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Human-Machine Cooperation for the deployment of automated trains: Driver assistance in a remote authority transfer situation

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PhD Thesis

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INSA HAUTS-DE-FRANCE,
and IRT RAILENIUM**

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Research unit:

Laboratory of Industrial and Human Automation control Mechanical engineering and Computer science
(LAMIH – UMR CNRS 8201)

**Human-Machine Cooperation for the deployment of
automated trains - Driver assistance in a remote authority
transfer situation**

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**Coopération Humain-Machine pour le déploiement du
train autonome – Assistance à la conduite dans une
situation de transfert d'autorité**

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RESUME

Dans le milieu ferroviaire, qui a été un des précurseurs des transports autonomes, notamment grâce au déploiement du métro automatisé, l'extension de l'automatisation à des grandes lignes ouvertes semble encore compliquée. Bien que les technologies et l'activité évoluent inévitablement en direction du « train autonome », l'expertise humaine est toujours nécessaire et le restera durant et après cette évolution. Pour compenser les limites actuelles d'exploitation de l'autonomie et faire face à diverses situations exceptionnelles, la téléconduite est considérée comme un possible moyen de reprise, permettant à un opérateur humain d'interagir avec le train et participer à l'activité sans être à bord de celui-ci. Dans ce contexte, la téléconduite est considérée comme un moyen d'assurer cette transition tout en gardant la possibilité de faire appel à une expertise humaine quand nécessaire. Naturellement, l'autorité et la responsabilité de l'humain diffèrent considérablement entre la conduite manuelle en téléopération et la conduite autonome, celle-ci étant très réduite ou nulle dans le dernier cas. L'étude se concentre sur la phase spécifique du transfert d'autorité entre le train autonome et un conducteur à distance depuis un poste de téléconduite. Plus précisément, la thèse s'intéresse aux besoins de l'opérateur humain lors de transferts alors que celui-ci est privé de la plupart des informations primordiales pour la conduite par rapport à une activité en cabine. Cette perte d'information est accentuée lors la prise en main d'un processus déjà en cours, pour lequel le téléconducteur ignore potentiellement l'essentiel du contexte du processus et de la mission avant d'y être assigné, en raison de la distance entre qui les sépare.

L'objectif général de la thèse est donc de comprendre cette phase de transfert d'autorité qui caractérise la reprise de la conduite, que ce soit par le téléconducteur ou par le système technique, en observant et centrant l'étude sur l'activité du futur téléconducteur et de ses besoins pour proposer de potentielles solutions d'interfaces et de systèmes d'aide adaptés. Pour cela, un modèle de coopération humain-machine et un modèle du processus de transfert définit par les interactions entre les agents sont proposés et des premières suggestions d'interfaces. Elles ont été développées et évaluées à travers deux campagnes expérimentales qui visent à tester leur utilisabilité et pertinence, tout en recueillant des avis d'experts de la conduite de train autour des thèmes du sujet de thèse et de l'évolution potentielle du métier de conducteur de train pour la téléconduite. Bien que de nombreuses barrières restent encore à franchir, ces

expérimentations visent à offrir des perspectives d'étude pour renforcer une évolution de ces métiers et systèmes techniques autour de l'humain. L'objectif est que les concepteurs de ces futurs systèmes de conduite continuent d'intégrer la présence et les besoins de l'humain pour créer un environnement coopératif efficace et adapté. Ainsi, si la téléconduite s'avère être un mode de reprise, même dégradé, viable du train autonome, ce qui est l'hypothèse actuelle, cette étude servira de première source d'information et de recommandations pour contribuer à la conception d'un tel environnement collaboratif en posant les fondamentaux autour de cette problématique de reprise à distance.

ABSTRACT

Rail transport has historically been a pioneer in terms of autonomous transport, notably with the deployment of automated metro systems. However, extending automation to open main lines still seems complicated. Although the activity and technologies will inevitably evolve in the direction of the "autonomous train", human expertise is still necessary and will likely remain so during and after this evolution. To answer the current limits of automation and to deal with various exceptional situations, teleoperation is seen as a means of recovery, allowing a human operator to interact with the train and take part in the activity without being on board. In this context, teleoperation is considered as a potential means of ensuring this transition towards automation, while retaining the possibility of relying on human expertise when necessary. Naturally, the authority and responsibility of a human operator differs considerably between manual driving in teleoperation and autonomous driving, with little to no responsibility in the latter case and changes of authority between two driving modes can prove difficult. Thus, this study focuses on the specific phase of transferring authority between the autonomous train and a remote driver from. Specifically, the thesis focuses on the needs of the human operator during transfers, when they are deprived of most of the information that is essential for driving, compared with the activity within the train cab. This loss of information is accentuated when taking over a process that is already underway and where the remote driver was unaware of most of the process and the mission before being assigned to it.

A general objective of the thesis is therefore to understand this authority transfer phase which characterises the recovery of the driving activity, by observing and focusing the study on the activity of future remote drivers and their needs in order to suggest potential interface solutions and adapted assistance systems . To this end, a model of human-machine cooperation and a model of the transfer process, defined by the interactions between the agents, have been proposed, along with initial suggestions for interfaces. These interfaces have been implemented and evaluated through two experimental campaigns aiming to test their usability and relevance in the context of the extracted drivers' needs. Although there are still many barriers to be overcome, these experiments provide a perspective for future studies to contribute to the transformation of the train driving activity and that of technical systems centred around human factors. The aim is for the designers of these future driving systems to continue to integrate the presence and needs of human beings to create an effective and appropriate cooperative

environment. Thus, if teleoperation proves to be a viable mode of recovery for autonomous trains, which is the current hypothesis, this study will serve as an initial source of information and recommendations to contribute to the design of a collaborative environment, laying down the fundamentals for remote recovery.

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LIST OF ABBREVIATIONS

A

- ABS : “Anti-lock Braking Systems”
- ACC : “Adaptive Cruise Control”
- ADAS : “Advanced Driver Assistance-Systems”
- ADS : “Automated Driving System”
- AGC : “Autorail à Grande Capacité”, a category of multiple unit train
- AI : “Action Implementation”
- ATO : “Automatic Train Operation”
- ATP : “Automatic Train Protection”

C

- CNES : “Centre National d'Études Spatiale”
- CNRS : “Centre National de la Recherche Scientifique”
- COFOR : “Common Frame Of Reference”
- CSUQ : “Computer System Usability Questionnaire”
- CWA : “Cognitive Work Analysis”
- CWS : “Common Work Space”

D

- DAS : “Driver-Assistance Systems”
- DM : “Decision Making”

E

- ERTMS : “European Railway Traffic Management System”
- ETCS : “European Train Control System”
- EU : “European Union”

F

- FA : “Function Allocation”
- FOV : “Field Of View”

G

- GAME : “Globalement Au Moins Équivalent”
- GOA : “Grades Of Automation”

H

- HMC : “Human-Machine Cooperation”
- HMI : “Human-Machine Interfaces”
- HMS : “Human-Machine Systems”

I

- IA : “Information Analysis”
- IBM : “International Business Machines Corporation”
- ID : “Interference Detection”
- IG : “Information Gathering”
- IM : “Interference Management”
- INFOQUAL : “Information Quality”
- INTERQUAL : “Interfaces Quality”
- INTERUSE : “Interfaces Usability”

K

- KH : “Know-How”
- KHC : “Know-How-to-Cooperate”
- KVB : “Contrôle de Vitesse par Balises”

L

- LAMIH : “Laboratoire d’Automatique de Mécanique et d’Informatique industrielles et Humaines”

M

- MASS : “Maritime Autonomous Surface Ships”
- MQTT : “Message Queuing Telemetry Transport”

N

- NASA : “National Aeronautics and Space Administration”

P

- PK : “Point Kilométrique”
- PSCHITT : “ Plateforme de Simulation Collaborative, Hybride, Intermodale en Transports Terrestres”
- PSSUQ : “Post-Study System Usability Questionnaire”

S

- SA : “Situation Awareness”
- SAE : “Society of Automotive Engineers”
- SNCF : “Société Nationale des Chemins de fer Français”
- SUS : “System Usability Scale”
- SYSUSE : “System Usability”

T

- TASV : “Train Autonome – Service Voyageurs”
- TC-Rail : “TéléConduite sur Rails”
- TCS : “Traction Control System”
- TER : “Train Express Régional”
- TOR : “Take Over Request”

U

- UAV : “Unmanned Air Vehicles”
- UGV : “Unmanned Ground Vehicles”
- UITP : “Union Internationale des Transports Publics”
- UPHF : “Université Polytechnique Hauts-de-France”
- UTO : “Unattended Train Operation”

INTRODUCTION

As the automation of technologies is on the rise, whether in production, logistics or transportation in general, there are still many applications where human activities are not yet fully automated. In the transport sector, although road vehicles are rapidly evolving, they are still limited to relatively low levels of automation. In the rail sector, which has been one of the pioneers of autonomous transport, notably with the deployment of automated metro systems, the extension of automation to open lines, such as regional and national main lines, seems much more complicated. Because of a number of different factors, including of course very strict safety standards and the current level of technology that is able to ensure them, human expertise is still essential to train operation, and probably will remain so for the foreseeable future. However, this does not mean that this expertise and the role of drivers remain the same. Without falling into the fatalistic observation that professions are to disappear due to automation, it must nonetheless be understood and accepted that as the railway industry is evolving, increasingly advanced technical systems will be gradually implemented, and that the automation of train operation, in any form, will be a reality. Human expertise will always be essential during and after this evolution, but how the activity itself will evolve is still uncertain. In this study, the aim is to imagine to what extent a human operator, outside the train, could assist in the driving activity, in order to complement the capabilities of an autonomous train, and to propose a framework for the design of interfaces and assistance systems to support the driver in this new activity. As the authority and responsibility of the operator between manual driving in teleoperation and autonomous driving differ greatly, the study focuses on the specific phase of authority transfer between the autonomous train and a train remote driver from a distant control station.

Despite the significant advances in the automation of trains in contained environments such as metros, train automation on main lines is a more recent topic, and the literature on the subject is still fairly limited. Remote control of such trains is also a new and little-explored subject. Fortunately, the experience in other fields, such as drone navigation or the development of autonomous vehicles in general, helps to identify challenges applicable to the railway environment, and offers prospects for solutions. In addition, this thesis is being carried out within the Railenium technological research institute as part of the Train Autonome - Service Voyageurs project (TASV), in a consortium of industrial partners: SNCF, Railenium, Alstom Crespin, Thales, Bosch, and Spirops and with the LAMIH UMR CNRS 8201 laboratory, attached to the Université Polytechnique Hauts de France (UPHF) and the Centre

National de la Recherche Scientifique (CNRS). It thus benefits from the knowledge and resources of the TASV project in the study of autonomous trains, as well as the laboratory's experience in automation and human-machine cooperation. In a broader context, the overall objectives of the TASV project were to study and implement for an autonomous passenger train. This involved advanced research in a number of domains, such as AI-based image recognition, remote transmission technologies, autonomous system safety and cybersecurity. Among the project's hypotheses, remote control is expected to be a possible means of resuming autonomous train operation when facing exceptional situations, such as following a technical failure of the autonomous driving system. Thus, this thesis continues the work already established with Railenium on train remote driving to explore the needs of a remote human driver in the context of the TASV project. More specifically, it focuses mostly on the needs of the human operator when taking over the driving activity in a context where they are deprived of most of the information essential for train driving, compared with in situ activity. This loss of information from teleoperation is accentuated when taking over a process that is already underway and for which a remote driver is potentially unaware of the essential context before being assigned to it.

The aim of this thesis is therefore to understand this authority transfer phase between the remote driver and the technical system, by analysing and focusing the study on the activity of the remote driver and their needs. In addition to the loss of information, what are the various obstacles to a remote recovery of the driving activity? How can the remote driver be assisted to build sufficient situation awareness to resume driving? More generally, what is the role of the remote driver and how do they interact with technical systems during a transfer of authority? The aim of this thesis is to contribute to answering these questions, offering potential solutions for human interfaces and assistance systems. To achieve these objectives, a model of human-machine cooperation and an architecture of the transfer process defined by the interactions between the agents are proposed.

To fully understand the challenges of this subject, this document explores three main axes: i) transport automation, ii) teleoperation and iii) transfers of authority, both generally for transport systems and then specifically for railways. The objective is to identify the issues and challenges specific to each of these themes, particularly from a human factors perspective, before linking them together for the remote transfer of authority with an autonomous train. The first three chapters of this document therefore explore each of these three axes separately.

Automation, at the heart of the literature study presented in Chapter I, consists of replacing all or some of tasks performed by a human operator in an activity, in this case train driving, and represents to the overall context of the subject. Being part of the TASV project, the thesis studies the interactions between a human driver and an “autonomous” train. How is an autonomous train defined and how can a human operator interact with it? Although the paper does not explore all the challenges from a technical or safety point of view, understanding the evolution of these technologies through a brief history of their deployment helps to determine the impact on the human activity when working with increasingly automated systems. Among the challenges, this thesis addresses the fact that a human driver might still need to occasionally intervene on the train while not being actually on board.

Train remote driving, presented in Chapter II, allows an operator to participate in the driving activity without being present within the train, and seems to be in line with the challenges of train automation. The study of train teleoperation in this document will be based on the extensive research that was initiated within Railenium in the TC-Rail ("TéléConduite sur Rails") project, as part of a public and private consortium including SNCF, Railenium and several industrial and academic partners. The initial foundations laid by the TC-Rail project to define and understand the activity of train remote driving, a new form of activity in railway transport, are re-centred around the subject of the thesis to determine the general and specific challenges that can be explored in the contribution. Among these, the remote driver, being separated from the cabin, must rely solely on the information that can be transmitted to them and which is sometimes limited or degraded. Besides, before taking over the control of a train, the remote driver must also be able to immerse themselves in an activity with potentially no prior knowledge of the mission. The aim is therefore to design interfaces and driver assistance to build and maintain the sense of presence in the activity and to help build situation awareness. This situation awareness is essential for authority transfers, the transition of driving modes between autonomous train driving and remote control. Chapter III of this document presents the notion of authority and compares it with the definitions of Know-How and Know-How-to-Cooperate in a multi-agent human-machine cooperation model. This model will serve as a basis to define the technical and human agents in the study, and to describe their interactions, notably during the transfer of authority.

The following chapter presents the contributions of the thesis, providing some answers and perspectives on approaches to tackle the main issues raised by the analysis and proposing

a human-centred approach, combining the results of studies in ergonomics and human-machine cooperation for the design of collaborative interfaces and technical systems, adapted to the needs of the human operator. To complement this human-centred study and to be able to evaluate interactions with systems, a conceptual model of the authority transfer process as perceived by the agents is also presented. This model is translated in the form of a state chart for the autonomous train system to be able to simulate authority transfer scenarios. Using recommendations from TC-Rail, physical and virtual interfaces have been developed and adapted to the needs of this project. In particular, new interfaces inspired by the study of relatively modern passenger train locomotive interfaces, such as the Regio2N models used in France, have been implemented to enable train teleoperation to be simulated. Specific interfaces to support the remote driver during the authority transfer process have then been integrated as part of the contribution of this thesis.

These different interfaces are presented in Chapter IV and evaluated in Chapter V through two experimental campaigns that aim to test their usability and relevance, while gathering important feedback from train driving experts on said interfaces as well as on the potential evolution of the train driving profession for train teleoperation. Thus, if teleoperation proves to be a viable means of taking over the autonomous train, even in a degraded state, this study can serve as an initial source of information and recommendations for the design of collaborative environment between the driver and the autonomous train, laying down the fundamentals of the remote authority transfer issues issue.

CHAPTER I

THE ROAD TO AUTOMATION IN RAIL TRANSPORT

I.1 Introduction

This chapter aims to present the first and broadest aspect of this research project: Autonomous mobility in the railway domain. While the main objective of the project is a more grounded application of cooperation principles for train remote driving, this first part is essential to contextualise the subject, explore the issues and understand what the current and future objectives for teleoperation are and will be.

Automation is defined in the Oxford English Dictionary (2021) as “the use of computers and machines for tasks previously done by people”. The purpose of automation may differ between each domain, but automated systems usually always aim to improve either the efficiency or the safety of a process, or reduce the complexity and workload for human operators within it (Parasuraman et al., 2000). In a significant number of cases, computer systems may carry out more simultaneous functions than a human operator, and do not suffer from fatigue or distraction issues. Consequently, the automation of human tasks can appear natural when a technical system is able to exceed the abilities of the human body or mind. There is still, however, an important number of human abilities that automated systems cannot faithfully replicate, especially when it comes to adaptability in “unstructured environment” (Goldberg, 2012) and unexpected scenarios for which fully automated systems may not yet be desirable in all industrial domains. For example, (Richard et al., 2021) mentions the case of a railway accident in 2015 in France (BEATT, 2016) in which an emergency shutdown of the system occurred after a collision but the train did not decelerate. This extremely unlikely scenario was linked to multiple technical failures but had never happened, forcing the driver to adapt to manage the situation as no procedure existed for such scenario.

A literature study on automated systems will provide a broad history of automation in the transport industry, presenting its goals and challenges and tracing its history from the advent of the first protection systems to today's fully or almost fully autonomous vehicles. This first chapter will thus present the evolution of driver assistance systems as well as means of identifying the level of automation of a system. This overview of autonomous mobility will explore the main domains of transport, from automobiles to aeronautics, with a separate focus on the field being studied: railway automation. The analysis on railway automation itself will be separated from the broader overview to emphasise the main aspect of this investigation. Comparing the different fields will help to understand the evolution of automation in transport

in general, but will also reveal the similarities between the field and the biggest differences when it comes to implementing automation, especially for rail transport.

When studying rail transport automation, it is important to distinguish between closed-world systems, such as metros, and open-world systems, such as mainline trains. While automated metro lines have now existed for a few decades, in the case of open-world railway systems, it is usually understood and accepted that the deployment of fully automated trains will remain a hard to achieve goal for many years. Despite the rapid progress of the technology or research, open-world train lines may remain mostly semi-automated.

One of the main aims of this chapter is therefore to define the current challenges and limits of railway automation when human presence still seems necessary, as well as the implications for train driving specifically. Among all the professions in rail transport where human operators are affected by the improvement and deployment of automated systems, this document will focus solely on the activity of train driving from the driver's point of view. A subsequent, more comprehensive study should also examine the various other activities and their interactions with each other.

I.2 A brief look at the history of automation in transport

This part aims to offer a relatively rapid overview of the concept of automation when applied to the transport systems, especially automobiles. Railway transport systems will be explored more in depth in section I.5 after the context and the objectives of automation have been presented.

At the time of writing, automated technologies have already completely transformed the transport sector in over a century. This includes the constant move towards increasingly autonomous, or even fully automated, vehicles, but it has also reshaped the industry, from the manufacture of vehicles to their safety and the areas of expertise required to control them. Examples of said vehicle include semi-automated cars like specific Tesla (Figure 1) or Google car models (Faisal et al., 2019), commercial or combat ships for the naval industry (Arciszewski et al., 2009), and for aeronautics in which the first autopilot systems have been developed over a century ago (Mcruer and Graham, 1981). Naturally, fully automated transport systems cannot be deployed for any type of activity. Section I.3 on safety will present the main obstacle to the implementation of such systems. While research on each domain is growing

strongly and prototypes that include new technology get increasingly more complex, such advances were made gradually over the last decades or more.

In the case of automobile automation, the first Driver-Assistance Systems (DAS) were produced at the end of the 20th century, around 1980 (Bengler et al., 2014). Their goal was to help stabilize the vehicle through proprioceptive sensors by analysing the car dynamics to avoid skidding for example. These systems had limited control over the car but were nonetheless able to influence its trajectory, speed, or even stop the car for emergency purposes. Interactions with the driver operating the car were inexistent and drivers would have to perform the driving activity with pre-emptive knowledge of how the DAS works to anticipate its behaviour.



Figure 1 Tesla autopilot with continuous objects detection from cameras (from Tesla promotional pictures)

The following DAS provided more interactions with the driver but were mainly informational. Their role was to alert the driver in case of specific issues such as blind spot monitoring or collision anticipation (Schubert, 2012) and systems that could control the car were limited to emergency protection systems. Following the rapid progress of the technology, more sophisticated systems were introduced around the early 2000s. These advanced systems, coincidentally referred to as Advanced Driver Assistance-Systems (ADAS), are capable to monitor the environment using multiple sensors such as cameras or radars that are processed in real-time by advanced algorithms. They allow the vehicle, or rather the assistance system embedded in the vehicle, to make predictions on the vehicle's behaviour and its environment

to give advice to the driver and share the control of the vehicle with the driver (lane departure warning systems, adaptive cruise control, etc.) (Sentouh et al., 2018). Today, a growing number of products are labelled as “autonomous cars” and commercialised by different manufacturers. However, they still operate on limited levels of automation and multiple significant challenges must still be overcome for the deployment of fully automated vehicles (Hussain and Zeadally, 2019). While unsupervised automated driving for cars have already been achieved at lower speed or under specific safety constraints, vehicles that can be manufactured and used on every road can only share parts of the driving activity with the human operator. For example, the current models of vehicle using the Tesla Autopilot, such as the Tesla Model S, require, in most places where they are allowed to operate, constant driver monitoring and are therefore not fully autonomous. Naturally, in addition to varying safety concerns, the regulations in place in each country may differ, and some countries may accept the introduction of autonomous vehicles of higher levels of autonomy when this would not be possible in neighbouring countries. The analysis, presented in this document, will be mostly influenced by the regulations in place in Europe and especially in France where safety measures in transport prevent most open-world applications of high-level automation. Means to identify and quantify the level of automation of a system will be explored in section I.4.

Regarding the aviation industry, planes are confronted to distinct challenges. While safety, efficiency or accessibility is as important as any other domain, the actual dangers and barriers that must be overcome differ. Automation in the aviation industry has already been

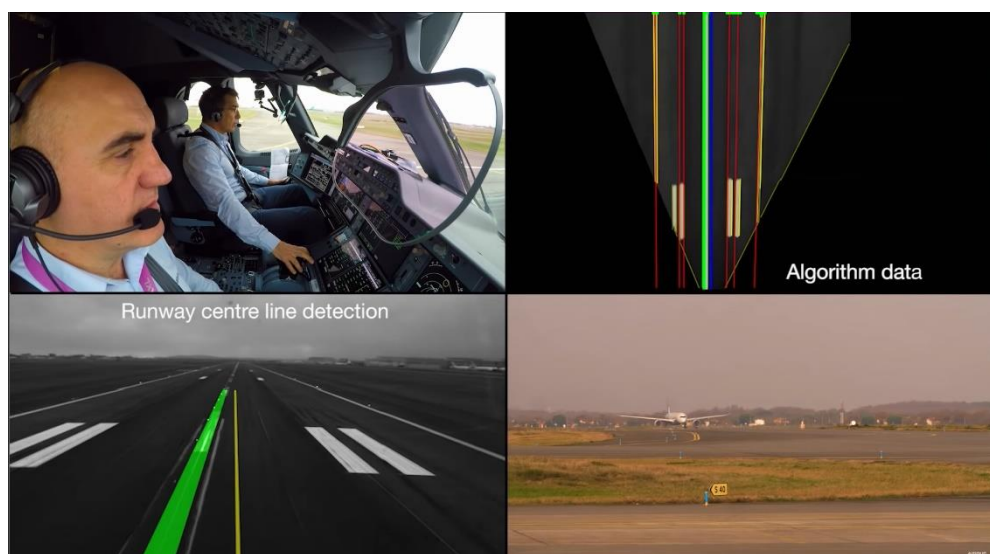


Figure 2 ATTOL: Autonomous Taxiing, Take-Off and Landing test flight (Airbus)

studied and experimented more than a century ago (Billings, 1991) (Evjemo and Johnsen, 2019) to reduce workload, notably. Today, airliners are equipped with multiple and complex assistance systems (Evjemo and Johnsen, 2019). For instance, some are equipped with autopilot systems that can maintain a trajectory, follow navigation guidelines, and operate during different parts of the activity. Take-off and landing of airliners are still operated through the control of a human pilot, but research is already working on automating these tasks as well. In 2019, Airbus realised the first take-off of an airliner through an autopilot system, monitored by two pilots within the cabin (Airbus, 2020), as seen in Figure 2.

It is of course also possible to trace similar developments in the naval field, although this sector is quite different from the automotive or railway fields, as much in terms of freedom of movement as in the major differences in the environment and the significant discrepancies the scales of different naval vehicles for the piloting activity. One of the uses of assistance systems is to improve naval military equipment. Of course, automated military applications also exist in all other areas of transport and technology in general. In this context, (Arciszewski et al., 2009) points out an interesting dilemma for automation as there is a challenge of finding the right balance between using automation for tasks that may require quick reactions or complex calculations while ensuring that humans remain responsible for the decisions and consequences of these automated actions. Although this question is not directly related to the subject of this research project, it is relatively easy to see how they have developed on a scale that goes beyond the simple military domain. Indeed, beyond the needs of combat management, questions of responsibility are at the heart of numerous debates as many systems can now make numerous and complex decisions with sometimes disastrous consequences.

However, despite possible concerns about the risk of errors and accidents, one of the main factors behind the industrialisation of increasingly automated systems is the desire to increase the safety associated with the use of such systems (Harris, 2011). The next section will explore this objective of automation in transport.

I.3 Safety and reliability through automation

There are undeniably many factors justifying the use of automated systems. Indeed, highlighted by the advent of production systems assisted by robots and computers, and even more so today in what is known as Industry 4.0, automation is a tool for competitiveness (Otoiu

et al., 2022). In the transport sector, for example, intelligent systems help anticipate, control and reduce energy consumption or to speed up and streamline traffic flows (Barwell, 1973). Although the use of autonomous systems for purely economic purposes is often the subject of debate, notably with the loss and transformation of human activity, one of the main arguments in favour of this development is the increased safety and reliability of these systems. Although safety concerns and requirements are outside the scope of this investigation, it is important to understand how the safety of a system is affected by automation, either positively or negatively. Indeed, these requirements will greatly influence what automated features are desirable and which can or cannot be implemented on a system. While it is debatable whether safety is the main factor in automation, in most cases it remains the main barrier to the implementation of new, potentially unsafe systems.

Safety is defined as “a state of freedom from any unacceptable loss” (Aven, 2022) (Leveson, 2012). In most cases, automation also (and sometimes only) affects a system’s reliability rather than its safety, ensuring that accidents (losses) happen less frequently. Designers usually achieve this result by reducing human error through automation and through the improvement of the technology or infrastructure, which is independent of automation. Human error is defined as “something [that] has been done which was: not intended by the actor; not desired by a set of rules or an external observer; or that led the task or system outside its acceptable limits.” (Senders and Moray, 1991). Indeed, (Perinet and Vu, 2010) indicates that in complex systems, which include transportation systems, organisational and human factors are at the origin of 61% of incidents and accident. In 1997, for aerial transport, Nelson reminds in (Nelson, 1997) that most accidents were due to human errors and proposes methods to identify and help correct such errors.

Human errors are defined in (Kragt, 1978) as a situation in which the human operator does not pursue the appropriate goal, or fails their task through wrong actions or inaction when necessary. In railway domain, (Qiu et al., 2015) based on (Kim et al., 2010), human error is defined as “a behaviour of the human operator which leads to accidents in railroad system”. Among other reasons, the origin of these errors can be linked to the lack of detection of a failure in the system from the operator or maintenance or unsafe behaviours (like the deactivation of protection systems to save time). A system designed to reduce human error may then act on at least one of these issues, either by helping with failure detection, decision making, or assist with the execution of tasks. As mentioned in part I.2, in the case of car driving, DAS were

introduced within vehicles to enhance safety. These were aimed especially for the populations who are prone to causing or being caught in accidents, such as elderly people or new drivers (Bengler et al., 2014). Such systems would initially rely on dynamic information of the vehicle through proprioception, odometers, or inertia (Galvani, 2019). Later, advanced sensors were used, such as cameras, radars, lidars or network communications, to build ADAS such as Anti-lock Braking Systems (ABS), Traction Control System (TCS), Adaptive Cruise Control (ACC) and later Autonomous Obstacle Avoidance or Autonomous Parking. These ADAS are able to control the vehicle on their own for different purposes and may act independently from the driver. In these cases, the semi-automated systems can replace the driver for certain specific tasks or may act together with the human operator to cooperate. This is known as “shared control” as both the human driver and the intelligent system can share the activity and assist each other. In a shared control environment, the driver is kept in the loop and retains a certain control authority. Control authority and cooperation principles will be explored in more details in Chapter III. In contrast, fully autonomous systems pull the human out of the loop and completely eliminate the risk of human error in the driving process. Of course, this is accompanied by new technical and manufacturing barriers, and potentially by ethical questions, and humans remain involved at other stages of the activity. These will not be explored in this document, which focuses solely on train driving from the point of view of the driver, as a human or technical agent.

The technical and safety problems have already been largely overcome in certain situations, such as closed-world environments. The autonomous metro is a perfect example of a closed transport system where driving has become completely automatic (see part I.5). Nevertheless, in more complex environments where these obstacles have yet to be overcome, full automation cannot be safely implemented yet. Thus, most transport systems must still perform under intermediary levels (or grade) of automation (LoA (GoA), see section I.4). This implies that automated systems or assistance systems must work in cooperation with human operators in a shared control environment. Such systems, where both computer systems and humans are integrated and share tasks in their activity, are called Human-Machine Systems (HMS).

However, while the objective of assistance systems is often to help the driver and improve the overall safety of the process, this type of joint activity can also lead to new errors or challenges and taking care of human factors is thus important when automating a process.

Regarding aircraft automation, for example, safety levels are very high and despite very good improvements over the years, the introduction of more aviation automation and technology was followed by increased accident rates. This was, at the time, partially due to “loss of situation awareness” and “loss of control” from automation (Evjemo and Johnsen, 2019). Since then, with more recent advances, accident rates have been greatly reduced and the overall safety level improved. However, accidents linked to higher levels of automation have remained significant (Evjemo and Johnsen, 2019). Similarly, railway safety is very complex and transforming the activity towards more automation is a laborious process. In (Richard et al., 2021), the authors have conducted an analysis of railway safety. Important and inevitable principles were established and reminded, notably that the safety level of the railway domain must not be degraded through automation. To meet the railway safety requirements, any modification to the activity must be supported by evidence proving that the overall safety level is globally at least equivalent to the current one (the GAME principle, which stands for Globalement Au Moins Équivalent).

Although the rest of this document does not dwell further on safety issues, this observation should be emphasised for any player wishing to participate in the development of the rail activity. Assistance systems and interfaces that are to be integrated in the future, whatever their purpose, must also and always help to improve or at least maintain the level of driving safety.

I.4 Levels of Automation

I.4.1 A scale for automation: general definition and examples

In any given domain of automation, and more specifically within transport domains, automated systems may alternate between multiple levels of automation. These levels represent the amount of authority given to the systems and their functions. The scales usually range from no automation to full automation, with intermediary levels in-between. Each sector usually accepts at least one conventional definition of levels, adapted to the domain of activity. In the automotive sector, SAE Levels of Automation (LoA) (On-Road Automated Driving (ORAD) committee, 2016) are divided into six steps (see Figure 3). In each step, the authority of the car driver, about the decision making, road surveillance or the implementation of driving tasks, is progressively shifted towards that of the Automated Driving System (ADS).

