal malfunction, obstacle), the driver reports it to traffic control and awaits instructions. Actions may involve reduced speed, standby mode, or restarting procedures. Delay due to external factors (person on the track, accident, switch malfunction), the driver stops the train according to safety regulations, reports the event, and awaits clearance. For minor delays, the driver can recover some time by adjusting speed and acceleration profiles where it is safe and possible.

#### 4.2.1.18 Train preparation/pre-departure: Inspection

The driver's pre-departure checks include system checks, such as brakes, doors, communications, and electrical systems. Safety systems and signalling equipment are verified. This activity is further described in the Operations process (see section 5.1)

#### 4.2.1.19 Train preparation/pre-departure: Start-up

Interior systems such as lighting, heating, power outlets are activated. If equipped, the onboard kiosk or bistro is made ready for service by the onboard personnel. See the sub-process: clarification (in Section 5.1) for further details.

#### 4.2.1.20 Post-arrival procedure: Inspection & Shut down systems

After the train stops at the terminal station, the driver applies the parking brake and confirms that the brake system remains active until the vehicle is at a standstill. Then, the traction system is in neutral (controller is set to neutral, traction power is cut off, and all passenger systems, such as doors and alarms, are checked). The driver disconnects and locks door systems so no passengers can board the train. Performs a visual check of the driver's cab and passenger areas to ensure that there are no people, objects, or visible damage inside. Checks interior lighting, toilets, and passenger information systems, which are then turned off.

### 4.2.2 Task analysis of onboard personnel, GoA1

Tasks performed by the onboard personnel, also called train host, in GoA1 operation at the Swedish Iron Ore Line.

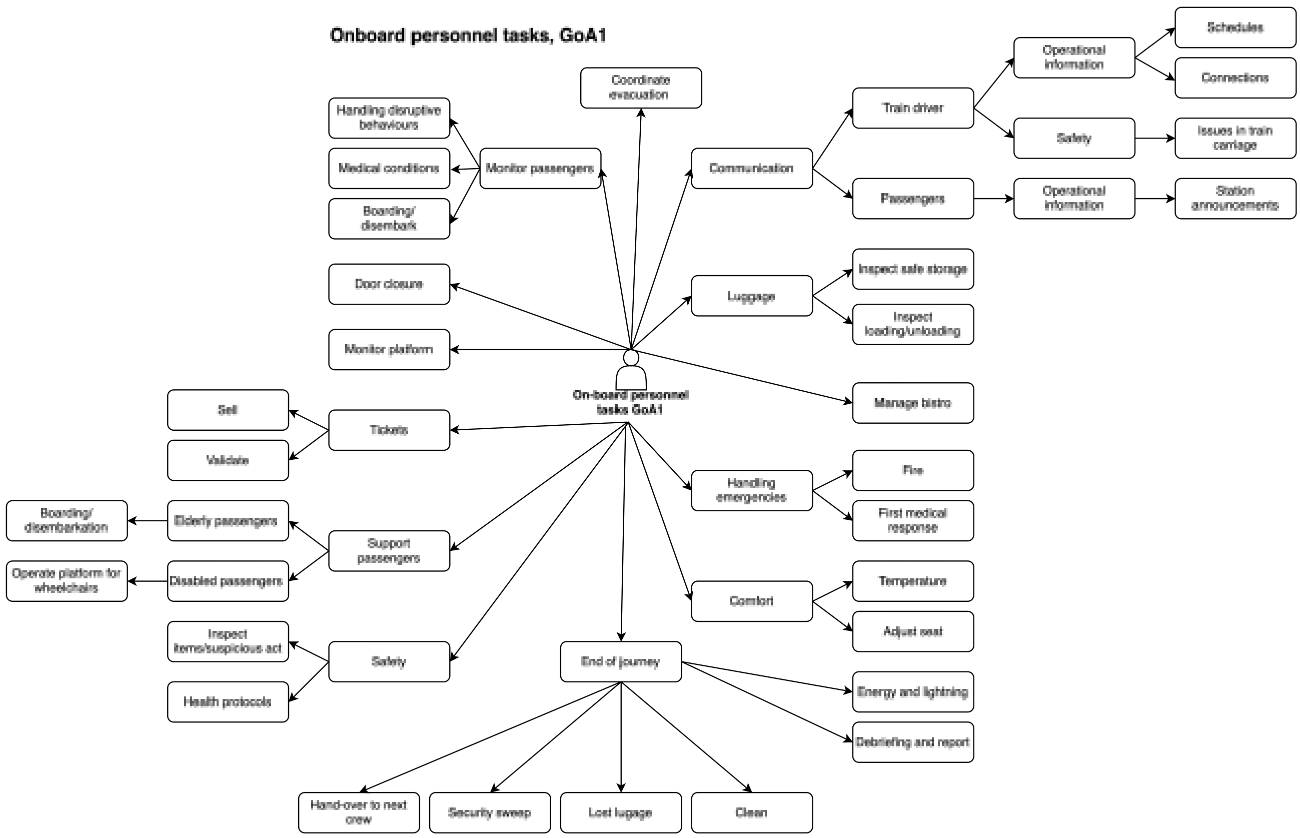


**Figure 11: Tasks performed by the onboard personnel in GoA1 operation at the Swedish Iron Ore Line**

#### 4.2.2.1 Communication: Train driver

Staff coordinate with the train driver regarding disruptions, report incidents on board, and follow the operator's safety instructions.

#### 4.2.2.2 Communication: Passengers

Provides passengers with timetable information, expected arrival details, and information about any delays. Staff are responsible for resolving seating disputes, managing complaints, and helping with unexpected events such as rebooking or delays.

#### 4.2.2.3 Luggage: Inspect safe storage & Inspect loading/unloading

Passengers are responsible for handling their carry-on luggage and may only bring as many bags as they can manage when boarding and exiting the train. Staff can assist passengers with special needs, such as people with disabilities or elderly passengers, by helping them carry or lift luggage between the door and the seat as needed. Staff inspect and ensure luggage is placed so as not to block aisles or emergency exits. Staff may refuse assistance or deny access to the train if luggage is too large, hazardous, or presents a safety risk.

#### 4.2.2.4 Manage bistro

Staff prepare and present food and beverages for sale, such as coffee/tea, sandwiches, snacks, and drinks. They also handle card payments and hand out products to passengers. Staff inform passengers about the bistro's opening; it may be closed during disruptions. They also restock products and keep the bistro area clean throughout the journey.

#### 4.2.2.5 Handling emergencies: Fire

Staff will locate the fire and attempt to extinguish it immediately using the train fire extinguishers and other equipment. If the fire is large or cannot be handled directly, evacuation is to be prepared following the train's emergency plans and instructions for the specific location.

#### 4.2.2.6 Handling emergencies: First medical response & Monitor passengers: Medical conditions

Staff assess the situation and determine if immediate first aid, such as CPR or stopping the injured person's bleeding, is needed. The train is equipped with a first aid kit and sometimes a defibrillator. If outside help is needed, staff contact emergency services and traffic control, providing the train's position and information about the type of assistance required.

#### 4.2.2.7 Comfort: Temperature & Adjust seat

They monitor climate settings via panels or displays in staff areas and can adjust the temperature based on passenger requests or current weather conditions. If passengers complain, they investigate and report technical problems if the issue cannot be resolved on board. The seating is designed for individual adjustment and is easy for travellers to use. Staff can assist passengers with special needs, such as those with disabilities.

#### 4.2.2.8 End of journey: Security sweep

Staff inspect compartments, vestibules, coaches, and toilets. They check that doors are closed and locked to prevent unauthorised access.

#### 4.2.2.9 End of journey: Lost luggage

Onboard personnel collect any lost or left-behind luggage, report and register lost property, and hand these items over to the train company's lost property department or, according to the operator's instructions, at the end of the journey.

#### 4.2.2.10 End of journey: Clean

Staff carry out basic cleaning of passenger compartments, seating areas, and restrooms, removing trash and checking for items in seat pockets or under seats. They report any problems or damages discovered during the journey or inspection.

#### 4.2.2.11 End of journey: Energy and lightning

Staff walk through the carriages to switch off or adjust lighting according to the operator's instructions, usually leaving basic and emergency lighting on when power remains connected.

#### 4.2.2.12 End of journey: Hand over to next crew & debriefing and report

Staff ensure all passengers have exited the train. Staff communicate with train management and station staff to coordinate train service, crew changes, and any operational updates needed for the next departure.

#### 4.2.2.13 Safety: Inspect items/suspicious act

Staff inform traffic control and follow instructions for further action, including stopping the train in a suitable location and waiting for security personnel or police. Communicate with passengers so that they remain calm to avoid panic, and coordinate evacuation if necessary.

#### 4.2.2.14 Support passengers: Elderly passengers & Disabled passengers

Assist passengers with special needs, such as disabled or older passengers. Operate a platform for wheelchairs. Help passengers board and disembark the train.

#### 4.2.2.15 Tickets: Sell & Tickets: Validate

Onboard staff check passenger tickets to ensure validity using a mobile device that scans QR codes or manually checks ticket references. ID is sometimes needed to verify that the ticket is valid for the passenger. The staff also assist with ticket sales or issues with the ticket.

#### 4.2.2.16 Monitor platform / Door closure / Monitor passengers: Boarding and disembarkation

Onboard staff position themselves close to the doors and visually check that no person is near the platform edge or at risk of getting trapped when the doors close. They ensure that all passengers have boarded and that no one is rushing to board or exit at the last moment. They inspect the entire platform section of their carriage. If necessary, staff inform passengers that this is the final opportunity to board. If any obstacle or risk is detected, departure is halted until the situation is resolved. Once cleared, the staff give the driver the ok that the train is ready for departure.

#### 4.2.2.17 Monitor passengers: Handling disruptive behaviours

For minor disturbances, such as staff request that the person comply by showing a ticket, quieting down, and follow the code of conduct. If the disruption is a risk to other passengers or staff, police are contacted for assistance. If the situation is acute, staff may also refuse departure for safety reasons.

#### 4.2.2.18 Coordinate evacuation

Staff work with the train driver and traffic control to receive clearance and instructions regarding the evacuation. Passengers are provided with information about the reason for evacuation, emergency exits, and assembly points. Depending on the train's location and situation, the safest evacuation route is identified. It can be through doors to the platform, through windows, or to the track level. Special care is taken with children, older passengers, and people with disabilities. After evacuation, staff provide feedback to traffic control and arrange onward transport for passengers.

# 5 SUMMARY OF ALL HUMAN FACTORS TESTS, SIMULATIONS AND DEMONSTRATIONS EXECUTED IN FP1, 2 AND 5

Section 5.1 describes the impact on human factors constraints for train drivers and onboard personnel with GoA2 based on the task analysis (for the current situation, GoA1) in Chapter 4. Section 5.2 summarizes the human factors assessment from the multi-actor human-in-the-loop simulation in FP1/WP16. Section 5.3 lists all tests, simulations and demonstrations from work packages in FP1, 2 and 5 that include a human factors component.

## 5.1 HUMAN FACTORS CONSTRAINTS LEADING OPERATIONAL ERRORS BY TRAIN DRIVERS IN GOA2

Building further on the task analysis of the current operations (GoA1) in Chapter 4, this section outlines the findings from the analysis of how human factors constraints may lead to operational errors by train drivers and onboard personnel with GoA2. A risk perspective on the tasks of train drivers and onboard personnel is adopted. Observations were done by researchers in order to gain additional understanding of the tasks that train driver and onboard personnel are conducting. Based on these insights an anticipated changes under GoA2 could be identified.

Section 5.1.1 presents the task analysis of train drivers in GoA2. Section 5.1.2 presents the task analysis of onboard personnel in GoA2. Section 5.1.3 consolidates the task analysis outcomes in section 5.1.1 and possible related anticipated impact regarding operational errors.

### 5.1.1 Task analysis of train driver, GoA2

This section analyses the train driver’s duties in future GoA2 operations, see Figure 12. The analysis is based on current practices used on the Swedish Iron Ore Line and derived from the tasks performed by drivers operating the X52 Regina at GoA1 (manual operation). It also integrates insights from relevant literature and research on GoA2 systems to identify how responsibilities and tasks are expected to change as automation increases.

The main changes for the train driver when transitioning from GoA1 to GoA2 are a shift from hands-on driving to supervisory and safety management roles, with ATO handling the actual train movement between stations (European Union Agency for Railways, 2024).

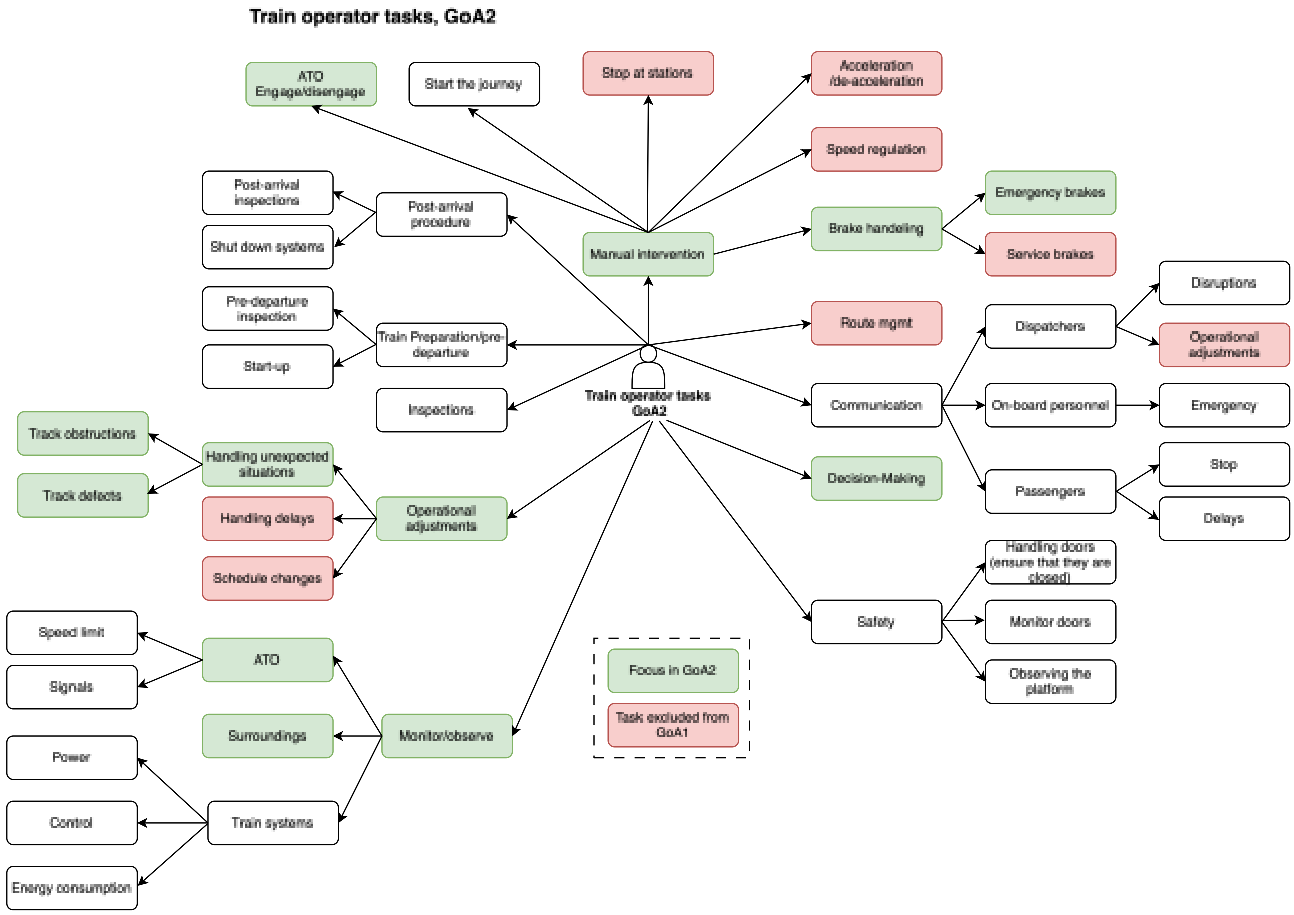


**Figure 12: Tasks performed by the train driver in GoA2 are based on the current operation at the Swedish Iron Ore Line, based on activities performed on the X52 Regina, and deepened by supporting literature on GoA2 operation**

#### 5.1.1.1 Stop at stations

When the system takes over the (stop at stations) task, the ATO will automatically manage the train's acceleration, running, braking, and station stops. The driver will remain in the cab but shift from active manual control to a supervisory and intervention role (Keevill, 2017). Instead of managing traction and braking continuously, the driver monitors the ATO system status and intervenes only if system performance is compromised (European Union Agency for Railways, 2023).

#### 5.1.1.2 Acceleration/de-acceleration

The ATO system automatically determines when to accelerate and decelerate based on parameters such as journey profiles, speed limits, headways, and operational requirements (European Union Agency for Railways, 2024). These parameters are programmed to be within design limits for comfort and safety. The intention is to enhance passengers' experience by smoother (more consistent) starts and stops compared to manual driving (Keevill, 2017). If the ATO system detects an obstacle or abnormal condition (such as degraded mode), the train driver is alerted and can manually intervene to override automation if needed.

#### 5.1.1.3 Speed regulation

The ATO system manages speed regulation with Automatic Train Protection (ATP) and European Train Control System (ETCS). The train must comply with speed limits, acceleration/braking curves, and timetable requirements while a driver supervises and can intervene if needed. ATO calculates the most energy-efficient speed profile to ensure the train follows the operational timetable. (European Union Agency for Railways, 2024).