These principles have naturally been extended to other sectors and similar definitions exist, such as IMO’s Degrees of Automation for Maritime Autonomous Surface Ships (MASS)

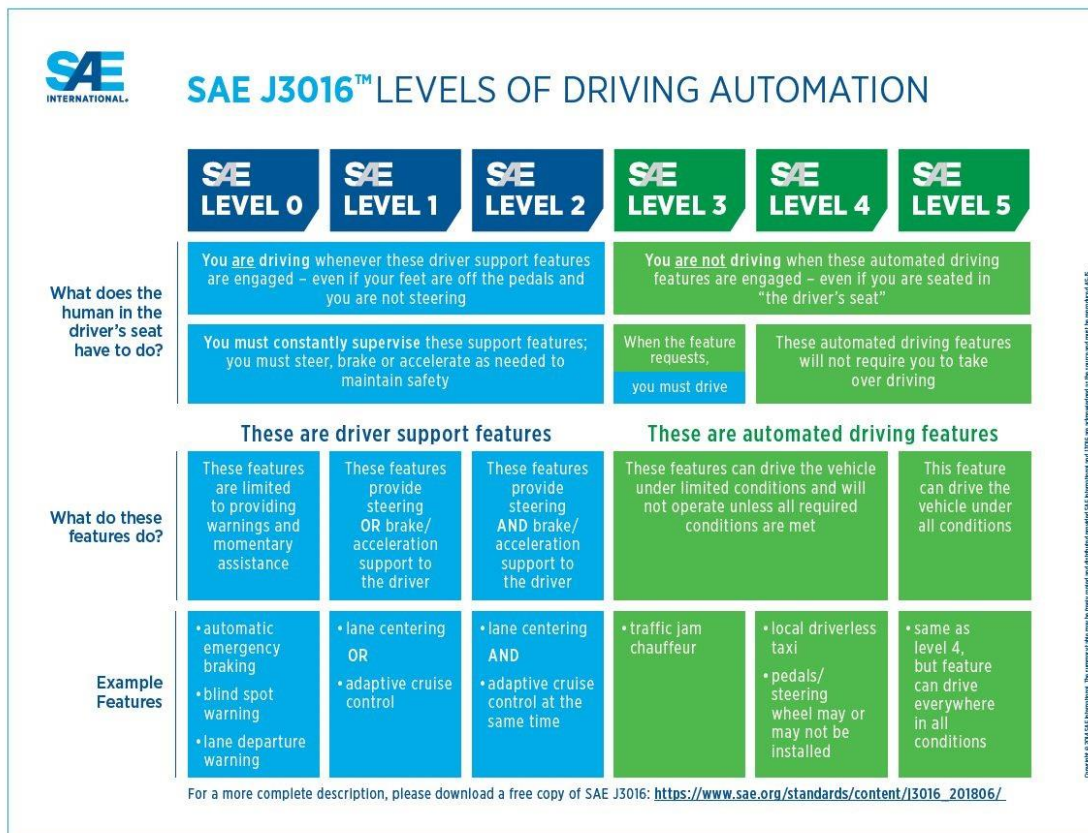


Figure 3 The six SAE Levels of Automation (On-Road Automated Driving (ORAD) committee, 2016)





(Maritime Safety Committee (MSC), 2018) and Grades of Automation (GoA) for railway automation. The following part will present GoA levels in detail as they will be the main tools to discuss automation levels for railways.

I.4.2 Definitions used for railway automation: Grades of Automation

The GoA scale was first introduced for metro automation and has been used as a staple for applications in the railway domain, including French Autonomous Train projects. As with SAE LoA, the definition of GoA degrees includes multiple levels, five in total (GoA0 to GoA4), with GoA0 being a completely manual driving, with no automation.

Figure 4 presents GoA degrees 1 to 4 and the authority shifts between the train driver and the automated system regarding each task. In this definition, trains operating at a GoA

Degree 1 are still manually controlled by the driver, but Automatic Train Protection (ATP) systems may exist. This is the situation for most trains circulating in Europe. Such ATP systems can, however, vary between countries or region. While the European Train Control System (ETCS), part of the European Rail Traffic Management System (ERTMS) is intended to become a standard for train protection in Europe, many countries, such as France, already have different and incompatible ATP systems. On higher degrees of GoA, the driver's authority for certain tasks, such as the control of braking and traction, is transferred towards the autonomous train, now capable of running Automatic Train Operation (ATO). Thus, a GoA3 system is considered driverless (Figure 4) as the control of the train becomes almost fully automated. The train attendant is only expected to be within the train to perform a limited set of tasks or act in case of emergencies. Finally, a GoA4 describes a train completely automated for Unattended Train Operation (UTO).

Grade of Automation	Type of train operation	Setting train in motion	Stopping train	Door closure	Operation in event of Disruption
GoA 1 	ATP with driver	Driver	Driver	Driver	Driver
GoA 2 	ATP and ATO with driver	Automatic	Automatic	Driver	Driver
GoA 3 	Driverless	Automatic	Automatic	Train attendant	Train attendant
GoA 4 	UTO	Automatic	Automatic	Automatic	Automatic

ATP - Automatic Train Protection
ATO - Automatic Train Operation

Figure 4 UITP Degrees of Automation (UITP, 2012)

These levels alone appear to be rather vague and sometimes not adapted for open-world train automation applications. This is thus necessary to redefine them according to the needs of a specific project. The investigation presented in the thesis were conducted as part of the TASV project for which and the description of each level have been adapted and extended to match with the activity. The following Table 1 presents the definitions used within the project (Rouzé, 2019). Although these definitions use the same levels as the UITP GoA

degrees, the project mentions different modes in which some automated tasks or driving assistance may be enabled or disabled at the same level. This implies that, even when driving under GoA2 or GoA3 levels, there might be intermediary driving modes. An example of intermediary levels can be found in (Habib et al., 2021) where authors are discussing tramway safety through assistance systems. In this paper, different tasks can be allocated to the tram’s automated systems, but multiple configurations can exist for the same GoA level.

GoA1	The driver is present on-board, within the train’s cabin and train protection is ensured by safety equipment and systems.
GoA2	The driver is still present within the train’s cabin and makes sure nothing will disrupt the course of the train (obstacles, defects on the infrastructure, ...). The autonomous system will, however, perform the driving activity by controlling the thrusting and braking of the train and respecting timetables and signalling.
GoA3	There is no more driver within the train’s cabin. The autonomous system performs the driving activity and detects any external event that requires action on the train (braking, whistles, communication, ...). However, there is still a train attendant able to perform safety procedures and managed degraded modes.
GoA4	There is no more train attendant able to drive the train if necessary. The train is completely autonomous. A supervising centre is able to communicate with the train and manage eventual degraded modes and drive the train remotely.

Table 1 - GoA levels defined in TASV (Rouzé, 2019)

The GoA levels defined in (Habib et al., 2021) are presented in Table 2. From GoA2 onwards, more authority is given to the automated system for the control of the train’s speed. However, other tasks or systems remain in the activity, such as stopping the vehicle or the validation of the dead man’s switch, in this example. Here, multiple configurations can thus exist, which led to introducing levels GoA-2.1, GoA-2.2 and GoA-2.3.

GoA	Acceleration/Deceleration	Stopping at the station	Dead man’s switch
GoA-0	Driver	Driver	Activated
GoA-1	Driver/System	Driver	Activated

GoA-2.1	System/Driver	Driver	Activated
GoA-2.2	System/Driver	System	Activated
GoA-2.3	System/Driver	System	Deactivated

Table 2 - GoA levels expanded for tramway automation (Habib et al., 2021)

Part IV.5.1 of Chapter IV will present the interfaces and assistance systems developed for the research project. Although the extension of GoA levels to accept similar intermediary levels accounting for different configuration of assistance is not the focus of the investigation, an extension of the levels was necessary, at least at an operational level, to implement both remote applications and detail transitions between levels.

I.4.3 Limits of Grades of Automation

The GoA scale is now primarily used for any application involving train automation. It is, however, not free from a certain number of criticisable shortcomings, very much like other definitions introduced in other sectors.

First, the main definitions were introduced for metro automation, which differs significantly from other activities such as freight train or mainline passenger train driving. While the key principles are similar, this nevertheless implies that such levels of automations need to be adapted and redefined in every project. For example, functions such as “operating doors” have no use for freight train driving. This is not a major issue, as such levels are meant to be used as guidelines, but it is important to remind designers that these levels should not be seen as a comprehensive and unchangeable scale. Additionally, the levels of automation, in any domain, are always rather vague as the activity is always simplified to only a handful of tasks (“monitoring the environment to avoid obstacles”, “controlling the braking/thrusting of the train” or “operating doors” (UITP, 2012)). Many other tasks of the activity are unfortunately not considered (managing side signalisation, railroad switches or level crossings, communicating with external agents, etc.). While the definition of every level cannot encompass the complete complexity of the studied activity, this also makes it difficult to place certain features within the scale. Similarly, in the context of train remote driving, how does one define levels where the train driver is always outside the train cabin? Tasks of a higher functional level (strategic or tactical) are also mostly absent from these definitions. For train automation, car automation and other domains, these levels can be seen as too technical. The final levels tend towards full automation, with no human, and are the primary goals of

manufacturers. Consequently, the sometimes-intricate interactions between the human operator and the computer system at earlier levels are rarely detailed and the human role tends to be reduced to “what is to be removed”, with little to no mention of possible human-machine cooperation. Finally, the definitions do not consider the important changes in the activity or the infrastructure, as well as their impact on the human operator, induced by changing levels of automations (Stayton and Stilgoe, 2020).

In summary, it is important, when designing cooperative systems, to not limit the reflection only to these basic levels of autonomy. Indeed, multiple layers of the activity and human factors are absent from their definitions. Nevertheless, it is possible to complete the definition of GoA levels to better suit the needs of a research project. This adapted framework will be part of the architecture proposed for the thesis. The definitions used for the thesis and presented in section II.3.2 of Chapter II take this into account by adapting the base levels used in the TASV project.

I.5 Tracing the evolution of automated systems in rail transport

While the previous parts have presented some general aspects of automation and applications to transport domains, mentions of train automation have been voluntarily limited until the context was properly defined and means of determining the level of automation of a system were identified. This section will thus present a history of train automation and explore the primary challenges for the development of automated trains and how they might differ from applications in other domains.

As presented in section I.4, the railway industry uses UITP’s GoA levels (UITP, 2012) to define automation levels for a train. The first level that includes some aspects of automation is GoA 1. Compared to the previous and first level on the scale, GoA0, the train is equipped with low level protection systems that are able to control and stop the vehicle in case of emergency. These systems are known as Automatic Train Protection (ATP) and are usually very basic, such as the “Automatic Train Stop”. They can constantly monitor the speed of the rolling stock and receive indications from external signals. The aim is to reduce human error by alerting the train driver when possible or prevent accidents by engaging in emergency procedures that would stop the train. The first ATP systems were initially limited to closed environments such as metros in the twentieth century (Woodland and Schmid, 2003), (Bailey

and Britain, 1995) or for rare advanced lines such as the Japanese Shinkansen, which began service in 1964. They were then added to most train lines. Most of such systems are still in use even when more advanced technology exists, as their deployment does not justify the cost induced by the replacement of the infrastructure. This effectively slows the progress regarding train protection and automation. An example of ATP on trains in France is the “Contrôle de Vitesse par Balises”, or KVB, introduced during the 1990s, controlling the speed of the train through beacons on the railway .



Figure 5 In-cab KVB display and KVB beacon on the rails

Following the development of ATP and because of technological breakthrough, Automatic Train Operation (ATO) systems were designed. They are able to automate some tasks of the train driver and are not limited to stopping the train in case of emergencies. This allowed new systems to function on higher levels of automation, from GoA2 to GoA4. First appearing in heavy railway in a regional line of Czech Republic (Lagay and Adell, 2018), ATO systems were then able to operate the traction of braking of trains while under the monitoring of the human driver and ATP (Bailey and Britain, 1995). . In Europe, however, in a concerted effort of multiple European Union (EU) countries, the deployment of the European Railway Traffic Management System (ERTMS) is expected to unify control systems and signalling between European countries, with components such as the European Train Control System (ETCS). Extracted from the ERTMS website, Figure 6 illustrates the difference between ERTMS signalling level 1, where Eurobalises (beacons similar to KVB) control movement authority in addition to already existing trackside signalling, and ERTMS level 3 where movement authority is done through radio block centres and no trackside signalling is necessary. Compared to ERTMS level 1, both level 2 and 3 are equipped with similar radio based technologies. The main difference is that in ERTM level 2, presented in Figure 7, the

system still uses the fixed blocks, known as “cantons”, to separate tracks between fixed points where only a single train can operate. Thanks to the radio technologies, side signalling is no longer necessary as all information and instructions can be transmitted directly to the train. In ERTMS level 3, the position of trains on the track is constantly monitored and sent to control centres define “moving blocks” specific to the train to make traffic on the line smoother and safer, with more precise blocks, or “cantons” around the circulating trains. ERTMS level 3 is however still conceptual and, while some hybrid technologies have been implemented, level 2 is currently the highest actual ERTMS level implemented. If properly unified between European countries, using ATO with ERTMS should help autonomous trains operate over multiple countries. However, its deployment is difficult because each country’s infrastructure differs from the other, with very different signalling rules and ATP on-board.

In closed-world environments, however, the deployment of ATO presents less challenge as systems are usually less affected by signalling issues or the potential presence of obstacles on the rails. Indeed, ATO has been added to multiple metro lines, such as in Lille, France, which has been fully automated since the early 1980s, and many others around the world afterwards. Currently, multiple metro lines are under conversion from manual control to being driverless, such as Line 4 of the Parisian metro (France) which has been fully automated in 2024 (DRIEAT, 2024). Information on such systems are however still scarce and multiple technological and legal issues are still to be faced, especially in terms of safety and security. Today, the research to deploy higher levels of automation for open-world systems, such as

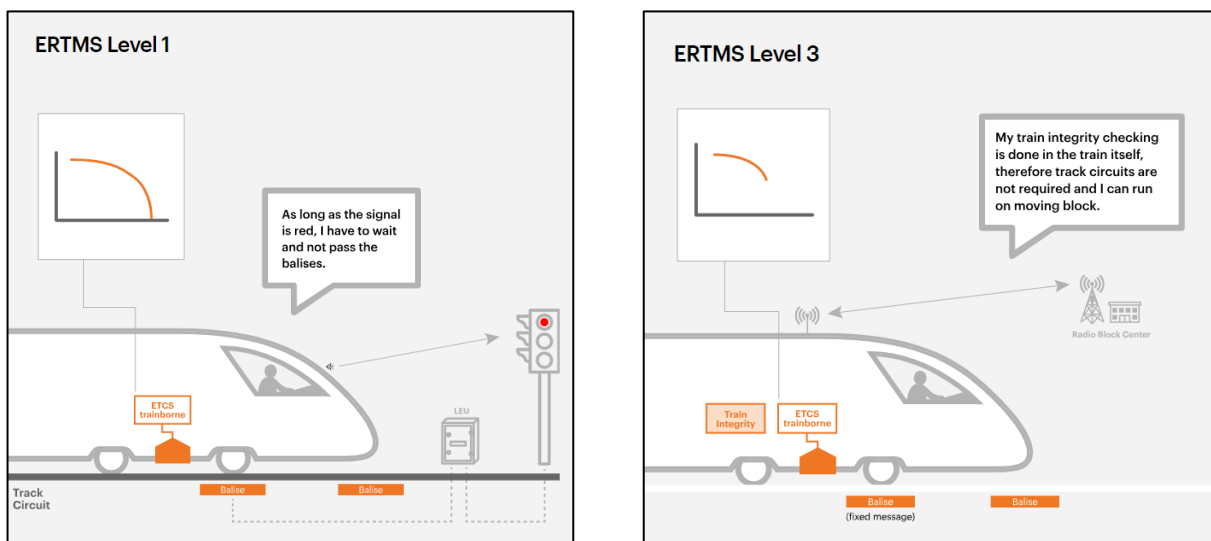


Figure 6 ERTMS Level 1 (Eurobalise) and Level 3 (Eurobalise + Euroradio (GSM-R) + Radio Block Center) – credit: ertms.net

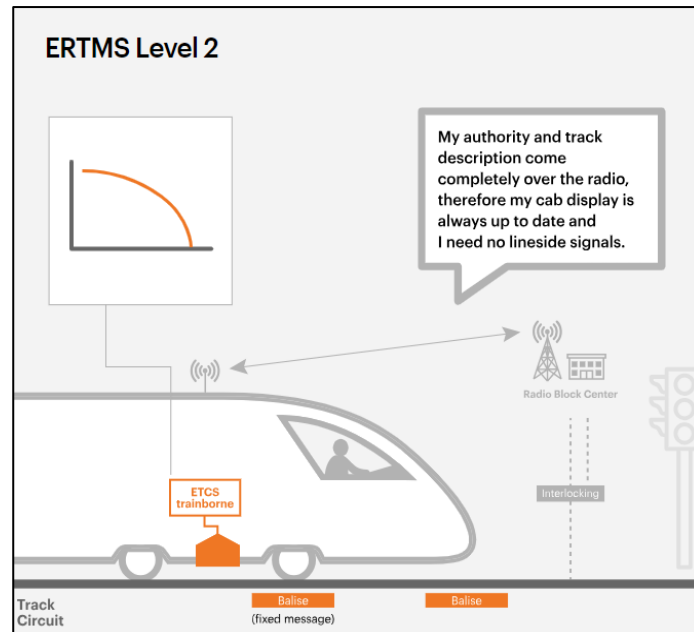


Figure 7 ERTMS Level 2 (Eurobalise + Euroradio (GSM-R) + Radio Block Center) – credit:

freight or passenger trains on bigger lines, is very active and multiple programs exist to build prototypes of these future trains. This research investigation is part of Railenium’s research programs on the autonomous train, in collaboration with the French railway company SNCF. Today, multiple other projects exist in France or in other countries, in Europe or the rest of the world, aiming to build the trains of the future such as SNCF’s TELLi (Berdal et al., 2023; Richer, 2023).

1.6 Human Factors in railway automation

Having presented the general context in which this project is evolving, it is now time to take a closer look at the issues directly related to the subject. As a reminder, the main objective of the thesis is to look at human factors specifically during a remote transition of control between an autonomous unmanned train and a human driver. Once again, it should be pointed out that the focus here is solely on the “direct” control of the train, from a distance, by the driver and not on all parts of the activity that include human components. In this context, the system studied is not fully autonomous (GoA 4), or is studied in a portion of the activity under shared-control, and a human operator is kept or added into the loop. The aim is thus to determine the main aspects in which the driver activity is influenced by the addition of intelligent systems. To this end, the authors of (Papadimitriou et al., 2020) carried out a study,

tallying and comparing the number of articles linking automation to the following themes: trust; situation awareness; experience and skill; shared control. Naturally, and as highlighted by the article, these themes have all been widely researched in the literature and represent the main factors that will be explored in this document. Other topics not directly related to human factors are also part of the authors' study, such as safety, but will not be explored further in this section.

I.6.1 Building and losing trust in the system

Among the main criteria that can influence the use of a machine or intelligent system by a human operator is the level of trust the human has in said system. Indeed, in addition to experience and other factors that will be explored later, it seems empirically easy to imagine that an individual who has a high level of trust in a machine will be more likely to use it. In (Zuboff, 1988), a study documents this link and observes several phenomena relating to trust. In particular, the author highlights the natural a priori that users feel when dealing with an unfamiliar system. At the same time, too much confidence in a system could lead to unsafe situations where users are unable to identify errors. (Lee and Moray, 1992) investigate the relation between trust and the use of automatic control systems, mostly following previous studies from (Muir and Muir, 1989). Their experiment had participants try to operate a simulated pasteurisation plant with both manual control tasks and the help of automatic control. The study revealed strong correlation between the user's perception of trust towards automated systems and the system's performance. Especially, participants' trust increases as they experience the system performing correctly, they seem to lose trust proportionally to the degree of failure from the system. However, even when the system behaves correctly afterwards, rebuilding participant's trust following important faults seems much slower.

When applied to transport systems, these dimensions of trust, notably based on a system's purpose and performance, a model of trust in automobile ADAS was constructed in (M. Itoh, 2011) to quantify a driver's trust in a technical system's ability to participate in the driving activity. This model is used to observe, understand and possibly anticipate situations of inadequate trust in a system. In particular, they point to two phenomena that occur when a user interacts with intelligent systems: overtrust and overreliance. Overtrust is defined in (Inagaki and Itoh, 2013) as "an incorrect situation diagnostic decision claiming that the object is trustworthy when it actually is not." while overreliance is defined as "an incorrect action selection decision based on an incorrect situation diagnostic decision regarding the ADAS".

The former is linked to the ability of the driver to analyse and understand a situation and the system and may affect their ability to make decisions and take actions on the process, represented by the latter. Similarly, opposite terms can be defined when trust and reliance on a system is inadequately low. Both instances can be equally as dangerous as an inappropriately high reliance on a system may lead to situations in which the driver does not understand when the system is operating beyond its limits, and a lack of trust may lead to drivers not using or ignoring said system, even when it plays an important role in the safety of the activity. For example, in (Parasuraman and Riley, 1997), the authors present a railway accident in which the driver, possibly due to a lack of trust in the assistance systems, ignored auditory warning while exceeding speed limits.

One of the clear objectives of the evolution of current assistance systems and the implementation of future systems is therefore their reliability and their ability to maintain an adequate level of trust with users. This means that systems need to be more accurate when analysing the process and diagnosing their own faults, but they also need to be able to communicate this information more efficiently.

I.6.2 Situation awareness in the activity, shared control and transition of control

In (Endsley, 1987) and (Endsley, 1995), Situation Awareness (SA) is defined as “the perception of the elements in the environment within a volume of time and space, the comprehension their meaning and the projection of their status in the future.”. This definition includes three main components being perception, analysis and comprehension, and projection. In its most complete form, Figure 8 presents Endsley’s model of SA and how it contributes to the decision making and the process in general.

In the application of this thesis, SA for train driving can be defined as the ability to gather information and understand the past and current state of the activity, the train’s state, and its environment, then to use this information to anticipate the system or process behaviour. Authors of (Parasuraman et al., 2000) observed that automation in general has a negative impact on SA. For example, reducing the implication of human operators affect their attention mechanisms which has a direct impact on SA.

In their activity analysis for train driving and literature study for teleoperation, authors of (Mouchel et al., 2020) and (Paglia et al., 2021) explain how teleoperation further affects SA,

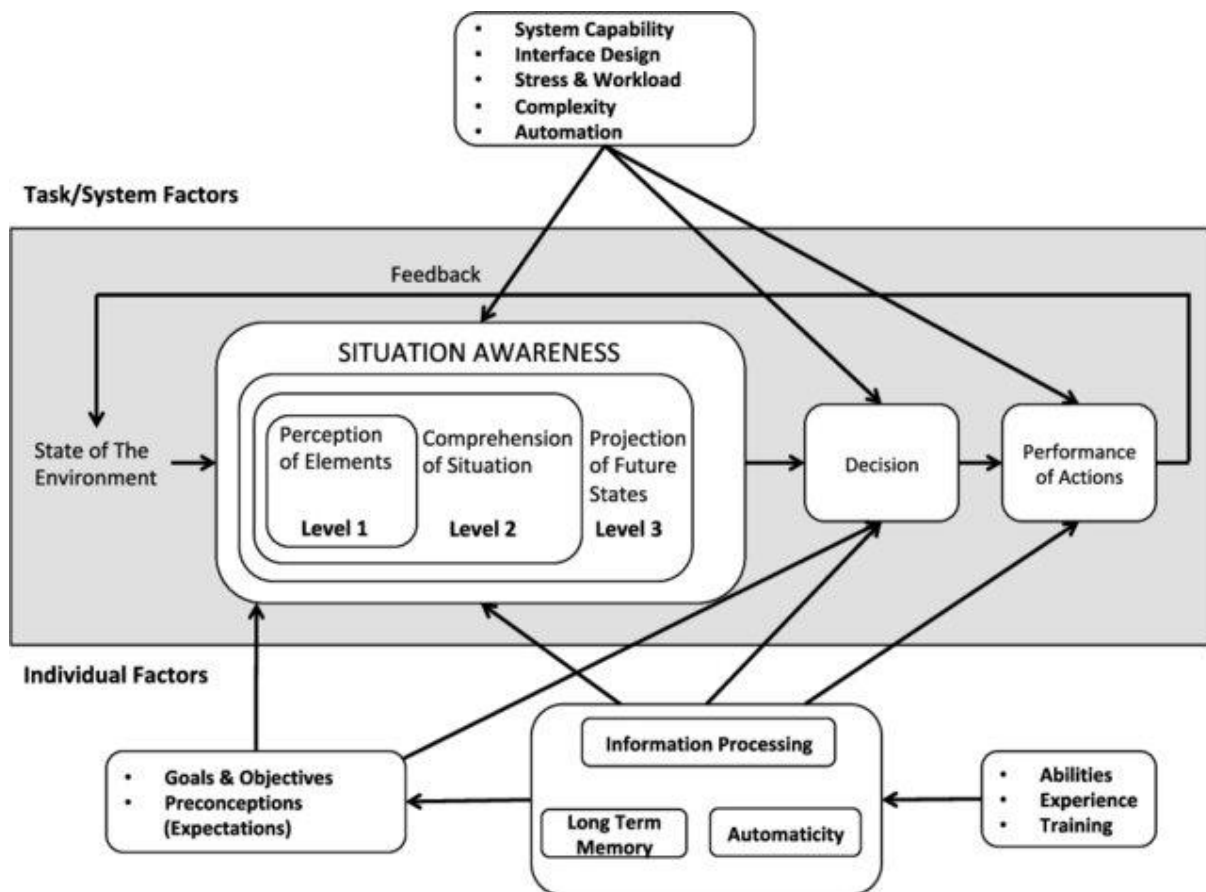


Figure 8 Endsley's model of situation awareness (Endsley, 1995)

notably because of important losses of sensory information. Considering the importance of issues associated with SA in a remote environment, it is preferable to present this subject in more detail after defining the context of rail teleoperation and the transfers between remote driving and automation. Thus, a more in-depth overview of how remote operations affect SA and recommendations for the development of intelligent systems will be given in Chapter II.

Similarly, shared control was mentioned in section I.3 and will be developed in Chapter III along with transition of control which encompasses both the mechanics of task allocation and the actual transfer of control of the activity between the agents, the autonomous system and the human operator.

I.6.3 Developing experience and skill

Finally, in any activity, it is generally possible to observe a direct correlation between human experience and performance. This has of course been widely researched and verified for all transport modes. For example, in (Nabatiyan et al., 2012), authors observed that

experienced car drivers could focus more easily on the driving environment and would perform better in complex driving tasks or while doing secondary tasks. (Underwood, 2007) also points out that novice drivers would be more prone to inattention on the road. Especially, they would find it harder to differentiate the more complex situations that require more attention. In the case of train drivers, (Du et al., 2022) also observed significantly more delays in the decision making of novice train drivers while experienced drivers were less susceptible to hazard occurrences, have shown better situational perception overall.

When modifying an activity with the use of new intelligent systems, the level of knowledge, experience and skills of already seasoned drivers will inevitably be affected. Indeed, most of these systems have the ability to completely change how the driving activity is performed or they will bring new physical and virtual interfaces to provide information or interact with the system. In these cases, regaining driving skills in the driving activity can be achieved the same way a novice driver acquired said skills, through training and experience growing over time.

Most assistance systems will thus aim to provide intuitive and clear information through optimised HMI to better understand and interact with the system (Yang et al., 2017) and to simplify their used for drivers and minimize their impact on the activity, or even improve the overall comfort and experience.

I.7 Conclusion

This general study of automation in rail transport and its evolution highlights how impactful automation has been to transform the rail industry. The first section, I.2, provides an understanding of the general context of automation in transport, which can then be brought into relation to the specific subject of rail transport. This retrospective was essential to understand the current state and the future potential of automated systems in rail transport and it provides an insight on the similarities and differences between the domains. Despite the considerable advances made by the rail sector in automation, as stated in part I.5, railway transport faces a strong inertia to technological innovation.

The focus on safety and reliability outlined in Section I.3 underlines the critical role these elements play in integrating automation. Strengthening safety protocols through automated technologies has not only improved operational reliability, but has also significantly

reduced the risks associated with human error. However, these innovations also bring new challenges that may require further safety analyses, making rapid integration difficult. Section I.5 traces the progress and specific applications of automated systems in rail transport, followed by an analysis of human factors in railway automation, presented in Section I.6. It highlights the importance of human interactions with automated systems and presents the basis for what needs to be monitored in relation to automation in the activity and human factors. Despite technological advances, the presence of human operators remains a crucial aspect of railway activities.

This first chapter aimed to both present the initial issues related to the research topic and to define the exact scope of this study within the broader goals of railway automation. Train automation is achieved by progressively reducing the tasks of the driver until the system can operate on its own and without an on-board operator. While the technology evolves rapidly, a train may not, initially, be completely independent in all situations of the activity and occasional human interventions may be necessary. In this context, this thesis explores the possibility of remote transfer between an automated train and an operator through teleoperation. One of the main problematics of the subject is thus to find how to combine an automated activity, with reducing human factors, with a teleoperated manual activity where the operator brought back into the activity. This introduces additional human factors challenges related to situation awareness, attention, or trust. The final goal is to make sure the automated train and the driver can always communicate and cooperate, particularly through the inclusion of human-machine cooperation principles, while ensuring this new form of cooperated activity can still answer the objectives of automation, notably safety and reliability.

CHAPTER II

THE PLACE OF REMOTE CONTROL IN AN AUTOMATION PARADIGM

II.1 Introduction

Along the automation of rail transport, the second key point of this research project is the introduction of train teleoperation as a driving mode. Teleoperation refers to the remote control of a machine or, in this context, a train. This represents a significant change in the operational dynamics of train driving, introducing a new dimension in the way trains are controlled and managed, and can be considered a new activity in its own right. This section explores the complexities and potential of teleoperation of railway systems, examining its implications for efficiency, safety and overall operational usability.

This chapter examines how teleoperation fits into the wider context of automation, specifically in rail transport. Indeed, while the development of automation is inevitable for transport, its application to the railway industry brings multiple challenges and remote control emerges as a potential support to automation, notably in degraded situations. However, introducing train remote driving is not merely a question of integrating new control and communication technologies; it represents a significant change in the way rail systems are operated and managed, including control, risk and flow management. It requires a reassessment of current practices, and a new perspective on the safety, efficiency and reliability of remote rail operations.

Introducing teleoperation in railways is still a very recent topic and marks a major transformation of the activity, prompting the need for in-depth research in various areas, including technology, safety, and human factors. While train teleoperation presents unique challenges, there remain teleoperation principles and solutions that can be adapted from other sectors. Following the general study of automation in the first chapter, this section will explore a variety of fields, not limited to railways, where diverse applications of remote control coexist with the development of increasingly autonomous systems. The aim is to extract the relevant challenges, specifically those linked to the human driver's activity, and solutions that can later be applied to train teleoperation. This provides a basis for understanding the current state of remote train control and will assist in determining prospects for future developments and potential solutions in this field.

II.2 Existing teleoperated systems in other transport domains

Like with automation, the deployment of remote-control technologies has significantly impacted every transport sector, with each application being particularly tailored to its specific domain. Despite its extensive use in road and aerial vehicles since the early twentieth century, remote driving for trains has been comparatively limited, often confined to specific functions within already automated systems in close-world environments like metros.

The teleoperation of flying vehicles, much like other significant technological breakthroughs, initially found its footing in military applications. In the aviation industry, "Unmanned Air Vehicles" (UAVs) have been used for training and reconnaissance since the first half of the twentieth century. These early UAVs, though larger than contemporary drones, were more compact and cost-effective compared to traditional aircraft, and they would usually not put the operator's life at risk, which is important and desired in most military operations. The evolution of drone technology has then been swift, branching out into civilian uses such as photography, film production, and package delivery, especially in areas where ground transportation poses challenges. Figure 9 presents the de Havilland Queen Bee, a radio-controlled variant of a British biplane, the DH.82 Tiger Moth, the first unmanned airplane that



*Figure 9 Launch of a de Havilland Queen Bee, 1941
(Imperial War Museum)*



Figure 10 First MQ-9 Reaper, 2007 (US Air Force)

has been categorised as a drone (Mátyás and Máté, 2019), a fitting name since drones are etymologically male bees.



Figure 11 UCUV - Unmanned Combat Underwater Vehicle, DGA,
2023

Figure 10 presents a more recent military drone, the MQ-9 Reaper that first took off in the early 2000s. The newer military UAVs of 21st century are predominant in today's warfare, both for surveillance and airstrikes (Mátyás and Máté, 2019; Mitchell et al., 2005). Thus, drone-related literature is likely among the most in-depth source of knowledge when conducting research on teleoperation and crucial for examining and developing teleoperation applications even in varied sectors, including rail transport, and most of the initial observations

and hypotheses for train teleoperation have either been already observed through research on UAVs or follow from such studies.

Teleoperated marine vehicles also constitute a significant segment of unmanned vehicle technology, encompassing a range of applications from military to industrial. In military contexts, these vehicles are often employed for purposes such as operating remotely controlled weaponry or anti-mine systems, reflecting their strategic importance in modern naval operations. Quite recently, in December 2023, the Directorate General of Armament (DGA) in France has announced the creation of an unmanned underwater combat drone demonstrator (DGA, 2024), presented in Figure 11. To perhaps a greater extent than aerial vehicles, the ability to operate remotely in underwater environments is not simply a matter of convenience but a necessity, given the inherent dangers and challenges associated with deep-sea exploration and operations in conditions that are often too dangerous or complex for direct human intervention. This allows for a variety of industrial applications, including but not limited to, exploration, environmental monitoring and cleanup, oil drilling, and oceanographic research (Fong and Thorpe, 2001). Overall, the evolution of marine teleoperated vehicles underscores their growing importance and versatility, particularly where operations involve high-risk environments.



Figure 12 Milrem's "Multiscope Rescue with Hydra, a firefighting UGV

The control of remote terrestrial vehicles, also known as Unmanned Ground Vehicles (UGV), also addresses the need to navigate dangerous or challenging environments, mirroring the utility observed in marine and aerial teleoperation. These systems offer critical assistance in various high-risk situations. For instance, as indicated by (Habib et al., 2018), they can be employed in search and rescue operations, aiding firefighters in locating injured individuals in

hazardous or inaccessible areas, or to help extinguish fires in such hard to reach areas, like Milrem’s “Multiscope Rescue with Hydra” in Figure 12.

The deployment of such systems for emergency response not only enhances the effectiveness of the rescue efforts but also ensures the safety of the rescue teams by reducing their exposure to potentially dangerous conditions. Another prominent and technologically advanced application of remote terrestrial vehicles is seen in space exploration. Unmanned space vehicles, like NASA's Mars Exploration Rovers (Washington et al., 1999), including the recent Perseverance mission (Figure 13), are prime examples of this. These rovers undertake extensive, long-duration missions in the harsh environment of space, conduct scientific research, and test technologies in conditions where human presence is currently impossible. Of course, the scope of applications for remote terrestrial vehicles extends beyond emergency response and space exploration. In the military sector, unmanned vehicles are increasingly becoming a staple, used for reconnaissance, combat support, and other operations where reducing risk to personnel is a priority.

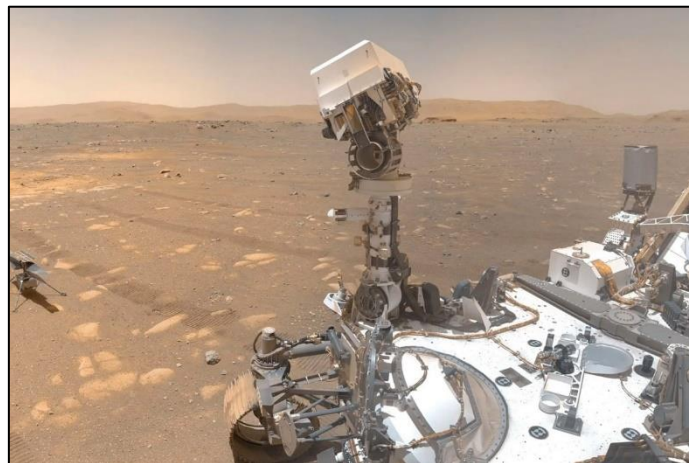


Figure 13 NASA Perseverance Rover on Mars

Among all different field, applications of teleoperation often share a common factor: they answer the need to operate in unknown, inaccessible, or highly dynamic environments where direct human involvement is not possible or poses significant risks, thereby broadening the scope of what can be achieved in terms of exploration, research and industrial operations. However, the transition from on-board to remote control of these vehicles introduces a new set of challenges, particularly for operators and pilots. As (Giese et al., 2013) points out, remote operation can lead to new factors contributing to human error, which constitutes most mishaps. Notably, one significant aspect concerns situation awareness - the operator's perception and

understanding of the activity and the environment of the vehicle. While train teleoperation has only scarcely been investigated, the insight gained from other domains will help understand its own set of challenges.

II.3 Towards train remote driving: is remote control possible for railway operations?

II.3.1 Why choose remote control?

Multiple domains of the transport industry have been mentioned in the previous sections, but what about train remote driving? Unlike previous applications, an unmanned train system does not allow access to different, possibly more dangerous environment, as trains remain limited to the already existing rail tracks. In this context, what could be the purpose of train teleoperation? As mentioned in the general introduction, this investigation on train teleoperation is part of the larger Train Autonome - Service Voyageurs (TASV) project aiming to lay the foundations for the development of future autonomous passenger trains in France. While the final objective of the project is the study of fully autonomous GoA4 trains, the



Figure 14 TC-Rail's demonstrator of a remotely controlled train, 2021

development of a remote human control mode may seem out of place. Indeed, leaving aside the technical and human difficulties inherent to remote control, it is perhaps more comparable to manual control but from a distant site, i.e. a level of automation of the order of GoA1 or GoA2, a long way from the overall objective.

First, in addition to the TASV, Railenium has participated in the TC-Rail (TéléConduite sur Rail) project, led in France by a public and private consortium including Railenium, SNCF, Thales, Actia Telecom, and the CNES. The project has contributed to the development of technical demonstrators of remote-controlled freight trains on main regional lines (Figure 14), using an innovative remote-control platform (Masson et al., 2019). The platform was both used for technical demonstrators, as seen in Figure 14, and adapted for use in a simulated environment for larger experiments (see Figure 15). A significant part of the study presented in this document was carried out for TC-Rail or builds on the studies initiated in the project. One of the main driving factors behind the project, justifying the benefits of remote control for freight train driving, was the potential to increase the competitiveness of the freight railway sector by optimising travel times, waiting times for deliveries to customers and rail traffic in general.



Figure 15 TC-Rail's remote driving simulator, 2022

Opinions among the scientific community, safety experts, and industry professionals about the feasibility of deploying fully autonomous transportation systems vary, especially when it comes to automobile (Stayton and Stilgoe, 2020), primarily due to technical challenges that need to be overcome. These include the ability of autonomous railway systems to operate in open-world environments and manage specific degraded modes due to technical failures or external factors such as obstacles or important weather changes. As such, an autonomous train may not be capable or permitted to operate independently at any time on any line, requiring the intervention of a human operator. This is of course prone to change with the evolution of future technical systems and their infrastructure as the exact frequency of potential incidents and the reliability of future autonomous systems hard to determinate. An unmanned autonomous train that must stop and wait for a human to intervene not only causes inconvenience to passengers but also significantly disrupts line traffic and incurs substantial costs. Since autonomous trains are designed to operate without onboard personnel to take control in emergencies, the primary benefit of teleoperation lies in its ability to allow for relatively quick interventions compared to dispatching drivers to the train's location. This can be particularly advantageous in cases where accessing the train physically is challenging (Gadmer et al., 2022). In this context, the TASV project identifies train remote operation as a viable contingency for autonomous trains (Rouzé, 2019).

II.3.2 How does train remote driving fit into GoA levels?

According to the definitions presented in Section I.4.2, a GoA4 train, the final objective of the TASV project, is defined as “completely autonomous “ and should thus be capable of responding to all the situations of its use cases. However, the definition also includes the presence of a "supervising centre” that is “able to communicate with the train and manage eventual degraded modes and drive the train remotely”. Indeed, technological and safety requirements, studies show that a human expertise might still be a necessity, even if occasional. However, in this investigation, and in the rest of the document, it seemed wiser to consider that, following the example of the automobile and other fields, this definition should be reviewed in a more restrictive way. Indeed, while a fully autonomous system must be able to operate without human intervention, even in degraded mode, any use case that admits the existence of situations where human expertise is necessary must be operated under lower levels of authority (On-Road Automated Driving (ORAD) committee, 2016), thus being GoA3 at the

most for railways. Of course, this does not include critical situations that require intervention, outside of the main use case, such as accidents. These occurrences, however, would follow specific emergency protocols and would likely be too critical for teleoperation to be applicable. In other automation levels defined in the project, however, teleoperation is excluded and they all assume the presence of a train attendant within the train.

These definitions are extended in (Gadmer et al., 2022) in two ways to make them applicable in the project, as seen in Table 3. The first is to change the focus of the definition on the agents' authority, defined in Chapter III, rather than the driver's position within the train. The second is to accept remote driving as a possible driving mode in levels GoA1 to GoA3 as it is comparable, regarding authority, to manual driving.

GoA1	The human operator has the authority regarding the driving tasks (braking, monitoring the environment, etc.) and is always either present in the train's cabin or connected to the train from a remote cabin to monitor the process. Train protection is ensured by safety equipment and autonomous systems.
GoA2	The human operator has the authority regarding the monitoring of the process and makes sure nothing will disrupt the course of the train (obstacles, defects on the infrastructure, ...) and is always either present in the train's cabin or connected to the train from a remote cabin. The autonomous system will, however, perform the driving activity by controlling the thrusting and braking of the train and respecting timetables and signalling.
GoA3	The control and monitoring of the process is attributed to the autonomous system. A human operator is no longer within the train cabin or connected to the train but is always available within the train or remotely to manage degraded modes.
GoA4	There is no longer a train attendant within the train or directly available as the train is completely autonomous within the limits of the use case.

Table 3 GoA levels defined for the thesis (Gadmer et al., 2022)

Throughout the rest of this document, whenever the "autonomous train" is mentioned as a cooperative agent (see section III.3), it is assumed to be functioning at automation levels

GoA1 to GoA3, as a GoA4 operational mode would exclude any human intervention, other than critical emergencies, outside the scope of this study.

II.4 Human Factors in teleoperation

The previous sections have examined various fields where teleoperated vehicles are beneficial. Studies in these domains will be the main source of information for this part. In many cases, teleoperation enables the completion of tasks that were either impossible or extremely difficult, while in other scenarios, they enhance safety and reduce operational costs. Nonetheless, most studies also underline that its integration is not without impact on the human operator and their performance (Smith and Smith, 1990).

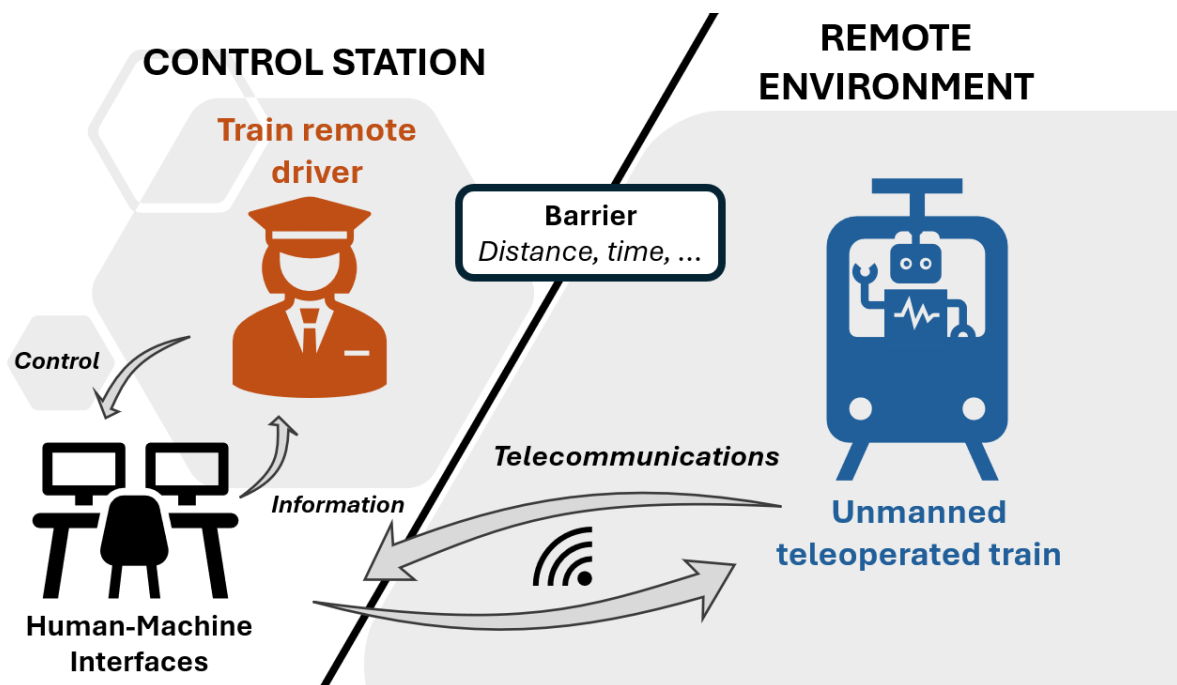


Figure 16 Teleoperation situation: Using Human-Machine Interfaces to communicate with the train and control it remotely

Figure 16 presents the teleoperation situation in the context of this study in rail transport, adapted from the more generic model in (Rybarczyk et al., 2004). The operator, a train remote driver, controls the remote train through specific Human-Machine Interfaces (HMI) and gathers information on the activity from it. The same interfaces communicate with the train to send commands through a remote communication network. These communications are greatly affected by different barriers that generate delays and information losses.

Building on the extensive research conducted in TC-Rail in (Anceaux et al., 2019), (Paglia and Richard, 2021), and (Paglia et al., 2021), this section will explore the critical issues of remote driving in relation to human factors and how they will affect the design of future interfaces and assistance systems. Notably, the authors of (Anceaux et al., 2019) suggest four axes of classification for human factors issues or recommendations: the completeness and quality of information; reduced sense of presence; task allocation between the human and the machine, according to their skills (Boy, 1995); and the physical design of the control interfaces for teleoperation. Each of these topics are equally important when studying the human factors aspects of teleoperation because they all affect, in their respective ways, the activity of the human operator. Excepting task allocation that will be developed in Chapter III, this part will explore these axes independently to gain insight and to draw potential solutions out for these challenges through interfaces and assistance systems.

II.4.1 Providing complete and comprehensive information

Problems relating to the completeness and quality of information could indeed be among the most apparent challenges when it comes to remote control. Indeed, when transitioning to an on-board driving activity to a remote-control activity, researchers and designers will immediately understand that the remote operator has been deprived of the ability to directly perceive the environment and the system. Therefore, one of the main tasks when designing remote controlled systems is to compensate for this sensory deficit by providing the remote operator with other sources of information about the activity.

Although a certain amount of information can be acquired and transmitted by sensors such as cameras and microphones, these often only provide a fragment of what could be directly perceived in the field. Furthermore, it is difficult, if not sometimes impossible, to fully reproduce the multisensory perception of an operator in the field via remote driving interfaces. As a result, the human operator has to perform tasks with only partial information (Chen et al., 2011), (Rea et al., 2017). Among the different sensory modalities, this document will briefly cover the following: the visual channel; auditory information; and kinaesthesia. Of course, all the perceptive modalities of the human body cannot be summarised here as exhaustively as in the analysis carried out in TC-Rail, but these are perhaps the broadest of them, which the new remote-control interfaces may be able to substitute most effectively.

Visual channel

This sub-section will be much longer than the following ones because of the crucial importance of this modality, both for gathering information and for conveying it in the remote control centre. The previous study points out how vision is arguably the most dominant sense for most people to interact and understand their environment both from a neuroscience perspective (Bear et al., 2002) and by observing the number of complex and extremely precise information-processing mechanisms linked to vision that operate in parallel. Indeed, vision enables the perception of shapes, colours, movement, depth and spatial relationships (Stone, 2012). When driving, for example, vision seems to participate greatly in the perception of speed (Colombet, 2010). The human eye is generally capable of detecting fine details and subtle variations in external elements. This accuracy is crucial for many attention-intensive tasks, such as driving. In remote control operations, the loss of direct visual perception is thus a major challenge. When an operator is physically present in the environment, their vision gives them an immediate global understanding of their surroundings. However, in remote control scenarios, this natural and intrinsic visual experience is lost. Instead, operators must rely on cameras to visualise the remote environment. This is often negatively affected by the camera's limitations such as the field of view (FOV) (Scribner and Gombash, 1998), its resolution, or the inability to provide a full three-dimensional perspective (Ziemer et al., 2009).

While all aspects have their importance in how they affect the activity, the most glaring factor is probably the sharp deterioration in visual quality. Indeed, the quality of the image that can be displayed on the remote driving platform will often be greatly affected, particularly when it has to be transmitted over long distances. While it is difficult to define what data transmission technologies will allow in the future, the experiments already carried out, notably as part of TC-Rail, have easily highlighted the current limitations. The communication systems tested during this project, 4G/LTE and SATCOM L/LEO technologies, could offer about a 1.25 Mbps data rate (Masson et al., 2022). Why remote control at low speed was successfully tested, all transmission technologies, however, had shown significant degradation to the visual restitution (Paglia et al., 2021). The image resolution was not only relatively low because of a limited bitrate, but was also prone to communication breakdowns. Additionally, some video technologies brought specific issues such as light flickering or long adaptation in high light contrast situations such as tunnel entrances and exits. Regarding the FOV, unlike the human eye which offers a wide FOV

centred along with the direction of the gaze, cameras in remote control systems generally have a fixed and restricted field of view that can exclude peripheral information. Various solutions could be proposed to compensate for changes in the FOV, such as widening the FOV on interfaces (using more advanced sensors again), dynamic changes in the FOV to reproduce the sense of speed or even tracking the driver's movements to change the orientation of the camera or reproduce a parallax effect. These proposals have already been put forward as potential study parameters, but have not yet been verified for train remote driving (Takeuchi and De Valois, 2000).

Although these specific issues are critical for remote control and may be enough to make it impossible, the answers to problems regarding visual information are essentially technical and will depend on the technological development of sensor and communication systems. For the purposes of an investigation on Human-Machine Systems and assistance, however, it will be necessary to determine situations where the current technology cannot easily transmit specific information visually, such as a precise sense of distance and depth, to new ideas and perhaps new sensory channels to transmit this information. In this document, however, the focus is more on control transition (see Chapter III) between remote agents. As such, the models explored here are not intended to provide solutions to the problems of perception and information restitution, even though some options will be mentioned. These studies must be carried out in parallel with projects covering the wider activity or, on the contrary, focusing on more specific parts of the driving process. However, if these studies are to be considered in the future, to pursue the research project presented in this document, it is necessary to assume, for the time being, that remote control is a viable, feasible and safe train driving method, regardless of current technological limitations or safety restrictions. This breakdown of the limits of teleoperation is nevertheless necessary to understand the limits which will affect the study, in particular the experimental phases for which solutions have not yet been studied. This will naturally lead to a certain number of biases that must be taken into account.

Auditory channel

Auditory information is also a crucial factor in observing and understanding the process and the environment. The driving activity analysis carried out in TC-Rail (Anceaux et al., 2019) is a key indicator of this, as it suggests that auditory perception can provide single or combined sources of information about system behaviour. Like visual or motion perception,

specific sounds may improve overall situation awareness when combined with other cues. For example, in addition to the visual channel, their study revealed that the auditory channel is also involved in the perception of speed when driving and that its absence led to a reduction in the comfort and behaviour of drivers, who tended to exceed speed limits more often (Hellier et al., 2011; Paglia et al., 2021). Certain elements of train operation can also be identified primarily, more quickly or precisely, by detecting specific sound cues. This can include the perception of bumps, engine issues, skidding or even the start of a fire. Similarly, spatial sound can enhance realism and immersion in driving tasks.

Secondly, in subsequent tests carried out in the TC-Rail project, in which train driving experts were involved in a simulator without sound reproduction, the analysis suggests that the participants were particularly disturbed by the absence of auditory feedback from the simulator. Thus, even before they needed to identify specific incidents or elements of the activity, the very absence of engine noise, sliding on the rails and other systematic elements had largely contributed to lowering their immersion. As (Paglia et al., 2021) suggests, however, the train remote driving environment should aim to simply reproduce the sound from the cabin by transmitting an audio recording. Leaving aside the major technical difficulties involved in recording and retransmitting the sound environment, in every detail from quality to spatialisation, care must also be taken not to overload the user with new information, potentially also degraded by communications, or to create the feeling of using a simulator. Thus, identifying the relevant auditory elements for transmission without overloading the remote operator's perceptual environment remains a crucial challenge.

Kinaesthesia

Kinaesthesia is the sense that detects the position of the body, the weight or movement of muscles and so on. It is a key element in our ability to perceive and interact with the world around us. This sense enables an individual to know where their limbs are in space without having to look at them, which makes it possible to coordinate movements. Kinaesthesia is often closely associated with proprioception, which is awareness of body position and movement. While proprioception is more concerned with cognitive awareness of body positioning, kinaesthesia focuses on the sensation of movement itself (Sherrington, 1907). This sensory system plays a crucial role in activities requiring hand-eye coordination, balance, or the ability to assess the strength and direction of movements.

Naturally, once the operator is no longer directly within the train's cabin, it is no longer possible to feel internal movements, speed, or acceleration. This can have a major impact on drivers' performance, particularly if they have a lot of experience in the cab and a lot of unconscious automatisms and habits have already set in. Some simulators are already equipped with a dynamic platform that reproduces the sensations of acceleration and movement. Such technology could be envisaged for rail teleoperation, but has not yet been tested. However, certain precautions need to be taken, as the addition of such a large and complex system can bring new constraints and limitations. Notably, such a device could be very distracting for the operator depending on how these movements are reproduced. In addition, as with visual information, the reproduction of vestibular information is subject to latency and communication issues. As a result, there can be serious discrepancies between the driver's actions, the expected behaviour of the train, the visual information being reproduced and the simulated sensory information (Pennel et al., 2002). Furthermore, although kinaesthetic information is naturally important in the driving activity, it would seem that their influence on performance is also linked to the type of train being driven. In particular, TC-Rail's studies of freight trains show just how much more complicated freight driving can be because of the nature of the train's load (Anceaux et al., 2019). For example, the trains are much heavier, the composition very varied and the braking system must be much more precise and attentive to avoid accidents. As passenger trains are much more stable and lighter, vestibular sensory information, such as resistance to braking or forward movement, has less impact. Moreover, according to some drivers, the cabins of some passenger trains are so well insulated that they perceive only reduced kinaesthetic and auditory information during the activity. Some of this information may nevertheless be perceived internally and unconsciously, underlining the importance of isolating which sensory information will really be useful and beneficial for teleoperation, which requires further study.

Furthermore, in addition to the transmission of visual information via a screen, this is perhaps the most obvious common point with most simulator experiences, when they are not equipped with dynamic platforms. This could also participate in reducing the operators' sense of presence, the nature of which is described in the following section.

II.4.2 Ensuring a proper sense of presence

The second point mentioned in (Paglia and Richard, 2021), regarding the sense of presence, suggests there might be a difference of behaviour from drivers in a remote environment, usually resulting in riskier driving behaviours (Fuller, 2005). This is the driver's subjective feeling of being in a real driving situation, even though the environment may be simulated or mediated by technology, as in the case of remote driving or driving simulators. A strong sense of presence is often associated with immersion and realism in the driving environment (Dagonneau, 2012). This includes the presence of most of the sensory information previously mentioned such as visual realism, accurate soundscapes, or other sensory responses such as tactile sensations. The more closely the simulated environment resembles real-life driving, the greater the sense of presence (Erickson-Davis et al., 2021; Servotte et al., 2020).

The lower sense of presence perceived in remote driving can be explained by different reasons such as physical or emotional distancing (Arseneau, 2016; Cummings, 2006). Notably, as the perception of the environment and the activity in general plays a huge role in the operator's sense of presence, it must be equally affected by the different losses in perceptive abilities mentioned in part II.4.1. In this investigation, while the sense of presence and potential ways of improving it will not be explored in depth, particular attention to these problematics must be paid when creating visual interfaces and simulation environments to guarantee a sufficient level of realism for the participants in the experiments. Indeed, while it will be impossible in this research project to seek and propose solutions to the reduction in the remote driver's sense of presence, the driving experts who will be questioned on their activity in Chapter V must have sufficient vision to immerse themselves in it. It will therefore be necessary to understand the biases brought by simulation and distancing.

II.4.3 Designing appropriate physical interfaces for remote control

A final important concern relates to the design of interfaces for remote control. The physical layout of the teleoperator's workstation is recognised as an important factor that directly influences the operator performance notably on the cognitive load (Zhang et al., 2016). It is essential to identify and implement optimal design features for these interfaces to mitigate cognitive load in scenarios involving complex tasks and harsh environmental conditions. Among the key design points are the layout of the controls, which must comply with a number

of standards and recommendations while adapting to the needs of the activity, and the presence of physical feedback. For example, in (Paglia and Richard, 2021), train driving experts expressed their concerns regarding virtual interfaces and the presence of physical buttons. They expressed the need for the interfaces to be similar to the physical control interfaces they were used to on trains. Furthermore, being able to feel the button reduces the cognitive load associated with using it. Indeed, unlike a touch-sensitive tablet for inputs, physical buttons can be more easily located without having to focus attention on them, through the user's sense of touch and proprioception.

Thus, the design of a remote-control platform requires a thorough analysis of the driving activity and the existing command inputs. Then, it is important to incorporate feedback from driving experts who can provide information based on their experiences with the system in realistic scenarios. This feedback loop helps to refine and optimise the system, responding not only to the technical requirements of the driving activity, but also to the practical needs and preferences of train drivers and future train remote drivers. Fortunately, as this project follows on from the investigations and tests of the TC-Rail project, it is already possible to couple the recommendations based on the first analyses of the activity with observations from the first user tests. Chapter IV will present the methods of presenting information and controls that have been retained in this project, notably based on previous recommendations from the TC-Rail project on freight train teleoperation.

II.5 Conclusion

The introduction of train teleoperation, especially within the global context of automation, is an important shift in the operational dynamics of train control and management. In particular, adapting the activity for remote driving introduces new and complex challenges and opportunities, requiring a reassessment of current practices and a new perspective on the safety, efficiency and reliability of rail operations.

In this chapter, the complexities, and the potential for teleoperation in railway systems have been explored, examining and comparing different transport domains and several aspects of its integration through technology and human factors. Teleoperation in railway systems has emerged as a potential degraded driving mode for an autonomous train. This role will remain particularly important if unmanned automated systems are faced with scenarios that exceed

their capabilities or unforeseen issues and challenges. In such contexts, teleoperation serves as an alternative control mode, allowing human operators to intervene remotely, saving precious time in mobilising emergency services and releasing passengers following incidents, notably. The aim is to guarantee continuous, safe train operation when automated systems are not capable of acting complete autonomously or when direct human expertise is deemed necessary for safety and operational efficiency. To this extent, a redefinition of driving modes in the context of railway automation has proved necessary. This provides a clearer framework for discussing and analysing the role of teleoperation in the wider context of automated rail systems, ensuring that its potential and limitations are well understood and appropriately integrated, while connecting definitions of autonomous modes to the authority of the agents and not simply their position in or out of the cabin.

However, the change towards train remote driving and the distancing from normal train driving activity has a significant impact on the driver's ability to perform said activity. Studying human factors therefore plays an essential role in understanding the limits and needs of human operators. In particular, the loss of information obtained in the remote centre negatively affects the operator's situation awareness and decision-making capabilities. This notably results from the absence of sensory feedback that operators typically rely on in traditional driving scenarios, such as auditory, visual and kinaesthetic cues. To alleviate this problem, it is necessary to explore and implement information transmission modalities that will effectively compensate for the sensory information that is lost through teleoperation. By providing a variety of ways of presenting information to the operator, these alternative modalities should aim to restore a global awareness of the operational environment, ensuring that the remote operator can perform the activity as effectively as if they were physically present. Nevertheless, it is important to be careful not to add too much information and varied modalities, which can sometimes be superfluous, or to overload a single information channel, particularly the vision channel.

Finally, it is important to remember that, even in an increasingly autonomous transport paradigm, the application of highly autonomous trains and a remote driving mode remains rather theoretical. Current systems are, for the most part and at the time of writing, still quite far from being able to operate sufficiently autonomously and safely in an open world environment to justify the absence of human expertise on board (Jansson et al., 2023). For example, the current technology cannot yet substitute the role of a driver in all situations, such

as for the evacuation of passengers in case of an emergency (Jansson et al., 2023). The number of probable unplanned events when compared to metro is still a high challenge to ensure the safety of the activity, especially when considering that there are fewer degrees of freedom to handle these unplanned events, as the trains cannot be manoeuvred outside the track (Mattsson and Jenelius, 2015), making railways less robust than other transport domains. This comes besides potential legislation issues to both certify the safety of said autonomous activity (Richard et al., 2021) and identify how responsibilities can be assigned between agents, especially as an artificial intelligence factor is involved (Besinovic et al., 2022).

That said, to explore the needs and limits of train remote driving, both train automation and teleoperation will be considered, in this investigation, as already exploitable and verified driving modes. While a lot of technical and human factors related challenges have yet to be overcome, this document will now focus on a much more specific problem: transfers of authority. The aim of the next chapter will therefore be to explain the main issues when combining teleoperation and automation in order to understand the mechanisms and challenges involved in a transfer of control between a human driver, from a distant site, and an autonomous train.

CHAPTER III
HUMAN-MACHINE
COOPERATION FOR AUTHORITY
TRANSFERS

III.1 Introduction

Having described both the concepts of train remote driving and railway automation, carefully exploring their evolution over the last century and their limitations, it is now necessary to understand the mechanisms that can combine these two technologies. Indeed, as the previous chapter suggests, train remote driving could be greatly beneficial, even in high automation. However, the transition from fully autonomous to manual driving is not without its own challenges, especially when manual driving is performed remotely through teleoperation. Understanding when and how these “authority transfers” occur is therefore one of the primary objectives for the deployment of these technologies.

This chapter aims to first complete the description of all three main axes of the research subject by defining what is meant by "authority" and how it is used in railway operations. The aim is to determine the extent to which it can evolve over the course of the activity. Building on the work initiated in the TC-Rail project on railway teleoperation, this document will use Human-Machine Cooperation principles to define the agents involved in the driving activity, explain their level of authority and the underlying mechanisms behind the transfer of authority between two agents.

The previous sections have already extensively discussed the various technical constraints of teleoperation and rail automation. This chapter will not go over them again, but they will naturally condition the needs studied for the activity. In particular, the distance-related limitations of teleoperation introduce significant information losses for the human operator. Together with the high degree of autonomy of the system, whose status and decision-making process may be difficult to discern, understanding the overall activity may be quite challenging for the remote driver. However, being able to obtain information on the train and the system, as well as their environment and behaviour, is crucial to the human operator situation awareness. Being the ability to understand the past, present and future of the whole process, situation awareness appears to be an essential variable in a transfer of authority. It is therefore necessary to determine what information is required for an agent, a human or technical operator, to regain control of the train, in order to design appropriate assistance systems. In particular, in addition to the most essential information required for driving, such as visual feedback or real-time signalling, it is important to provide the human operator with the information they need before regaining control, to help them develop their situation awareness.

Similarly, assistance systems must allow agents on the ground and the autonomous system on board to communicate effectively with each other in order to carry out the authority transfer process.

Therefore, the aim of this chapter is also to give some initial ideas on how the study of human-machine interaction, together with the previous studies of activity, can help enable transfers of authority.

III.2 Review of authority in transport

III.2.1 Definition

The first step before delving into the issues behind railway automation and transition of control is to define precisely what a transfer of authority means in the context of this research project, and before that, what is understood as “authority”.

In 2022, “authority” is defined in the Oxford Dictionary as “the power to give orders” or “the power or right to do something”. It is thus linked to the notion of power and permission. In this investigation, it can thus be assumed that authority is the power of an agent to act on a process or to give instructions to another agent. An agent, in this context, is an actor on the process and can be a technical system or a human operator. They can directly control the process and interact with each other. All agents may not have the same power and instructions regarding the control of the train or other tasks in the activity. Their authority, then, is the amount of control they have on a process and on other agents at a given time. Other definitions in the Oxford Dictionary are linked to organisational positions or great expertise in a domain. For example, one can say that a train driver is under the authority of their team manager and director. However, these definitions are not the focus of this study. For the rest of this document, the term authority will only refer to the first definition detailed above.

Authority, however, must not be confused with responsibility, which implies moral obligations and accountability (Oxford Dictionary). The notion of responsibility can sometimes be rather fuzzy, especially in the context of automation where finding who is accountable for actions or decisions is still a controversial subject. Of course, as the authors of (Flemisch et al., 2012) point out, authority and responsibility are not completely independent as one can only be responsible for what is among their authority, and can only have authority on tasks within

their abilities. However, in this study and the rest of this document, responsibility issues will not be explored further.

Authority can also be confused with the term “ability”. Indeed, authority is the *ability to do something* in the activity, thus the two notions are inherently linked. The abilities of an agent, however, describe the entirety of their skills, whether it is to act on the process or communicate with others. It is defined in (Flemisch et al., 2012) as “having the necessary competence, skills and resources (e.g. time, tools or personnel) to execute control, including perception, action selection and action”. It is something unique to the agent that depends on their experience and training for human operators. It can be understood as what the agent are able to do. Authority, however, is always given to that agent by a higher instance and determines what they are allowed to do according to what they are able to do.

Finally, authority can also be linked to the concept of “control”. In this document, the notions of “authority transfer” and “transition of control” are used in a rather interchangeable way. The two terms, however, are slightly different. Control relates to actions on the system. An agent may have a control authority that allows them to act on the process (to control the train, for example). Authority, however, may be given to roles not directly linked to controlling the process, as explained in the following part. Thus, control can be considered as a part of the authority, related to actions on the process.

The following part will present the first elements used to describe human-machine interactions, which will be used to describe and understand the authority of each agent in a cooperative process.

III.2.2 Breaking down the authority of an agent

To act on the process, an agent must first have the proper ability to do so, and then be allowed (have the authority) to do it. However, there are multiples other tasks that an agent may possess skills for and be allowed to accomplish, such as perception or decision making. In (Gadmer et al., 2022), (Gadmer et al., 2021) and (Pacaux-Lemoine et al., 2020), a Human-Machine Cooperation model was applied to train remote driving, using definitions used in other works in automation and adapted from principles defined in previous staples such as (Schmidt,

1991) or (Parasuraman et al., 2000). In these works, the ability of an agent is known through their Know-How (KH) and their Know-How-to-Cooperate (KHC).