If the train enters an ATO inhibition zone or if there is a system failure, the driver must take over operation; otherwise, automatic emergency braking is applied (Nolte, 2021).

#### 5.1.1.4 Route management

The journey and segment profiles (route) are transmitted from the TMS to the train's ATO, allowing the train to adjust its driving strategy automatically as conditions change. Updates to journey profiles are based on live timetable and infrastructure data and are updated during ongoing operation. If a delay occurs, the ATO recalculates its driving profile to best fit the prescribed timetable by either minimizing the delay or adjusting arrival times as needed. (Nolte, 2021)

#### 5.1.1.5 Monitor/observe

Monitoring and observation behaviour changes significantly in GoA2 (Naumann & Thomas-Friedrich, 2024). In GoA1, the driver's main task is controlling, adjusting, and continuously monitoring signals and speed. In GoA2, these tasks are controlled by ATO. Driver's role shifts to monitoring. The driver focuses on observing the system, instrument panels, and surroundings (Brandenburger et al., 2024).

The driver moves from hands-on control and direct reactions to mostly supervising automated processes. Work tasks decrease leading to workload reduction, and drivers report increased fatigue and vigilance decrement, leading to lower performance during long monitoring sessions because of less active involvement (Fan et al., 2022; Schackmann & Bosch, 2024).

In GoA2, the driver must stay mentally prepared to interpret and react rapidly to potential system faults or deviations, despite the train running automatically (Schackmann & Bosch, 2024). Clear screen interfaces are vital for the driver to understand what the ATO system is doing and why. They are also essential for the supervisory role in GoA2, where the driver must be ready to detect system deviations and intervene rapidly (Transportation Canada, 2021). Technical aids, such as vigilance pedals, are sometimes used to maintain attentiveness, but research highlights ongoing challenges in situation awareness and response readiness over extended periods (Naumann & Thomas-Friedrich, 2024).

#### 5.1.1.6 Service brakes

ATO system handles service brakes (primarily electrodynamic with blended pneumatic braking) automatically, controlling braking based on the current speed requirements and the ETCS braking curve without the driver intervening under normal conditions. The driver can always take over manual braking when entering an ATO inhibition zone or in case of a fault. In poor grip conditions, ATO automatically limits braking force according to the segment profile or real-time data, to prevent axle locking and maintain brake protection. (Nolte, 2021)

#### 5.1.1.7 Handling unexpected situations & ATO engage/disengage

The drivers (handling unexpected situations) in GoA2 are fundamentally different from those in GoA1. In GoA1, the driver maintains direct control, is continuously engaged, and is ready to quickly recognise and handle obstacles, system failures, or emergency situations (Naumann & Thomas-Friedrich, 2024).

In GoA2, the driver must shift from monitoring the automation and the external environment to intervening crucial (Jing et al., 2022). When an unexpected event occurs, the driver must recognise anomalies by observing cab interfaces and the external environment, often with reduced direct feedback compared to GoA1 operation. Override the ATO system using manual controls to stop the train by service or emergency brakes (Naumann & Thomas-Friedrich, 2024).

#### 5.1.1.8 Decision making

Decision-making in GoA2 centres around recognising exceptions, such as obstacles, technical faults, alarms, or degraded operational modes. The driver must choose when to suspend automatic operation and assume manual control, acting correctly during rare but potentially critical situations (Brandenburger & Pourian, 2023).

The number of operational decisions decreases, but the responsibility for safety-critical interventions increases. Drivers must maintain vigilance and situation awareness during long periods of low workload, ensuring readiness to intervene at any sign of abnormality or emergency (Naumann & Thomas-Friedrich, 2024).

Studies highlight risks of decreased engagement and slower reaction times in GoA2. Monitoring leads to drops in alertness. System design and training must support the driver's ability to process alerts and warnings efficiently so that urgent decisions are made correctly. (Cogan et al., 2025; Kevil, D., 2019)

In GoA2, precise information and well-designed interfaces are essential. The driver relies on accurate, timely cues from the automation and signalling systems to inform exception handling. Proper man-machine interaction and systematic alert prioritisation are crucial (Jing et al., 2022). Poor interface design may lead to mode confusion, where the driver is uncertain about whether the train is in automated or manual mode, increasing the risk for delayed or incorrect actions (He et al., 2024; Transportation Canada, 2021). Interfaces should provide timely, intuitive feedback on automation status, current operation, and requests for intervention. Multi-modal warning systems (auditory, tactile, and visual) are effective for rapid driver response (Jing et al., 2022).

### 5.1.2 Task analysis of onboard personnel, GoA2

This section analyses the duties of onboard personnel in future GoA2 operations, see Figure 13. The analysis is based on current Swedish Iron Ore Line practices and derived from the tasks performed by onboard personnel on X52 Regina at GoA1. The analysis is deepened by integrating supporting literature on GoA2 operation to identify how increasing automation is expected to change responsibilities and tasks.

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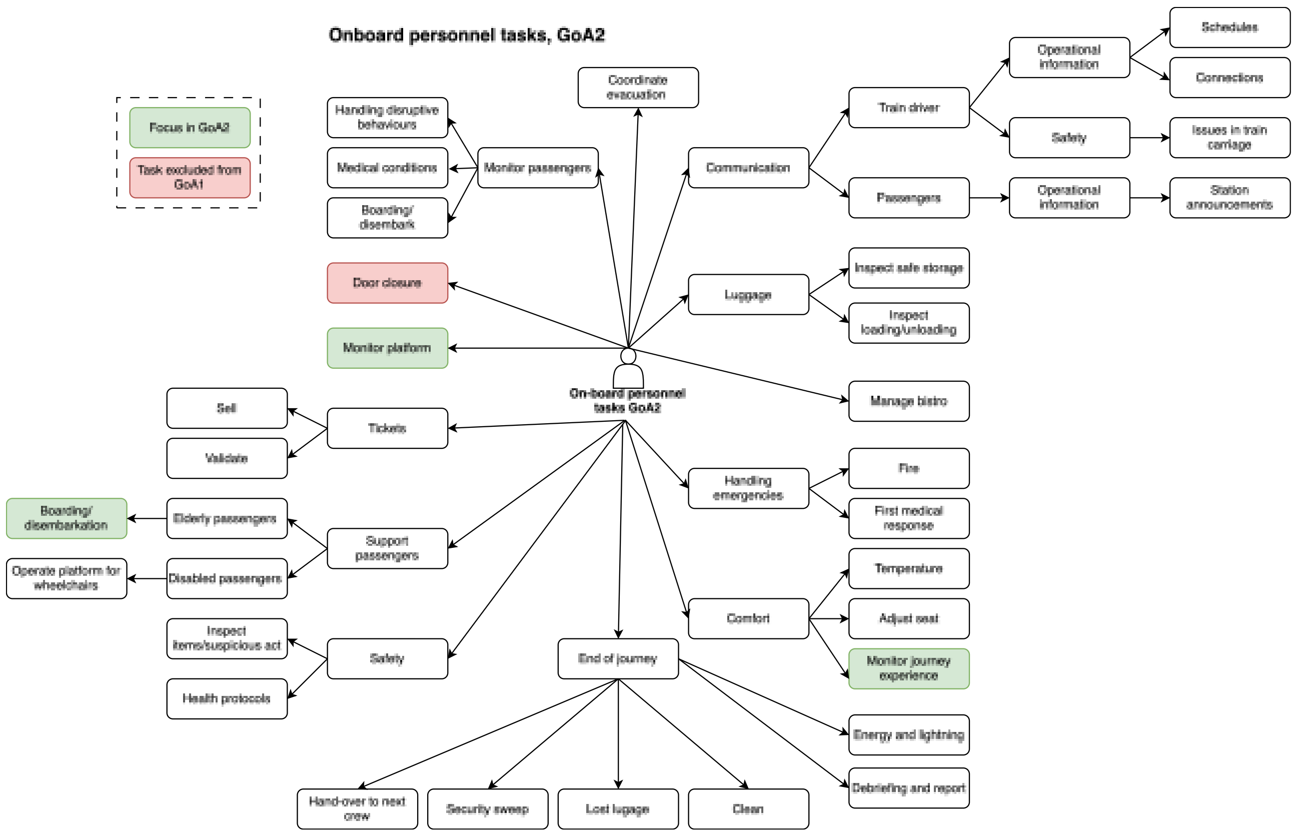


**Figure 13: Tasks performed by the on-board personnel in GoA2 are based on the current operation at the Swedish Iron Ore Line, based on activities performed on the X52 Regina, and deepened by supporting literature on GoA2 operation**

#### 5.1.2.1 Door closure

This task is excluded in GoA2. In the study of X52, the train attendant closes the door in cooperation with the driver (in GoA1). According to the ERTMS/ATO operational principles, the driver closes the doors in GoA1 and GoA2 (European Union Agency for Railways, 2024).

#### 5.1.2.2 Monitor platform / Boarding/disembark

In GoA2, the train attendant's role regarding platform monitoring typically does not change from GoA1 operations; they remain actively responsible for supervising the platform area during station stops and supporting door operations (European Union Agency for Railways, 2024). However, train drivers focus more on monitoring train systems and ATO/ETCS than on direct track observation, especially during automatic movement between stations (Keevill, 2017). The train attendant becomes more critical as the (eyes and ears) on the platform, since the automation cannot adequately ensure passenger safety around train doors and the platform gap (In higher levels of automation, protective doors are installed on the platform).

#### 5.1.2.3 Comfort: Monitor journey experience

A train attendant may note deviations, such as abnormal train running or abrupt manoeuvres, or comfort issues, such as jerky starts, harsh stops, and missed station alignments (Keevill, 2017).

### 5.1.3 Train driver tasks and risks for operational error when transitioning from GoA1 to GoA2

The goal of this analysis was to connect the train driver's current tasks and identify the anticipated risks that may arise when these tasks are modified or reduced in a GoA2 setting. By examining how individual activities are performed in current operation, the analysis highlights where changes introduced by higher automation levels may create new vulnerabilities, shift workload, challenge situational awareness or lead to fatigue.

Figure 14 presents an overview of human factors constraints and effects on the train driver's role during the transition from GoA1 to GoA2 operation. It addresses key human factors areas, such as trust in automation, mental models and vigilance and attention. Furthermore, communication, training, and competence are important, illustrating how increased automation affects each area.

The figure also outlines how the shift from active driving to more passive monitoring changes the train driver's role, which leads to reduced active engagement and delayed system feedback. This change may also lead to reduced situational awareness and fatigue due to boredom. The supervisory role set new demands on the driver to understand the automated system's behaviour, interpret alerts, and intervene when anomalies occur.

These human factors constraints give rise to effects that increase the likelihood of operational error. Some important effects include vigilance decrement, mental underload, complacency, de-skilling and slower reaction to system failures. There are also potential issues with delegating control to automation due to low trust, and with taking control back during emergencies due to over-trust or delayed manual intervention.

Finally, the figure illustrates that manual override functionality and intervention skills are important for risk mitigation in GoA2 operations.

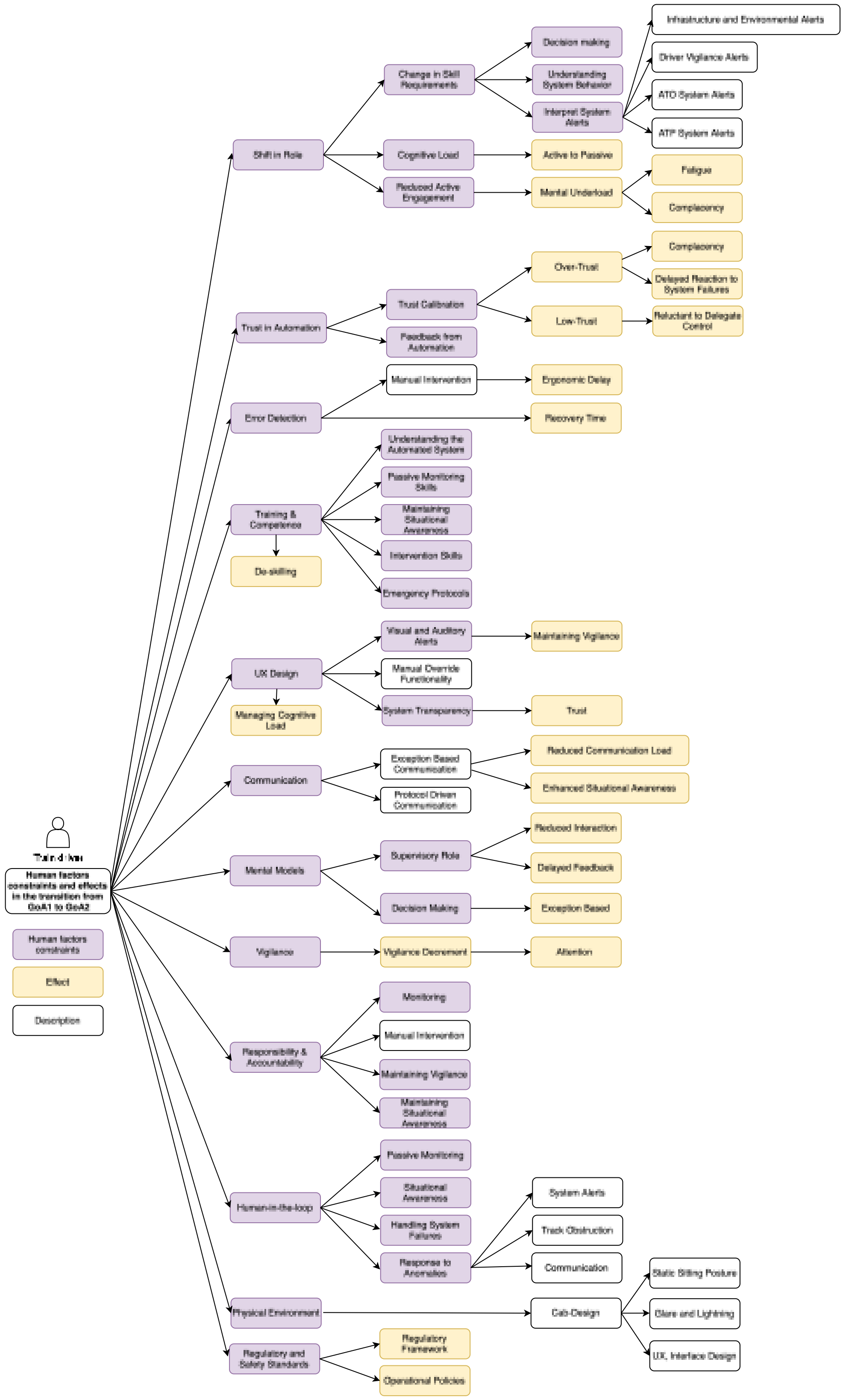


**Figure 14: Human factors constraints and effects for the train driver of transitioning from GoA1 to GoA2 operations in a Swedish context**

#### 5.1.3.1 Limitations study and future work

Validation of the task analysis and the resulting set of anticipated risks should be conducted, for example, through expert workshops or field observations, to assess whether the identified tasks and risks accurately reflect real GoA2 operations.

The findings should be generalised to other European countries by considering different regulatory frameworks, operational practices, and technical solutions to understand how transferable the identified tasks and risks are beyond the Swedish context.

Future work could include other operator roles, such as onboard personnel and traffic control operators, to capture how their tasks and responsibilities interact with those of the train driver and how GoA2 may redistribute risks.

Future work may also include translating the anticipated risks into concrete risk treatment measures, including proposals for interface design changes, revised procedures, training and competence development, and role adjustments.

## 5.2 MULTI-ACTOR HUMAN-IN-THE-LOOP SIMULATION ON TMS-ATO GOA2

This section describes the human factors assessment from the ATO-TMS human-in-the-loop simulation (HITL) study in FP1-MOTIONAL-WP16. The study focuses on the research question what the impact is of driving with ATO GoA2 on operational actors and on the network system. In this Dutch context four operators are involved: two train traffic controller, one network controller (from ProRail) and one train driver (from NS). The primary focus will be on collaboration and communication between operators, as well as on the implications of the ATO–TMS interaction for traffic control, given that this is the first human factors study to concentrate on traffic control operations. NS has previously conducted human factors studies using more representative HITL simulations for train drivers.

A full report of the context, technical description of the simulation environment and results can be found in D16.1. The current section focuses on the human factors output relevant for FP2/D32.1.

### 5.2.1 Experimental setup

#### 5.2.1.1 Workspace

The simulation rooms consist of three separate but interconnected workspaces. The first is a room for traffic control operations, containing two train traffic control workstations and one network controller workstation (Figure 15).

**Figure 15: Simulation room 1: traffic control center**

In another room, a train-driving simulation is set up (Figure 16).

**Figure 16: Simulation room 2: train driver workstation**

Between the two simulation rooms is the control room for the simulation environment (Figure 17). Communications between rooms is available through a connected phone system, similar to what is available in current rail operations.

**Figure 17: Simulation room 3: simulation leader/facilitator workstation**

#### 5.2.1.2 Simulated area

The simulation took place at the ProRail simulation facilities in Utrecht, Netherlands. The simulation covers areas from Hoofddorp to Weesp, which includes the Schiphol Airport station. The choice for this setup is aligned with the area for the capacity study in FP1-MOTIONAL-WP8-9. Figure 18 illustrates which part of the infrastructure in the Netherlands is simulated.