In (Pacaux-Lemoine and Itoh, 2015), the KH of an agent is defined as the “internal ability to solve problems”, using their skills, expertise or processing abilities, and the “external ability” to get information and act on the process. The KHC, on the other hand, is the ability to understand other agents, get information from them, and communicate with them. Both are more detailed in Figure 17.

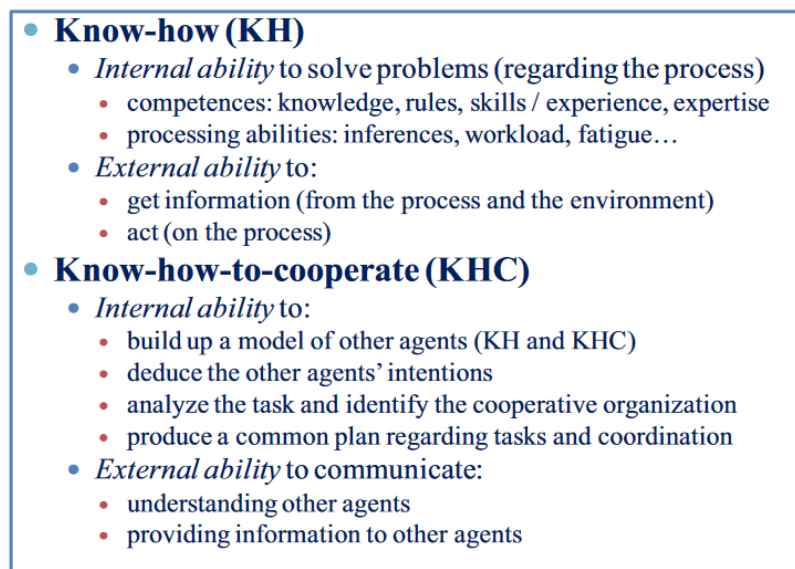


Figure 17 Cooperative agent (Pacaux-Lemoine and Itoh, 2015)

The KH of an agent is directly linked to the abilities of that agent. In (Parasuraman et al., 2000), the authors break down the human information processing in four sub-functions that represent the four stages of the KH. In later work, including the train remote driving cooperation model, such simplified framework of the KH was applied to any agent in the cooperative process, as seen in Figure 18. The four functions are Information Gathering (IG) on the process and the environment, Information Analysis (IA), Decision Making (DM) and Action Implementation (AI). Naturally, these are in line with the different aspects of KH described earlier, IG and AI being related to the ability to perceive information and act on the

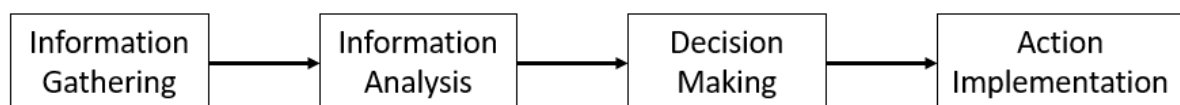


Figure 18 Know-How (KH) of an agent (Pacaux-Lemoine and Itoh, 2015)

process while IA and DM are related to problem solving using the agent’s abilities and knowledge. This model of the KH might be a simplification of the intricate complexity of an agent’s abilities, but it helps understand the different forms of these abilities and can then help us determine specific authority for each of these functions.

In this model it is relatively easy to understand how control is only one element of an agent’s KH, but an agent may also have authority on tasks regarding information gathering (IG) or decision making (DM).

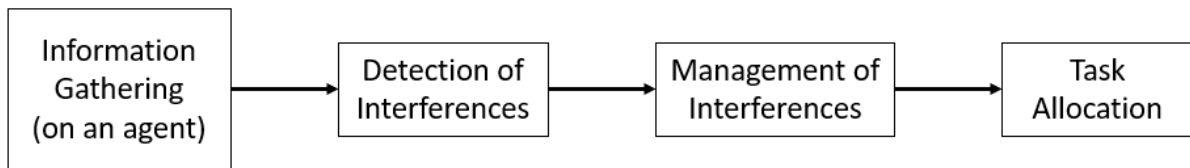


Figure 19 Know-How-to-Cooperate (KHC) of an agent (Pacaux-Lemoine and Itoh, 2015)

However, as described earlier, functions of the KH are not the only abilities of an agent as they also must be able to communicate with each other and organise the cooperative process. This is known as the KHC, defined in Figure 17. It is the ability to cooperate with other agents by understanding them, getting information about them, and building an internal model of their functioning, i.e., the ability of the agent to determine the Know-How, the KHC and the state of the other agents. This helps determine the other agents’ situation awareness and anticipate their intentions.

Again, KHC can be broken down into four sub-functions: Information Gathering (IG), Interference Detection (ID), Interference Management (IM) and Task Allocation (TA), sometimes known as Function Allocation (FA). When referring to the KHC, IG is the ability to acquire information about other agents to build an internal model of their functioning and decisions. It is directly affected by the other agents’ KHC and their external ability to provide this information. When several agents are in a cooperative process, the actions of one will likely interfere with the activity of the others. These interferences can be beneficial when the actions help other agents in their respective goals, or become negative when the actions, errors or limitations of one agent can lead to negative consequences within the cooperative process. Anticipating, identifying, and managing these situations is therefore essential. ID is the ability of the agent to spot these situations and IM determines how these interferences are managed between the agents. This will determine how agents should cooperate. In (Schmidt, 1991),

Schmidt presents three forms of cooperation. The “augmentative” form when multiple agents share capacities (KH) and can work together on similar tasks. In the “debative” form, agents share the same tasks but compare their results and analyses. They can then debate them in case of conflict (for example, both the driver and the automated system on a train could monitor the environment at the same time and the protection systems may be able to detect something the driver missed). And finally, in the “integrative form” of cooperation, agents have complementary KH and are affected different tasks that suit their abilities (Milot and Pacaux-Lemoine, 2013). The result will then involve changes in authority between the agents. TA refers to the ability to adapt one's authority and to have the authority of other agents changed according to the needs of the activity, the state of the cooperative process between the agents, and their KH and KHC. The framework of KHC is summarised in Figure 19. Of course, each agent may have various and varying levels of authority regarding each aspect of their ability to

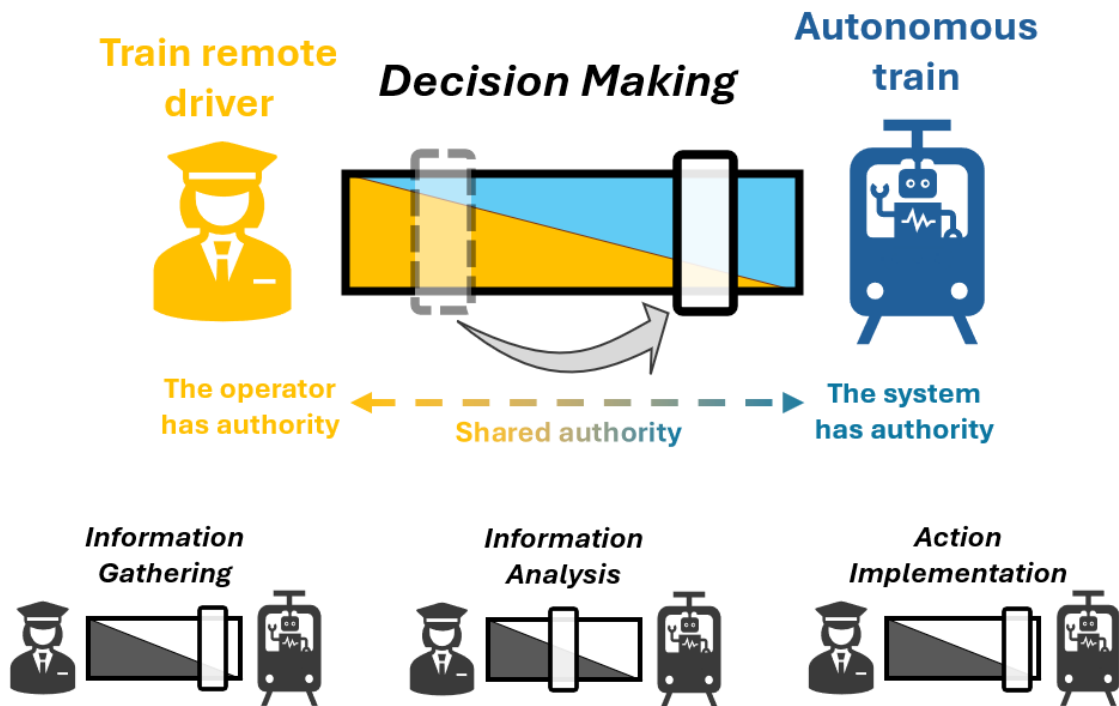


Figure 20 Agents' Know-How and shared authority resulting from Task Allocation

cooperate. This is especially true with the more active ones, IM and TA. In particular, TA is the ability of an agent to organise the cooperative process by modifying the authority of other agents. This is essentially the ability of an agent to coordinate a transfer of authority, that will be explored in the following part.

With these definitions, the authority of an agent can be precisely allocated to their respective tasks. An agent may have a specific set of abilities to either control and interact with

the process or to work in collaboration with other agents, but they may have a variable authority regarding each of these functions, depending on their role in the process and the current authority of other agents. Resulting from TA the authority of agents from a specific subset of functions from their KH or KHC can change. Figure 20 illustrates a change of authority on the DM function of the KH. The “level of authority” of the train remote driver and the autonomous train is presented with a slider that can vary between “full operator authority” and “full system authority”. Anywhere in-between is a situation of shared authority. The authority of agents can be described this way for each sub-function of either KH or KHC to define their current level of authority in the process. It must then be updated appropriately every time an authority transfer happens. It has not yet been explained how this authority can change as a result of TA, why such a change would be necessary and who is able to initiate such a demand. The following part III.4 will attempt to draw a more precise picture of authority transfers by exploring how they happen in other transportation domains, mainly through the better documented automotive industry. Before delving into the notion of authority transfer between agents, a cooperation model will be presented in part III.3 to properly define said agents.

III.3 Human-Machine Cooperation Framework for train remote driving

III.3.1 Presentation of the framework

The previous chapters have highlighted the need to provide more assistance to the train remote driver in the context of this activity. For this project, building on the work started in remote driving and presented previously, Human-Machine Cooperation (HMC) has been chosen as the main driver of the study. As the name suggests, the aim is to focus on interactions between the human operator and technical systems in a cooperative process, i.e. when multiple agents work together towards a common goal. More specifically, the aim of a study built around HMC is to "put the human operator back in the loop" and to foster not a purely technical approach to system design, but rather a human-centred approach.

Figure 21 presents the four agents in the cooperation model for train remote driving, defined in (Gadmer et al., 2021), in their respective environment. Within the remote control cabin is the train remote driver, on the left in Figure 21, the human operator controlling the train in teleoperation. They are assisted by an Advanced Driver Assistance System (ADAS),

the “in-cabin ADAS”, that is also located directly within the train remote cabin. Equipping the remote cabin with assistance systems enhances interactions with the remote driver, especially for activities that demand fast response for either agent or for providing guidance, such as scheduling and speed recommendations. To provide assistance to the operator, the in-cabin ADAS can use virtual and physical interfaces from the cabin, such as screens, sounds or haptic devices. The proximity makes it easier for the in-cabin ADAS information about the remote driver. For example, this allows the system to perform tasks such as monitoring the human operator's attention and state of fatigue. Moreover, the amount of technical equipment that can be added within the train, without significantly modifying the infrastructure and the rolling stock used, is limited. More powerful systems could thus theoretically be deployed within the

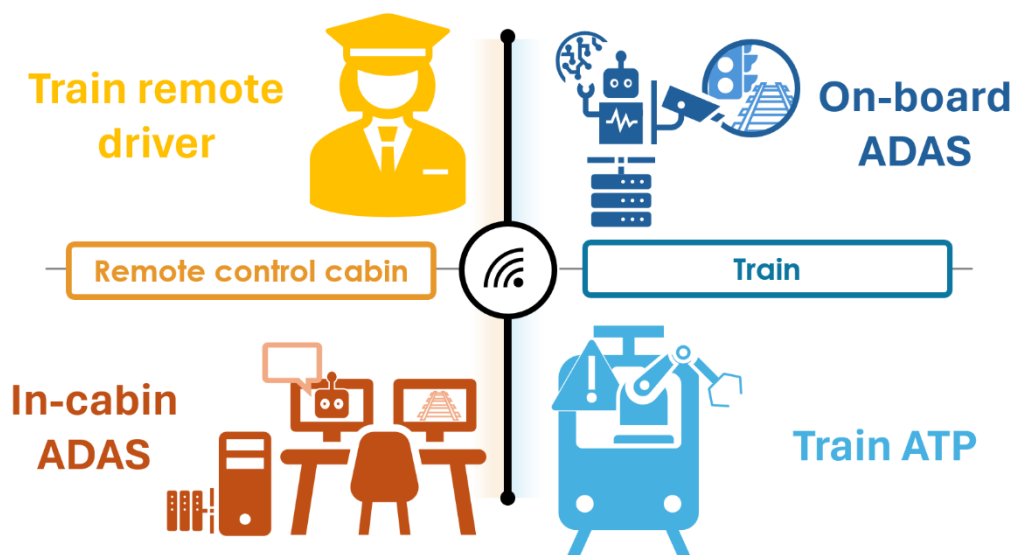


Figure 21 Four agents in cooperation for train remote control

remote driving platform instead. This would make it possible to carry out advanced analyses and make predictions about the evolution of the process. Nonetheless, due to the separation from the train, the in-cabin ADAS faces similar constraints as the remote driver and relies on external agents for information. Both the remote driver and the in-cabin ADAS are connected to the train through a communication network.

Within the train, two agents are defined, on the right of Figure 21. First, the Automatic Protection Systems (ATP) corresponds to the already existing “intelligent” systems within most trains and which possess authority to control the train in case of emergency situations. In (Gadmer et al., 2021; Pacaux-Lemoine et al., 2020) where this cooperation model was applied

and agents defined, these protection systems could not be modified and the train ATP is thus an agent, able to act in the process by controlling the train. As it is already existing within the train, and corresponds to the base system without any additional functionality, the agent is often referred to as just the “train” indistinguishable from the train itself which is the vehicle being controlled. This agent, however has only limited capacities regarding information gathering, analysis and control, being used only for very specific critical situations such as failure to follow signalling instructions. Similarly, the train, by itself, has very limited KHC and can barely communicate with the operator, especially remotely. To complement these functionalities, a system with higher control and cooperative capacities must be added to the train to operate the train remotely. In Figure 21, the on-board ADAS is the final agent, directly connected to the train’s actuator from the cab to control the train and interfaced with multiple sensors monitor the environment. Its first role is thus to obtain information about the train’s state and about its environment, as this is no longer directly possible for the train remote driver from the distant site. Visual information is naturally among the main data acquired, using on-board cameras and transferred to the train remote driving cabin, but the on-board ADAS could also obtain information from other sources, such as sounds or vibrations. The presence of the on-board ADAS within the train also means that actions can be implemented much more quickly following a decision of the ADAS, as it is not affected by the latency between the train and the remote cabin. This means that the DM authority could potentially be shared between the remote driver and the on-board ADAS, particularly when rapid action is required, in emergency situations for example, completing the abilities of the train’s ATP. In this initial model, the ATP and the on-board ADAS are separated, but in the contribution of this thesis, presented in Chapter IV both will be treated as a unique agent, the “autonomous system”, that will interact with the remote driver and the ADAS from the remote cabin.

Using the previous definitions of KH and KHC, a framework for cooperation can be used to contrast the abilities of two agents in order to identify when they complement each other and how two agents can interact. This framework for two-agents cooperation has been previously applied in different domains such as automobile in (Millot and Pacaux-Lemoine, 2013) or (Pacaux-Lemoine et al., 2015) and was adapted for train teleoperation in (Gadmer et al., 2021; Pacaux-Lemoine et al., 2020). Figure 22 presents the model used in the TC-Rail project to apply this framework to train driving. Here the human operator, the train remote driver in Figure 21 and the computer system within the train, the train ATP in Figure 21, are

two agents and their KH and KHC are represented. Following the TA, the authority of the agents on each of their KH functions, represented with a slider similar to that of Figure 20, is being shifted towards one agent, the other, or both simultaneously.

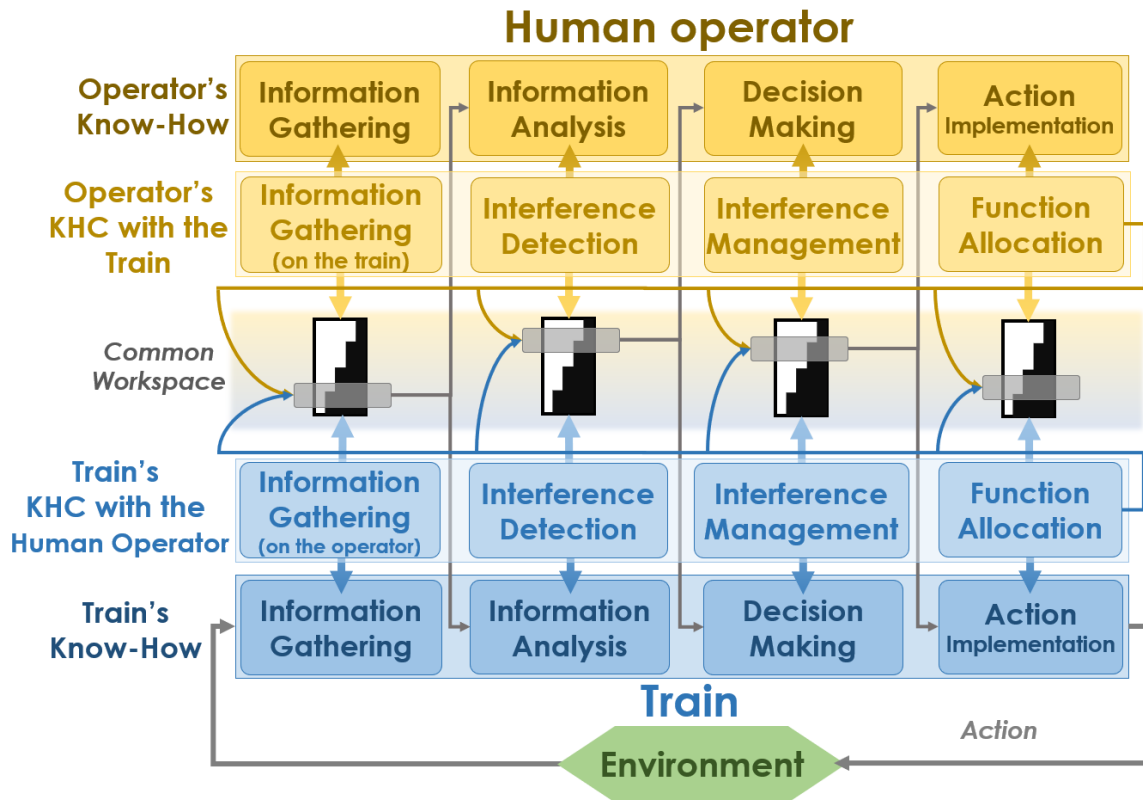


Figure 22 Human-Machine Cooperation Framework applied to train driving in the TC-Rail project (Pacaux-Lemoine et al., 2020)

The support for cooperation between the agents is called the Common Work Space (CWS). It is a “common language” between them, including the physical interface for the human operator, and virtual networks and interfaces between technical agents. The CWS provides situation awareness of the state and environment of the process, which covers the past, present and future activity, and it is complemented by that of all agents that communicate through it (Millot and Pacaux-Lemoine, 2014). Chapter IV will explore how agents use the CWS for cooperation.

The model presented in Figure 22 was then extended to integrate the relations between all agents, as seen in Figure 23. This upgraded version of the framework includes the remote driver, the train, and the two ADAS previously presented. The model has been simplified to be more readable, but each pair of agents can potentially interact with each other depending on

authority. Nevertheless, using the tool and the framework has highlighted a few caveats. First, this model does not take into account simultaneous interactions between more than two agents. Indeed, even if all links are represented on the framework, to study each of them, it is necessary to isolate them from the rest of the model. Thus, it can sometimes become easy to forget the complete architecture of the system and the most complex links between agents. For example, when two agents have limited KH for a task in the activity (such as IG for the remote driver and the in-cabin ADAS), or when their KHC does not allow them to manage a conflict with an agent, it can be difficult to understand how the situation can be resolved at all without observing concurrent interactions with other agents.

Then, this framework does not effectively portray the different abstraction levels of the activity. Indeed, the train driving, and remote driving, activity may have objectives or effects at different timescales, and can therefore be broken down into different levels of abstraction: strategic; tactical; and operational (Michon, 1985). Of course, these levels are not actually from HMC as they are central to the definition of the KH and KHC of agents and depend on many factors such as the type of activity or its hierarchical organisation (Pacaux-Lemoine, 2020). The abstraction levels were described for train remote driving in (Gadmer et al., 2021). At the strategic level, the tasks and processes aim at identifying and defining the objectives of the missions while planning and organising their timing. This is a relatively long-

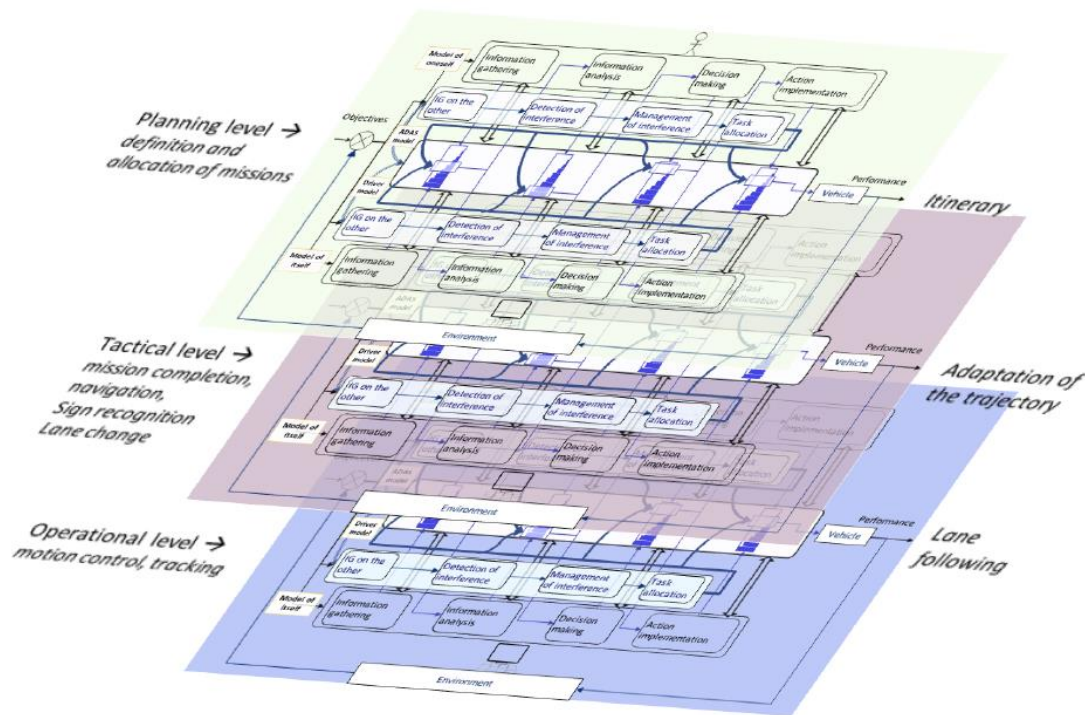


Figure 24 Multi-level cooperation in (Pacaux-Lemoine and Itoh, 2015)

term scale and the decisions taken at this highest level of abstraction of the activity will influence the missions carried out at the lower levels. For the tactical level, the focus is shifted towards achieving the missions defined at the strategic level, as well as monitoring and maintaining their objectives. In a more medium-term scale, these objectives may evolve during the activity, because of internal or external circumstances, which would affect how the overall mission is carried out as well as how each decision is made at the lowest level. Finally, the lowest level of abstraction is the operational level, where control tasks are performed on shorter time scale.

To properly integrate them to the representation of the model, a fuller version could thus superimpose multiple versions of the framework with interactions specific to each level of abstraction such as represented in Figure 24 (Pacaux-Lemoine and Itoh, 2015) or Figure 25 (Berdal et al., 2023).

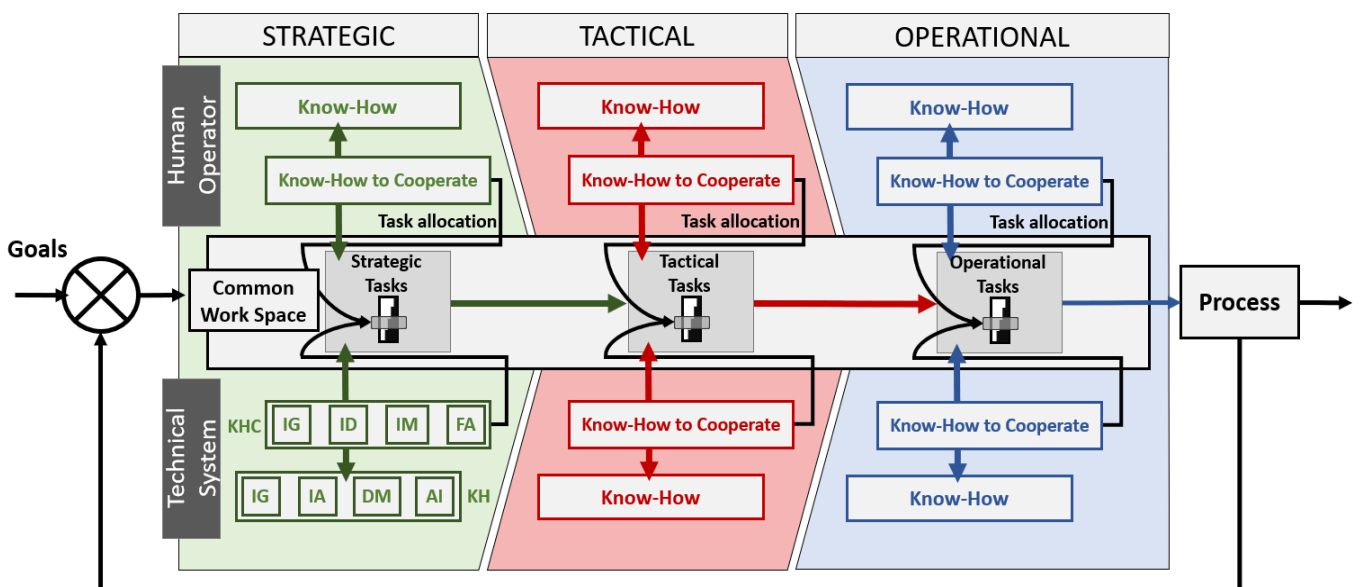


Figure 25 Multi-level cooperation, translated from (Berdal et al., 2023)

In the case of this research project, however, the model will only be used to define the general architecture and to understand the base KH and KHC of agents in the activity. This investigation will propose an initial approach to authority transfers in the context of train teleoperation and automation using HMC to support the definition of this architecture. As it is still relatively early in the context of this investigation to explore precisely individual interactions for all levels of abstraction, this level of detail is not yet necessary. The contributions from Chapter IV, although not directly mentioned, can still be attributed to

specific levels. Most of the base interfaces and common issues regarding remote driving are tied to the operational level, the control of the train itself. This includes, getting continuous information from interfaces and sending commands, and will mostly follow recommendations from the TC-Rail project. In this thesis, the focus is rather on the authority transfer process which implies challenges for each abstraction level. The strategic level implies the planning of transfers beginning when a remote driver is assigned a remote recovery mission and for which they must obtain general information such as the mission's rules and objectives. In the scenarios of Chapter IV, some authority transfers can even be programmed as part of their mission, which happens at this planning level. In the tactical level, the remote driver must anticipate and prepare for the upcoming transfer(s) when possible. Additionally, when a Take-Over Request (TOR) is issued by either the remote driver or another agent, the transfer process is engaged and will change the plan at a tactical level. Finally, following the authority transfer process by interacting with the systems and interfaces happens at the operational level.

Beyond these first challenges, and to further expand the use of HMC for train teleoperation, more precise elements of the overall activity and the results obtained from the experimental phase of this research project must be reinjected into newer studies.

III.4 Transfer of authority between agents

III.4.1 Understanding transfers of authority

Once the notion of authority has been established, understanding what a transfer of authority means is not difficult. In a cooperative process, a transfer of authority between two agents simply refers to a situation in which the authority of both agents is changed. In this scenario, the authority of one agent will increase while that of the other is reduced. There may be cases in which only the authority of one agent is reduced, or the authority of both agents will increase together. An example for this could be a situation in which the abilities of one or multiple agents are reduced, impacting their authority, as seen in part III.2.1. For instance, when entering a tunnel, if the track is no longer visible, the ability to see the environment is naturally affected, greatly reducing the ability to analyse visual information. Thus, the authority of agents, regarding information gathering and analysis, is expected to change in this situation as they will rely exclusively on other information. In these cases, however, the notion of "authority transfer" does not apply as it is neither really a transfer nor a transition of authority

between two agents. As such, a transfer of authority is not only the change in the authority of one agent but an exchange between two so that the role of one agent with a previously higher authority is effectively given to other, as already represented in Figure 20 (part III.2.2). Technically, more than two agents could be involved in such a transfer as these definitions could be extended for systems for which it would make sense. This document, however, will usually only consider transfers between only two agents, usually the train remote driver and the autonomous train when applied to the thesis' study.

The notion of a transfer is relatively straightforward and quite separate to a simple modification of the authority of one agent independently to that of others, but why do these transfers occur? When is a transition of authority necessary? In the first chapter, automation levels for railways, Grades of Automation (GoA) were presented and autonomous trains can be classified between GoA0 and GoA4 (UITP, 2012). These different levels are also known as “driving modes” for which the autonomy of the system increases along with the GoA level.

In the definitions of GoA, the main difference between two levels actually lies in the difference of authority between the technical system and the human operator. As levels increase the authority of the human operator regarding the control of the train, the monitoring of the environment or the management of critical situations is shifted from the driver to the autonomous system. As such, a transfer of authority occurs when the driving mode of the system changes. The main implication is that a transfer of authority occurs when there is a

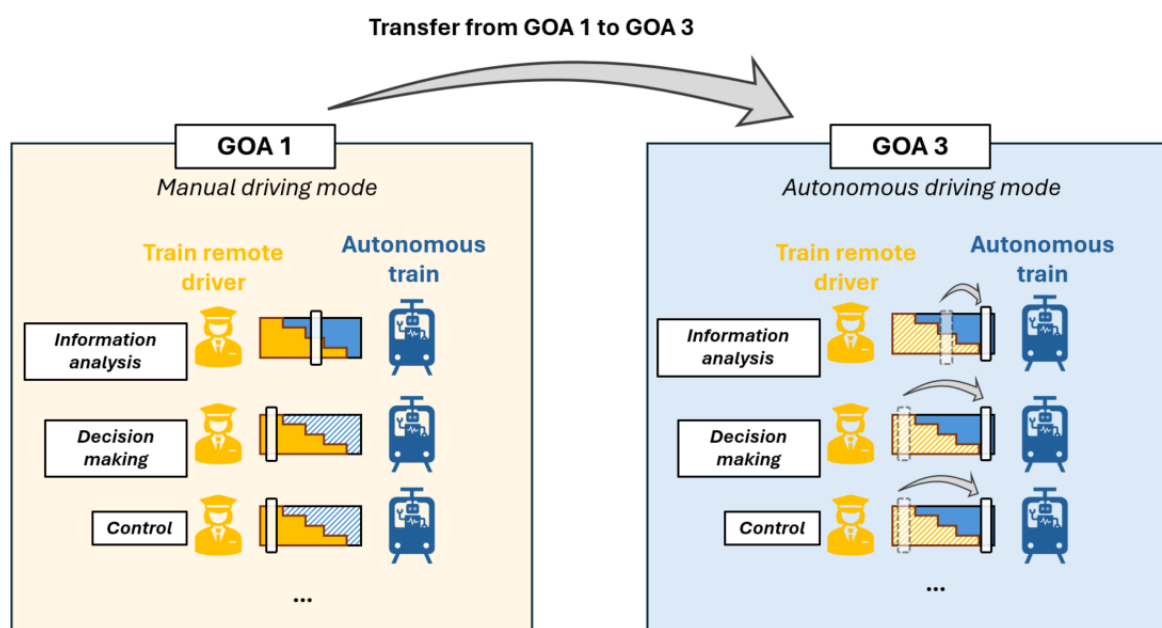


Figure 26 Change of authority during a transfer from GoA 1 to GoA 3

change between a limited number of pre-established levels. Without being tested or demonstrated in this study, it seems difficult to imagine the possibility that an agent's authority could be independently micro-adjusted for each type of task they might perform and continuously during their activity. Indeed, this could potentially hinder the accurate understanding of each agent's level of authority, and thus lead to further difficulties when determining their level of responsibility. Instead, through a limited number of driving modes, the remote driver must only be aware of the exact level of authority of each agent for these modes, and should always know them by being aware of the driving mode only. As such, the transfer of authority could be illustrated by Figure 26, where the shared authority between two agents for a few tasks is represented with a slider with fixed steps that should only move when changing driving modes.