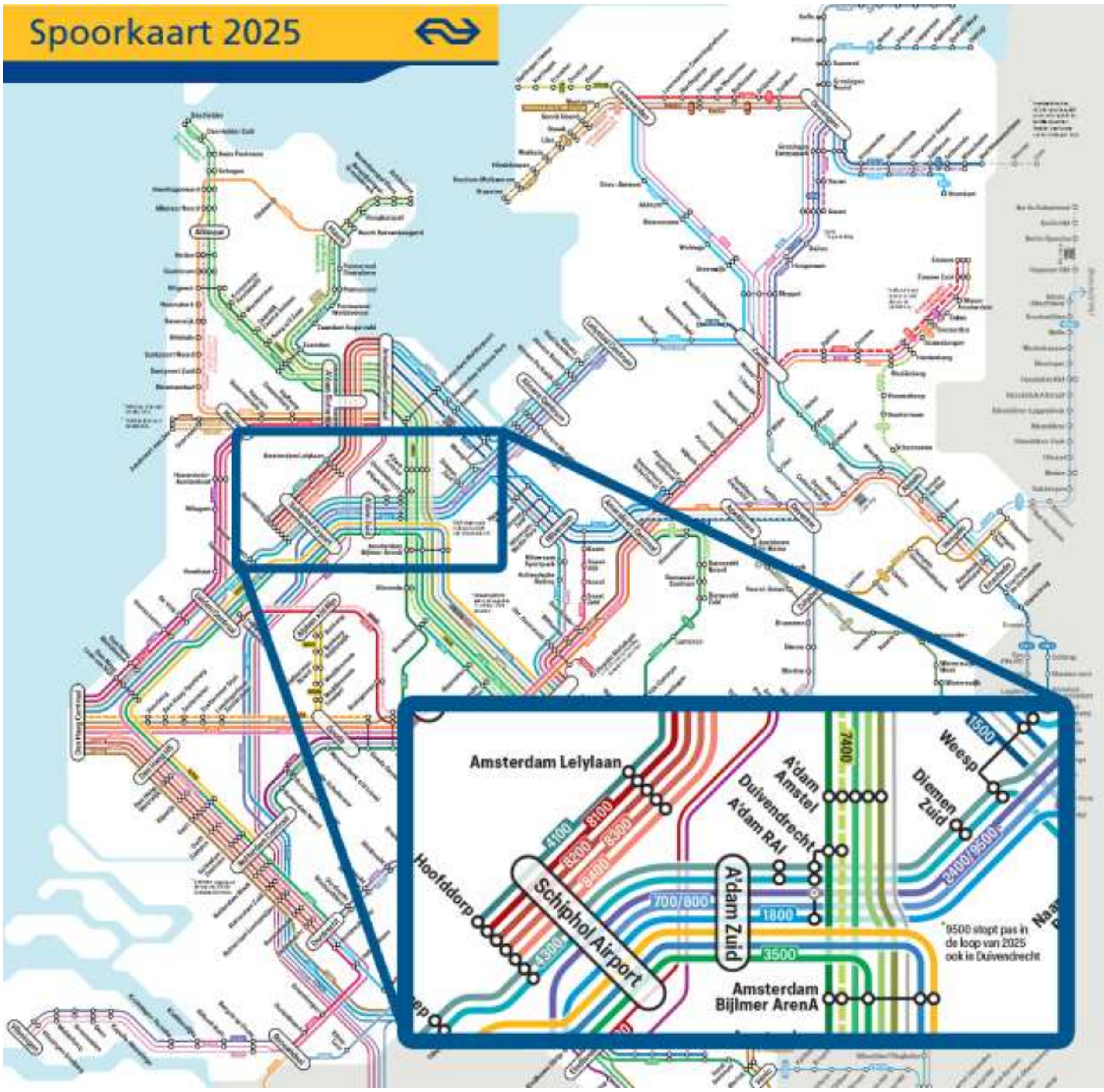


**Figure 18: Map of Hoofddorp-Weesp within the Netherlands**

Zooming in on the area, Figure 19 depicts the TCS view of two combined geographical areas of traffic controllers.

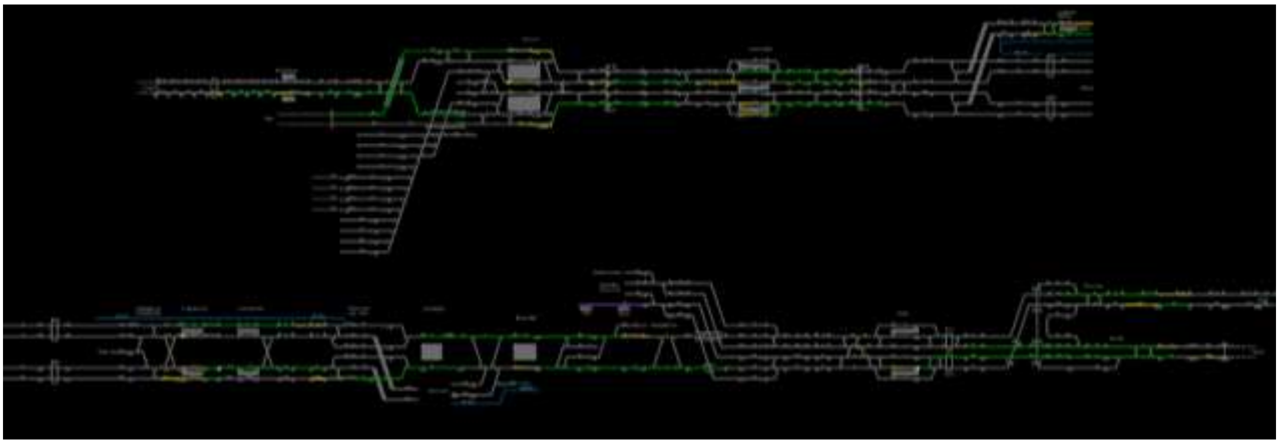

**Figure 19: Traffic controller area in the simulation**

#### 5.2.1.3 Human-in-the-loop simulator

The current simulation setup includes the following ATO components is indicated in Table 1 below.

| Component | Active/ passive | Description |
|---|---|---|
| ATO OB (provided by CAF) | Active (onboard intelligence) | Train trajectory optimization is available, i.e. the ATO OB provides a new estimated time of arrival (ETA) |
| ATO TS | Passive | No train path envelope (TPE) optimization is performed, i.e. no optimization is done to resolve conflicts e.g. by adding extra timing points. |
| TMS | Passive | No conflict detection or resolution is provided |

**Table 1: ATO components in the HITL simulation**

For a technical description regarding the architecture of the simulation environment and used subsets see FP1/D16.1.

#### 5.2.1.4 Conditions

The full simulation study employs a 2 by 2 design which produces a total of 4 simulation runs for each day. Each simulation is assigned an experimental situation and a scenario. There are two experimental situations in the simulation:

1. Current situation: this condition simulated the Dutch railways without ATO trains with the driver operating a train with current specifications.
2. ATO situation: Railway system with 100% ATO GoA 2 trains with the driving operating a train with ATO GoA 2 capabilities.

#### 5.2.1.5 Scenarios

Due to limitation in the technical implementation of ATO components no incident or calamity could be simulated. For an elaborate description see D16.1.

There are two scenarios that happens in each situation

1. Delay/disturbance scenario: multiple trains (+6, +7 and +10 min) are introduced, which lead to secondary delays.
2. Disruption scenario: The simulation environment runs an undisrupted train operation experience for 10 minutes, followed by two disruptions on two areas, which are a police intervention on station Schiphol airport (train cannot depart) and a switch malfunction in Diemen Zuid. Traffic controllers can reroute trains and the network controller can reschedule or cancel trains. No disruption mitigation procedure is implemented.

#### 5.2.1.6 Participants

For each simulation run, a traffic control team was formed with two traffic controllers and one network controller. In general, the railway traffic control room operations in the Netherlands consist of traffic controllers responsible for among others route setting, managing incidents and communication with drivers, etc. as well as network controllers, who work focuses on e.g. rerouting, replanning and cancellation of trains and are responsible for implementing an alternative timetable due to disruptions and/or incidents. The network controller and traffic controllers usually operate in the same railway traffic control room, and a network controller oversees several traffic controller areas.

Operators from both ProRail and NS were recruited for participation in this simulation: 16 traffic controllers and 8 network controllers from ProRail, as well as 8 train drivers from NS. The total number of operators who participated were 13 traffic controllers, 6 network controllers and 7 train drivers. One traffic controller and one network controller reported ill and due to external events one simulation day was cancelled. To cover the missing position, one of the simulation experts with operational traffic control knowledge stepped in to substitute for the absent role.

#### 5.2.1.7 Procedures

The general schedule of activities for each simulation day is included in Table 2. Generally, the simulation day starts with an introduction to the research and simulation workplace, followed by simulation sessions with a break in the middle, and ends with a debriefing and reflection session.

| Activity |
|---|
| Welcoming participants and introduction to research purpose |
| Introduction to simulation workplace including training |
| Session 1 – current situation with delay scenario |
| Session 2 – current situation with undisrupted (10 min) and disruption scenario (20 min) |
| Debriefing per simulation room |
| TMS & ATO demo |
| Lunch |
| Short training to familiarize with the new ATO functionalities |
| Session 3 – ATO situation with delay scenario – identical scenario as in session 1 |
| Debriefing per simulation room |
| Session 4 – ATO situation with undisrupted and disrupted scenario – identical scenario as in scenario 2 |
| Debriefing per simulation room |
| Debriefing and reflection with all participants |

**Table 2: Program simulation day**

#### 5.2.1.8 Data collection

There are several parallel data collections during the simulation sessions, consisting on individual and team metrics. At least one observer is required to be present in each simulation room. Logs of the phone communication were kept in the system, which includes timestamp, duration, and direction of call during the simulation. Additionally, video and audio of the experiment sessions were recorded. The call logs and video and audio recordings were not analysed and reported in this report.

In each of the four sessions, a sheet of paper with a list of questions was handed to be completed by the participants. The question list varies by session. The full questionnaire for the study is included in deliverable D16.1 of FP1-MOTIONAL/WP16.

| Measure | Description |
|---|---|
| Control question | Two questions were included in the questionnaire to account for mental model development i.e. learning of operators taking place about the geographical area and timetable. As identical scenarios were used to compare the no ATO train vs ATO train situation, a control question was included as well to measure whether it was easier to conduct the ATO scenario as they were familiar with the scenarios. |
| Task performance | Individual task performance for each operational role was initially intended to be measured. However, due to technical issues simulation runs sometimes needed to be paused or interrupted. As such, system log files were not analysed to measure task performance. |
| Workload | Workload measures are collected after each simulation session. The instrument used is a modified DLR-WAT 7-point scale indicating workload intensity (translated to Dutch). This scale was included in the question sheet of all four sessions. |
| Trust in automation | Five items from the Trust in Automation scale (Körber, 2018), translated to Dutch, was included in the question sheet of the first and last session. The items are statements regarding perception of automated systems to be evaluated on a 5-point Likert scale. |
| Simulation validity | A HITL simulation validity scale from Lo, et al. (2016) was included in the question sheet at the second session. The scale consists of 9 items on a 5-point Likert-scale. The scale functions to test how the simulation matches the real work environment of operators. Each item falls into one of three categories: psychological reality (the degree of similarity in structure, such as of physical objects in the simulated and the reference system), structural validity (the degree to which the participants perceive the simulated system as realistic), and process validity (the degree of similarity in processes, such as communication between the simulated and reference system). |
| Operational transitions/change management | Each operator was asked to evaluate a list of factors affecting operational readiness for technology transition towards ATO systems from the perspective of train drivers and rank the top 10 based on what they judge to be relevant. The items have been partially based on the literature review in Section 6.2. |
| Communication and collaboration | For communication between driver and traffic control room telephone calls were logged. For communication between traffic and network controllers, the in-room observer notes the frequency of communication of communication between operators. In the plenary debriefing with all participants, questions were included about the experienced communication and collaboration. |

| | |
|---|---|
| Control question | Two questions were included in the questionnaire to account for mental model development i.e. learning of operators taking place about the geographical area and timetable. As identical scenarios were used to compare the no ATO train vs ATO train situation, a control question was included as well to measure whether it was easier to conduct the ATO scenario as they were familiar with the scenarios. |

**Table 3: Overview of measures**

### 5.2.2 Results

The current section describes the results based on questionnaire data and debriefing after the simulation session.

#### 5.2.2.1 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. 5 out of 13 traffic controllers were familiar and no network controllers were familiar with the geographical area.

#### 5.2.2.2 Mental model development

##### *6.2.2.2.1 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 = 1.0).

##### *6.2.2.2.2 Learning effects*

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 =1.0; traffic controllers: M = 4.2, SD =1.0; network controllers: M = 3.7, SD =0.6).

#### 5.2.2.3 Simulator validity

The averaged simulation validity scores across all 9 items across all participants is 3.5 with a standard deviation of 0.6 in the original 1-5 scale . Figure 20 shows the distribution of simulation validity scores for each role in a boxplot. Pairwise nonparametric testing with the Wilcox test discovers that the average score for traffic controllers (M = 3.9, SD = 0.5) are significantly higher than those of train drivers (M = 3.1, SD = 0.6) (p-value = 0.03) but not with network controller (M = 3.4, SD = 0.5)(p-value = 0.4). There is also no statistically significant difference between train driver and network controller (p-value = 1.0).

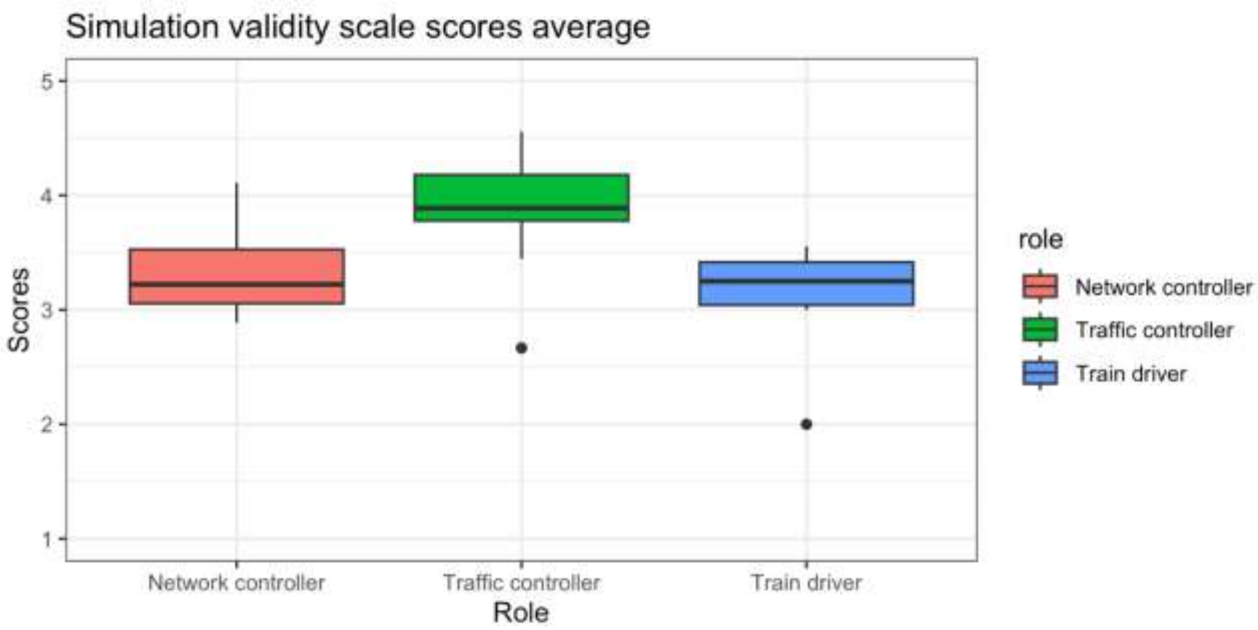


**Figure 20: Boxplot of simulation validity scores by role**

### 5.2.2.4 Workload

Workload was analysed as a 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 21.

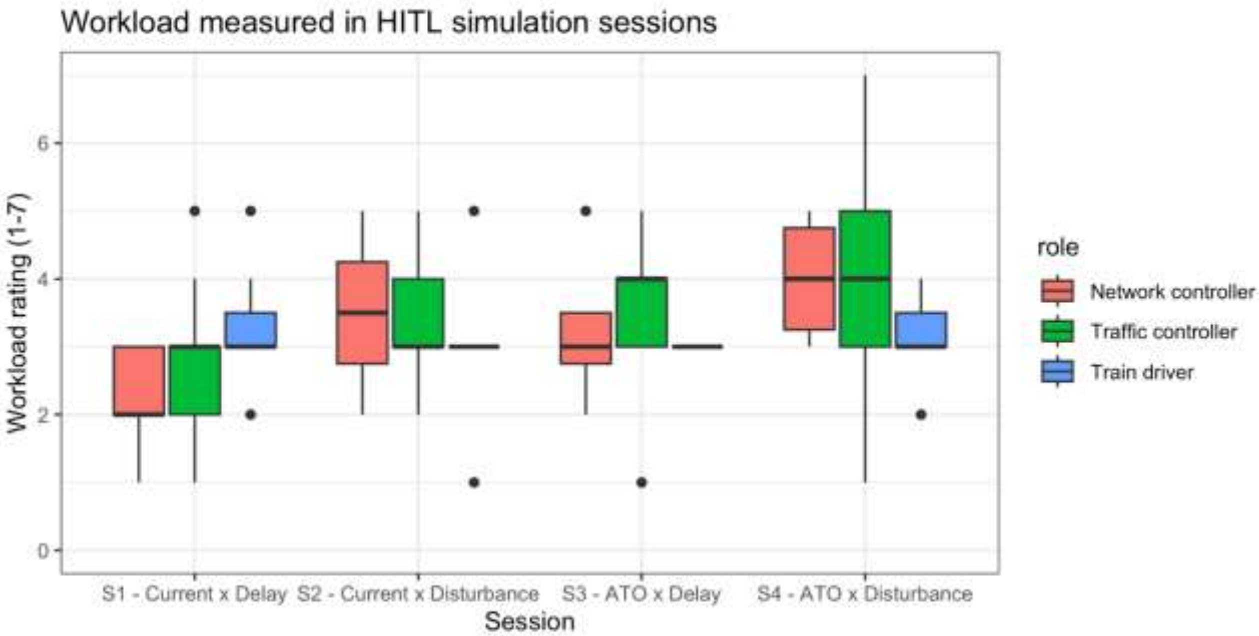


**Figure 21: Boxplot of workload rating by session and role**

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 (Cogan and Milius, 2022; Hunter and McDermid, 2022) 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 roles and the aggregated values across all scenarios is shown in Table 4.

| Scenario | Role | Situation | | | | | |
|---|---|---|---|---|---|---|---|
| | | Current (with ETCS) | | | ATO (with ETCS) | | |
| | | n | Mean | SD | n | Mean | SD |
| Workload delay scenario | Train driver | 6 | 3.3 | 1.0 | 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 | 1.0 | 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 | 1.0 | 13 | 4.0 | 1.6 |
| | Network controller | 4 | 3.5 | 1.3 | 6 | 4.0 | 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 |

**Table 4: Mean values of workload rating by role across sessions**

#### 5.2.2.5 Trust in automation

Trust in automation was collected prior to the first session and after the last session. The breakdown of the averaged means across all items and standard deviation is indicated in Table 5 with the original scale range of 1-5.

| Role | Trust in Automation Score | | | | | |
|---|---|---|---|---|---|---|
| | Before experiment | | | After experiment | | |
| | n | Mean | SD | n | Mean | SD |
| Train driver | 7 | 3.5 | 3.0 | 6 | 3.4 | 3.0 |
| Traffic controller | 12 | 3.5 | 1.5 | 12 | 3.1 | 2.6 |
| Network controller | 5 | 3.7 | 3.7 | 6 | 3.1 | 4.1 |
| Everyone | 24 | 3.5 | 0.5 | 24 | 3.2 | 0.6 |

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

Figure 22 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).

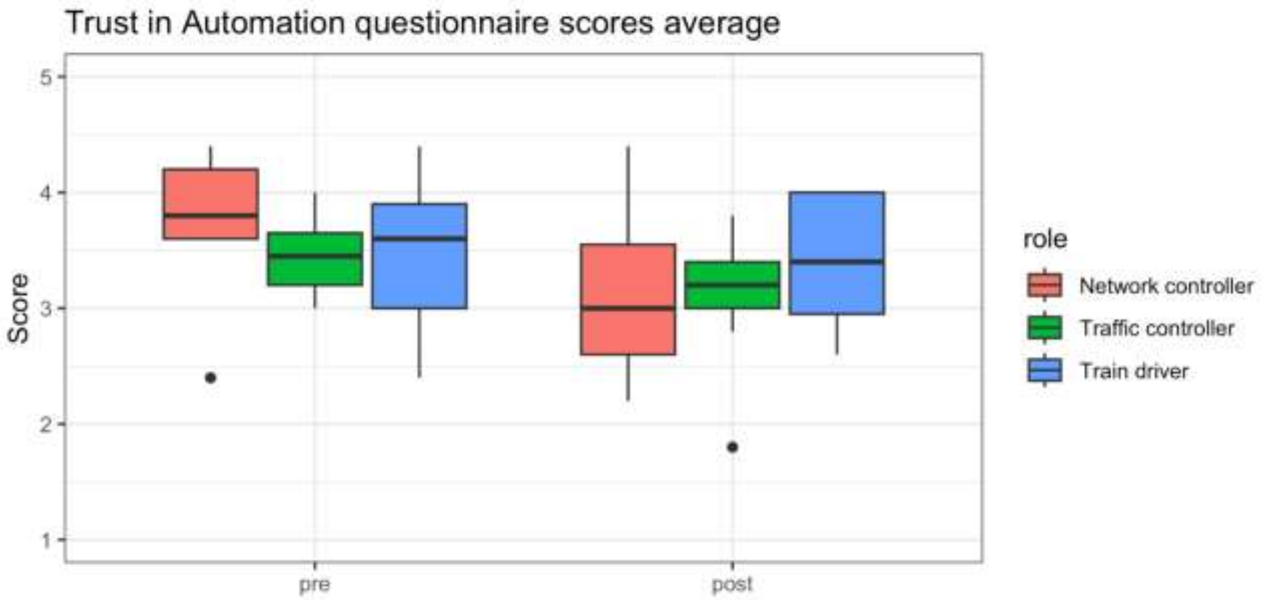


**Figure 22: Boxplot of trust in automation scores by role**

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.

#### 5.2.2.6 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 held accountable 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.

### 5.2.2.7 ATO GoA2 risks and benefits

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

| | 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 of the ATO train | |

**Table 6: Debriefing results**

### 5.2.2.8 Operational transition

The results of this analysis is outlined in section 6.2.2 on operational transitions.

### 5.2.2.9 Communication and collaboration

#### *5.2.2.9.1 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.

#### *5.2.2.9.2 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.

#### 5.2.2.10 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 done in operations. This is not directly observed in the ATO study, however operators wonder how ATO will deal with these types of issues are practice. Traffic operators experience that in practice:

- errors in the designed planning are found, e.g. a 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 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 traffic control. These are points that should be further discussed and/or investigated as part of the ATO operational concept.

#### 5.2.2.11 ATO acceptance

5 out of 7 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 6.2.2.4). Additionally, misalignment in current procedures were identified: traffic controllers resolve delays locally to preserve planned passengertrain 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.

### 5.2.3 Reflections

The current 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.

#### 5.2.3.1 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 limited 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, with the current set-up delays are 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 to 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.

#### 5.2.3.2 Train drivers

Although participants recognize that ATO negatively affect their role as train drivers (a.o. 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 of 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.

#### 5.2.3.3 Passengers

The HITL simulation results reveals 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 (see Section 6.1 on passenger acceptance).

#### 5.2.3.4 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.

### 5.2.4 Limitations study and future work

Firstly, the sample size of seven teams is relatively small compared with the total population of traffic controllers, network controllers, and train drivers in the Netherlands. Moreover, the train drivers participating were test drivers and thus not fully representative of all NS train drivers. As a result, any generalization of the findings should be made with caution. Additionally, generalization of the results to other European countries may also be limited to differentiating task division in traffic operations. An initial mapping of task has been reported in FP1/D16.1. However further analysis is needed.

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.

It should be noted that occasionally there were technical issues with the simulation environment, which is the reason why no operator or network performance data has been used in the analysis. This should be included in future work.

Another limitation that has been previously discussed is that the current study included developing ATO-TMS components (TRL 5) or still need to be developed (e.g. Train Path Envelope generator as part of the ATO-TS or TMS) or still under development (e.g. decision-support functionalities in the TMS). The results provide a first insight in the impact of TMS-ATO GoA2, but should generalization is limited given the overall low maturity level of the system (TRL 5) and low Human Readiness Level (HRL 3) for traffic operators.

## 5.3 OTHER HUMAN FACTORS RESULTS FROM TESTS SIMULATIONS AND DEMONSTRATIONS IN FP1, 2 AND 5

### 5.3.1 Aim and approach

The aim of this activity was to provide an overview of other relevant human factors developments implemented in the form of either technical enabler tests (TE tests), simulations, or demonstrations in FP1, 2 and 5 of Europe's Rail. The focus was on surveying developments that show a potential operational impact of individual or combined DATO components in terms of added-value to rail transportation and human factors. To collect the information of interest, a questionnaire was developed and sent to work package leaders in FP1, 2 and 5 with a request for a reply. The questionnaire is attached to this deliverable in Appendix B.

### 5.3.2 Results: Overview of DATO activities

The results are summarized in the following in the form of short activity profiles that give the name of each activity, show which FP, WP and task it belongs to, and characterize the type of the activity (TE test, simulation, demonstration, other) as well as its areas of expected operational impact (capacity, cost, energy, business cases, human factors). If results are already available, the respective deliverables are named and links to the results are provided if available; otherwise, the time of the expected availability of results is specified where possible. The data collection provides an overview of the relevant activities but does however not claim completeness, as inputs could be received from most, but not all WPs. The activities are presented in ascending order by FP, WP and task. The findings below include only relevant development with a human factors focus.

#### 5.3.2.1 Collaborative disruption management solution, related tools and methodology for HMI design (FP1, WP14, T14.1-2).

- Type of activity: Demonstration.
- Main focus: Capacity gains, human factors.
- Results: expected in June 2026.

- More detail: Demonstration of a collaborative DSS (decision support system) for efficient and effective disruption management at TRL 4/5, and demo of HMI for TMS based on User Experience (UX) design and user input for TRL 8. Representative data samples to feed the DSS demo are obtained from FP3-IAM4RAIL/(WP 3-4).

#### 5.3.2.2 Improved traffic plans using C-DAS data, operational performance and human factors of TMS-ATO solutions (FP1, WP16, T16.3-5)

The results from this work package are described in this deliverable in Section 6.2.

#### 5.3.2.3 Perception system prototype (FP2, WP11, T11.2)

- Type of activity: TE test, demonstration.
- Main focus: Capacity gains, Human Factors, Other (Validation of advanced perception system ready for ATO GoA3-GoA4).
- Results:
  - Perception system test report based on test scenario on field linked to perception requirements specification, preliminarily internally available from

    https://cooperationtool5.eu:443/documents/details/9bf41ff9-f4c8-4155-a5c3-f98b882f2da1
  - Final version of deliverable expected for 8.5.2026 as per DDP.
- More detail: The activity is about the installation of WABTEC Perception system in an AZD Edita Locomotive, the system works in standalone mode, there is no interaction with the Train.

#### 5.3.2.4 Remote driving demonstrator in shunting/stabling operations (FP2, WP38, T38.2, T38.3, T38.6, T38.7)

- Type of activity: Demonstration.
- Main focus: Human Factors.
- Results:
  - D38.1 and D38.7 in JU review, D38.2 and D38.6 in SC review, D38.3 in WP internal review.
  - D38.3 to be done.
- More detail: Demonstrations of remote driving were done at NS and SBB, resulting in insights on human factors concerning workplace and process design, insights in process times, and training materials. Work on staff productivity KPIs remains to be done (T38.9).

# 6 ADOPTION OF AUTOMATED OPERATIONS

The transition or migration to higher levels of automation affects infrastructural costs, organizational structures, operators, and users or customers - the latter particularly when changes in automation translate into perceivable changes in the service experience. A well-established principle in human factors research is that people tend to resist change, whether positive or negative, and that the legacy configuration of a system or service tends to be the preferred one. This phenomenon, often referred to as the *status quo bias*, has been extensively documented in decision-making and technology adoption literature (Samuelson & Zeckhauser, 1988; Kim & Kankanhalli, 2009). Users develop mental models and habitual expectations around existing systems, and deviations from these established patterns - even beneficial ones - can provoke discomfort, distrust, or rejection (Parasuraman & Riley, 1997). In the context of transport automation, this resistance may be further amplified by concerns related to perceived safety, loss of human oversight, and unfamiliarity with the technology.

In this chapter, Section 6.1 examines the potential transition to automated train services from the perspective of future passengers, in order to formulate recommendations regarding the implementation of the transition. Section 6.2 identifies factors and conducts an initial exploration with operators - specifically train drivers and traffic controllers - regarding aspects that might positively or negatively affect the transition to higher levels of train automation, with the goal of establishing guidelines to facilitate that transition.

## 6.1 PASSENGER ACCEPTABILITY STUDY

### 6.1.1 Previous work on passenger acceptability of autonomous trains

Acceptability studies, intended as investigations of people' expectations regarding future use of autonomous trains were conducted in recent years. To scope the current landscape of opinions and to build upon previous knowledge a systematic search was conducted following the PRISMA guidelines (Page et al., 2021). Specifically, the review process aimed to investigate how passenger experiences with automated trains operation (ATO) have been studied and what aspects of the passenger experience have been examined to date. Two research questions guided the review:
**(RQ1)** *Which research methods and measurement tools have been used to collect ATO passenger acceptability?*
**(RQ2)** *Which aspects of the passenger expected experience have been most frequently explored, and what key findings have emerged?*

The review included peerreviewed journal articles, conference papers, or book chapters published from 2015 onward, written in English or German, and explicitly reporting methods used to study passenger experiences in the context of automated trains. Studies were excluded if they lacked peer review, were unavailable through the University of Twente, discussed rail travel without a specific focus on automated trains, or addressed autonomous vehicles without including ATO. Searches were performed in Web of Science and Scopus using predefined keywords. After removing duplicates (n = 9) and screening titles and abstracts according to the eligibility criteria (n = 92 excluded), 13 articles proceeded to full text review. Following evaluation by the three researchers and consultation with two external experts, nine studies remained. One additional paper (Wang et al., 2021) was later excluded due to its engineering focused scope, resulting in a final set of eight studies (Appendix C provide details about the review process). Table 7 summarize methods and findings per each individual item.

| Item | Main methods | Key Findings |
|---|---|---|
| Lemonnier et al. (2023) | In-depth, semi-structured interviews | GoA3 widely accepted; GoA4 rejected. Main concerns: safety, trust, jobs. Women more positive toward AT. |
| Arzer et al. (2024) | Multimethod qualitative study combining focus groups | Staff presence, safety, and clear communication key to acceptance. Comfort improvements suggested. |
| Fraszczyk et al. (2015) | Questionnaire | Gender gap in acceptance (women more resistant). Technical and communication concerns primary. 62% unconcerned about job losses. |
| Fraszczykk & Mulley (2017) | Online questionnaire | Users less concerned about drivers than non-users. Price and frequency prioritized. 60% want visible driver cabin. |
| Cogan et al. (2022) | Online survey and choice-based conjoint analysis | GoA3 preferred (53%) over GoA4 (13%). Safety and reliability crucial. Young users prioritize cost savings. |
| Detjen et al. (2021) | Q-methodology | Four user clusters identified: technical enthusiasts, social skeptics, service-focused, and technology-focused non-enthusiasts. |
| Pakusch & Bossauer (2017) | Online survey | 78% accept autonomous transport. Prior experience increases acceptance. Gender difference in willingness. |
| Morast et al. (2023) | Online survey adapted from CTAM | Experience increases acceptance. Age affects acceptance. Cybersecurity concerns significant. |

**Table 7: Methods and findings per individual item.**

Taken together the previous studies suggest the following eight aspects might potentially affect acceptability of ATO:

Users vs. Non-users: Research consistently demonstrates significant differences between regular users and non-users of conventional train services (Cogan et al., 2022; Fraszczyk & Mulley, 2017; Morast et al., 2023). Morast et al. (2023) found that individuals who used trains several times per month demonstrated higher acceptance than daily users, suggesting that moderate users may appreciate automation benefits while not being constrained by established habits.

Prior experience with autonomous vehicles: Pakusch et al. (2017) reported that 88% of individuals with prior autonomous transportation experience supported autonomous public transport implementation. Similarly, Cogan et al. (2022) found that respondents with autonomous vehicle experience were three times more likely to strongly support driverless trains than those without such experience.

Safety in automated trains: Fraszczyk and Mulley (2017) found that Sydney Trains users prioritized safety as a critical service attribute, with 50% of regular users and 67% of non-users expressing specific safety concerns.

Service improvements: Cogan (2022) identified that reduced delays and service consistency were key motivators for passengers considering teleoperation acceptance. Both Cogan (2022) and Fraszczyk (2015) found that passengers considering autonomous trains placed greater emphasis on service quality factors than on potential cost savings.

Rail personnel presence: Lemonnier et al. (2023) documented significantly higher acceptance of Grade of Automation 3 (GoA3) trains, which maintain onboard staff, compared to widespread rejection of Grade of Automation 4 (GoA4) systems that rely solely on remote supervision. This finding was corroborated by Arzer et al. (2024), who identified staff presence capable of assuming control of the train as a key determinant of passenger comfort and perceived safety. Fraszcyk & Mulley (2017) reported that 60% of study participants preferred maintaining a driver's cabin as a visible safety fallback, even in fully autonomous train designs where it would serve no operational purpose. Arzer et al. (2024) identified communication quality as a key factor influencing passenger experience with autonomous trains.

Broader societal concern: Lemonnier et al. (2023) identified employment impacts as a key factor influencing acceptance. Interestingly, however, Fraszczyk et al. (2015) reported that 62% of respondents did not perceive Grade of Automation 4 (GoA4) as posing a significant job threat.

Automation level preference: Lemonnier et al. (2023) documented a strong preference hierarchy, finding high acceptance of GoA3 systems (which maintain onboard staff) but widespread rejection of fully autonomous GoA4 systems (with only remote supervision)

Demographic differences: Some studies suggest older participants may show lower acceptance and greater safety concerns (Cogan et al., 2022; Morast et al., 2023). Findings on gender are less consistent, with some indicating women might be more hesitant or prefer a driver's cabin (Frasczyk et al., 2015; Fraszczyk & Mulley, 2017).