The next step is thus to determine how, when and why a system changes its level of automation. Use cases for railway automation, in the context of this study, will be detailed in Chapter IV that defines specific scenarios for the study. These use cases, however, will still remain rather theoretical as research on railway shared control is still new. An analysis of the activity, its needs and the marketplace will therefore be necessary at a later date. As these questions are relatively new, especially for the railway sector, it is once again necessary to examine neighbouring domains. The next part, III.4.2, will explore early applications in different domains, mainly the automotive sector, where such systems have already been studied and implemented, in order to understand future railway challenges.

III.4.2 Authority transfers in transport

The development of automation for the automotive industry is currently thriving and numerous new active systems are being deployed in vehicles designed for the general public. These active assistance systems are able to take control of one or multiple tasks. The first that were introduced were usually presented as unique and isolated options that could be activated or deactivated by the driver when necessary. This includes Advanced Driver Assistance Systems (ADAS) such as Cruise Control (CC), and later Adaptive Cruise Control (ACC) (Bu and Chan, 2012), or Lane Keeping Systems (LKS) (Netto and Chaib, 2004). When these ADAS are activated, a change in authority happens and the activity is considered in a driving mode in which some control tasks are automated. For car automation, this is equivalent to going from no assistance in Level of Automation 0 (LoA0) to slight control assistance (LoA1, only

longitudinal or lateral control) or partial automation (LoA2) (On-Road Automated Driving (ORAD) committee, 2016). These systems are activated by the car driver and they will usually stay active until they are deactivated by the driver. As such, the transfer of control from the driver to the vehicle is easy and happens smoothly, by demand of the driver. The driver must only yield control to the vehicle, which is immediately able to perform the activity under its performance limits, which are the limits of their applicability. For most systems the driver is considered to have final authority when requesting to resume to manual driving. To take-over the control of the vehicle, drivers must only perform an action on the actuators. Using the car's braking or acceleration pedals or moving the wheels will instantly initiate a TOR to the system. In some cases, when the command is not abrupt, the car may try to keep the control to avoid potential errors and will move the actuators with haptic feedback (Benloucif, 2018; Sentouh et al., 2018). However, if the driver insists or pushes the actuators beyond a certain threshold, the system will automatically yield control back to the driver.

The most advanced systems may be able to determine by themselves their performance limits, but that is not always the case. For example, early ACC could only maintain the car speed when vehicles ahead are moving but they could not alert users when reaching obstacles or stopped cars in traffic or road tolls (Makoto Itoh, 2011). The risks of over-trust or accidents linked to the use of more automated systems were mentioned Chapter I. When technical systems can detect performance limits, they may alert the driver and issue a Take-Over Request (TOR), inviting the driver to take-over the control of the vehicle. Otherwise, assuming the driver is able to detect such a situation, they can initiate the transition on their own. For most situations, including other domains, this will be the scenario anytime a transfer of authority is engaged by an agent. In the first example of the driver activating an ADAS, for example an ACC, the driver asks the system to take-over some control of the vehicle either completely or in a shared-control mode. Newer generations of semi-automated cars have recently been achieved with vehicles such as Tesla Model S or the latest generations of Audi A8 (Dimitrakopoulos et al., 2021). In these vehicles, the control of the car can be completely given to the autonomous system in specific use cases. Thanks to a wide range of sensors, they are able to perform much more involved driving tasks, such as simultaneous lane keeping, lane changing and merging, cruise control or obstacles and weather detections (Tatarek et al., 2017). However, they are still limited as they cannot always if at all read road signs or perfectly detect merging lanes and they are not adapted to every possible situation (construction works, etc.).

As such, they cannot be considered LoA3 as a driver is always expected to monitor the driving activity (On-Road Automated Driving (ORAD) committee, 2016). On paper, this greatly facilitates TOR scenarios as the driver is expected to be ready to react to a situation in which the system might ask for a transition of control and should even be able to anticipate it or take control before the system detects its performance limits. More details on how TOR are issued to the driver will be explored right after the presentation of the most recent automated systems, that bring new difficulties by leaving the driver partially out of the driving activity.

Indeed, the limitations of LoA2 semi-automated systems are now supposedly gone with the arrival of Mercedes-Benz DRIVE PILOT or Honda L3 Traffic Jam Pilot (Katzorke, 2022), the first approved level 3 driving automotive systems. Once in LoA3 driving mode, the car is able to drive automatically while the driver is not actively monitoring the activity and may perform other unrelated activities. In the railway domain, this could be equivalent to a step between GoA levels 2 and 3, leading more towards GoA3 but with the driver still immediately able to intervene if asked to. This, of course, does not mean the systems can and will be able to drive under all circumstances, hence their level 3 limitations and the need for the driver to be available at any time, but it means some driving modes in which the drivers are not attentive to the activity are now allowed. Obviously, this raises the question of how transfers of authority happen following a TOR from the system and how much the lack of constant monitoring affects the time to respond to the request. The driver not being attentive means the system must find a way to get the attention of the driver and present all the necessary information for them to understand the situation and its gravity to ensure an appropriate response. This step of recreating the context for the driver is also called “onboarding”, describing the acclimatisation process for the human driver. This is a decisive step for which the time is often very limited as systems usually fail under unexpected and often critical situations (Casner et al., 2016). It has also been found that the time to respond in this scenario is usually proportional to the level of automation. Because of this, the time difference for the management of limits between LoA2 systems and that of systems beyond LoA3 becomes quite significant (Brandenburg and Chuang, 2019).

Studies have also been conducted in the aviation sector in similar situations of semi-automated driving, in which autopilots have been used for a longer time. In (Casner et al., 2013), experiments on trained pilots have shown that, despite their training, pilots’ responses to abnormal events in usually familiar tasks were not always appropriate and varied a lot

between each pilot. In relatively unpredictable environments, such as open-world railways, the operator's response to a TOR, especially when out of the loop with limited SA, could be just as unpredictable. Additionally, studies in (Casner et al., 2014) have shown that long periods of automation negatively alter the performances of pilots, especially when considering cognitive skills. Regarding car automation, these results are not promising for a smooth transfer of authority as both the unpredictability of the situation and the potential prolonged period of automated driving will affect the driver's response. The automotive sector in particular is especially susceptible for unexpected events such as the behaviour of pedestrians and other vehicles, especially in urban areas (Campbell et al., 2010). In (Chauvin et al., 2020), the authors study responses to a TOR from car drivers under LoA3 automation while performing distracting tasks on a tablet. Under the specific circumstances of the experiment, some behaviours could be isolated. Firstly, and quite expectedly, the time to resume control of the vehicle increases as the driver is distracted by other tasks. Secondly, most participants show more comfort and appropriate responses as they are given more time to resume control, allowing them to have a mental preparation. This result is also observed in (Merat et al., 2014). Finally, in situations where drivers had a short time to resume control, take-over actions are much faster, close to reflex behaviours and may lead to abrupt braking or unnecessary stops.

How then can the automated system present the TOR in a way that will induce the best response from the driver? The results from (Chauvin et al., 2020) or similar experiments in (Gold et al., 2013) could suggest that technical systems could adapt the TOR to provide

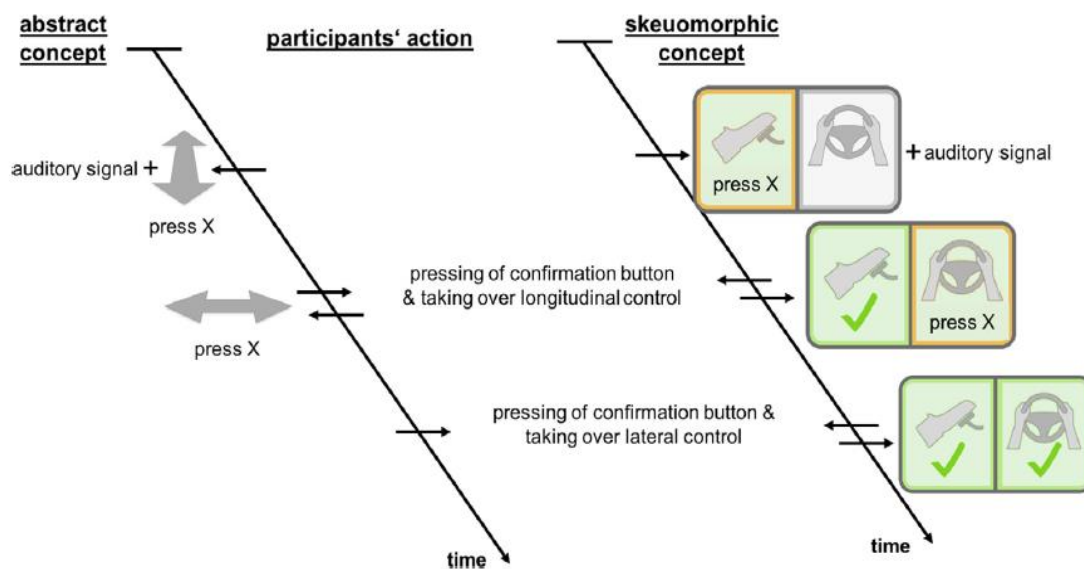


Figure 27 Two TOR concepts, studied in (Brandenburg and Chuang, 2019)

different information to the driver depending on how predictable or critical the situation is. In (Brandenburg and Chuang, 2019), the authors also suggest exploring adaptive requests as time critical scenarios require fast, clear and concise information but a two-step TOR procedure could be beneficial on uncritical situations. To provide the information to the driver, any medium that is able to get both their attention and communicate a clear message in the best way should be considered. The main ways to communicate information would be through visual cues, audio signals or haptic feedback. While the latter is interesting in case of shared-control or lower levels of automation (Saito et al., 2018), haptic communications might be quite limited if the driver is potentially distracted and cannot feel signals from the control actuators (wheel or brake pedals for cars). For visual information, it is important to choose the right way to convey information with either words or pictograms to avoid visual cluttering. In their experiment, authors of (Brandenburg and Chuang, 2019) have tested different designs to visual HMI when presenting a TOR. They compared the use of abstract visual concepts with geometric shapes, such as arrows, and skeuomorphic designs resembling real mechanics or actions, as seen in Figure 27.

The authors of (Brandenburg and Chuang, 2019) have drawn multiple conclusions from their experiments. The use of skeuomorphic concepts can be effective for simple messages, especially under critical situations. Besides, such concepts were usually preferred due to the familiarity of their design. For more less critical situations, however, skeuomorphic concepts can be unnecessarily complex, especially if the system needs to present more detailed information. In both cases, however, the study shows that having longer headway significantly improves the response from the driver. Finally, for auditory messages, when comparing speech-based messages to generic auditory cues, the authors of (Forster et al., 2017) observed that users found speech-based systems relatively more favourable. When using such systems, participants were able to react much faster and leave distracting non-driving tasks to resume the activity.

Currently, the implementation of Automatic Train Operation (ATO) in European railway applications are still mainly limited to closed world environment such as automated metro lines. Some mainline trains are able to operate in GoA2 such as the German Continuous Train Control (LZB) (Sporleder, 1989) also used in Austria and Spain. Using these systems, the train driver was able to activate an autopilot function in the train that can maintain appropriate speed depending on the line, the mission's timetable and the position of other trains

on the track. This allows to operate more efficiently at higher speed while the driver is still monitoring the environment. However, until the deployment of the new European Train Control System (ETCS), these systems remain rather rare in Europe. For GoA3 trains, the driver is replaced by a train attendant that isn't necessarily within the train cabin but only intervenes in case of emergency. This implies that authority is given to the train attendant only after an emergency procedure in which the train has stopped. Like in automotive applications, resuming the activity requires establishing the context of an incident. The main difficulty, however, will come with the introduction of train remote driving that introduces an even greater degradation of the driver's ability to build situation awareness (see Part III.4)

III.4.3 Who can change authority?

Specifically in the case of a change in control authority, the authors of (Lu et al., 2016) have established a classification of transitions of control through three questions. The first question, or the first dimension of their classification is "Who initiates the transition?". Indeed, as presented before, there are important differences when the system or the driver initiates the transfer, especially for higher automation when the human operator may be inattentive to the process. The second question, that necessarily follows, is "Who is in control after transition?". This includes knowing which agent has control authority, but also who is responsible for monitoring and ensuring the safety of the activity. Finally, the final dimension in their classification asks "Why is the transition happening?" to determine the reasons for the transfer and if it's potentially mandatory and critical.

In the thesis, the HMC framework presented in this chapter is adapted to study the interactions of three main agents in a train remote driving process (Gadmer et al., 2022). The complete framework developed for this project will be presented in the next chapter along with the contributions. These agents are the train remote driver, the autonomous system of the train and an assistance system within the remote control cabin, as presented in Part III.3.1. The autonomous train system and the remote driver can be considered as the two main agents that may be given the control of the train. When a transfer is initiated, the answer to "Who is in control after transition?" should thus be one of them. To describe more precisely the role and responsibility of the agents after the transition, the question could possibly be extended to "Who is in control after the transition and under which driving mode?". Indeed, if there are important distinctions between a change from GoA1 to GoA2, where the driver is still

responsible of the activity and monitors the process, and a change from GoA1 to GoA3. The transfer, however, might be initiated by each of the agents. The driver or the system can issue a TOR if they think it is necessary, similarly to previous automotive examples. For the railway application, the ADAS within the remote cabin is a new agent that aims to support interactions between a remote driver and the autonomous system, and to help the driver face the challenges of remote authority transfers. As such, the ADAS may also suggest TOR when it detects an agent in control isn't able to continue the activity (failure for the technical system, fatigue of the driver, etc.).

Determining who can initiate the transition of control, and under which situations, is an important first step. This can also be extended to any authority transfer. However, it does not completely answer the question “Who can change authority?”, or in other words “which agent has the final authority to allocate tasks?”. There is no currently final answer to determine when an agent may have the final take on a transfer of authority as choosing the safest procedures sometimes requires the human operator to impose a transition, while sometimes the system might have to force the transition instead, especially in critical situations when an emergency procedure happens. The latter case is already applied for train protection systems that will stop the train automatically, when necessary, potentially overruling the driver. Sometimes, agents may not agree on the result of a transfer of authority that has been initiated. Depending on who has the final authority, and the information provided, the transfer can thus be accepted or rejected. However, this process can be extended through negotiation where agents will provide further information for others to update their model of knowledge and potentially change their decisions (Schmidt, 1991) (Gadmer et al., 2021).

III.5 Situation awareness

As highlighted in previous chapters, the main challenge with teleoperation is possibly the absence or deterioration of information. While technological advances may be able to overcome some of these obstacles in the future, there are cases where immediate solutions remain lacking or where technology may always be unable to address them. Chapter I has defined SA for the needs of a thesis as “the ability to gather information and understand the past and current state of the activity, the train's state, and its environment, then to use this information to anticipate the system or process behaviour”, using base definitions from

(Endsley, 1995), and mentioned how teleoperation negatively affects SA because of this information deterioration. In such scenarios, for this research project, the choice was made to investigate the potential of assistance systems to help mitigate this information deficit and help preserve or build Situation Awareness (SA) for the remote driver who was potentially out-of-the-loop. In terms of HMC, the challenge is to complement the remote driver's reduced KH regarding IG on the process through their KHC and that of assistance systems.

The nature of information that are most affected by teleoperation and that influence the activity the most are visual information, auditory information and kinaesthesia (Paglia and Richard, 2021). Additionally, other sensory channels, like olfactory information, also play a role in the driver's SA in a lesser extent, as mentioned in Chapter II

For trains that could potentially operate under GoA3, a train driver is only expected to be available to take-over control of vehicle when necessary and when requested by the system. The driver may not always be within the train cabin and is considered as only a "train attendant" in most GoA definitions, such as the early definitions from the TASV project (Rouzé, 2019). The "train attendant" in this definition is an agent within the train that is able to reach the cabin and operate the train when necessary. In this thesis research, the scope of GoA3 level has been extended so that a train could operate without a train driver or a "train attendant" on-board but may require assistance from a remote site, through teleoperation (see Chapter II). However, there are necessarily important differences between an on-board train attendant taking-over control of the train and a potential remote driver that was out-of-the-loop before the request. Indeed, being on-board means a potential train attendant may still be aware of the train's location, its itinerary, its dynamics, and potential incidents that could happen and can more easily access the cabin and assess the situation before taking-over control of the train. In a remote environment, the driver is expected to be assigned on the train only when the authority transfer process is engaged, that is, after the autonomous system issues a TOR or when the transfer is scheduled in the mission. In this first case, the remote driver has limited time to gather information on the train, its state, and the reasons behind the TOR.

A key objective of future assistance systems, that will be explored in the next chapter is thus to simplify the process of authority transfers in remote driving situations by providing operators with all the tools they need to build situation awareness quickly and effectively on the process, to be able to proceed to the authority transfer.

III.6 Conclusion

This chapter concludes the final theoretical investigation of the key themes in the subject: automation, remote driving and authority transfers. Each of these chapters has aimed to present a state of the art focused on these topics, completed by an analysis of the specific needs of the railway domain, while opening up on the perspectives and approaches that could be chosen to meet these needs. In particular, having presented the major constraints of the activity in this project, this chapter proposes and presents a tool to answer these needs.

First, the concepts of authority and transfer have been explored extensively to fully understanding the situation at the heart of the subject. Indeed, while remote driving and automation are broader contexts for study that needed to be properly presented, the scenarios that are investigated in this project are specifically the phases of transfer of control between the human operator, from a remote site, and the autonomous train. Authority is naturally connected to an agent's abilities, as one cannot possess authority without the necessary and related skill. However, authority is above all a form of “permission” granted to an agent to use these skills in the activity. To understand an agent's authority, and most importantly to relate it to that of other agents involved in the driving activity, a particularly appropriate approach has been chosen for this subject, Human Machine Cooperation. A framework for HMC in railways has been presented in this chapter, along with a description of all main agents: the remote driver, the train and its protection systems, and two Advanced Driver Assistance Systems, one being directly within the train and the other in the remote cabin with the driver. This framework has been used previously in the TC-Rail project (Masson et al., 2022), already mentioned in the previous chapter. However, the framework must still be adapted to fit the need of this project. The model developed for this study, in which a new agent, the autonomous train, will replace the train and the on-board assistance system, will be presented in the next chapter. This cooperation model displays the various interactions and exchanges between agents. These interactions will be at the heart of the study, presented in the rest of this document, focusing on exchanges between agents and the means of communication during a transfer of authority. In particular, a state diagram of the autonomous system presenting different driving modes will be presented in order to implement and test this transfer process.

An in-depth understanding of the environment and agents states and behaviour is required for the individual decision-making of agents. This chapter presents the authority

transfer process in different domains and suggests that it is negatively altered in situations of high autonomy. Indeed, taking the human operator out of the loop hinders their situation awareness, which is essential for the driving activity. This issue is greatly amplified in remote driving situations, where the user is faced with distance biases and, above all, has much less information about the activity in general. Building and maintaining situation awareness is therefore a major challenge, and one that is essential to overcome to consider the possibility of any transfer between a human and a technical operator. Therefore, the purpose of the next chapter will be to present possible solutions investigated in this study, in particular via the help interfaces on the remote driving desk, which will aim to support the user before, during and after the transfer.

Some of these ideas have been implemented and will be tested in two experimental campaigns, presented in Chapter V. The aim of these tests is to study the usability and utility of such interfaces, and to gather opinions from driving experts, which will be essential to maintain a feedback loop, necessary for these ideas to evolve into applicable solutions.

CHAPTER IV
COOPERATIVE INTERFACES:
DESIGNING HUMAN-MACHINE
ASSISTANCE SYSTEMS FOR A
REMOTE TRANSFER OF
AUTHORITY

IV.1 Introduction

Chapters I, II and III have outlined the main areas of this investigation, being automation, teleoperation, and authority transfers. For each area, the fundamental challenges have been presented, specifically for railways, and a human centred approach has been proposed to support the design of cooperative systems and interfaces. But how can this cooperative approach be used to address the previously mentioned barriers? How can informational losses associated with remote control be overcome? How to interact with an automated technical system? In what context is it necessary and desirable? How to assist the human operator for an authority transfer by helping in the development of situation awareness?

This chapter will suggest some initial answers which are the primary contribution of this research project. An application of the previously presented multi-agent cooperation model is proposed. It adapts its structure and principles to the project's needs to identify and study the links between agents in this activity, their roles, and their interactions. The two main agents, the train remote driver and the autonomous train, are able to control the process and are at the centre of the authority transfer process. Indeed, they are the agents that will trade authority when the driving mode changes. Understanding their interactions is a first step to understand how the authority transfer could unfold, from the initial transfer request to the transition of control. In particular, this chapter suggests a model of the decision-making process of the autonomous system during an authority transfer. Although simplified and not exhaustive, this will help a simulated environment that integrates this model. Then, as the aim of this research is also to propose cooperation interface solutions, primarily for the remote driver. This chapter thus suggests initial solutions that will serve as a basis for the upcoming experimental campaigns, to observe the transfer and gather user feedback. Of course, the nature of this relatively new project in the railway sector means that developing and testing more general interfaces initially is necessary before experimenting more specific and advanced solutions.

Before presenting these suggestions, it is however important to define the scope of this study. Indeed, one of the initial objectives at the beginning of this research project was to define use cases for remote driving takeovers. Not all possible situations of the train driving activity can be studied simultaneously, and it was necessary to establish a general context for authority transfers. Thus, the first part of this chapter will present different scenarios that will define the scope of this study and serve as a basis for the following experimentations.

IV.2 Scenarios for railway remote authority transfers

Being aware of the challenges and the state of research and technology for train teleoperation, the first step of this investigation was to define precise scenarios for the transfer of authority between the autonomous train and the remote operator. The objective is to frame the scope of the study and help define use cases for the systems and interfaces that have been implemented and studied or that will be suggested for the future. Since the objective is not to conceive a system to be industrialised, the scenarios presented in this part may not completely define a proper and complete use case, but should remain sufficient to frame the study. In this context, a “scenario” describes a potential situation where the system is used, with all its initial parameters. It is a more specific application of the system in a define use case.

Regarding train remote driving, Section II.3.1 and III.3 has given initial answers to the questions “why?” and “for whom?”. Assistance systems and interfaces have been suggested as potential support for a remote human driver when human expertise may still be required on an unmanned autonomous train. In this part, three scenarios were extracted and will be presented in more details. They have been chosen as potential cases where a remote authority transfer could be beneficial. As the systems studied are still prototypes and recommendations, the aim here is not to define exhaustive use cases, in the way that would be done when designing a complete system that is to be industrialised. However, in order to be as precise and comprehensible as possible, the elements used to describe each scenario are taken from recommendations for defining use cases in any industry domain. Use cases are defined in (Cockburn, 2001) as “a description of the possible sequences of interactions between the system under discussion and its external actors, related to a particular goal.”. This definition already provides the most important aspect of a use case: “actors” interact with a “system” to reach a particular goal. Thus, these elements appear as the most important to define to properly describe scenarios. (Cockburn, 2001), (Kulak and Guiney, 2000) and (Bittner and Spence, 2003) describe other elements of a use case, such as the description of the environment, initial circumstances or the success and failure conditions of an interaction.

In the following scenarios, some of these elements will be identical as they all remain within the bounds of the same objectives. These parameters will be described in the following part.

IV.2.1 Common parameters for all retained use cases

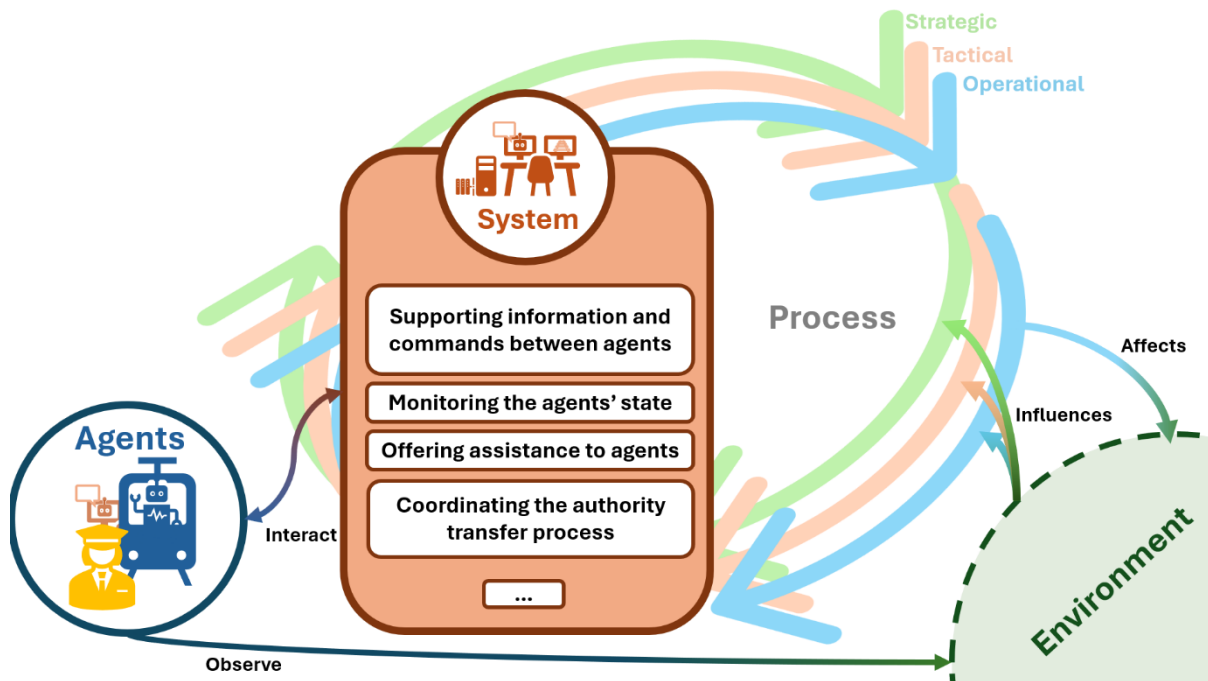


Figure 28 Main parameters for the definition of use cases: System and agents interactions in the process

Between each scenario, described in the following parts, the objectives, environment, and interactions may evolve. In any case, however, the agents and the overall interfaces and system remain the same. This section will provide a description of the “system” and agents for all three use cases described in the following parts. They are all represented in Figure 28.

- *Process*: The process corresponds to the various stages of the activity studied in the context of the use case, that is, while the studied system is used. The process can be observed under several levels of abstraction, i.e. strategic (defining objectives, long-term planning of the mission and the role of agents), tactical (carrying out the mission, evaluation and anticipation) and operational (sequence of actions in real time).

In the following scenarios, the process can refer to the train driving activity in general, including events following or leading to authority transfers and the transition of control itself. In Figure 28, both the agents and the system take part in the process to complete the mission, driving the train and its passengers to the destination or to safety.

- System: Among the main uses of use cases is the documentation and description of a system that is used to achieve specific objectives, often while the system is still under development. The purpose of a use case is therefore to present the interactions between a system, the item, entity or concept that is being created or studied, and external agents while figuring out its role, its behaviour, and its evolution during the process. This study focuses on the implementation of computerised technical systems and physical interfaces for train remote driving, but the framework of the study could theoretically be extended to wider systems that encompass technical subsystems and potentially human agents, as a service or company for example, depending on the needs and scope of the study.

The “system” in this context, refers to the “teleoperation system”, which is composed of the remote cabin’s interfaces and assistance (on the platform and from the remote cabin ADAS, as presented in part IV.3.1), but it may also integrate specific cooperation tools implemented on the autonomous train. It describes all the elements that are added to support the cooperation between agents, mainly the remote driver and the autonomous train, so they can fulfil their role in the process. To avoid confusion between the “studied system” in this general definition and other occurrences of the word system, such as the “autonomous system”, this document should always precise the context and will usually treat specific elements of the “teleoperation system” separately, as the physical interfaces, the virtual ones, assistance systems or the communication systems.

- Agents: Most definition models for a use case will include the definition of “external actors” that will use and interact with the system (Cockburn, 2001). In this framework, and to link it to the previously presented cooperation model, the term “agent” is used. Agents are the entities that can intervene on the process by interacting with the system. The main agents are those who have immediate Know-How (KH) regarding the control of the process to steer it towards a precise goal and Know-How-to-Cooperate (KHC) to interact with the system. Indeed, with this definition, the studied system can also be considered as an agent when it can directly interact with the process, and it can potentially extend to multiple agents. In this

framework for the definition of use cases, however, the system is separated from other agents in order to differentiate the technical part developed with the aim of helping the other agents in accomplishing the mission.

- *External environment*: The external environment refers to all elements and conditions external to individual agents. Naturally, the actions of agents can affect the external environment and the external environment can influence the process. However, the environment does not willingly or directly act on the process and do not share the goals of the activity. In the following scenarios, with the exception of the initial conditions which may vary, the influence of the environment on the process be minimised, with little external obstacles, such as difficult topography or the presence of a level crossing, as the aim is not to study the activity itself. The train's position on the line, signalling and the state of the infrastructure are among the information that can be perceived from the environment, often visually.

The three scenarios retained for this study will now be presented. These scenarios were developed for this investigation on the basis of the needs identified in the bibliography and the activity analyses for train teleoperation presented previously. They will be used during an experimental campaign (Chapter V) which will also help to refine these needs and the constraints specific to them.

IV.2.2 Scenario 1: Taking-over an autonomous train after a technical failure

In this scenario, the train starts its mission autonomously until it is forced into an emergency stop following a failure in its information analysis systems (obstacle detection, sign detections, etc.). A driver is then dispatched to take-over the control of the train from a remote driving station. The remote driver's objective is to route the train to the next station and place the train in security while freeing the track so potential passengers can be evacuated and the train can be taken over, by an on-board agent, to deal with the initial incident.

In this scenario, it is assumed that the train runs in a GoA3 mode without a driver on board, according to the extended definitions suggested in II.3.2. The exact type of the fault requires that teleoperation to be unaffected to allow remote recovery. In practice, it is not yet evident which cases could, safely, allow such a recovery. In some cases, it may be questionable whether it really is possible to determine, from a distance, if the train is able to run after an

incident or malfunction. It is likely that, in the absence of advanced monitoring systems, current and future safety standards will not allow for a remote recovery without prior human expertise. This would imply direct intervention and would reduce the value of teleoperation in this case. Nevertheless, this scenario assumes that such a case is possible. Figure 29 below illustrates this first scenario.

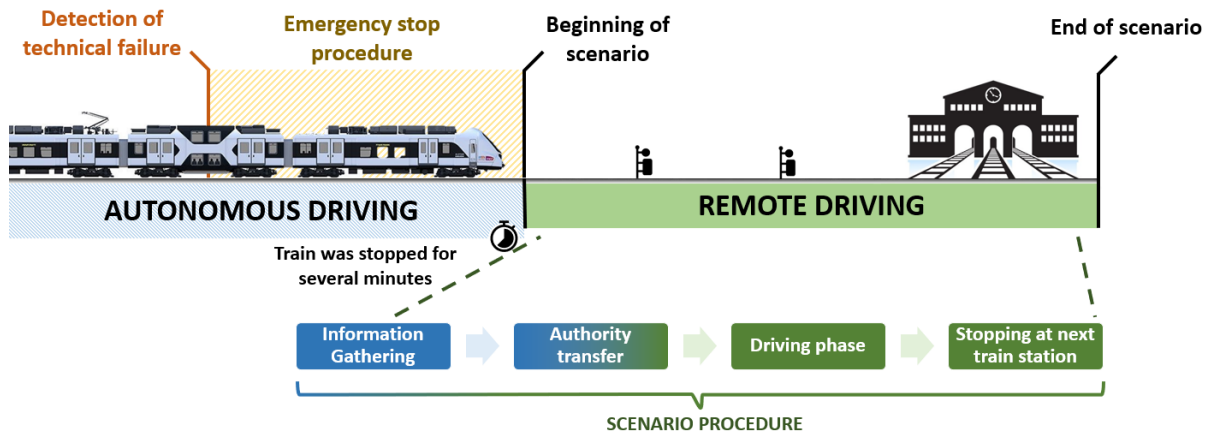


Figure 29 Scenario 1: Taking-over an autonomous train after a technical failure

As mentioned in Section III.4, constructing sufficient Situation Awareness (SA) for the remote driver is necessary to perform the driving activity. In this scenario and because of the unpredictable nature of the incident, the remote driver has no information about the train's position, its mission or the reasons why it is stopped prior to being dispatched. The remote driver's first tasks will therefore be to obtain this information as soon as their mission begins. The interfaces on the remote driving cabin as well as assistance systems must provide all the necessary data and help complete the mission and carry out the transfer of authority. In addition, the takeover is also intended to unfold relatively quickly, to secure the train and passengers. The appropriate time for the transfer has yet to be determined, but the objective is to be significantly faster than a direct intervention on the train, justifying the remote recovery.