Overall, the studies indicate a general acceptance of unattended trains, with a high intention to use GoA3 trains (Lemmonier et al., 2023). However, there are strong reservations regarding GoA4 trains. The primary concern for GoA4 trains is the absence of on-board staff (Arzer et al., 2024; Lemmonier et al., 2023; Cogan et al., 2022, Frascyzik et al., 2015). Passengers fear being abandoned or left unable to manage unexpected situations like assaults or illness without staff present and express a lack of trust in remote communication and supervision for assistance.

The European Union has committed substantial resources toward integrated rail systems through the Europe's Rail Joint Undertaking, with autonomous operations representing a key pathway to enhanced capacity, efficiency, and environmental sustainability. However, technological advancement alone cannot guarantee successful deployment; public acceptance remains an essential precondition. Previous research on passenger attitudes toward rail automation has been conducted primarily within single-country contexts using varied methodologies, limiting cross-national generalisability.

Building on previous work aiming to comprehensively investigate acceptability of ATO in Europe a multilingual survey was developed and distributed across diverse European countries.

## 6.1.2 Survey study methodology

### 6.1.2.1 Participant recruitment

The research team collected data through two channels. An initial cohort of 165 valid responses came from voluntary participants recruited via social media. Subsequently, 381 additional valid responses were obtained through a commercial panel service, with each participant receiving €1.50 compensation. After excluding incomplete responses and statistical outliers based on completion time, the final analytical sample comprised 519 European residents.

### 6.1.2.2 Survey design

The questionnaire was administered in five languages: English, Dutch, German, Italian, and Spanish. The instrument contained four substantive sections covering demographic characteristics and commuting behaviour, current service quality perceptions and future expectations, anticipated changes regarding communication and security needs, and preferences regarding automation levels alongside usage intentions.

### 6.1.2.3 Data analysis

Statistical analyses employed exploratory factor analysis to identify latent attitudinal constructs, followed by genetic algorithm-based model selection to determine optimal predictor combinations for five outcome variables: driver type preference, preferred automation grade, deployment support, usage intention, and employment concerns.

## 6.1.3 Results

### 6.1.3.1 Sample characteristics

The participant cohort had a mean age of 37 years with considerable range from 19 to 81 years. Male respondents comprised 61.3% of the sample. Approximately 37% reported prior experience with at least one autonomous transport system. The main demographics are summarized in Table 8.

| Characteristic | Distribution |
|---|---|
| Residential Setting | |
| Urban | 58% |
| Suburban | 26% |
| Rural | 15% |
| Declined to specify | 1% |
| Risk Tolerance | |
| Moderate risk-takers | 65% |
| High risk-takers | 14% |
| Low risk-takers | 21% |
| Rail Industry Connection | |
| No connection | 70% |
| Family or friends employed in rail | 23% |
| Personally employed in rail | 7% |
| Train Usage Frequency | |
| Daily | 6 |
| 3-4 days weekly | 7 |
| 1-2 days weekly | 12 |
| 1-3 times monthly | 31 |
| Less than monthly | 34 |
| Not used in past 12 months | 10 |

**Table 8: Demographic profile of survey respondents**

Responses came from 23 European nations, though the distribution was uneven. Southern European countries (Italy, Spain, Portugal, Greece, Slovenia, Croatia, Serbia) accounted for 48.8% of participants. Western European nations (France, Belgium, Netherlands, Germany, Austria, Switzerland) contributed 25.8%. Eastern European countries (Poland, Czech Republic, Slovakia) represented 17.7%, while Northern European nations (Norway, Sweden, Finland, Denmark, Estonia, United Kingdom, Ireland) comprised 7.7%.

#### 6.1.3.2 Service quality priorities

Respondents identified reliability and safety as paramount considerations when evaluating rail service quality, followed by cost, passenger comfort, and accessibility. Environmental sustainability ranked lowest among current quality concerns (see Table 9).

| Quality Aspect | Mean Rating | Standard Deviation |
|---|---|---|
| Reliability | 4.58 | 0.60 |
| Safety | 4.50 | 0.74 |
| Ticket Cost | 4.24 | 0.79 |
| Passenger Comfort | 3.91 | 0.78 |
| Accessibility | 3.70 | 1.03 |
| Environmental Sustainability | 3.42 | 1.07 |

*Scale: 1 = Not important at all; 5 = Extremely important*

**Table 9: Importance ratings for service quality dimensions**

As suggested in Table 10, when asked about anticipated benefits from automation, respondents prioritised extended operating hours, increased service frequency, and reduced fares. Energy efficiency improvements ranked as the lowest priority among expected changes.

| Expected Change | Mean Rating | Standard Deviation |
|---|---|---|
| Extended Operating Hours | 4.16 | 0.82 |
| Increased Service Frequency | 4.15 | 0.77 |
| Reduced Ticket Prices | 4.10 | 0.88 |
| Reduced Operator Risk | 3.86 | 1.02 |
| Energy Efficiency Gains | 3.55 | 1.06 |

*Scale: 1 = Not important at all; 5 = Extremely important*

**Table 10: Importance ratings for expected automation benefits**

### 6.1.3.3 Attitudinal dimensions

Factor analysis of survey items concerning automation attitudes revealed four distinct psychological constructs (Table 11). The first factor, General Apprehension Toward Autonomous Trains, captured overall safety concerns and discomfort with unattended operations. The second factor, Operator Presence Requirements, reflected the perceived importance of having human staff available onboard. The third factor, Acceptance of Remote Alternatives, measured receptiveness to technological substitutes for direct human presence. The fourth factor, Cybersecurity Anxiety, encompassed concerns about digital vulnerabilities and potential cyberattacks.

| Factor | Mean Score | Standard Deviation |
|---|---|---|
| F4. Cybersecurity Anxiety | 3.55 | 1.15 |
| F2. Operator Presence Requirements | 3.81 | 1.04 |
| F3. Acceptance of Remote Alternatives | 3.50 | 1 |
| F1. General Apprehension | 3 | 1.17 |

*Scale: 1 = Strongly disagree/Not important; 5 = Strongly agree/Extremely important*

**Table 11: Mean scores for factors (descending order importance)**

Cybersecurity emerged as the predominant concern, with participants expressing notable anxiety about cyberattacks affecting automated transport systems. Attitudes toward the safety of unattended trains remained relatively neutral, suggesting uncertainty rather than outright rejection.

### 6.1.3.4 Preferences for human involvement and GoA

When asked whether they would choose trains operated by humans, autonomous systems, or either option, participants showed the following distribution:

- 53% expressed indifference between human and autonomous operation.
- 35% preferred human-operated trains.
- 12% preferred autonomous operation.

This pattern indicates that while outright preference for automation remains limited, the majority of respondents do not actively resist it.

Respondents were presented with detailed descriptions of each automation level and asked which they would find most acceptable for their travel (See Figure 23).

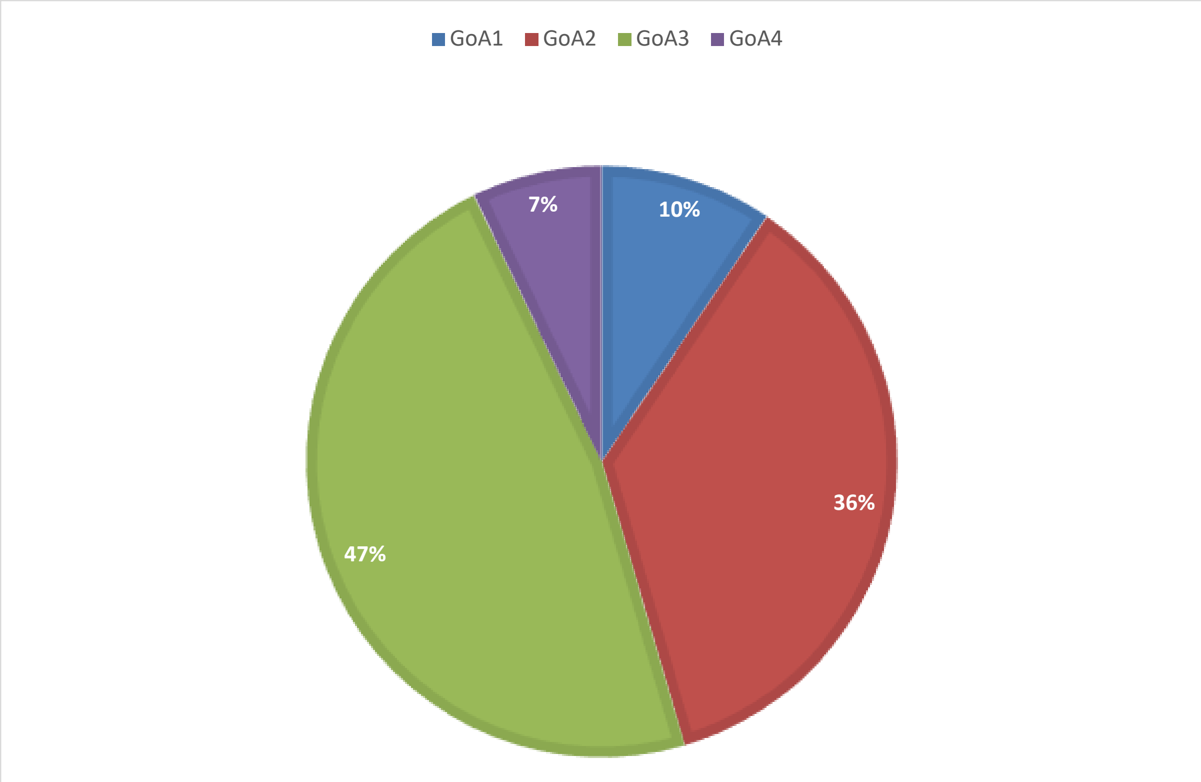


**Figure 23: Preferred Grade of Automation (GoA) level**

The overwhelming preference for GoA 2 and GoA 3 (combined 83%) demonstrates that European citizens favour automation that retains meaningful human presence. Only 7% of respondents accepted fully unattended trains, indicating substantial resistance to complete automation at present.

#### 6.1.3.5 Usage intentions and deployment support

Participants expressed moderate intention to use autonomous trains regularly once available (M = 3.50). Overall support for autonomous train deployment was similarly moderate (M = 3.56). Belief that automation would increase operator unemployment was relatively low (M = 2.48), though this represents a notable concern for a substantial minority.

#### 6.1.3.6 Predictive Modelling

Model selection techniques were applied to identify factors associated with each outcome variable. Model performance varied considerably across outcomes (see Table 12).

| Outcome Variable | McFadden's $R^2$ | Model Quality |
|---|---|---|
| Driver Type Preference | 0.479 | Strong |
| Deployment Support | 0.329 | Moderate |
| Automation Grade Preference | 0.263 | Moderate |
| Usage Intention | 0.235 | Moderate |
| Unemployment Concerns | 0.082 | Poor |

**Table 12: Predictive model performance**

The model for driver type preference explained nearly half the variance, indicating that measured factors effectively capture the determinants of this choice. Models for deployment support and automation grade preference achieved moderate explanatory power. The model for unemployment concerns performed poorly, suggesting that beliefs about automation's employment effects are driven by factors outside the measured variables, potentially including political orientation or media consumption patterns.

### 6.1.4 Key predictors of automation acceptance

#### 6.1.4.1 Autonomous or human driven

Table 13 summarized the main results. Overall, people with the highest support autonomous train deployment are the ones who mainly opt for autonomous trains (OR = 28.42) compared to human driven trains. Higher risk tolerance was associated with greater preference for automation (OR = 3.74). Frequent car drivers showed elevated preference for autonomous trains (OR = 1.43), while those who highly valued accessibility showed reduced preference (OR = 0.56).

Conversely, people prefer Human Drivers when they have high general apprehension toward autonomous trains (OR = 4.26). Female respondents were more likely than male respondents to prefer human drivers. Frequent users of taxis and ride-hailing services also showed elevated preference for human operation (OR = 1.60).

| Preference | Variable | Odds Ratio | 95% Confidence Interval |
|---|---|---|---|
| Autonomous Operation | | | |
| | Deployment Support (linear) | 28.42 | 7.15 – 112.97 |
| | Deployment Support (cubic) | 13.16 | 2.98 – 58.19 |
| | Deployment Support (quartic) | 0.05 | 0.01 – 0.33 |
| | Unemployment Concerns (cubic) | 0.22 | 0.08 – 0.59 |
| | High Risk Tolerance (vs. moderate) | 3.74 | 1.46 – 9.59 |
| | Unpaid Participant (vs. panel) | 0.24 | 0.09 – 0.66 |
| | Train Commuting Frequency | 0.63 | 0.43 – 0.91 |
| | Car Commuting Frequency | 1.43 | 1.11 – 1.82 |
| | Accessibility Importance | 0.56 | 0.36 – 0.85 |
| Human Operation | | | |
| | GoA Preference (linear) | <0.01 | 0.00 – 0.00 |
| | GoA Preference (quadratic) | <0.01 | 0.00 – 0.01 |
| | GoA Preference (cubic) | 0.03 | 0.02 – 0.06 |
| | Deployment Support (linear) | <0.01 | 0.00 – 0.00 |
| | Deployment Support (quadratic) | 1721.43 | 450.97 – 6571.01 |
| | Deployment Support (cubic) | 0.02 | 0.01 – 0.06 |
| | Unemployment Concerns (linear) | 0.19 | 0.05 – 0.72 |
| | Male (vs. female) | 0.44 | 0.22 – 0.85 |
| | Car Commuting Frequency | 1.33 | 1.11 – 1.61 |
| | Ride-hailing Frequency | 1.60 | 1.10 – 2.33 |
| | Operator Risk Reduction Importance | 0.65 | 0.46 – 0.92 |
| | General Apprehension (Factor 1) | 4.26 | 2.48 – 7.34 |

*Note: Reference category is respondents who expressed indifference between driver types*

**Table 13: Predictors of preference for autonomous versus human-driven trains**

### 6.1.4.2 Automation grade preference

Support for autonomous train deployment predicted preference for higher automation levels (OR = 6.32). Regional differences were pronounced: compared with Southern European respondents, those from Northern Europe (OR = 0.31) and Western Europe (OR = 0.54) were significantly less likely to prefer higher automation grades. Concerns about cybersecurity (OR = 0.80), requirements for operator presence (OR = 0.59), and general apprehension (OR = 0.65) all reduced preference for higher automation levels. See Table 14 for all the predictors.

| Variable | Odds Ratio | 95% Confidence Interval |
|---|---|---|
| Preference for Human Drivers | 0.30 | 0.17 – 0.52 |
| Deployment Support (linear) | 6.32 | 2.55 – 15.63 |
| Western Europe (vs. Southern Europe) | 0.54 | 0.32 – 0.92 |
| Northern Europe (vs. Southern Europe) | 0.31 | 0.14 – 0.69 |
| Car Commuting Frequency | 1.19 | 1.08 – 1.32 |
| Ride-hailing Frequency | 1.32 | 1.04 – 1.64 |
| Accessibility Importance | 0.80 | 0.65 – 0.99 |
| General Apprehension (Factor 1) | 0.65 | 0.48 – 0.88 |
| Operator Presence Requirements (Factor 2) | 0.59 | 0.44 – 0.80 |
| Cybersecurity Anxiety (Factor 4) | 0.80 | 0.65 – 0.98 |

*Note: Higher odds ratios indicate greater likelihood of preferring higher automation grades (GoA 3–4 versus GoA 1–2)*

**Table 14: Predictors of preference for higher automation grades**

#### 6.1.4.3 Deployment support

Table 15. details all the factors that affect people decisions to support the deployment of autonomous trains. Overall, the main aspects seem to be: 1) Intention to use autonomous trains regularly was the most powerful predictor of deployment support (OR = 17.52). 2) Preference for higher automation grades predicted greater support (OR = 5.41). 3) Northern European respondents showed higher support than Southern Europeans (OR = 3.36). 4) Acceptance of remote alternatives to onboard staff increased support (OR = 1.44), while 5) strong preferences for operator presence reduced it (OR = 0.60). 6) Respondents who prioritised service reliability showed greater support (OR = 1.84).

| Variable | Odds Ratio | 95% Confidence Interval |
|---|---|---|
| Preference for Autonomous Operation | 3.82 | 1.84 – 7.93 |
| Preference for Human Drivers | 0.17 | 0.10 – 0.29 |
| GoA Preference (linear) | 5.41 | 2.28 – 12.83 |
| Usage Intention (linear) | 17.52 | 7.33 – 41.86 |
| Usage Intention (cubic) | 2.08 | 1.22 – 3.54 |
| Unemployment Concerns (linear) | 0.34 | 0.18 – 0.64 |
| Unemployment Concerns (quadratic) | 0.46 | 0.25 – 0.85 |
| Northern Europe (vs. Southern Europe) | 3.36 | 1.51 – 7.48 |
| Reliability Importance | 1.84 | 1.33 – 2.53 |
| Ticket Cost Importance | 0.72 | 0.53 – 0.97 |
| Reduced Price Expectation | 1.32 | 1.00 – 1.73 |
| Operator Presence Requirements (Factor 2) | 0.60 | 0.44 – 0.81 |
| Remote Alternative Acceptance (Factor 3) | 1.44 | 1.05 – 1.96 |

*Note: Higher odds ratios indicate greater likelihood of expressing stronger support for ATO deployment*

**Table 15: Predictors of support for autonomous train deployment**

### 6.1.4.4 Factors associated with usage intention

As summarized in Table 9. Support for autonomous train deployment was overwhelmingly the strongest predictor of usage intention (OR = 17.72). General apprehension toward autonomous trains represented the most substantial barrier (OR = 0.30), corresponding to a 70% reduction in intended use for each unit increase in fear. Counterintuitively, cybersecurity concerns were positively associated with usage intention (OR = 1.32), suggesting that security-conscious individuals may become early adopters if adequately reassured. Urban (OR = 1.96) and suburban residents (OR = 1.84) showed higher usage intention than rural residents. Rail industry workers showed significantly lower intention to use autonomous trains (OR = 0.29). Table 16 offers the full perspective.

| Variable | Odds Ratio | 95% Confidence Interval |
|---|---|---|
| Preference for Human Drivers | 0.57 | 0.34 – 0.96 |
| Deployment Support (linear) | 17.72 | 7.31 – 42.97 |
| Rail Industry Employment (vs. non-rail) | 0.29 | 0.10 – 0.90 |
| Suburban Residence (vs. rural) | 1.84 | 1.03 – 3.28 |
| Urban Residence (vs. rural) | 1.96 | 1.16 – 3.32 |
| Unpaid Participant (vs. panel) | 0.53 | 0.32 – 0.87 |
| Age 56–65 (vs. 36–45) | 5.91 | 2.14 – 16.33 |
| Train Commuting Frequency | 1.31 | 1.04 – 1.64 |
| Metro Commuting Frequency | 1.28 | 1.10 – 1.49 |
| Ferry Commuting Frequency | 0.62 | 0.45 – 0.85 |
| Car Passenger Frequency | 1.27 | 1.09 – 1.49 |
| Energy/Sustainability Expectation | 1.43 | 1.18 – 1.73 |
| General Apprehension (Factor 1) | 0.30 | 0.22 – 0.41 |
| Cybersecurity Anxiety (Factor 4) | 1.32 | 1.09 – 1.59 |

*Note: Higher odds ratios indicate greater likelihood of expressing higher intention to use autonomous trains*

**Table 16: Predictors of intention to use autonomous trains regularly**

### 6.1.4.5 Unemployment and ATO

When examining beliefs about whether autonomous train deployment would increase operator unemployment, the predictive model achieved poor explanatory power (McFadden's $R^2 = 0.082$), indicating that the factors measured in this survey capture only a small portion of what drives these concerns. Nevertheless, several meaningful associations emerged (See Table 16). Respondents who expressed support for autonomous train deployment were substantially less likely to believe that automation would cause job losses (OR = 0.09), corresponding to approximately a 90% reduction in the odds of expressing unemployment concerns for each unit increase in support. This inverse relationship suggests that those favouring automation may either discount employment effects or view workforce transition as manageable. Paradoxically, participants who preferred human drivers also reported lower unemployment concerns (OR = 0.58). This counterintuitive pattern may indicate that those preferring human operation do so for reasons unrelated to employment protection, such as personal safety or comfort considerations. Recruitment method influenced responses, with unpaid volunteers showing reduced odds of expressing unemployment concerns compared with compensated panel participants (OR = 0.56). This difference highlights the importance of accounting for sample composition when interpreting findings. Several factors were positively associated with unemployment concerns. Respondents who rated service reliability as important were more likely to believe automation would displace workers (OR = 1.60). Similarly, those expecting automation to reduce ticket prices showed elevated unemployment concerns (OR = 1.26), possibly reflecting an implicit understanding that cost savings might come through workforce reductions. General apprehension toward autonomous trains predicted stronger unemployment concerns (OR = 1.55), suggesting that broader anxieties about automation encompass worry about its societal and economic consequences alongside personal safety considerations. The weak overall model fit indicates that beliefs about automation's employment effects are likely shaped by factors not captured in this survey, potentially including political orientation, economic ideology, media consumption patterns, or personal experience with technological displacement in other sectors.

| Variable | Odds Ratio | 95% Confidence Interval |
|---|---|---|
| Preference for Human Drivers | 0.58 | 0.36 – 0.95 |
| Deployment Support (linear) | 0.09 | 0.04 – 0.24 |
| Unpaid Participant (vs. panel) | 0.56 | 0.36 – 0.87 |
| Reliability Importance | 1.60 | 1.21 – 2.11 |
| Reduced Price Expectation | 1.26 | 1.04 – 1.54 |
| General Apprehension (Factor 1) | 1.55 | 1.19 – 2.03 |

*Note: Higher odds ratios indicate greater likelihood of expressing stronger concerns about automation-related unemployment*

**Table 17: Predictors of concerns about operator unemployment due to automation**

### 6.1.5 Implications for European policy and deployment strategy

**Recommendation 1: Communicate automation benefits through reliability and sustainability.** Passengers prioritise reliability and safety above all other service attributes. Communication strategies should emphasise how automation enables improved punctuality, reduced delays, and more frequent service. Although environmental sustainability ranked lowest among current quality concerns, energy efficiency emerged as a significant predictor of usage intention, suggesting that framing automation around environmental benefits may resonate with particular segments of the population.

**Recommendation 2: Pursue staged implementation aligned with public preferences.** The strong preference for intermediate automation (83% favouring GoA 2 or GoA 3) indicates that phased implementation will encounter less resistance than rapid transition to fully unattended operations. This finding aligns well with Europe's staged approach to ATO specification development. Infrastructure managers should anticipate extended periods of intermediate automation while gradually building public familiarity and trust.

**Recommendation 3: Develop high-quality remote communication systems.** Acceptance of remote alternatives to onboard staff positively predicted deployment support, identifying this as a high-leverage intervention point. Passengers demonstrate willingness to accept reduced onboard staffing if credible alternatives exist. However, robot-based communication received the lowest acceptability ratings, indicating that technological solutions must retain human-mediated qualities. Investment in trained remote personnel, high-quality communication interfaces, and visible safety systems will be essential for generating acceptance.

**Recommendation 4: Address cybersecurity through transparency rather than minimisation.** Cybersecurity emerged as the predominant concern among respondents. Rather than downplaying digital vulnerabilities, decision-makers should communicate transparently about security investments, incident response protocols, and the advantages of standardised systems. The positive correlation between cybersecurity awareness and usage intention suggests that security-conscious citizens may become adoption advocates if adequately informed.

**Recommendation 5: Engage rail industry workers as potential ambassadors.** Rail workers displayed higher acceptance of advanced automation grades yet significantly lower personal intention to use autonomous trains. This pattern likely reflects complex attitudes shaped by professional knowledge and occupational identity. These individuals represent potential opinion leaders whose credible endorsement could influence public attitudes, but only if their concerns about implementation challenges and workforce transition receive genuine attention.

**Recommendation 6: Tailor strategies to regional contexts.** The heterogeneous patterns across European regions indicate that uniform deployment approaches may prove suboptimal. Southern European contexts may benefit from emphasising the reliability and efficiency gains of automation, while Northern European communications might focus on maintaining quality oversight even as automation advances. Cross-border technical harmonisation must be accompanied by regionally adapted stakeholder engagement. Geographic patterns revealed different attitudes in terms of acceptability of ATO. Northern European respondents demonstrated the highest support for autonomous train deployment yet the lowest preference for advanced automation grades. Southern Europeans showed the opposite pattern: lower deployment support but higher tolerance for advanced automation. Western Europeans displayed the lowest acceptance of higher automation levels among all regions. These patterns suggest that contextual factors including existing rail infrastructure quality, cultural attitudes toward technology, and prior exposure to automated systems shape expectations in complex ways that resist simple generalisation.

### 6.1.6 Conclusion

Our sample of European citizens demonstrate cautious openness toward autonomous train operations, with clear preferences for intermediate automation that balances technological capability with human oversight. The path toward successful deployment requires more than technical innovation; it demands sustained attention to public concerns about safety, cybersecurity, and the quality of remote assistance. Regional variation in attitudes underscores the necessity for differentiated communication and engagement strategies. To our knowledge, this study proposes the largest multilingual survey on the acceptability of train automation in Europe. The cross-sectional nature of the data collection precludes causal inference. Nevertheless, the findings support a gradual, phased approach to automation that maintains meaningful human involvement during the transition period. Decision-makers who invest in transparent communication, high-quality remote support systems, and genuine workforce engagement will be best positioned to realise the capacity, reliability, and sustainability benefits that autonomous rail operations promise.

Future work could focus on respondents that already have experienced ATO GoA4 in operations and investigate to what extent this experience changes their perception and attitudes.

## 6.2 Assessment of operational transitions

This section focuses on how organizations effectively can manage operational transitions (i.e. operational changes or migrations) in large scale socio-technical system changes. Section 6.2.1 presents a systematic literature review identifying the main facilitators, barriers, and lessons learned from automation and digitalisation efforts across transport domains. Section 6.2.2 complements this with operator perspectives gathered through a HITL simulation, highlighting which transition factors practitioners consider most important. Finally, Section 6.2.3 combines insights from both sources to formulate high-level guidelines for supporting successful system development and implementation during the move toward more automated operations.

### 6.2.1 Literature review

The transport sector, especially rail, faces increasing pressure to integrate automation technologies such as Automatic Train Operation (ATO) and the European Rail Traffic Management System (ERTMS). European targets aim to significantly reduce journey times and increase network capacity by 2040. However, implementing these technologies requires managing complex operational transitions that extend beyond technical deployment to encompass human, organizational, and procedural dimensions.

A systematic literature review identified the factors influencing operational transitions related to automation and digitalization across transport domains, with particular focus to the rail sector. Following PRISMA guidelines, the authors searched three databases (Scopus, Web of Science, IEEE) for publications from 2000–2025, ultimately identifying 14 eligible articles after screening 130 initial items.

The review addresses a central research question: What are the most commonly reported facilitators, barriers, and transferable lessons learned for operationalizing technological change in rail?

#### 6.2.1.1 Methodology

##### *6.2.1.1.1 Search strategy*

Three databases were accessed for this systematic literature review: Scopus, Web of Science, and IEEE. The search focused on operational changes or similar terms, automation, and digitalization in multiple transport domains with a particular focus on rail service. The following code was used for the search: *"change management" OR "operational transition" OR "operational readiness" OR "operational change*"AND automat* OR "ATO" OR digit* AND rail* OR aviation OR maritime OR transport.*

##### *6.2.1.1.2 Eligibility criteria*

We selected items published from 2000 to 2025 that were published as journal or conference articles or book chapters and that presented empirical or theoretical insights regarding operational transitions in the transportation domain. We focused on items in which the authors discussed automation or digitization of technological components in transportation services. Items were excluded from the review if they focused on the development of technology instead of the implementation of procedures for using the technology and its organizational consequences. Additionally, we excluded articles that did not focus on the automation of transportation, e.g., logistics, or that discussed innovations unrelated to technological components. As summarized in appendix D, the initial extraction of 130 items included 24 duplicate items. After the title and abstract screening 67 items were excluded. In total, 28 items were excluded based on criterion 1, 32 items were excluded based on criterion 2, and 7 items were excluded based on criterion 3. Out of the 39 articles selected for full reading 7 were not retrievable e.g. unavailable for access by the University of Twente. Out of the 32 articles screened, 18 were excluded. Finally, 14 items were considered eligible for data extraction with the agreement of all the authors.

##### *6.2.1.1.3 Data extraction*

The final list of items was reviewed searching in the text information regarding cases of technological transition in transport domains, with a particular focus but not limited to the rail service. Specifically, the following main aspects were investigated:

- Facilitators and Barriers – intended as all the reported attitudes, actions, procedures, events etc. that the researchers identified having a positive (facilitator) or negative (barriers) impact on the transition process.
- Lessons learned – defined as all those actions or aspects that must be performed or considered before and during the implementation of a transition to successfully change the operation. Such actions are meant to maximize the effects of facilitators and minimize the negative effects of the barriers.

##### *6.2.1.1.4 Data synthesis*

The information reported about facilitators, barriers and lesson learned were grouped under common labels e.g., every time an item highlighted the importance of participatory design or involvement of the stakeholders to facilitate the transition etc. the item was grouped under the label "Facilitator -

Stakeholder involvement". These labels were assigned in discussion with all the authors. These labels were used to establish the frequency of appearance of each identified facilitator, barrier and lesson learned in the 14 selected items. Finally, facilitators, barriers and lessons learned were clustered in the following aspects: Cluster 1 - "Organizational management and human factors aspects" which emphasizes people-centric aspects crucial for ATO adoption in railways e.g. stakeholder involvement or perceived usefulness of the innovation; Cluster 2 - "Process and risk mitigation strategies" which focuses on methodologies to navigate ATO's implementation process and support its safe deployment; Cluster 3 - Infrastructure and System integration which refers to e.g. system requirements, interoperability and system standardization. Although we acknowledge substantial differences among the domains discussed in the selected items, for the scope of this article, we consider all barriers, facilitators and lessons learned as transportable across domains to aid in facilitating operational changes.

### *6.2.1.1.5 Sample characteristics*

The final sample (Table 18) comprised six journal articles, seven conference articles, and one NASA research paper. Domain distribution included five rail-focused studies, four maritime studies, four aviation studies, and one multi-domain study.

| ID | REF | Type of publication | | | Type of contribution | | Domain |
|---|---|---|---|---|---|---|---|
| | | JA | CA | NRP | E | T | |
| 1 | Aditya, I.E.; Wisdarianto, A.; Raharjo, T. (2022) | | X | | X | | M |
| 2 | Austrian, E.; Berry, K.; Sawyer, M. (2015) | | X | | X | | A |
| 3 | Elgafoss, S.; Skramstad, T.; Dalberg, V. | | X | | | X | M |
| 4 | Gharehbaghi, K.; Farnes, K. (2018) | X | | | | | R |
| 5 | Golub, I; Radojevic, B. (2016) | | X | | | X | M-A-R |
| 6 | Janmethakulwat, A.; Thanasopon, B. (2022) | | X | | | X | M |
| 7 | Molin, F.; Norrman Brandt, E. (2023) | X | | | X | | R |
| 8 | Molin, F.; Norrman Brandt, E. (2025) | X | | | X | | R |
| 9 | Morin, X.; Olsson, N.O.E.; Lau, A. (2024) | X | | | | X | R |
| 10 | Patriarca, R.; Di Gravio, G.; Mancini, M.; Costantino, F. (2016) | X | | | | X | A |
| 11 | Rodriguez Hernández, M., Sánchez-Herguedas, A., González-Prida, V., Contreras, S. S., & Crespo Márquez, A. (2024) | X | | | | X | R |
| 12 | Utomo, D.; S. E. Hiererra; A. Kharizsa; N. Sari; C. Lavinia; M. I. Wijaya (2024) | | X | | X | | M |

| | | | | | | |
|---|---|---|---|---|---|---|
| 13 | Watkins, C.B.; Burns, T. (2015) | X | | | X | A |
| 14 | Young, S.D.; Ancel, E.; Dill, E.; Moore, A.; Quach, C.; Smalling, K.; Ellis, K. (2022) | | X | X | | A |

**Table 18: Items included in the final review, type of publication i.e., Journal Article - JA, Conference article (CA) or NASA Research Paper (NRP); and type of contribution: Mainly empirical (E), Mainly Theoretical (T)**

#### 6.2.1.2 *Key Findings*

The analysis identified 17 distinct facilitators, 17 barriers, and 18 lessons learned across the reviewed literature. Organizational and human factors (CN 1, Table 2) emerged as the dominant category for both barriers and facilitators, while infrastructure-related factors (CN 3, Table 19) received minimal attention.

| Facilitators | F% [CN] | Barriers | F% [CN] | Lessons Learned | F% [CN] |
|---|---|---|---|---|---|
| Stakeholder involvement | 43 [1] | Highly complex, uncertain or degraded systems | 50 [2] | Operator/stakeholder alignment | 21 [1] |
| Utilization of existing support units (i.e. centralized tools for information dissemination) | 36 [2] | Poor System adoption | 29 [1] | Active (middle) management is beneficial | 21 [1] |
| Project based activities (incl. clear responsibility assignment) | 21 [2] | Silo thinking / Departmental fragmentation | 21 [1] | Maintain trust in automation | 21 [1] |
| Utilization of (shared) mental models/distributed cognition | 21 [1] | Lack of coordination in implementation and development | 21 [1] | Provide adequate training | 14 [1] |
| Leadership/management involvement | 14 [1] | Lack of training | 21 [1] | Strict safety conformance and procedures | 14 [2] |
| Interoperability & Standardization of systems | 14 [3] | Stakeholder misalignment | 21 [1] | Account for post-implementation adaptations | 7 [2] |
| External motivation/incentive | 14 [1] | Lack of expertise | 14 [1] | Create understanding for the reason of the transition | 7 [1] |
| Clear documentation | 14 [2] | Lack of organizational readiness | 14 [1] | Incentive use facilitates transitions | 7 [1] |
| Theoretical process development | 7 [2] | Mismatch with currently used mental models | 14 [1] | Maintain system consistency | 7 [3] |

| | | | | | |
|---|---|---|---|---|---|
| Appropriate risk management | 7 [2] | Resistance to change | 14 [1] | Organizational Readiness | 7 [1] |
| Previous successful digital initiatives (lessons learned to draw upon) | 7 [2] | Lack of legacy/new system coherence | 7 [3] | Mapping distributed cognition and responsibilities within teams | 7 [1] |
| Iterative processes | 7 [2] | Misevaluation of safety and stability | 7 [2] | Phase transitions | 7 [2] |
| Data driven | 7 [2] | Lack of perceived urgency | 7 [1] | Early identification of transition opportunities | 7 [2] |
| Perceived usefulness | 7 [1] | Lack of management support | 7 [1] | Prioritize Human-centred design | 7 [1] |
| Structured communication and learning systems | 7 [1] | High implementation costs | 7 [2] | Apply existing, validated frameworks | 7 [2] |
| Human-Centred design | 7 [2] | Skill degradation due to automation | 7 [1] | Change management inclusion | 7 [1] |
| Strong communication between stakeholders | 7 [1] | Insufficient resources | 7 [2] | Structured prioritization of changes | 7 [2] |
| | | | | Shared outcomes between stakeholders are critical | 7 [1] |

**Table 19: Extracted Facilitators, Barriers and Lessons learned by order of frequency of appearance in the selected items (F%) and associated cluster number [CN]: Cluster 1 - "Organizational management and human factors aspects"; Cluster 2 - "Process and risk mitigation strategies"; Cluster 3 -"Infrastructure and System integration"**

#### *6.2.1.2.1 Primary barriers*

System complexity and uncertainty emerged as the most frequently reported barrier, appearing in 50% of reviewed articles. Poor system adoption followed at 29%, while silo thinking, lack of coordination, inadequate training, and stakeholder misalignment each appeared in 21% of cases. These findings suggest that organizational fragmentation and insufficient preparation for change pose greater challenges than technical limitations.