IV.2.3 Scenario 2: Routing a moving train outside an unauthorised area for the autonomous driving mode

In the first scenario, the remote driver begins the activity with limited knowledge of the mission, the train or the potential incident that led to the Take-Over Request (TOR). In this second scenario, the train does not stop unexpectedly during the activity. Here, the objective of

the mission is to drive the train manually in an area where the train cannot run in autonomous mode. This implies that the remote driver can be given information about the mission or the train in advance, and that building appropriate SA in time should be easier.

It is still unclear whether such situation will exist in the future, where an autonomous train must traverse a known non-automated area. If this is possible, several elements could lead to this scenario:

- Not all lines where the autonomous train could be deployed may initially be equipped with the necessary infrastructure elements (trackside signalling, network, etc.) for the deployment of the autonomous train. Some specificities, due to the complexity of the area, might not allow autonomous systems to perform the driving activity. Similarly, these systems may exist on the line but be temporarily unavailable, making it impossible for autonomous trains to operate.
- A portion of the line may temporarily become unusable by the autonomous train because of, for example, weather conditions, the presence of construction or repair workers on the line, or previously identified elements near the line that could interfere with the train's perception systems.

This second scenario is illustrated in Figure 30. Another difference with the first scenario is that it ends with the autonomous system resuming driving when the train leaves the

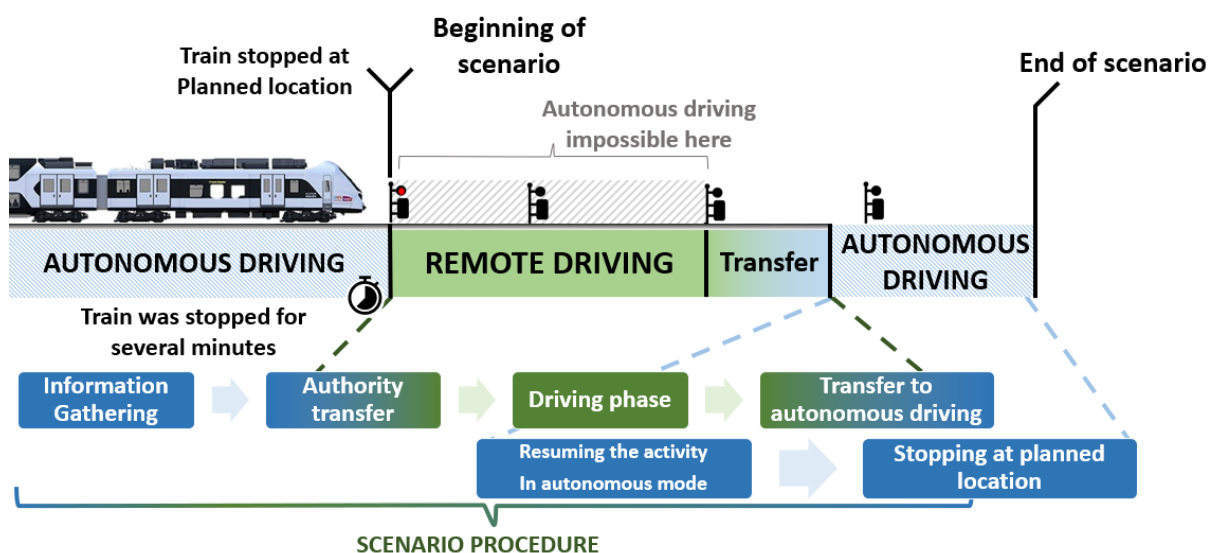


Figure 30 Scenario 2: Routing a moving train outside an unauthorised area for the autonomous driving mode

section of the line not authorised for autonomous driving. Although this is technically as simple as switching on the autonomous mode when the transfer is accepted (see Section IV.3.1), the remote driver must ensure and confirm that the autonomous train has regained full control of the train and that their presence is no longer required. Finally, in this scenario, the transition towards automated driving at the end occurs while the train is still in motion, in manual control. The objective is to observe the reverse transition, a shift from manual to automated driving, and explore how the train can progressively regain control of the driving activity while ensuring a seamless and safe transition. Further analyses on driving behaviour and safety/security in a similar context to this transition will determine whether it is desirable to carry out the transfer while the train is moving, rather than when it is stationary.

IV.2.4 Scenario 3: Taking-over an autonomous train while it is running

The remaining type of transfer that can be studied is the transition from autonomous train driving to remote control while the train is running. As for the previous scenario, a transition while the train is in motion can be relevant, especially to increase availability, but it implies multiple difficulties and the possibility of such an application, in relation to the various safety constraints, is still to be determined. In this case, the remote driver must gather information in a limited time because they must be ready to take control of the train as soon as the transfer of authority is necessary. It is therefore necessary to be able to anticipate the takeover well in advance. Therefore, the use case for this scenario seems to exclude any situation following an incident for which it is essential to secure the train before human intervention. Several situations that could potentially benefit from this scenario have been identified, among which are the following:

- Certain complications on the line can negatively affect the abilities or safety of the autonomous train (weather, repair works, etc.);
- A (potentially autonomous) train that has previously crossed the same line or a nearby line has detected an unidentified element in the vicinity of the tracks, or a potential risk for the train or the infrastructure.

In both cases, additional human expertise for monitoring tasks may be sufficient to ensure the safety of the train without interrupting the mission (transfer from GoA3 to GoA2 with the remote driver). Again, estimating the time required to assign a remote driver and for them to become ready for the transfer is still challenging. Consequently, the relevance of these

scenarios remains hypothetical and further examination of the activity might identify more appropriate use cases or, conversely, question the relevance of this method for transferring authority.

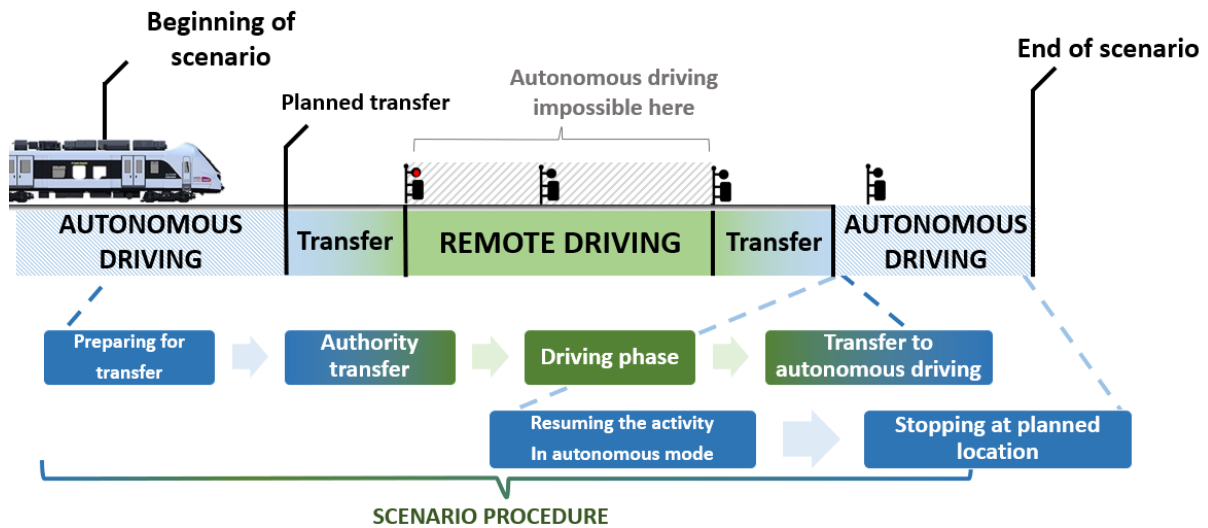


Figure 31 Scenario 3: Taking-over an autonomous train while it is running

As for scenario 2, the remote driver must have access to as much information as possible to perform the driving activity before taking control of the train. In order to facilitate the transfer on the run, the remote driver could be given the opportunity to connect to the train in advance to gain knowledge of the environment. Further assistance to facilitate this step are given in Section IV.5.1.

IV.3 Cooperation principles for a transfer of authority

This section will present the application of Human-Machine Cooperation (HMC) principles that have been introduced in III.3 in this project for remote transfers of authority of autonomous trains.

IV.3.1 Multi-agents structure for train remote driving

In the previous chapter, a framework for HMC in the context of train remote driving featuring four main agents: the human operator (the remote driver), the train and its protection systems, the “on-board Advanced Driver Assistance System (ADAS)” and the remote “in-cabin ADAS”. Their role in the process is detailed in Part III.3. The same architecture has been

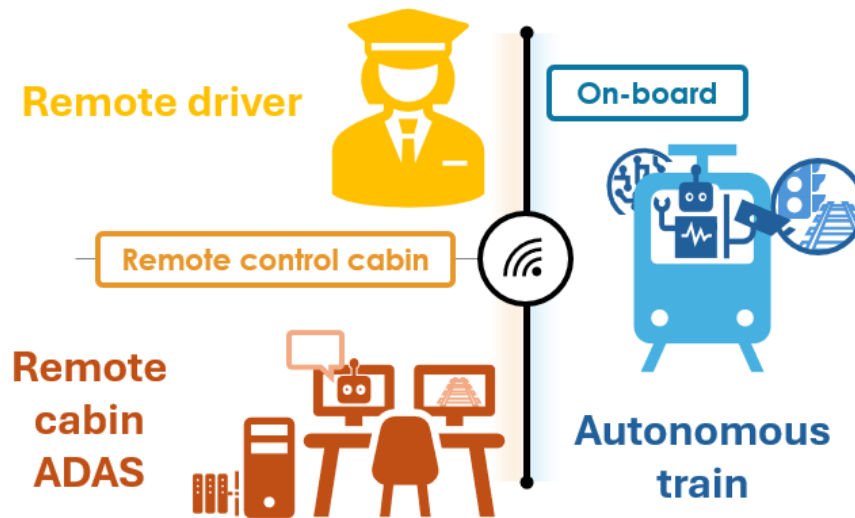


Figure 32 Three agents in updated cooperation for train remote control

kept in this project, with the exception that the train and the on-board ADAS are grouped together as a single agent. Indeed, the “autonomous train” is now not only equipped with protection systems but it is also in charge of all tasks which could have been attributed to the on-board ADAS. The three remaining agents are presented in Figure 32. Thus, the autonomous train can now be considered as a single agent that takes on the role of the train protection systems and the previous “on-board ADAS”. Of course, combining all the sub-systems that compose the autonomous train is a major simplification that does not portray its inner complexity. Similarly, in this framework, the autonomous system is expected to both participate as a single train operator in high automation levels, but also as a cooperative agent in situations of remote control. However, the sensors or information analysis and decision-making systems may be different between the autonomous system and the one implemented for teleoperation. Both could potentially exist simultaneously and work together or independently. For example, the train could be equipped with a specific set of cameras optimised for computerised image analyses, along with cameras aiming to provide the best visual representation of the environment to a human operator. In practice, it is not yet possible to predict what the complete teleoperation system will look like in the future, and it is simpler to consider the on-board autonomous system as a single agent, potentially simplifying its inner interactions. Consequently, each subsequent mention of the ADAS will refer to the “remote cabin ADAS”, the only ADAS agent in the application of the HMC as part of this thesis.

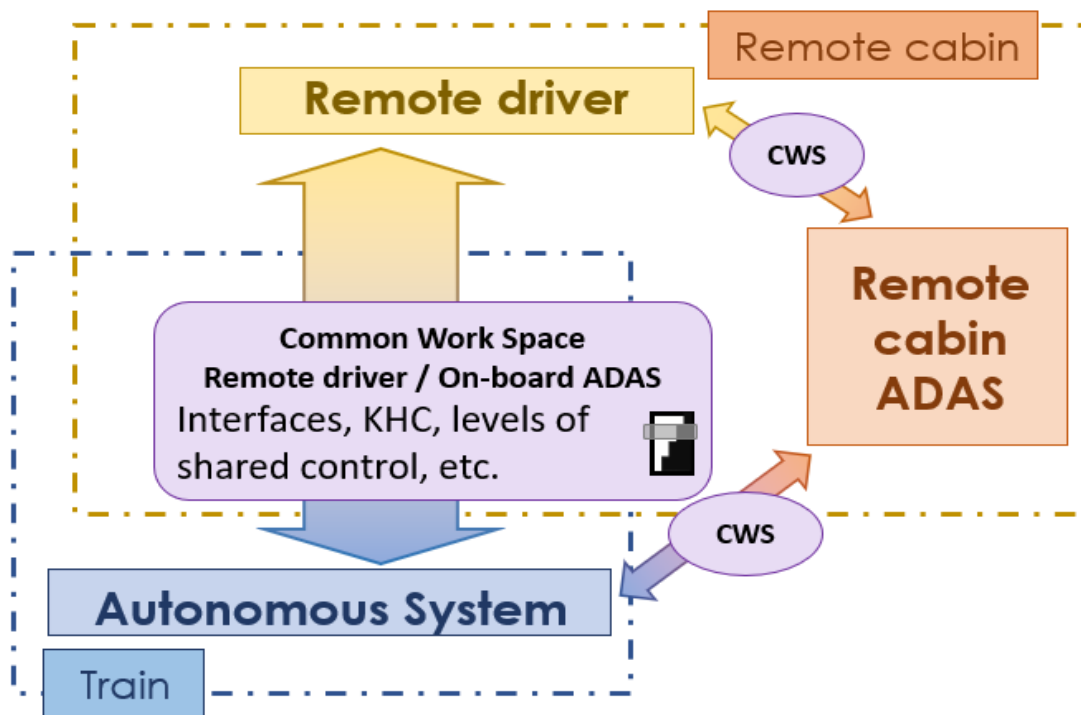


Figure 33 Multi-Agent HMC framework applied to the project

Figure 33 displays a simplified view of the cooperation model presented in Part III.3 which has been adapted to include only the three agents mentioned above. The three agents are featured and placed within larger areas, limited by dotted lines which represent the location where these are present, within the train and the remote cabin. Between each of them, an arrow illustrates all interactions. They are simplified versions that encompass the many exchanges depicted in the larger representations of the model, along with the breakdown of their Know-How (KH), Know-How-to-Cooperate (KHC) and authority. To be in line with the previous definition and uses of the HMC framework, in the figure, the agents are connected via their Common Work Space (CWS) (Pacaux-Lemoine and Debernard, 2000; Millot and Pacaux-Lemoine, 2013), the support of cooperation between them. The CWS was only briefly introduced in the previous chapter as a "common language" between agents, spoken through the various interfaces and communication network. Its role is to be an external support to the Common Frame Of Reference (COFOR) (Pacaux-Lemoine and Loiselet, 2002), a common presentation of the process and agents' state. This helps agents maintain a shared situation awareness on the situation and can extend to allow each of them to inform others on their activity, internal understanding of the process or communicate their diagnoses and orders to other agents. An in-depth understanding of this inner individual and shared representation, especially regarding

the “mental state” of the human operator, will not be necessary at this stage of the research process. In this model, the CWS is used to represent the means of communication between the agents to share their knowledge, resolve conflicts and assign authority without delving into more complex interpretations of how this knowledge participates in creating a “team situation awareness”.

Each pair of agent has specific and possibly unique ways of communicating together, and they require a unique set of common knowledge. As such, the CWS is unique for each pair of agent: the Human operator / Autonomous train, the Human operator / ADAS, and the Autonomous train / ADAS. In most cases, however, communications involving the human operators will be performed through the train remote control platform, including the visual interfaces to display information, and the train controls. Additionally, as the protocols and systems for communicating with the autonomous train are not the subject of this study, the remote driving platform can be considered as the support for this communication, acting as a direct interface between the train and other agents. Thus, in this section, studying CWS involves identifying what information must be shared between agents and the format in which it is transmitted via the remote driving platform. In fact, these are the main elements that will be developed in the following sections. Indeed, while understanding the KH of each agent helped to understand their inner abilities and role in the process, these are more related to the knowledge of the activity and the experience of the driver or the implementation of technical systems. According to the assumption made for the thesis in previous chapters, the autonomous train is assumed to exist, at least for the use cases presented in part IV.2. Similarly, it is assumed that the train remote driver profession has already been defined and that the technologies are functional.

In the rest of this document, the study of the CWS and KHC is implicit and they will not, or barely, be mentioned. The following sections will instead describe the main interactions between agents around transfers of authority, detailing the links described by the framework in Figure 33 and Chapter III with a more practical approach to design interfaces. Besides, as the links between the ADAS and the autonomous train are purely technical, and have functional or safety purposes, such as monitoring the operating status of the system or its ability to communicate, they will not be developed in this human-centred study. Thus, the point of view will only focus the human operator’s interactions with the other agents.

IV.3.2 Breaking down interactions during the authority transfer process

A transfer of authority is characterised by a change in the driving mode and role of each agent. Initiating this transfer is done via the CWS by issuing a Take-Over Request (TOR) and the reasons for initiating such a transfer are specific to the activity, mission, and decisions of the agents, which are dependent on their ability to allocate tasks through their KHC. The overall transfer process thus starts when an agent starts preparing for an upcoming transfer or, if unexpected, decides a TOR is necessary. The TOR is then issued and analysed by other agents until they can also make a decision regarding the transfer. This process is achieved through the agents' KHC, involving their ability to communicate and manage “interferences” together. In the following part it will be described as the TOR management phase. Depending on the global decision, the driving activity will either resume normally if the transfer is not accepted, or the driving mode and authority of agents will change. In critical situations, a failure to take the appropriate decision in time might also result in an emergency procedure. When the authority of each agent has changed and the activity has successfully resumed in the new driving mode, the transfer will be complete. The following sections detail these different phases and the interactions in each of them.

Understanding the authority transfer process

To illustrate the transfer process, the third scenario presented in Section IV.2 will be used. In this scenario, the remote driver takes over the control of the train while it is still moving, making it the broadest application. For transfers from manual to autonomous driving, or in cases where the train is stopped before the transition of control, the same definitions should mostly apply, with probably less time constraints.

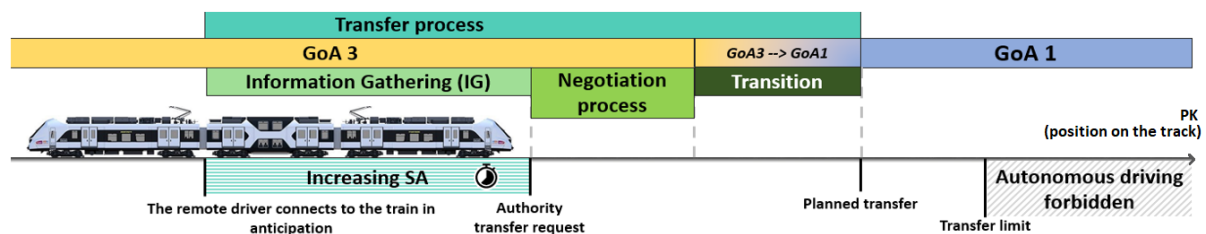


Figure 34 Breakdown of a transfer process for a train going from GoA3 to GoA1

To take-over the moving train, the transfer of authority must be expected in the mission, as safety measures would otherwise require an emergency stop in the event of unexpected incidents. Specific hypotheses as to the reasons justifying such a transfer are

proposed in Section IV.2. A certain amount of time before the transfer becomes necessary, a train remote driver can connect to the train, through the remote driving platform, and prepare for the transition by gathering information on the mission and the train before the TOR is issued by either agent. In Figure 34, this is represented in the “Information Gathering” part of the timeline, during which the remote driver is increasing their SA.

The overall transfer process is represented in Figure 34 and is divided into three steps: Information Gathering (IG), Negotiation and Transition. The duration of the process and each of its steps is hard to estimate as it depends on multiple factors including profession specific rules and the train’s speed. In this case, the process is presented in relation to the train's course on the line, disregarding potential time constraints. In Figure 34, the position of the train is tracked on the “PK” line. PK, or “Point Kilométrique” in French, are milestones measured in kilometres that are used in France to indicate the position on the line. Assuming the train is moving during the whole process, Figure 34 presents two important milestones for the transfer, that are associated with successive positions on the line: where the transfer is planned in the mission (“planned transfer”) and the “transfer limit”. The former is the position on the line from which the driving mode is expected to have changed. The transfer limit, however, is the last point on the line, or PK, where the train can circulate in the original driving mode. If the transfer has not been successful past the transfer limit, an emergency procedure is expected. The distance between the two milestones may vary depending on the situation. In the case of the other scenarios, if the autonomous train was initially stopped, all steps of the transfer would happen at the same location, in their limited time frame.

When the process begins, the train remote driver connects to the train, which is located at an earlier position (PK) on the line than the transfer limit, offering expectedly enough time to gather information and build Situation Awareness (SA) when ready, the driver can issue a manual TOR or accept the request from another agent, so the transition of control can happen as the train reaches the planned transfer milestone, and before it crosses the limit. Following the TOR, the transfer enters the “Negotiation process” phase, where each agent reacts to the TOR and make decisions accordingly (see part 0). Finally, the transition of control happens during a progressive transfer (see part 0).

Information gathering and analysis regarding the authority transfer

The first phase is arguably the most important during the process and will differ depending on whether the train is moving or not during the transfer. In the first case, which is probably closer to what could be the overall process in the future for a remote recovery, the train stops before issuing a TOR. A remote operator is available for the take-over and is assigned the mission, but was not part of the activity before and has therefore no prior SA. This first step is thus crucial as the remote driver now has a limited time, that remains to be defined, to understand everything necessary to take part in the activity. The extent of “everything necessary” depends on multiple factors but the following can undoubtedly be cited: the type of train that must be taken-over, the current location of the train and its itinerary, the reason a transfer is necessary and whether an incident occurred, the presence of passengers, the objective of the recovery, and of course the time allotted to this mission. Hypothetically, most of this information will be provided to the operator before even connecting to the train as they are assigned with the recovery task and the role of interfaces will not necessarily be to provide them. Some of them, however, can still be made available on the remote driving platform, which may display real-time information on the train and its passengers. Thus, when the driver connects to the train, they should already have some information on the general situation, but they may be missing crucial information about the past and what happened before the TOR, as well as lacking immersion and a sense of presence in the activity.

When taking-over a train that is moving, the driver may be aware of the upcoming TOR sufficiently long before a transition becomes necessary, or they may already be part of the activity, doing monitoring tasks on a remote GoA2 driving mode, for example. In both cases, as the physical interface to the CWS, the platform should be used by all agents to communicate on their current state and availability. Thus, the remote driver should be able, when possible, to use the virtual interfaces to determine whether a transfer of authority is possible under the conditions specified in the mission. Based on this information, the following lists present the information that must, hypothetically, be provided by the train and ADAS to help build SA. The aim of the project in the phase is therefore to increase, via the interfaces, the capacities and KHC of the agents to provide and obtain this information, and then to test their importance, relevance and completeness from user experiments. This list is certainly not exhaustive and contains only elements that should help the operator to build SA into the process

in preparation for an authority transfer. Information that is crucial for the control part of the activity may be omitted.

Information that must be communicated by the autonomous train:

- Position on the line;
- Current status of the autonomous system;
- Dynamic state of the train (speed, acceleration, etc.);
- Technical failures;
- Integrity of the rolling stock and infrastructure;
- Current driving mode, including transitions;
- Train view.

In this model, the autonomous train uses the CWS to communicate on its own state. The remote cabin ADAS is expected to complement this information with the following:

- Mission details and itinerary;
- Current status of the remote driving system;
- State of the communication network (connectivity, latency, etc.);
- Details and explanations for TOR;
- Assistance to anticipate and prepare for upcoming authority transfers;
- Current state of the remote driving platform.

More detailed suggestions for formalisms and interfaces for communicating this information are explored in section IV.5. Having acquired enough information on the process, the remote driver is now able to issue or respond to a TOR. Naturally, at the end of this information gathering phase, the human operator is not necessarily the agent making the transfer request. First, when the train has stopped, due to a technical failure for example, and the remote driver is tasked with the recovery of the train, a TOR from the system is already implied or explicitly issued even before the operator enters the activity. When the train is moving and when the moment is appropriate, the remote cabin ADAS, with information on the mission, may suggest the TOR itself. Similarly, the autonomous train itself could issue the TOR if it has sufficient knowledge on the mission and the limits of its authority. From this point onwards, the transfer process enters a second phase named in Figure 34 the “negotiation process”.

Interferences between agents in the process: Management of conflicts and negotiations

When all agents have either issued a transfer request or are able to make decisions about a transfer, having acquired sufficient SA, the transfer process enters a second phase in which agents react to the TOR. In in Figure 34, it is presented as a “negotiation process” which is rather reductive as this step does not necessarily imply “negotiations” between agents. Indeed, this TOR management phase uses the KHC capabilities of the agents to understand and analyse the requests from other agents, and then react to these decisions.

The initial analysis can result in two main outcomes. The first and simplest outcome is that all agents accept the take-over and the transfer can thus happen. If, however, any agent refuses the request or fails to communicate their decision, the process can become more difficult as multiple factors could influence how the process unfolds, notably how the decision making authority is shared among agents. In most cases, an agent will have “final authority” on decisions and may be able to impose their decisions to others. Currently, due to the technical limitations of computer systems and safety requirements, the human operator in a Human-Machine cooperative activity has final authority and the system must follow their decisions and input except perhaps during emergency protocols. This is the main philosophy for assistance in aircrafts (Orlady et al., 2017) but (Muir, 2016) points out that this could also lead to serious errors, especially when the operator is not “in-the-loop” with a high enough SA. The evolution of the train remote driving activity is still uncertain, but it is reasonable to assume that in most situations, the remote driver will have the decisive authority to refuse a TOR and terminate the process, or to impose the transfer even if it had been refused by another agent. (Rothfuß, 2022) points out the benefits of sharing the same decision-making authority between agents, prompting negotiations in case of conflicts. The driver, autonomous train and ADAS all have a unique perspective on the process, because of their specific roles and the way they comprehend it. Each of them has an internal model of rules and knowledge they used to make their decisions. When they conflict with those of other agents, each agent that is able to do so can attempt to argument in favour of their decision by providing additional elements so other agents can update and complete their SA in order to find a common ground (Klein et al., 2004). This is done through CWS, using interfaces to provide more insights into one’s decisions, arguments, etc. It is currently rather difficult for a human operator to communicate specific and complex ideas to a computer, especially within a limited time frame. Thus, the remote driver

will usually only be able to choose from a limited set of instruction, while the technical agents can more easily communicate their knowledge and analyses.

When a decision has been made among all agents, the process will either resume in the current driving mode or the actual transition of control will begin. With regard to the objectives of this investigation, the first case can be seen as a transfer failure. This may be temporary, the system refusing a running transfer in a delicate situation, or due to a technical fault, but the exact consequences will not be explored and studied here. The next part will present how the transition phase is expected to happen.

Transfer completion: Progressive transition of control

In this final phase of the transfer process, when the driving mode changes, the role of each agent evolves, their authority changes but so does their responsibility (III.2.2) and it is important to understand when exactly that happens. To properly transition between modes, it is therefore necessary to explore in more detail the safety issues during and after the transfer, as well as the potential liability issues in the event of a problem. These issues are necessary and must be addressed for the future deployment of train teleoperation and autonomous driving, alongside the implementation of the necessary technologies and the security of the autonomous train against attacks and cyber-attacks. While this project does not aim to explore these problematics, it is important to imagine the general course of this transition phase. Indeed, as the finality of the transfer process, this step is crucial to understand for the agents in the process.

This section will present two hypothetical ways the transition phase could unfold. Only one will be chosen for the rest of the investigation, and for the experiments presented in Chapter V, the other could be an interesting approach for the future development of more detailed assistance systems and shared driving modes. For the remote driver, the question that emerges in relation to this phase is the following: "How does the system switches from one driving mode to another?". More specifically, how does the system switches from an automation level to another? Does the transition happen instantly? Are there intermediary steps where the authority has not been switched yet, especially for transitions between high autonomy (GoA3) to manual driving (GoA1) or the other way round? Of course, these questions seem to be more relevant for a transfer while the train is still moving. Indeed, when the train has stopped and the initial problematics of the first phases have been answered, the transfer is relatively

transparent to the user and is akin to simply starting the train up in a “regular” teleoperated activity.

The first transition method is simply to switch directly from the initial driving mode to the final driving mode. Because of the difficulties of remote control, including latency, this transition may not be instantaneous as there may be transmission and processing times. Remote interfaces must ensure that the driver is fully aware of the transition and assist them to estimate

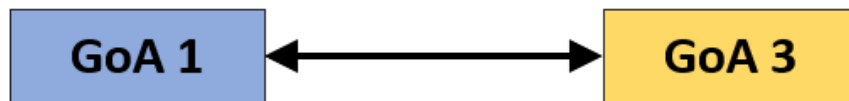


Figure 35 Immediate change of driving modes after transition between GoA1 and GoA3

when the driving mode has effectively changed, and therefore their level of authority and responsibility have changed.

Figure 35 above presents this transition between two driving modes, GoA1 and GoA3, which are the two modes chosen in the in the project’s scenarios. Of course, the framework should also allow transitions between other driving modes, such as GoA2 with GoA1 and GoA3, as shown in Figure 36. While only the transitions between GoA1 and GoA3 are explored in this project (Figure 35 and Figure 37), further investigations on more or different modes should study all pairs of driving mode transfers separately as the difference of authority change is unique for each kind of transfer. In this approach, the authority of an agent is always exactly as defined by the current driving mode.

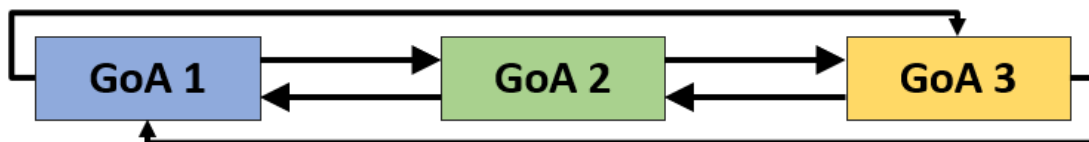


Figure 36 Immediate change of driving modes after transition between multiple drive

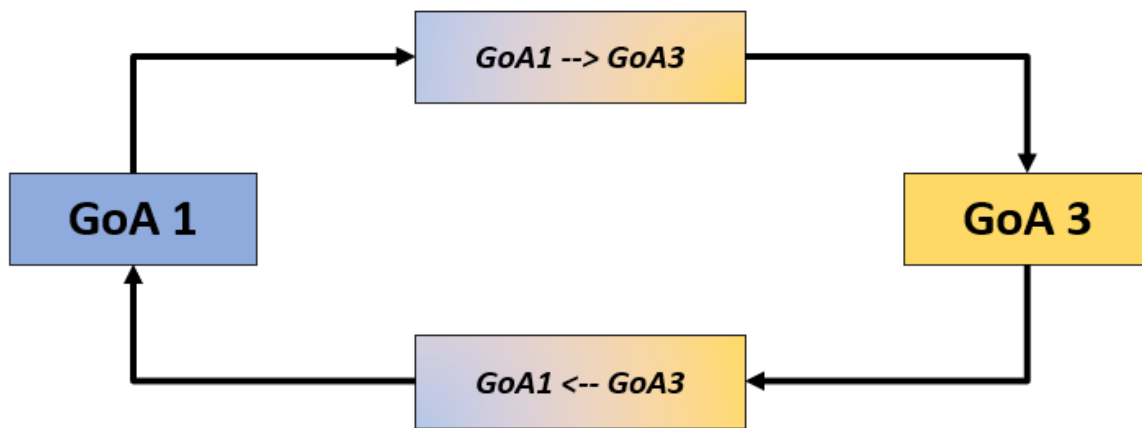


Figure 37 Progressive transfer of authority between two driving modes: GoA1 and GoA3

In the second approach, the transfer between one mode to another would be done through an intermediary transition level, where the authority of agents could be progressively changed to match that of the destination automation level. For example, before switching from GoA3 (autonomous with occasional human assistance required) to GoA1 level (manual with automatic train protection), the authority of the monitoring tasks could be shared by the train and remote driver before being progressively given to the driver. Similarly, the driver could progressively receive authority regarding the control of the train, perhaps sharing the driving activity with the autonomous train for a certain time. Each transition having specific authority levels before and after the transfer, these intermediary transition modes would be unique to each of them. Figure 37 and Figure 38 present this process for transitions between two and more automation levels.