#### *6.2.1.2.2 Primary facilitators*

Stakeholder involvement dominated as the leading facilitator at 43%, reflecting the importance of participatory approaches in managing transitions. Utilization of centralized support tools appeared in 36% of cases, while project-based activities and shared mental models each appeared in 21%. The predominance of people-centric facilitators aligns with systems thinking approaches increasingly adopted in transportation research.

#### *6.2.1.2.3 Lessons learned*

Three lessons emerged with equal prominence at 21% each: the importance of operator-stakeholder alignment, the beneficial role of active middle management, and the need to maintain trust in automation. These findings emphasize that successful transitions require sustained attention to interpersonal and organizational dynamics throughout implementation.

##### *6.2.1.2.4 Cluster analysis*

The thematic clustering revealed a pronounced imbalance across categories. Organizational and human factors (Cluster 1) contained twelve of seventeen identified barriers and twelve of eighteen lessons learned, yet only seven facilitators. This asymmetry suggests that while organizational challenges are well-documented, corresponding mitigation strategies remain underdeveloped in the literature. Process and risk mitigation strategies (Cluster 2) showed the inverse pattern, containing eight facilitators but only four barriers, indicating that procedural approaches may offer underutilized potential for addressing organizational challenges. Infrastructure and system integration (Cluster 3) received minimal attention across all three categories, with only one barrier (lack of legacy/new system coherence), one facilitator (interoperability and standardization), and one lesson learned (maintain system consistency) identified.

#### 6.2.1.3 Implications for rail pperations

The findings carry direct implications for rail operators implementing ATO and ERTMS systems. Transition planning should prioritize stakeholder alignment, active middle management engagement, and structured training programs rather than focusing exclusively on technical readiness. The relative absence of infrastructure-related concerns in the literature suggests that practitioners may treat technical integration as a design-phase responsibility rather than an operational challenge, though this assumption warrants scrutiny in specific implementation contexts. The review acknowledges several limitations. The evidence base of 14 articles provides a foundation but remains limited for definitive conclusions. The assumption of cross-domain transferability, while reasonable given the trans-domain nature of digitalization challenges, requires validation through rail-specific research. Future research should incorporate grey literature (e.g. RU/IM documentation (involving ERTMS)), and operator interviews to expand the evidence base, while longitudinal studies tracking real-world implementations would help validate which facilitators prove most effective in practice.

This review demonstrates that successful operational transitions in public transport depend primarily on addressing human and organizational dimensions rather than technological capabilities alone. The predominance of organizational barriers coupled with the relative scarcity of documented facilitators highlights an important gap requiring attention from both researchers and practitioners. For rail operators facing imminent automation transitions, these findings underscore the necessity of comprehensive change management strategies that extend well beyond technical deployment considerations.

### 6.2.2 Operator priorities in operational transitions

#### 6.2.2.1 Study design

Alongside the findings of the literature review, a questionnaire was given during the HITL simulation (see Section 5.2) to operators (network controllers, traffic controllers and train drivers, N= 26). Out of 26 operators, N = 1 had no opinion due to feeling that implementation of the system was thus far away that they were unable to form an opinion the factors provided. Furthermore, N = 3 incorrectly filled out the ranking questionnaire. For this reason, N = 4 participants were excluded from the final dataset. This questionnaire consisted of 15 factors, given in Dutch, and operators were asked to rank 10 of these 15 factors based on importance (1 = most important, 10 = least important within their ranking, Figure 24). Ultimately, the data of 22 participants was used. N=17 were operators from traffic control, whereas N = 5 operators were train drivers. This represent an initial and exloratory assessment of the factors that should be further extended in future studies.

The factors in the questionnaire were:

- F1: User involvement in the development of ATO.
- F2: Sufficient training.
- F3: Well-functioning ATO system.
- F4: Validated ATO user processes.
- F5: Benefits of ATO for operators.
- F6: Risks to changing the operational roles, i.e. deskilling due to automation.
- F7: Rate of implementation of ERTMS throughout the country.
- F8: Rate of implementation in RU assets (ATO OnBoard).
- F9: Rate of necessary system changes at IM (ATO Trackside and TMS).
- F10: Percentage of trains running on ATO.
- F11: Degree of choice in driving with ATO.
- F12: User involvement during the implementation of ATO.
- F13: Accounting for concurrent operational changes.
- F14: Implementation order of automation levels (i.e. starting with DAS, then ATO GoA2).
- F15: Communications towards operational personnel regarding the changes.

#### 6.2.2.2 Data analysis

An analysis in the form of a heatmap was conducted so that the top 10 selected factors from the perspective of the traffic controllers and network controllers together (traffic control, TC) and from the perspective from the train driver (DR) could be obtained. Additionally, an overall score was calculated as follows: Overall Score = (Selection Rate) × (16 - Mean Rank). This way a weighted score of a factor could be provided.

#### 6.2.2.3 Results

Based on the ranking provided (Figure 24), operators appeared to value F1, F2 and F3 most, appearing 21, 21 and 22 times in operators' ranking with a mean rank of 2.5, 3.6 and 4.1 between all operators respectively.

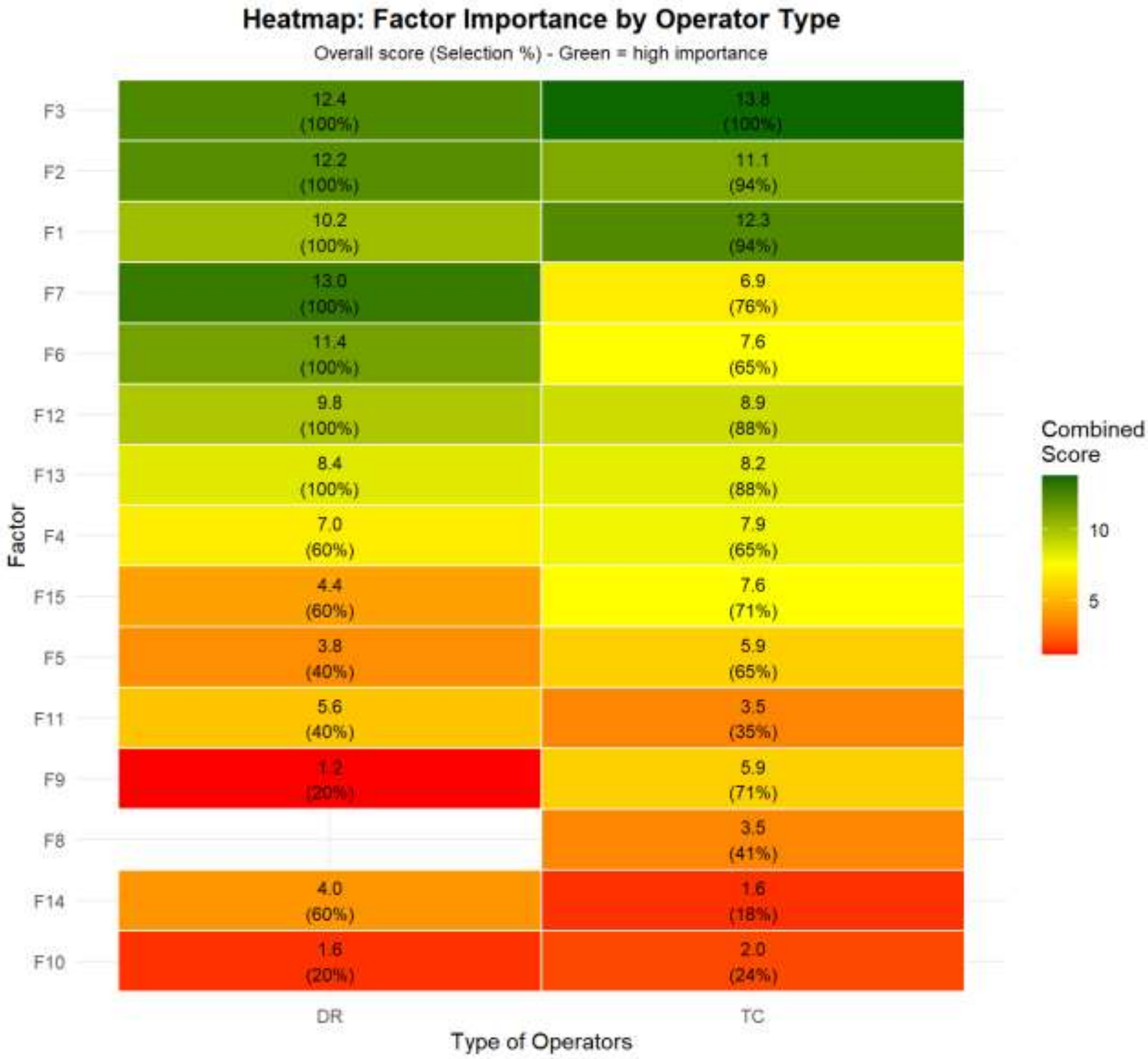


**Figure 24: Heatmap of factor ranking by type of operator**

It should be noted that all seven train drivers selected the implementation speed of ERTMS throughout the country (F7), a well-functioning ATO system (F3), sufficient training (F2), risks to changing the operational roles (F6), user involvement in the development of ATO (F1), user involvement during the implementation of ATO (F12) and accounting for concurrent operational changes (F13) as important in their top 10 list. All 17 operators from traffic control selected a well-functioning ATO system (F3) as most important. In Table 20, the top five ranking for each type of operator and the overall top five ranking is listed.

| Rank | Factors for traffic control (TC) | Factors for train driver (DR) | Overall Rank |
|---|---|---|---|
| 1 | F3: Well-functioning ATO system | F7: Rate of implementation of ERTMS throughout the country | F3: Well-functioning ATO system |
| 2 | F1: User involvement in the development of ATO | F3: Well-functioning ATO system | F1: User involvement in the development of ATO |
| 3 | F2: Sufficient training | F2: Sufficient training | F2: Sufficient training |
| 4 | F12: User involvement during the implementation of ATO | F6: Risks to changing the operational roles, i.e. deskilling due to automation | F12: User involvement during the implementation of ATO |
| 5 | F13: Accounting for other operational changes underway at the time | F1: User involvement in the development of ATO | F6: Risks to changing the operational roles, i.e. deskilling due to automation |

**Table 20: Top 5 factors rated as most important per type of operator, and overall rank**

### 6.2.3 Guidelines for optimal guidance to transition to automated operations

The output of the literature review and the findings from HITL simulation are consolidated in this section. This leads to a set of high-level guidelines. Without the intention to be exhaustive of all the aspects involved in the transition, the present report focused on two system stages of a transition due to the implementation of a new technological system:

i) System development: In line with system thinking and resilience engineering (Flach et al, 2019), a proper transition to a new system requires a new or adapted way of working. This adaptation must already be considered during the development phase. Specifically, we must consider how the system will change current practices and its impact, i.e., how much operators and the company should change to accommodate the transition to the new system or way of working.

ii) System implementation: Once the new system is ready to be deployed, it is necessary to verify and validate that it is working as intended and to identify and report any unexpected issues or unmet needs after full implementation. During this phase of the transition, large-scale testing of the system and operator training can help identify ways to balance individual and organizational needs to maximize the positive effects of the transition while minimizing emerging and unexpected issues. Since the system is implemented in this phase and only minimal technical changes are possible, the burden of adjusting to maximize the benefits of the transition falls on humans and companies.

#### 6.2.3.1 System development phase

**Guideline 1: Prioritize the user in the system development process using participatory design as a process**

Actively involving stakeholders during system development through the means of participatory design and centralized support tools will in turn aid in reducing system complexity and uncertainty, aiding system adoption (e.g. Bannon et al, 2012). Participatory approach is essential to gather input from users during specific phases and to ensure products meet the practical needs of the users. The use of early on simulation of operational processes is perceived as important and valuable by operators, see the highly rated factor F1 user involvement in the development of ATO section as part of the multi-actor human-in-the-loop TMS- ATO GoA2 simulation (Section 5.2).

*[Facilitator: Stakeholder involvement, F1: User involvement in development; Barriers: Poor system adoption, Stakeholder misalignment; Cluster 1: Organizational management and human factors]*

### Guideline 2: Co-design and active stakeholder alignment

Co-design (in parallel with participatory approach) means actively involving stakeholders to co-decide and co-design solutions for removing organizational barriers such as silo thinking between departments, lack of coordination, and stakeholder misalignment. Implement centralized support tools for information dissemination, communication between stakeholders, and joint work environments. A well-functioning system maintains operator trust, ensures efficient use of existing mental models, and performs tasks consistently and as intended. During technological development, prioritize the creation of adequate training protocols pre-implementation to ensure seamless system adoption and prevent skill degradation due to automation.

[*Factors: F3: Well-functioning ATO system, F2: Adequate training for ATO operation; Facilitators: Stakeholder involvement, Utilization of shared mental models/distributed cognition, Project-based activities; Barriers: Stakeholder misalignment, Lack of organizational readiness, Silo thinking between departments, Lack of coordination between departments and stakeholders; Lessons learned: Maintain trust in automation, Mapping distributed cognition and responsibilities within teams; Cluster* 1*: Organizational management and human factors*]

### Guideline 3: Align technical maturity (technology readiness level) with organizational and human readiness

Technical system readiness must progress in parallel with operator requirements and organizational capacity. Operators prioritize a well-functioning ATO system supported by validated user processes, but development of system functionality alone is insufficient. Misalignment between technical deployment and organizational processes can manifest when systems are not participatory designed with users (see an example in the conducted human factors study described in Section 5.2). Additionally, misaligned between technological and organizational readiness can be an issue if this is early introduced before operators understand their role changes, before training programs are complete, or before supporting infrastructure is ready.

*[Factors: F3: Well-functioning ATO system, F4: Validated ATO user processes; Facilitators: Project-based activities, Iterative processes; Barriers: Highly complex/uncertain systems, Lack of organizational readiness, Misevaluation of safety and stability; Lessons learned: Phase transitions, Early identification of transition opportunities; Clusters 1, 2 & 3: Organizational readiness, Process strategies, and Infrastructure integration]*

### Guideline 4: Reduce system complexity through design and validation

System complexity and uncertainty represent the most significant barrier to successful transitions, especially with increased levels of automation. Complex automated systems increase the likelihood of human error, particularly when operators must manage degraded modes or unexpected system states. Reduce complexity through human-centered design approaches that prioritize intuitive interfaces, clear system feedback, and transparent automation logic. Facilitate iterative testing of system behaviour with end-users to identify and resolve sources of confusion before deployment. Ensure operators can maintain accurate mental models of system states and develop appropriate distributed cognition within operational teams. This directly supports operators' top priority of a well-functioning ATO system and helps prevent skill degradation due to over-reliance on opaque automation.

*[Factors: F3: Well-functioning ATO system; Facilitators: Human-centered design, Utilization of shared mental models/distributed cognition, Iterative processes; Barriers: Highly complex, uncertain or degraded systems, Mismatch with currently used mental models, Skill degradation due to automation; Lessons learned: Maintain trust in automation, Prioritize human-centered design, Mapping distributed cognition and responsibilities within teams; Clusters 1 & 2: Organizational management and human factors, Process and risk mitigation strategies]*

#### 6.2.3.2 System implementation phase

**Guideline 5: Ensure sufficient time and resources for the training of operators**

In order to facilitate system implementation, the main factors have been identified: user involvement during implementation, ensuring that phasing of transitions are feasible without major disruptions to operations and ensuring operators are sufficiently trained before system implementation. Adequate training is essential for successful system adoption and safe operations. Insufficient or inadequate training represents a significant barrier that directly undermines system implementation. Operators must be sufficiently trained before system deployment to develop competence, maintain safety, and work efficiently with new technologies. Training programs should be developed in parallel with technical system maturity, ensuring operators have time to build appropriate mental models and understand their evolving roles. Structured training protocols prevent skill degradation due to automation and support operators in managing degraded modes or unexpected system states. Combine training initiatives with stakeholder involvement and active middle management engagement to ensure organizational alignment and training resource allocation throughout the transition process.

*[Factors: F2: Adequate training for ATO operation, F1: User involvement in development; Facilitators: Stakeholder involvement, Project-based activities, Iterative processes; Barriers: Inadequate training, Poor system adoption, Lack of organizational readiness, Skill degradation due to automation; Lessons learned: Active middle management, Operator-stakeholder alignment; Cluster 1: Organizational management and human factors]*

**Guideline 6: Position middle management as a champion of transition**

Middle management engagement is critical for bridging strategic decisions and operational reality during technological transitions. Lack of management support represents a documented barrier, while active middle management championship emerges as a key lesson learned. Middle managers maintain momentum, resolve emerging issues, and ensure organizational readiness by translating high-level objectives into practical operational changes. Address management gaps by assigning clear responsibilities within project-based structures, enabling managers to coordinate between departments and stakeholders. Active middle management prevents silo thinking, supports training implementation, and ensures that organizational capacity develops in parallel with technical system deployment, directly supporting seamless integration of well-functioning ATO systems.

*[Factors: F2: Adequate training for ATO operation, F3: Well-functioning ATO system; Facilitators: Project-based activities, Stakeholder involvement; Barriers: Lack of management support, Lack of organizational readiness, Silo thinking between departments, Lack of coordination between departments and stakeholders; Lessons learned: Active middle management, Assign clear responsibilities; Cluster 1: Organizational management and human factors]*

**Guideline 7: Create awareness of ongoing operational changes and of the importance of operator (shared) mental models**

Successful transitions require a continuous awareness of ongoing operational changes across the entire ecosystem, as well as effective communication structures that enable a shared understanding among stakeholder groups. Mismatch with operator mental models or frequent updates of mental models can undermine system adoption when operators are confused or lack clarity about how automation changes their tasks, or when communication gaps create confusion about system states. Techniques such as Cognitive Work Analysis (CWA), Hierarchical Task Analysis (HTA), Functional Resonance Analysis Method (FRAM) can be used by human factors experts to visualize these changes and connections between different elements.

*[Factors: F3: Well-functioning ATO system, F4: Validated ATO user processes, F1: User involvement in development; Facilitators: Utilization of shared mental models/distributed cognition, Stakeholder involvement; Barriers: Mismatch with currently used mental models, Lack of coordination between departments and stakeholders, Stakeholder misalignment; Lessons learned: Mapping distributed cognition and responsibilities within teams, Maintain trust in automation; Clusters 1 & 2: Organizational management and human factors, Process and risk mitigation strategies]*

**Guideline 8: Conduct validation and verification tests with users**

Centralised support tools should be implemented for information dissemination, and communication protocols that map distributed cognition and responsibilities within teams should be established. This will support operators' need for validated ATO user processes and well-functioning systems, ensuring that all stakeholders understand operational changes, maintain accurate mental models and can coordinate effectively during normal and degraded operations. Testing should evaluate system behaviour across operational scenarios, verify training effectiveness, and confirm that operators can manage degraded modes. This directly supports operators' priorities for system functionality and validated processes while addressing poor system adoption through proven, user-validated technology.

[Factors: *F1: User involvement in development;* F3: Well-functioning ATO system, F4: Validated ATO user processes; Facilitators: Iterative processes, Human-centered design, Stakeholder involvement; Barriers: Highly complex, uncertain or degraded systems, Poor system adoption , Mismatch with currently used mental models; Lessons learned: Prioritize human-centered design, Maintain trust in automation, Early identification of transition opportunities; Clusters 1 & 2: Organizational management and human factors, Process and risk mitigation strategies]

# 7 CONCLUSIONS

The current deliverable aimed to 1) assess the human factors impact of GoA2 on operators through a desktop analysis and human-in-the-loop (HITL) simulation, 2) identify the barriers and facilitators that passengers and operators encounter when transitioning toward higher levels of ATO and provide guidelines to support this transition, and 3) build a theoretical foundation that connects human factors components to business case elements.

Firstly, findings from the literature review (Chapter 2), task analysis (Chapter 4), desktop analysis (Section 5.1), and HITL simulation (Section 5.2) showed that GoA2 fundamentally reshaped train driver tasks, workloads, and cognitive demands. Train drivers shifted from active train handling to supervisory monitoring, which increased risks such as underload, vigilance loss, slower reaction times, and skill degradation. In contrast, traffic and network controllers experienced higher workload and procedural misalignment due to mismatches between the TMS architecture and current operational roles and procedures in the Netherlands (Section 5.2). These findings provided initial insights into the operational impact of ATO GoA2. Additionally, the developed HF Toolkit (Chapter 3) proved valuable in the HITL simulation study and may benefit the wider rail human factors community by supporting standardisation of HF testing in the rail sector.

Secondly, the results confirmed that public acceptance is significantly lower for GoA4, primarily due to concerns about safety, staff absence, and cybersecurity. The findings highlight the importance of gradual implementation, high quality remote support systems, and transparent communication strategies to increase acceptance (Section 6.1). A key finding for operational adoption is that successful automation represents not just a technical transformation but also an organisational and human one. Participatory design, clear communication, and dedicated change management programmes are essential for ensuring a smooth transition (Section 6.2). It is strongly recommended that organisational readiness and Human Readiness Level (HRL) frameworks be used alongside Technical Readiness Levels (TRLs).

Finally, the development of the HF-BuCa interface model offered a theoretical foundation linking human factors components with business case elements (Chapter 2). By mapping human factors components through risk identification and risk treatment to business case factors, the model could support decision-makers in understanding the organisational and financial consequences of adopting ATO technologies.

It is recommended that future work focuses on the further development and validation of the HF-BuCa model, especially for GoA4 and HTD, as well as examining the HF benefits of ATO. Further testing is also needed to increase HRL levels and to assess more mature TMS/ATO components (higher TRLs) using HITL simulation environments with different technologies (e.g., C-DAS, GoA2, GoA4, HTD, TMS) and varying implementation scenarios (e.g. 100% GoA2 trains versus mixed GoA level trains). For future passenger acceptance research, studying individuals with existing experience of GoA4 systems (e.g., metro lines) may provide valuable insights into attitudes toward and experiences with driverless transportation.

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# APPENDIX A: SUMMARY OF HF CONSTRUCTS AND MEASURES

See Section 12.3.3.1 in FP1/D15.2.

**Table A.1 Overview of human factors measurement techniques for human factors constructs.**

| **Construct** | | **Methods of measurements** | |
|---|---|---|---|
| | | **Objective** | **Subjective** |
| Task Performance | Train Driver | • Takeover time<br>• Speed maintenance<br>• Acceleration variability<br>• Braking errors<br>• Driver to interface response time<br>• Driver to emergency response time<br>• Rate of intervention by Train Protection System<br>• Signal failure detection | |
| | Traffic Controller | • Response Latency<br>• Punctuality, Arrival/Depart Delay<br>• Maintenance of free track order<br>• Platform consistency | • Observational scoring system |
| | All | *Additional validated and used methods from other domains and applications:* Safety performance | |
| User Experience/ Usability/ quality in use | | *Performance measures are usually incorporated in usability and UX assessments with a focus on efficiency and effectiveness* | • General experience by interviews<br>• User Preference by A/B Testing Scales<br>• Questionnaire Measuring Subjective Consequences of Intuitive Use<br>• Subjective Acceptance<br><br>*Additional validated and used scales from other domains and applications*<br>o System Usability Scale (SUS)<br>o Software Usability Measurement Inventory (SUMI)<br>o Expectation rating<br>o Post-Study System Usability Questionnaire (PSSUQ)<br>o Usability Metric for User Experience (UMUX) |
| Situation Awareness | Individual | • Eye movements<br><br>Querying techniques<br>• Situation Awareness Global Assessment Technique (SAGAT)<br><br>*Additional validated and used methods from other domains and applications:*<br>o Situation Presence Assessment Method (SPAM) | • Situation Awareness Rating Technique (SART)<br>• Low-Event Task Subjective Situation Awareness (LETSSA)<br>• Mission Awareness Rating Scale (MARS) |

| | | | |
|---|---|---|---|
| | | Expert evaluation techniques and mixed methods | |
| | Team/ network | | • Mission Awareness Rating Scale (MARS) for teams |
| | | • Communication content through network analysis<br>• Perceived coordination and communication | |
| Workload | Individual | • Heart rate variability<br>• Eye movements | • Instantaneous Self Assessment (ISA)<br>• Rating Scale Mental Effort (RSME)<br>• NASA – Task Load Index (NASA-TLX)<br>• DLR – Workload Assessment Tool (DLR-WAT)<br>• Integrated Workload Scale (IWS) |
| | | *Additional validated and used methods from other domains and applications:*<br>Stress management measures | |
| | Team/ network | | Communication flow |
| Fatigue and sleepiness | | • Heart rate variability<br>• Brain activity | • Visual analogue scale to evaluate fatigue severity (VAS-F)<br>• Observation (Physical Characteristics)<br>• Sleepiness scales<br>▪ Karolinska Sleepiness Scale (KSS)<br>▪ Stanford Sleepiness Scale (SSS) |
| Attention | Attention allocation | • Time in areas of interest by eye tracking | • Task related time allocation by observation |
| | Vigilance | • Psychomotor vigilance task (PVT)<br>• Safety Critical Event Detection Task | • Mind-Wandering Scale (MWS) |
| Communication | | • Observation, including:<br>○ Frequency of communication<br>○ Length of communication<br>○ Direction of communication<br>○ Voice tone | |
| Trust in automation | | *Validated methods utilised in other domains and applications:*<br><br>Eye movements (glance) | • Direct self-report<br><br>*Validated methods utilised in other domains and applications:*<br>○ Dynamic reporting of trust<br>○ Trust in automation scale<br>○ Checklist for trust |
| | | Other methods of measuring trust, including:<br>• Level of monitoring automated system<br>• Reaction to automated warning<br>• Reaction to conflicting information | |

# APPENDIX B: SURVEY INVENTORY TEST, SIMULATIONS AND DEMONSTRATIONS IN FP1, 2 AND 5

*Dear work package leader,*

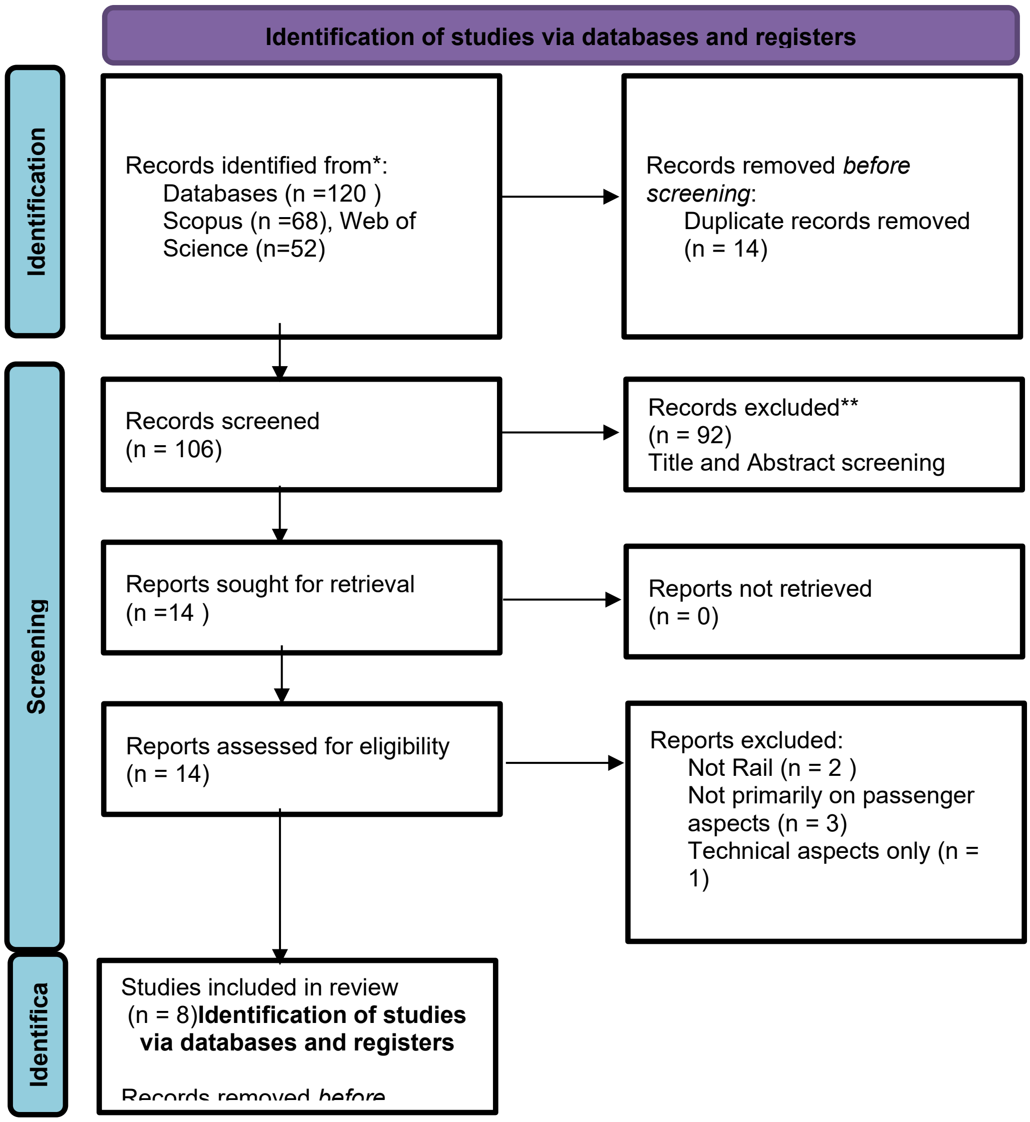
*our goal in FA2 WP32 is to give a **wrap-up of all technical enabler tests, simulations or demonstrations** in FA1, 2 and 5 that show the **potential operational impact** of **DATO components** (**digital up to autonomous rail operation**) in terms of **added-value to rail transportation**. To gather the relevant information, we kindly ask you to fill in the following short questionnaire:*

| | | |
|---|---|---|
| 1 | Please indicate which FA you are referring to: | Klicken oder tippen Sie hier, um Text einzugeben. |
| 2 | Please indicate which work package (WP) you are referring to (number + name): | Klicken oder tippen Sie hier, um Text einzugeben. |
| **3** | Does the indicated work package involve any **technical enabler tests**, **simulations** or **demonstrations** that show the **potential operational impact of DATO components** in terms of added-value to **rail transportation** (e.g. changes in railway capacity, efficiency or safety of human processes, operational costs etc.)? | ☐ Yes<br>☐ No |
| | ***If "yes", please answer the following questions**. If there are **multiple of the mentioned activities**, please **answer the questions separately for each** of these (copy questions 5-12 in this case).*<br>*If "no" stop here.* | |
| 4 | Please indicate the task in which the activity took place: | Klicken oder tippen Sie hier, um Text einzugeben. |
| 5 | Please name the activity in a short form: | Klicken oder tippen Sie hier, um Text einzugeben. |
| 6 | Please characterize the activity: | ☐ Technical enabler test<br>☐ Simulation<br>☐ Demonstration |

| | | |
|---|---|---|
| | | ☐ (Other, but I think it is relevant): Klicken oder tippen Sie hier, um Text einzugeben. |
| 7 | What was the main focus of the test or analysis?<br>*Multiple answers are possible.* | ☐ Capacity gains<br>☐ Cost savings<br>☐ Energy savings<br>☐ Business cases<br>☐ Human Factors<br>Other: Klicken oder tippen Sie hier, um Text einzugeben. |
| 8 | What kind of results did you gain or do you expect?<br>*Please describe in a short form.* | Klicken oder tippen Sie hier, um Text einzugeben. |
| 9 | Are the results available yet? | ☐ Yes<br>☐ No |
| 10 | Please add links to relevant reports on results here if applicable (or attach the documents when you send back the filled questionnaire): | Klicken oder tippen Sie hier, um Text einzugeben. |
| 11 | If "no" on item 9: When do you expect to have the results? | Klicken oder tippen Sie hier, um Text einzugeben. |
| 12 | If there is anything else you think we should know, please let us know here: | Klicken oder tippen Sie hier, um Text einzugeben. |

**Thank you a lot!**

# APPENDIX C: DETAILS REVIEW PROCESS PASSENGER STUDY




Source: Page MJ, et al. BMJ 2021;372:n71. doi: 10.1136/bmj.n71.



## Search Terms for Literature Review (March 2025)

("passenger" OR "public perception" OR "passenger experience" OR "user acceptance" OR "technology acceptance" OR "trust" OR "confidence" OR "acceptance" OR "reliance" OR "intention to use" OR "usage intention" OR "willingness to use" OR "adoption" OR "attitude" OR "perception" OR "survey" OR "questionnaire" OR "study") AND ("autonomous train*" OR "driverless train*" OR "autonomous railway*" OR "automated rail*" OR "railroad automation" OR "unattended train operation" OR "UTO" OR "GOA4" OR "automated train" OR "autonomous public transport" OR "driverless public transport" OR "automated transport" OR "autonomous railway") AND ("urban rail" OR "mainline rail" OR "safety" OR "implementation" OR "exposure" OR "experience" OR "familiarity" OR "interaction" OR "relationship" OR "correlation" OR "association" OR "link")

# APPENDIX D: DETAILS REVIEW PROCESS OPERATIONAL TRANSITION STUDY