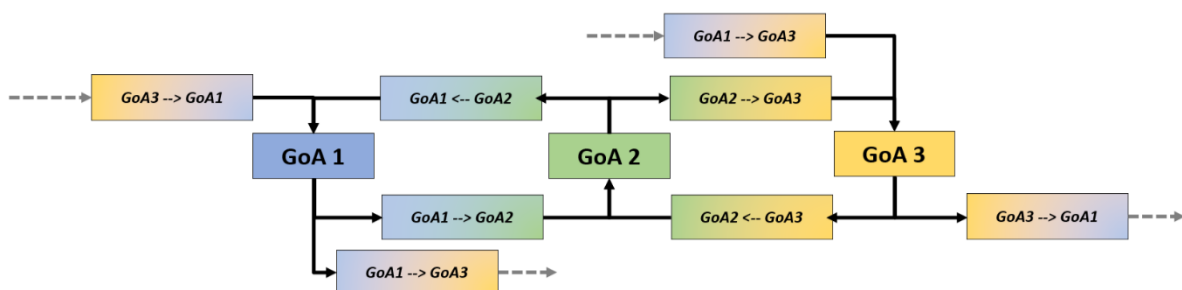


Figure 38 Progressive transfer of authority between multiple driving modes

In this hypothetical intermediary mode, the authority for all tasks of the activity could be fluctuating between agents, becoming quite hard to evaluate at any time. Thus, determining

who is in control during the transition, and who is responsible for each task can be complicated. In this project, the decision was made to retain the first, simpler approach. First, it seems difficult to imagine that future railway standards and safety requirements would adopt dozens of new intermediary driving modes, specific to each type of transition and dependent, perhaps, on the very context of these transitions. Moreover, it is also crucial for the driver to be able to understand precisely the levels of control and authority of all agents during the activity. It therefore seems important to limit as far as possible the driving modes in which these levels change. Although train drivers are not necessarily aware of the concept of Grade of Automation (GoA1, GoA3, etc.), it is very easy to understand the differences between manual and autonomous modes, and therefore the authorities and responsibilities associated with them. Adding potentially numerous intermediate modes could make this understanding more difficult and lead to certain modes being confused, potentially leading to errors. Nevertheless, since most vehicles today have a limited number of driving modes, or even only one, more studies are necessary to affirm that increasing the amount of driving modes, through progressive transition modes, can be a source of human error.

Having defined the transition process in the context of the study scenarios, particularly from the point of view of the remote driver, it is now time to describe how the system operates during these transfers. In the next section, the internal model of the autonomous system during a transfer of authority will be presented, enabling its implementation to test interactions with a human operator.

IV.4 Modelling the system's behaviour during a transfer of authority: An automation point of view

IV.4.1 Architecture for the autonomous train's different driving modes

Throughout this document, there have been several mentions of the user's need to effectively communicate with other agents and comprehend their analyses and decisions, especially with the autonomous system. The primary objective of this project is largely centred on examining and proposing interfaces to facilitate these communications among agents during the authority transfer. Thus, while the study is primarily human-centred, this breakdown of the system and its internal states is crucial for its implementation and that of the associated interfaces.

This section does not intend to provide a description of the technical autonomous train control system, the algorithms enabling autonomous driving, environmental analyses, or other functions of the activity. These objectives are among the aims of broader projects related to autonomous train, including the TASV project. However, it is important to propose a potential approach to the decision-making process during the authority transfer phase, at least to be able to implement it later. This approach is represented in Figure 39 in a form of a simplified state chart, illustrating the various states of the system during transfers between GoA1 and GoA3 modes. This framework primarily serves as an illustrative model for cooperation and will be the foundation of the following experiments (see Chapter V). It should, however, prove to be a simple enough breakdown of the transfer process, as implemented in the autonomous system, for the purpose of this study.

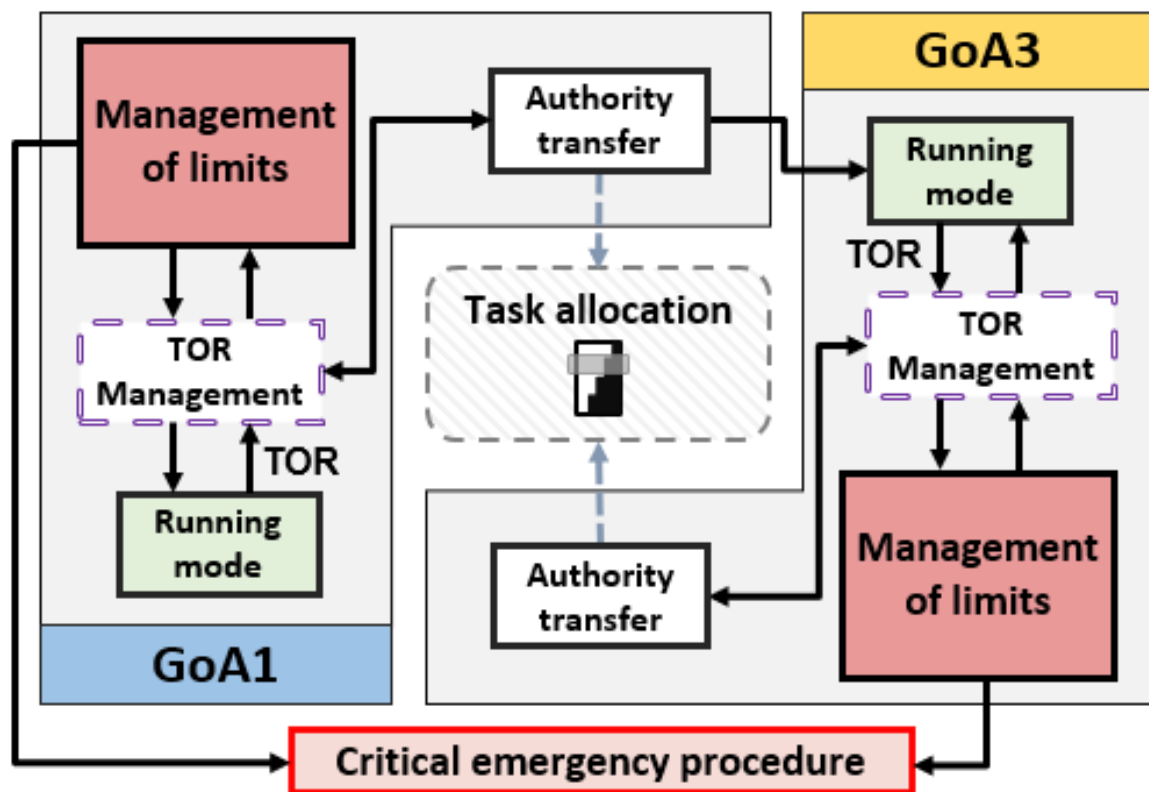


Figure 39 Simplified model of the autonomous system's state diagram with transitions between GoA1 and GoA3 driving modes

In Figure 39, the system can initially be in three main states: “GoA1” for manual driving, “GoA3” for autonomous driving and a “critical emergency” state for critical procedures that are outside the scope of the aforementioned scenarios. Each of these states

encompasses several sub-states which will be briefly explained. Specifically, for GoA1 and GoA3 modes, the system would start within a sub-state named "running mode" which corresponds to the nominal driving mode. In the context of the scenarios, these correspond to the driving or waiting phases outside the transfer process, prior to the first TOR. The different substate are connected to others through specific transitions that correspond to the result of the actions taken in these steps. Apart from the initial TOR, that can be issued by any agent, they are not explicated in this model, but the progression of the process is relatively implicit and follows what has been presented in part IV.3.1. Following the TOR, the system enters a “TOR Management” phase that is represented in more details in Figure 40.

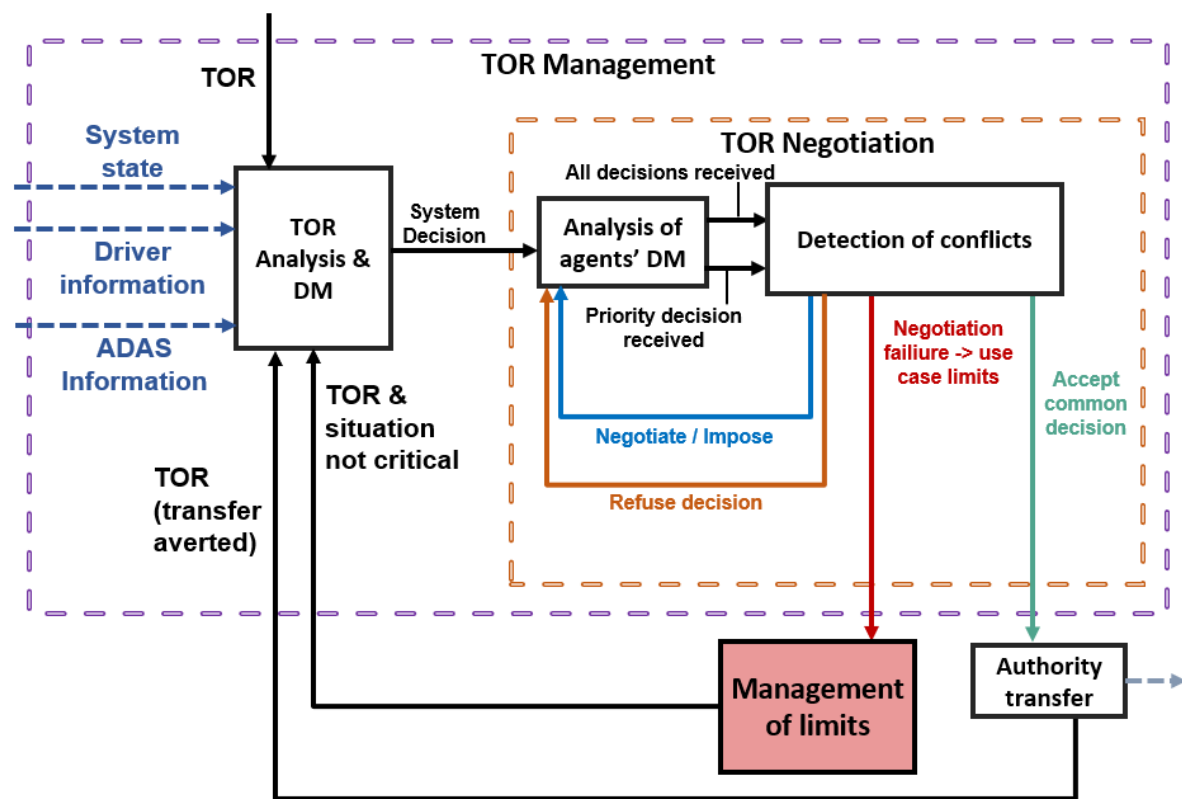


Figure 40 Detailed diagram of the TOR Management state

During each or most steps of the transfer process, the system must be able to communicate about its current state, its analyses and its decisions during the negotiation phase and the interfaces on the remote cabin, usually virtual ones through on-screen information, will display these communications for the remote driver. In this framework, when the transfer negotiations fail, maybe because of a lack of common agreement or the decision was too late in the process, the system enters a “management of limits” phase. The functioning of this stage remains hypothetical and simplified here but the objective is for the system to determine

whether the transfer process can resume until it transitions to the appropriate driving mode or if an emergency protocol must be engaged, usually meaning an emergency stop of the train, if not yet stationary, and a completely different recovery process that is not explored in this study. According to the decision mentioned in part 0, the system remains within a certain top-level state until the last phase of the transfer process, the actual “authority transfer”.

IV.4.2 Example of a transfer process with the respective system’s transitions

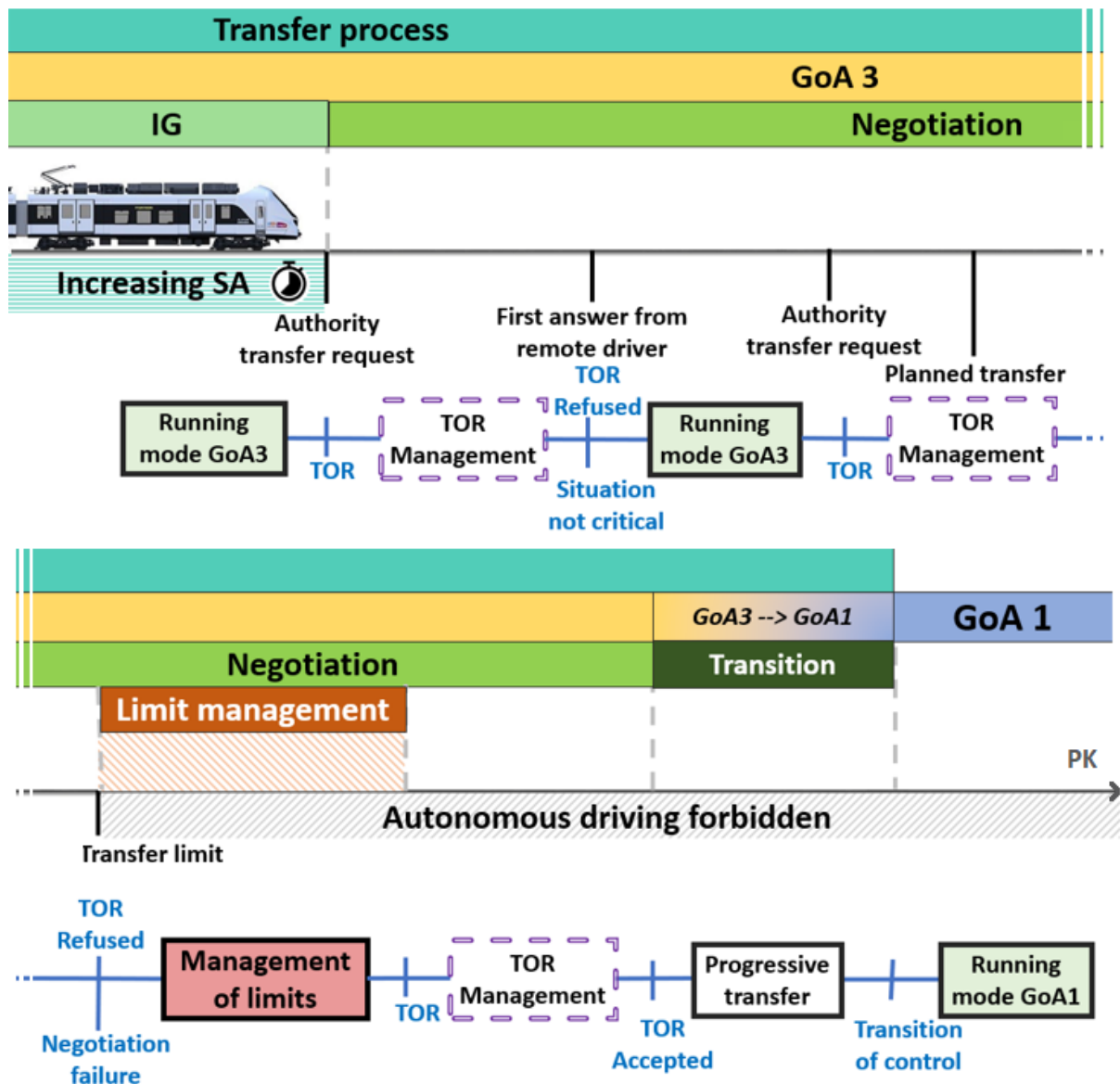


Figure 41 Breakdown of a complex transfer process for a train going from GoA3 to GoA1 with negotiation failures and the corresponding autonomous system’s states

Figure 34 of part IV.3.2 has presented the transfer process and its different stages. In Figure 41, this process is described along with the associated states of the autonomous system according to the previous model. This transfer illustrates the third scenario proposed in part IV.2.4 with a transfer to manual while the train is moving. Again, Figure 41 will present a transfer from an autonomous GoA3 level to a GoA1 level. The reverse transfer would function similarly, with the exception that the initial and final authorities, as well as interactions with the human operator, would differ. In this example, the process is voluntarily relatively more complicated as the transfer will not be immediately accepted by agents to illustrate the negotiation process. For example, when the first TOR is sent by the autonomous system, the remote driver may not be available as they may need further information because of an improper SA. The first negotiation resolves with a refusal of the TOR from the driver and the system continues to operate on a GoA3 level. It must however still transfer as it approaches the transfer limit after which it cannot operate autonomously and the train would stop. A second phase of negotiation occurs and fails again but after the transfer limit is reached. This time, the communication network might not work properly and the in-cabin ADAS refuses the transfer. Because it reaches the transfer limit on a GoA3 level, the autonomous system must stop the train as part of the safety procedure. The autonomous system then requires a take-over from the remote cabin and the train is not allowed to resume its course before the system has completely transitioned to level GoA1.

IV.4.3 Implementation

The advantage of representing the system's decision process in the form of a state chart is that it facilitates its implementation through the help of tools like Matlab. Matlab and its Simulink module provide a comprehensive environment for modelling and simulating dynamic systems, enabling the translation of state charts representations into executable programs. Simulink, specifically, offers a graphical interface for designing and simulating dynamic systems that is particularly suitable for visualizing and testing the functionality of state-based systems (stateflow). This tool was thus used to develop the authority transfer module of the autonomous train. The program further refined with the assistance of engineers from the LAMIH, the research laboratory hosting this project, and CNRS (The French National Center for Scientific Research). An overview of the final state graph developed in Simulink is presented in Figure 42 and provided as Appendix 1 for readability. In addition to helping with

the state chart implementation, they also provided a customised module for the autonomous distributed control systems for the PSCHITT simulator, presented in Section V.3.2 in the next chapter. As the framework and state chart operate, the possible outputs of the process are the different states of the system. When the system switches to a GoA3 autonomous mode, the autonomous driver is activated and takes control of the simulator. The control loop simply maintains speed according to the train's position on the line, with the other decisions taken by the train and exchanges with the user being controlled by the Simulink model. The interactions between the platform, PSCHITT and the Simulink model are illustrated in Figure 43 below.

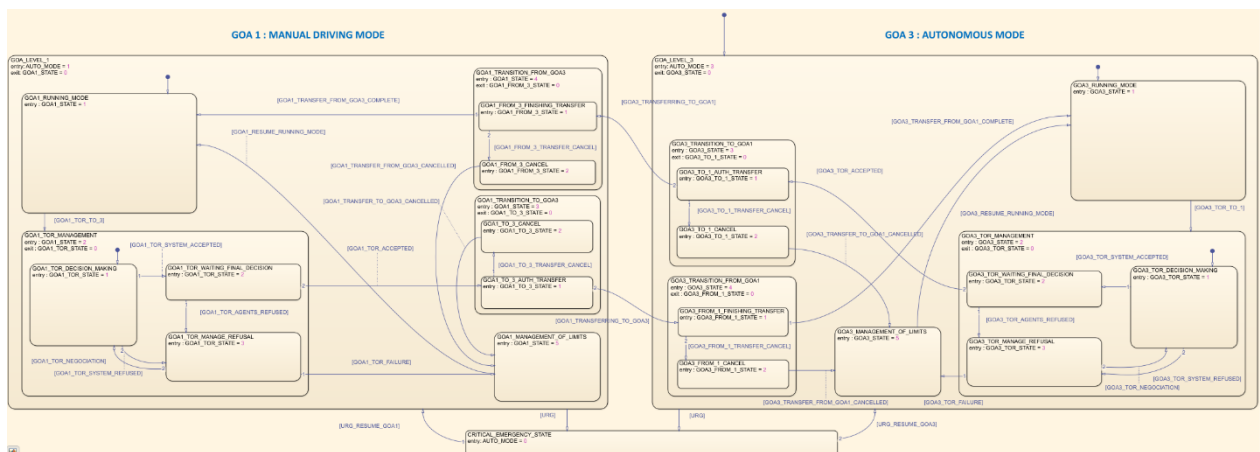


Figure 42 Autonomous system's state diagram in MATLAB Simulink

In this graph, the states generally correspond to those proposed in Figure 39 and Figure 40, and each is linked by specific transitions. In this part, “transition” refers to the link between states and substates in the Simulink model, and not the actual transition of control resulting from the authority transfer process. Each transition is explicitly and descriptively named, such as “GOA3_RESUME_RUNNING_MODE” or “GOA1_TOR_ACCEPTED”. This facilitates easier identification for implementation in external programs, which will be presented later, and helps ensuring clarity throughout the development. In this implementation, each transition is a Boolean assigned with a default value of False, becoming True when the transition conditions are met. For implementation and flexibility purposes, these conditions are examined outside of this graph through a program analysing the system states, the transfer status, and the human operator responses to determine the system’s decisions following simple rules. This program thus represents a rule-based version of the autonomous train analysis system, greatly simplifying its actual functioning for the purposes of this project. The results of these conditions serve as input in the Simulink model and communicated using the MQTT (Message Queuing

Telemetry Transport) protocol, which standardises exchanges across all devices and programs (Figure 43).

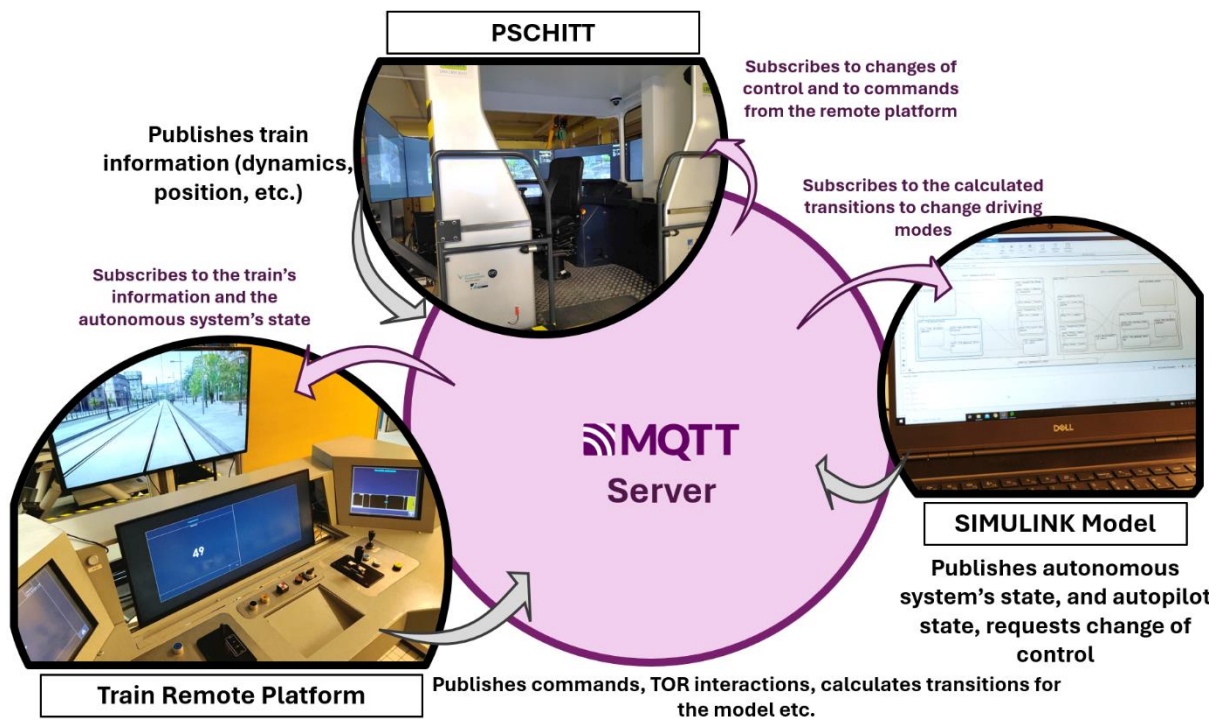


Figure 43 Communication between the train remote platform, the implemented system's model and the PSCHITT simulator environment through MQTT

This model underwent functional validation with the assistance of the PhD supervisors, who were able to participate under the conditions of the second experimental campaign's scenario (Chapter V). Figure 44 presents the Simulink program being used during the driving experiments to control the different driving modes of the system. Following some adjustments made after testing each eventuality, the complete structure of the decision-making process of the autonomous train system during an authority transfer was ready and testing all interactions with other agents in this scenario was then possible.

Having presented the general context, the needs of each agent and the cooperation model that structures interactions between agents along with the process of authority transfer, it is time to examine the various interfaces that could be used to support the human operator during these interactions. The next section will present a number of ideas for solutions explored by the project or which appear to be of interest, and the next chapter will detail how these interfaces have been tested in two experimental campaigns.

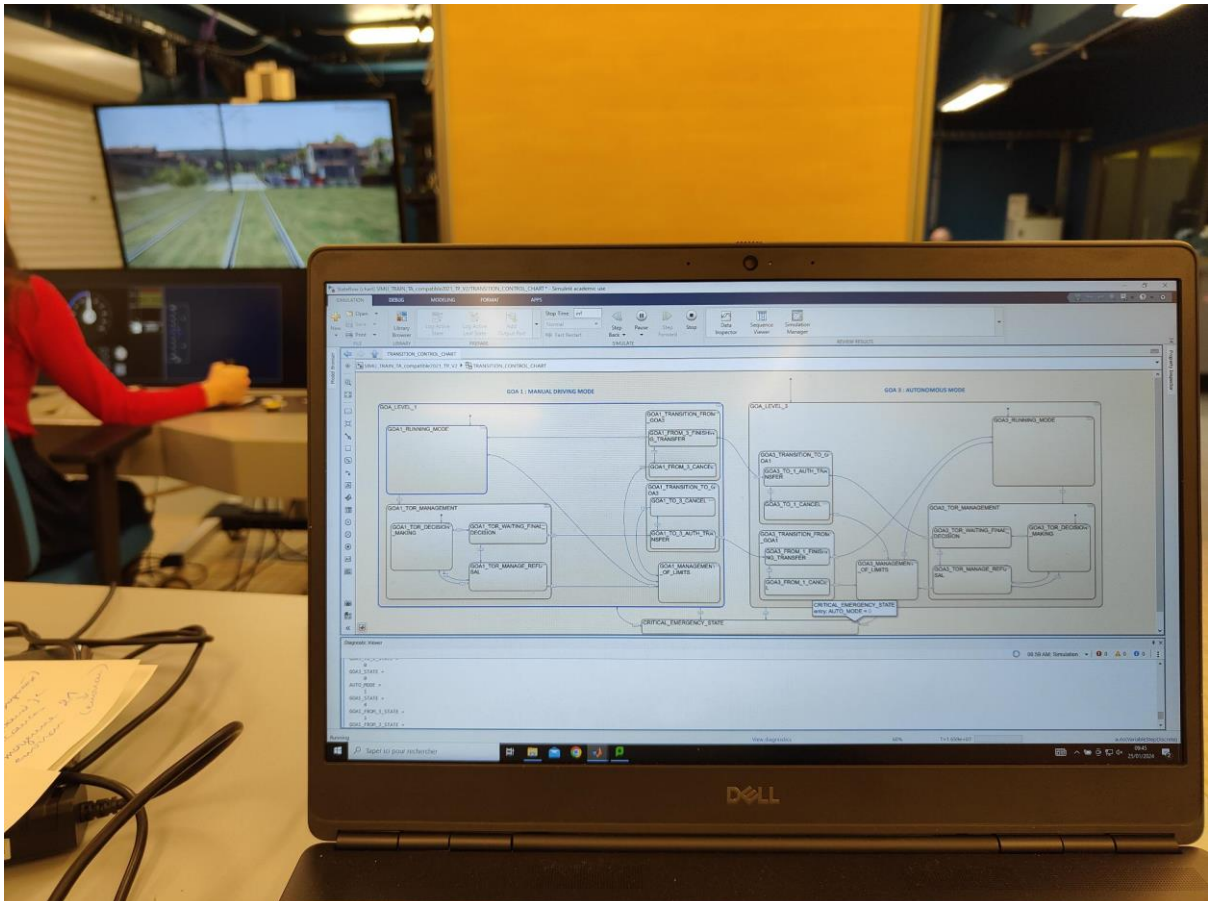


Figure 44 MATLAB Simulink's Autonomous system's state diagram being used during driving experiments to control the transitions between modes

IV.5 Human-Machine interfaces and assistance systems

IV.5.1 Interface solutions explored within TASV

Main interfaces: train controllers and essential displays

The main components selected for this study had to contain the essential interfaces for remote control. This includes at least a means for the remote driver to obtain information about the train and its environment, and a means of sending commands to the train. Many more elements are, of course, necessary to allow for a safe remote activity, as explained in all previous chapters, but these can arguably be considered as the very minimum to simulate part of the train driving activity. These have been previously examined within the TC-Rail project and are the base for the remote control platform. While these interfaces were not directly designed and chosen in this very project, they are presented here as they will necessarily be

used for tests and it introduces the physical platform onto which additional interfaces will be added.

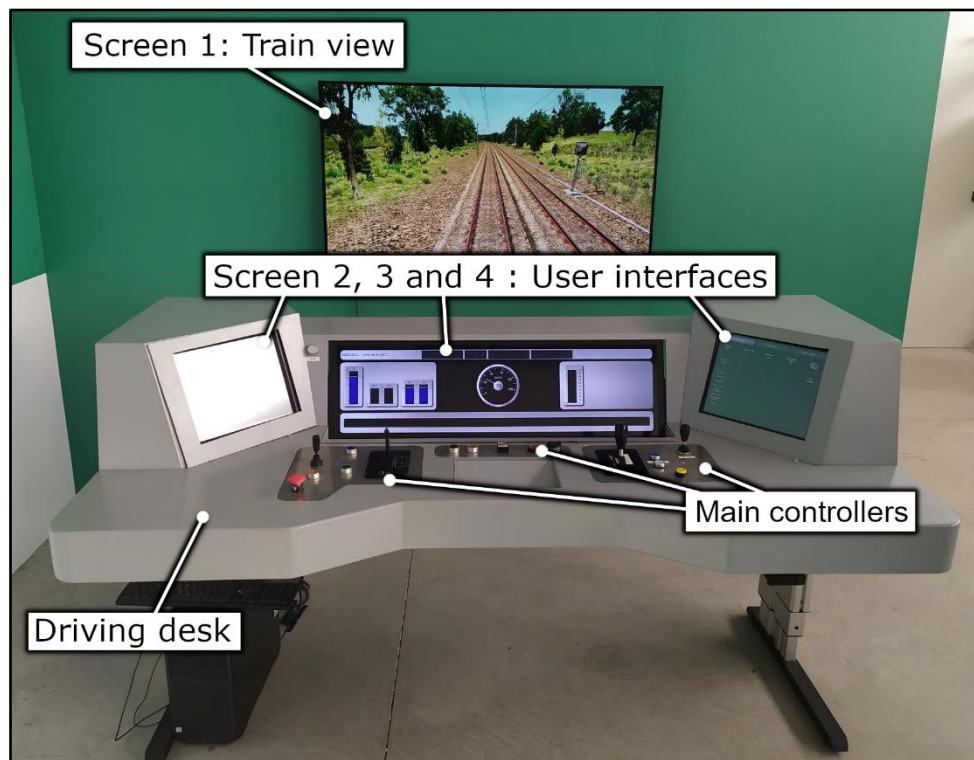


Figure 45 Overview of the remote driving platform

Regarding information acquisition interfaces, Chapter II highlights the importance of the visual channel in assessing the external environment and developing situation awareness. In the premise of this study, remote driving is carried out with the same railway signalling and, in general and as far as possible, with the same constraints and standards as in-cab driving. However, when driving a train, information on the operational scale (signalling, obstacles, level crossings, signal boxes, etc.) is obtained essentially, if not exclusively, through vision from the cab. This is true at least in France and Europe, in the absence of a widespread implementation of more advanced systems such as the European Train Control System (ETCS), which at its most autonomous could determine signalling in the cab via systems such as the European Railway Traffic Management System (ERTMS) (Janhsen et al., 1997). Thus, the unavoidable informational interface of the remote driver station is the retransmission of the view of the train, as captured from the locomotive, with of course all the constraints and degradations mentioned in Chapter II. The train view is available from the remote cabin with a single large screen, visible in Figure 45 as “Screen 1”.

To send commands to the train, the remote platform is equipped with specific controllers. The remote driving desk, as presented in Figure 45, was designed and used in the TC-Rail project (Masson et al., 2022). Since this project was limited to the remote driving of freight trains, some elements of the desk's design are specifically linked to freight trains only, such as the freight locomotive "SNCF Class BB 60000" that was used in the TC-Rail project. However, the desk was designed to be versatile, with a focus on interoperability between locomotives. Thus, the main controllers, such as that of breaking and thrust, were chosen to be easily used for any type of locomotive. Because of this, the desk could still be used for a simulation of most other locomotives for freight or passenger trains and no additional change was necessary on the physical elements of the platform.

To complement the view of the train, the most basic interfaces must also inform the user of the dynamics of the train and the status of the controls via indicators such as a speed gauge or pressure indicators for traction and braking. The aim of this section is primarily to present the concept of the interfaces studied. The specifications of the controllers required depend on the type of train being controlled and the context of the activity, the exact elements used for the study and the experimental campaigns, as well as the details of the virtual interfaces, will be presented in the next chapter.

The following sub-sections will now present specific interfaces explored that aim to answer to the multiple needs mentioned previously, specifically for the transfer of authority process. They will be separated by their main purpose but are not ranked in any order of importance. These initial suggestions cannot provide an exhaustive solution to the problems raised but serve as a first approach to enabling these remote transfers. The experimental campaigns in this study will help evaluate these suggestions, but further studies will subsequently be needed to test other approaches, compare them, and lay the foundations for guidelines for the design of suitable interfaces. Some of these interfaces may already exist in certain on-board railway or automotive systems, and although they are not yet widely used in today's train cabs, they may be of interest to the business, particularly in remote control. Finally, all the suggested solutions in this section are virtual interfaces that transmit visual information. These sometimes require user action via touch screens, through the screens 2 and 4 on the left and right of the desk in Figure 45, but the interactions will be mostly visual. While Chapter II specifies the importance of the visual channel, it also explains why it is crucial not to overload it and that interfaces should favour the use of several information transmission channels. Since

the implemented interfaces are still mainly visual, suggestions for tactile, auditory, or haptic interactions are proposed in part IV.5.2.

Communicating the state of the process and agents

First, an essential requirement for the process is that all agents are aware of their roles, authorities, and responsibilities in the activity. In a context where a change in driving mode and authority is to occur, this implies that all agents are already familiar with the limited number of different modes and are aware in advance of their authority respectively. This is assumed to be known in advance by agents, especially the human operator, and the study expects that the driver must only know the driving mode (autonomous or manual for the selected use cases), the transition phases, and the emergency state. The objective is thus to inform the remote driver of these states. This is firstly indicated in multiple locations of the interfaces through visual indicators placed on the main driving interface or on the assistance screen where interactions for the transfer of authority will take place. An example of these indicators is presented in Figure 46 where “CM” stands for “conduite manuelle” (manual driving), and “auto” stands for “conduite autonome” (autonomous driving). Similarly, a striped pattern indicator appears during the transfer process as shown in Figure 47. The choice of the pattern is only speculative, the idea is that the striped pattern will first attract attention to the box to immediately convey the information but will also figuratively represent the “ongoing” state of the process, so the user understands that a change is occurring between the two states.

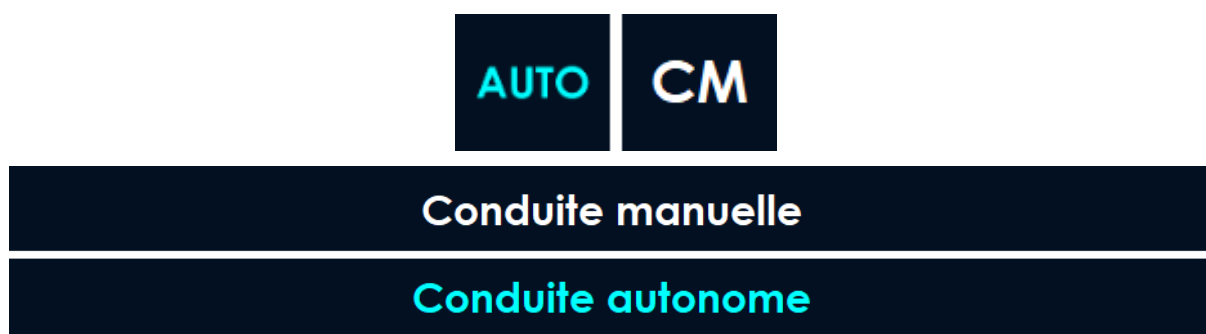


Figure 46 Example of driving mode indicators

TRANSFERT D'AUTORITÉ EN COURS

Figure 47 Example of an indicator showing that a transfer of authority is happening

While presenting this information is important, the objective was nevertheless to avoid making this information overly verbose, increasing the mental workload for the driver. Therefore, two solutions are proposed to help make the understanding of the driving mode clear and immediate in an instinctive manner, while also providing clarification through indicators as previously mentioned. The first suggestion is already visible from the previous examples. Using a specific colour coding to represent information related each of the two states could increase awareness of the nature of the information without the need to actually read the text itself. The interfaces developed as part of the project for the tests in Chapter V do not necessarily strictly adhere to the various French railway user interface norms, sometimes prioritising clarity of information. However, they were still designed trying to remain as faithful as possible to these standards. For example, conventional information is often presented in white or blue, such as gauge values or textual information. Yellow and red colours are used to communicate information that requires urgent action from the user or emergency procedures. Finally, certain colours such as green are prohibited or limited to very specific uses. Thus, although this colour is not part of the existing norms today, the project interfaces use a cyan blue for information related to autonomy (autonomous mode, transition to autonomous mode, etc.), as seen in Figure 46 or Figure 47. This colour remains close to the already used white and

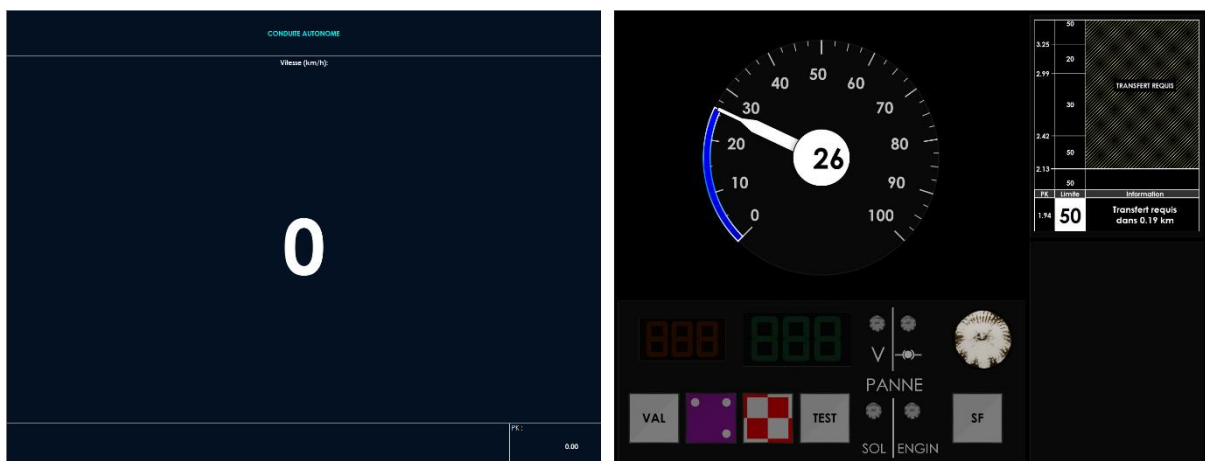


Figure 48 Different virtual interfaces between the autonomous mode (left) and the manual mode (right)

blue colours but is immediately identifiable while being quite different to those related to emergency states, such as yellow, orange, and red.

The second suggestion may be even more striking for the remote driver, as the idea is to distinctly differentiate the driving interfaces for the autonomous mode and the manual mode. Thus, the contrast between the two, before and after the transfer, is expected to become quite evident, and the user would immediately be aware of the change. Without additional context, Figure 48 illustrates an example of the difference between the main driving screen, displaying the train speed, between the autonomous mode on the left and the manual mode on the right.

Increasing situation awareness to prepare for a transition of control

One of the main barriers to a remote takeover, is the lack of situation awareness regarding the process prior to transfer. Another important objective of these interfaces is therefore to help develop this situation awareness by enriching the information available to the remote driver. As mentioned in Chapter III, a first step is to provide the operator with complete details of their mission, including the equipment they are dealing with, the context, etc. Then, the interfaces can also provide some information that is already available in the cabin, such as previous summaries train failure diagnoses or known points of interest along the line. When the train is already stopped, for a recovery after an incident, this may be enough information to initiate the transfer. In the context of a transfer of a moving train, the remote driver must be able to engage in the activity and anticipate the upcoming transfer.

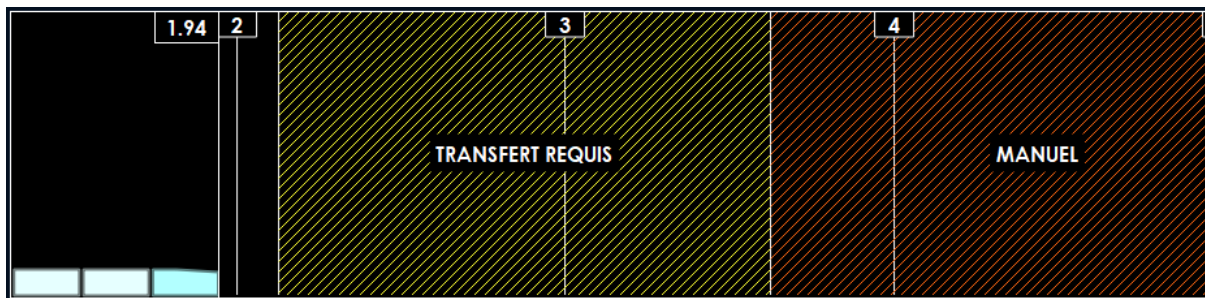


Figure 49 Example of an interface tracking the train position on the line with upcoming authority transfers

A proposition to complement these preliminary pieces of information and anticipate authority transfers is to supplement the previous information with interfaces that can assist the user in tracking the train's position along the line while providing them information regarding upcoming signals and transfers. An idea, experimented in the second experimental campaign,

could be a line profile tool featuring the train's position on the line with specific points of interests. For example, in Figure 49, the tool presents the train and its respective position as a PK on the line. In yellow is an area where the remote driver is expected to initiate and complete an authority transfer towards a manual mode. If the train reaches the limit of this area and crosses over the "red" portion of the line in autonomous mode, the transfer fails and the train enters an emergency procedure, as described in part IV.4.

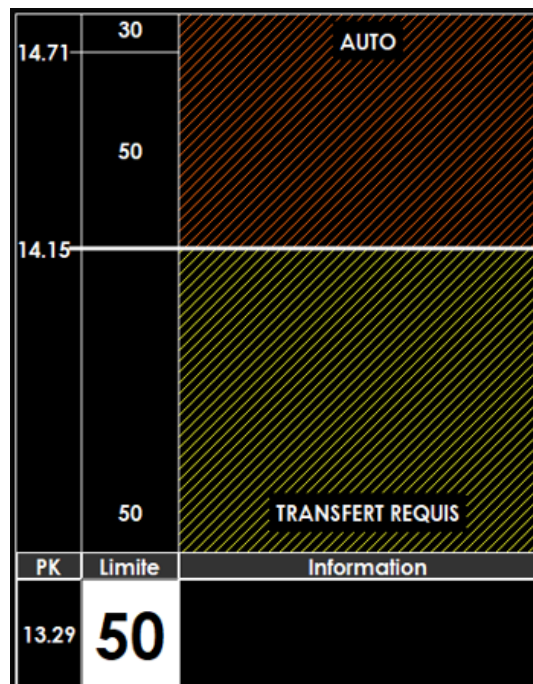
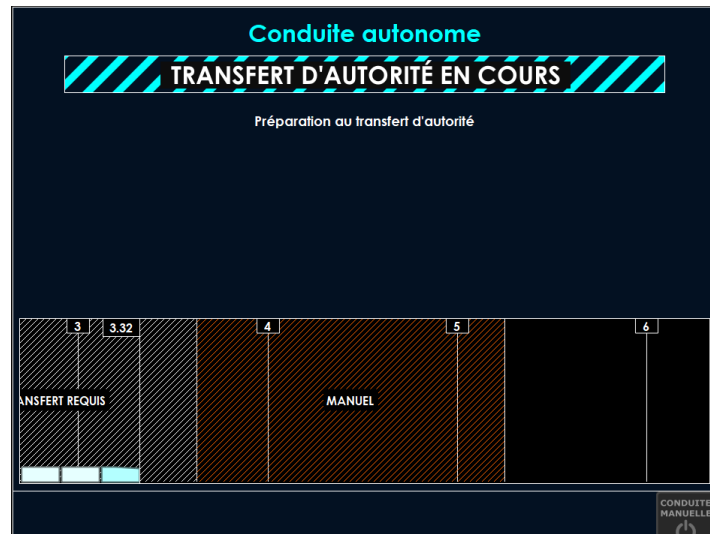


Figure 50 Horizontal widget tacking the train's position, upcoming transfers and speed instructions

In the experimental campaign testing these suggestions (Chapter V), the track profile widget shown in in Figure 49 is displayed on the touch screen to the right of the driving desk in autonomous mode only. In this mode, the driver's attention is not required on the main screen and they can more easily access information from peripheral interfaces. Another version of this interface is proposed for manual mode driving, where the most important information is closer to the central screens to minimize the time when the driver is not looking at the track. Figure 50 presents an example of this interface, that can also be seen on the second screen in Figure 48. Instead of a horizontal scrolling from left to right, the information scrolls from top to bottom according to the train's position, its PK along with upcoming instructions. This change in format was also expected to visually distinguish the mode change as explained previously, while concentrating the information near the speed indicator at the centre.

Assisting the remote driver during the transfer process



*Figure 52 Transfer assistance panel example:
Transition of control from autonomous driving to manual
driving*

The remaining interfaces developed specifically for the transfer are the interaction screens between the autonomous system and the driver to request a transfer and to follow the different phases of the process presented in part 0. All possible interactions will not be displayed here but the main objective for the following tests is to first experiment and evaluate the previously presented framework for the transition process and whether these interfaces can effectively guide the user through the process. To this end, the assistance interfaces indicate



*Figure 51 Transfer assistance panel example:
Autonomous train issues a TOR to switch to autonomous
driving*

the current driving mode, as previously mentioned, along with the status of the transfer. When necessary, instructions are provided through a text field, which indicates when the system sends a TOR, or asks for input, for instance. Indeed, when a user action is required to communicate their own decisions, virtual buttons on the interface can be used.

Figure 52 and Figure 51 present two examples at different stages of possible transfers to illustrate what these screens could display. In Figure 52, the transfer has been accepted by all agents and the transition begins; the driver is informed that the transition to manual mode is in progress but the system is still in autonomous mode. In Figure 51, the system is in manual mode and the autonomous train requests other agents to take control of the train.

IV.5.2 Enhancing remote driver support: exploring additional solutions

Unfortunately, this type of remote-control application is still rather new, and there is relatively little information available to determine whether these initial elements can provide a sufficient layer of assistance to envisage the remote takeover of a train. Further studies are needed to observe their use, gather user experiences, and generally improve the model of knowledge regarding technical systems and human operators for the activity. Thus, it may not yet be desirable to immediately test more advanced general systems that could complement these initial interfaces. Moreover, the technical and time constraints of this project did not allow for the exploration of certain other solutions that had been considered, particularly the use of additional channels for information transmission. This section proposes various axes for future studies that have been explored during this study but were not retained at this stage of research. With feedback from the first experiments and using future activity analyses, a new research loop will help improve the initial models and suggestions from this study and allow the exploration of new solutions.

Other visual interfaces to complement the driver's situation awareness?

Once again, the future objective is to optimise the visual information offered so as not to overload the operator and induce mental workload. On the other hand, a few other ideas for visual interfaces have been considered and could prove useful for resuming driving. One of them is mainly targeted at the recovery of a train that is stationary on the line. The remote driver will connect to the train and will be able to study the reasons that lead to the takeover request, as well as potential system failures, but will not have much information on the train's recent

past. The past signalling, the first signs of a failure, the detection of elements on the track that would have led to the train asking for a human expertise could all be useful to the remote driver when gathering information. An interface idea to explore could be to provide the operator with a means to review the activity's history, through points of interest captured by the train, enabling the observation of the line at certain key points. If necessary, it could even be possible to allow the user to immerse themselves in the past activity through video capture of the events before the train stopped.

Providing auditory information

The use of sound to convey information is mentioned in Chapter 2 but has not been explored further in this study. The two simulators that will be used to test these interfaces in Chapter V can reproduce the sounds from the train cab, within their limitations, which contribute to immersion and a sense of presence. However, none of the virtual interfaces presented previously include sound components to attract attention, alert, or provide instructions. Yet, the auditory channel is a very simple way to convey information that does not require the driver's attention to be focused on a specific point, and therefore it could be suggested as a primary alternative to some visual interfaces. Of course, research time must be dedicated to studying the various auditory formalisms to be exploited, the messages that can be conveyed by sound, and those that are not suitable.

An example in the case of authority transfers could be to add adapted sound messages for the different stages of the process, such as a sound alert when a TOR is issued and instructions during phase changes.

Suggestions for using haptic manipulators

Another potential means of interaction with the remote driver is the use of haptic elements within the interfaces, taking advantage of the user's ability to touch and feel their environment (Biggs and Srinivasan, 2002). Similar to sound, haptic feedback does not require visual attention and can effectively complement visual information. One suggested approach for remote driving activity is the use of haptic manipulators. These devices can provide feedback to the remote driver through vibrations and forces, allowing the system to guide the operator when desirable, in case of shared control driving for example.

However, apart from the driving activity itself, haptic interfaces could also be interesting for the transfer process. Information, for example, could be conveyed through vibrations, but it is imperative to ensure that no intrusive or uncomfortable elements are created for the user. Additionally, albeit slightly different, in the event of a takeover when the train is moving, the remote driving platform could attempt to synchronise with the remote cabin using motorised manipulators. This could help prepare the physical environment for the transition to manual mode and avoid destabilising the remote operator during the mode change if the platform's elements are in a significantly different state compared to their counterparts in the train cabin.

Monitoring agents' attention and availability

The cooperation model adopts three main cooperating agents, including an assistance system known as the remote cabin ADAS. Throughout this chapter, interactions with this agent have been relatively overlooked or sidelined to highlight the exchanges between the two other agents that actually exchange control of the train during the transfer: the autonomous train and the remote driver. However, the remote cabin ADAS is an important element of this model which is directly integrated into the remote driving platform. Actually, a significant amount of the previously suggested interface is linked to the knowledge and Know-How-to-Cooperate of the ADAS, which complements the other two, such as interfaces to anticipate TORs that are planned in the activity and known by the ADAS.

One of the roles that has not been explored in this study, however, is the possibility for the ADAS to participate in exchanges between the other agents during a transfer procedure. In particular, the ADAS could serve as a safety barrier, authorising or denying certain transfers based on process conditions such as the position on the line or the state of other agents. Indeed, the ADAS could be tasked with monitoring the train's state, its decisions, and the network's state, as well as that of the remote driver. Specifically, attention or availability analyses on the human operator could be used to ensure that the remote driver is ready to engage in the activity while helping them if not. Indeed, as a very monotonous and long activity, train driving is especially prone to driver's inattention and fatigue (Dunn and Williamson, 2011). In other domains, like automobile, similar studies on driver hypo vigilance exist can be used as reference to design assistance systems (Popieul et al., 2014, 2003).

IV.6 Conclusion

This concludes the presentation of the project's contributions for remote authority transfers in railways. First, the study's use cases were explored through three scenarios covering the main modalities of authority exchange between the remote driver and the autonomous train. These include the manual takeover of the train, that has stopped because of a system failure. This case is possibly the simplest for the remote driver to engage in the activity as the remote takeover will face a similar experience to a regular takeover of the train, only remotely. Thus, the main priorities in this scenario are to assist in understanding the circumstances leading to the train stopping and the current state of the train and its surroundings. In this scenario, starting the train generally requires the same technical requirements as for “normal” railway remote driving activity, which was already assumed as possible and mastered in this study. Of course, it is only an assumption to focus on the authority transfers itself, but there remain multiple barriers to train teleoperation today. This scenario concludes with the train stopping at the station as the main objective, allowing the remote driver to free passengers and the train track. The other scenarios, on the other hand, aim to explore manual to autonomous or autonomous to manual transfers while the train is still in motion. Although this involves much greater safety constraints and the applicability of this application is still not clear today, they allow for the study of more advanced needs for the remote driver, particularly in terms of situation awareness before and during the transfer. Moreover, these “extreme” scenarios, in which the activity transitions, while the train is in motion, from a purely autonomous mode to an almost exclusively manual mode, open the door to implementing intermediate driving mode transfers. Notably, it is perhaps possible to request human expertise during the activity, to complement the analysis of the autonomous train for example. A human operator could connect to the train in GoA2 mode, gaining authority only for monitoring tasks and to act in case of necessity.

Two models are proposed in this study. One adapts the multi-agent cooperation model already studied for railway remote control in (Gadmer et al., 2022), adding to the autonomous train / remote driver pair a new Advanced Driver Assistance System (ADAS) agent. The ADAS is connected to the remote driving platform to assist the remote driver and help interactions between the two other agents. This model is used to define the basic interactions that occur at the different stages of the authority transfer process, as imagined in this project. The second model proposed is more control system-oriented than the rest of the study and helps

understanding and simulating the decision-making process of the autonomous train through a state graph that uses the decisions of agents in cooperation as transitions between states. While these frameworks are still very broad, they offer a structure that can be studied to understand the interactive part of the authority transfer process. The next step of the study is to apply the models in a simulated environment and observe the course of the transfer process. For this purpose, and to answer the needs of the human operator, assistance systems and interfaces adapted for cooperation are proposed, hence the presence of the remote cabin ADAS in the loop. These environments have been developed for the project and internally validated to prepare for an experimental campaign where expert opinions and feedback on train driving and remote authority transfers can be gathered.

The next chapter is dedicated to presenting this campaign, divided into two different testing phases. The first involves railway driving experts who participated in a very instructive open exchange session and who have driven on a simulator. The objective was to better understand the real constraints of authority transfers, as seen in the project, from the driver's perspective. For the second testing phase, expert drivers could not be invited again. Engineers familiar with the railway sector have tested the second and third scenarios of the project on the simulation platform of the UPHF LAMIH CNRS laboratory. Despite significant time constraints and limitations, these two testing phases provided valuable user feedback that will help complete future studies for railway teleoperation.

CHAPTER V

EXPERIMENTATIONS

V.1 Introduction

This final chapter presents the main results of this research project, which ended with two test campaigns, each with several different objectives. The preparation and realisation of those experimentation campaigns extended into the final months of the project and were marked by multiple challenges. Nonetheless, this experimental phase provides valuable insights into the various questions surrounding the project themes and the suggested solutions mentioned in the previous chapters.

Just like the tests, this chapter is divided into two main and relatively independent sections, one for each experimental campaign. For both, all objectives, contexts, procedures, participants, and study results will be detailed. The sections will also outline the possible limitations and biases associated with each study that must be considered when using the analyses and results presented. In particular, because of the status of this project, which is still laying the foundations for railway teleoperation and automation, the initial suggestions tested in these experiments are still quite general and cannot explore advanced solutions for interfaces and assistance systems. Definitive answers and conclusions cannot be drawn at this stage of research, and it was not an objective of the project. Thus, the results presented in this chapter consist of initial assessments and functional validations of the implemented systems and interfaces, as well as analyses of the qualitative exchanges with participants. Nonetheless, this information is valuable as it can serve as input for future research projects in railway teleoperation and can be used to draw, if not precise conclusions, potential research hypotheses to explore.

V.2 First campaign: Acquiring feedback from train driving experts

V.2.1 Objectives and context

The first campaign was carried out in late Summer 2023. The aim was to confirm the previously assumed needs and potential difficulties for a train remote driver during a remote transfer of authority of a passenger train in order to propose interfaces and assistance systems adapted to these needs.

Drawing from the preliminary study on train remote driving as well as insights from prior projects such as TC-Rail ((Masson et al., 2022), (Gadmer et al., 2021)) and the specific requirements linked to the automation of advanced driving tasks, several recommendations have been made for the design of interfaces and assistance systems. Furthermore, Railenium has developed a train simulation platform (see Chapter III) for the TC-Rail project. This platform was used for the purposes of this experiment. The aim was both to test the functionality of simulation environment and the relevance of the systems and interfaces implemented, while also identifying the limitations of these proposed systems or their implementation.

Because of the distance between the train and the remote driving cabin, the driving interfaces have to transcribe, and sometimes reinterpret, a large amount of information obtained mainly from on-board sensors. Beyond the functional validation of these systems, and in a human-centred approach, the objective was also to obtain direct feedback from the participants to identify as many opinions, observations, concerns, and user needs as possible, especially from participants with a great expertise in the field of train driving. This type of feedback is necessary to enhance the comprehension of train driving in general but, more specifically, train remote driving, to better understand the needs for the authority transfer process. It also plays a crucial role in refining the knowledge of human drivers and their activity, which is integral to the development of future cooperation models.

Furthermore, these discussions with train driving experts, through this experiment, aim to help evaluate the design choices of interfaces to ensure that:

- They allow the driving activity to be continued or started from a remote driving cabin by providing the remote driver with all the necessary information they need to know and understand their mission and the status of the train (geographical position, potential faults, dynamics, etc.). Specifically, participants will be asked to evaluate the interfaces relevancy and usability regarding the following aspects:

- Reading and understanding the “braking journal” or “bulletin de freinage” in French, detailing the train’s composition;
- Reading and understanding the diagnosis of faults and incidents on the train as well as faults of the autonomous system;

- Reading and understanding information on the train dynamics such as speed, acceleration, as well as braking and thrusting efforts;
 - Reading and understanding of the train position as well as the last signalling elements or points of interest encountered by the autonomous train;
 - Reading and understanding the train's level of autonomy before, during and after resuming the driving activity.
- The choice of information to be presented to the remote driver is relevant.
 - The means to convey the information are appropriate.

Given the study's primary focus on transfer of authority scenarios, specifically the transition of control between an autonomous train and the human operator, this experiment also intended to address the following objectives:

- Determining whether the interfaces for initiating or taking part in the transfer of authority process are intuitive, understandable and easy to use, or identifying design-related issues to correct them in future updates;
- Ensuring a smooth and safe transition of the authority. Specifically, ensuring the human operator, the remote driver, can easily regain control of the driving activity.

However, it is important to specify that the developments were still ongoing and that the simulation environment cannot faithfully replicate the intricacies of train driving and teleoperation. The following section will present the driving platform, its constraints, and limitations and how it is used in the project.

V.2.2 Remote driving platform: Description, usage and limitations

The remote driving simulator is made up of two distinct and relatively independent main elements: the simulation environment, which contains the train driving model, and the remote-control desk, which corresponds to the physical and virtual interfaces of the remote station.

Remote driving desk: Physical interfaces

The train remote driving desk was presented in Chapter IV. In this experiment, the physical interfaces have been remained unchanged while all virtual interfaces developed for TC-Rail have been adapted to this project's requirements.

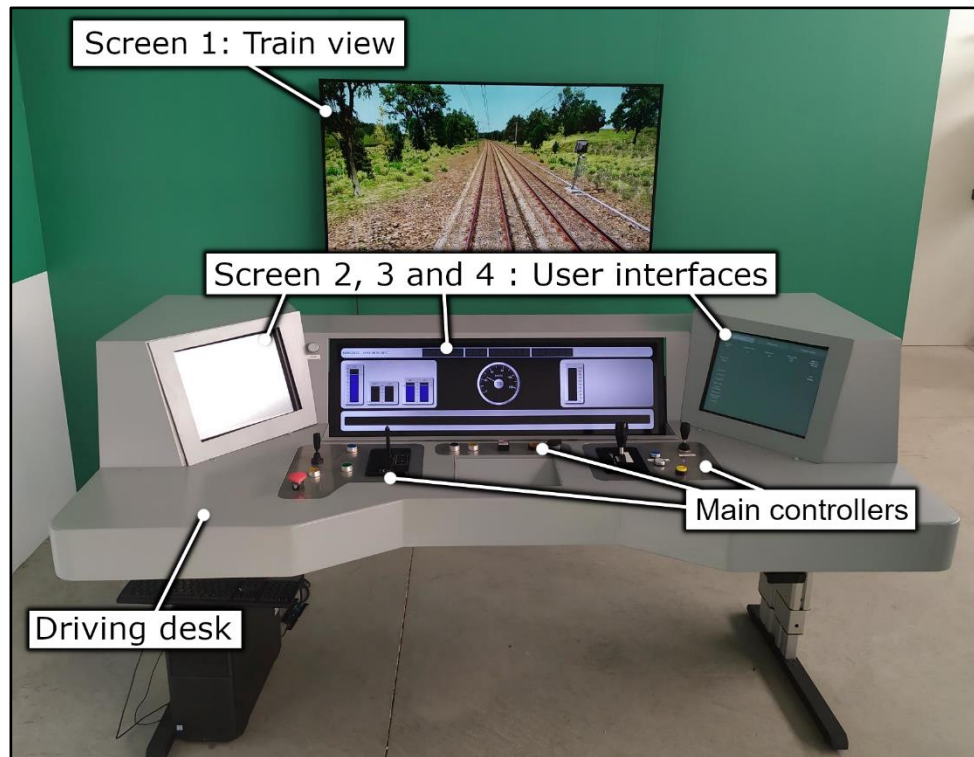


Figure 53 Overview of the remote driving platform used in the TC-Rail Project

The physical desk in Figure 53 consists of 4 screens, adjustable plates containing the driving controllers, a wooden body which contains most of the interfaces. All of them are mounted on a height-adjustable support so the desk height could be adapted to the needs of the operator. While the latter parameter ended up not being necessary in this limited experiment, it is an interesting reminder that the desired adaptability of this remote driving desk, and that of future designs, is not only limited to being able to control different sorts of locomotives. Indeed, it must also cater towards the individual needs of future remote drivers and possibly their individual experiences.

Among the four screens, visible in Figure 53, one is used to transmit the train view in the remote cabin. That screen will only display what can be directly observed from the front of

the train using cameras. In this experiment, the view is provided by the simulator software presented later in this section. The middle screen is a wide stretching screen that is used to

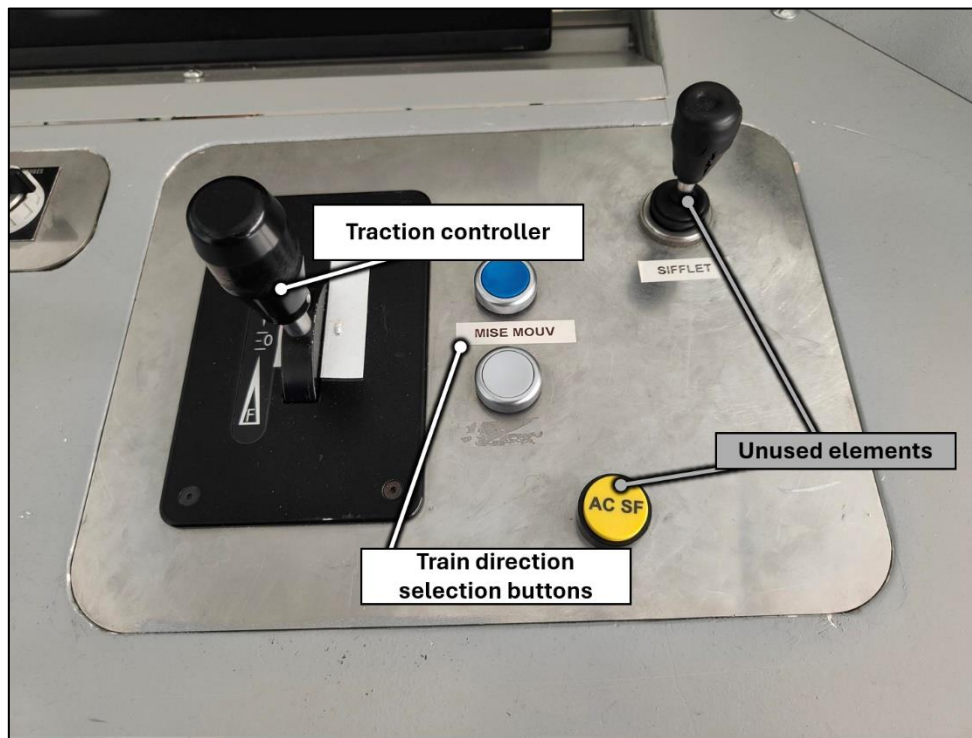


Figure 54 Commands on the right side of the remote driving platform

display information of higher priority and importance in the driving activity such as the speed and traction gauges (Anceaux et al., 2019). Finally, two additional touchscreens on the left and right of the driving desk can be used to display additional information of lower priority that currently exists in train cabins, such as radio tools or the train maintenance logs. They can also display new visual interfaces, such as the Take-Over Request management interfaces, presented in Section IV.5.1 of the previous chapter.

The train controllers on the adjustable plates are visible in Figure 55, featuring the traction controller, and in Figure 54, featuring the brake controller and emergency brake button. While a few other buttons or switches used in the driving activity are present, these are limited to only those necessary to perform the simplest driving tasks. Thus, while these elements are sufficient to control the traction and braking of the train or specific procedures such as emergency stops and signal acknowledgement, the platform lacks the great majority of controllers that may be expected in a driving cabin. For example, a real train cabin could include, among other elements, an electrical panel, pantograph and steam sandbox controllers,

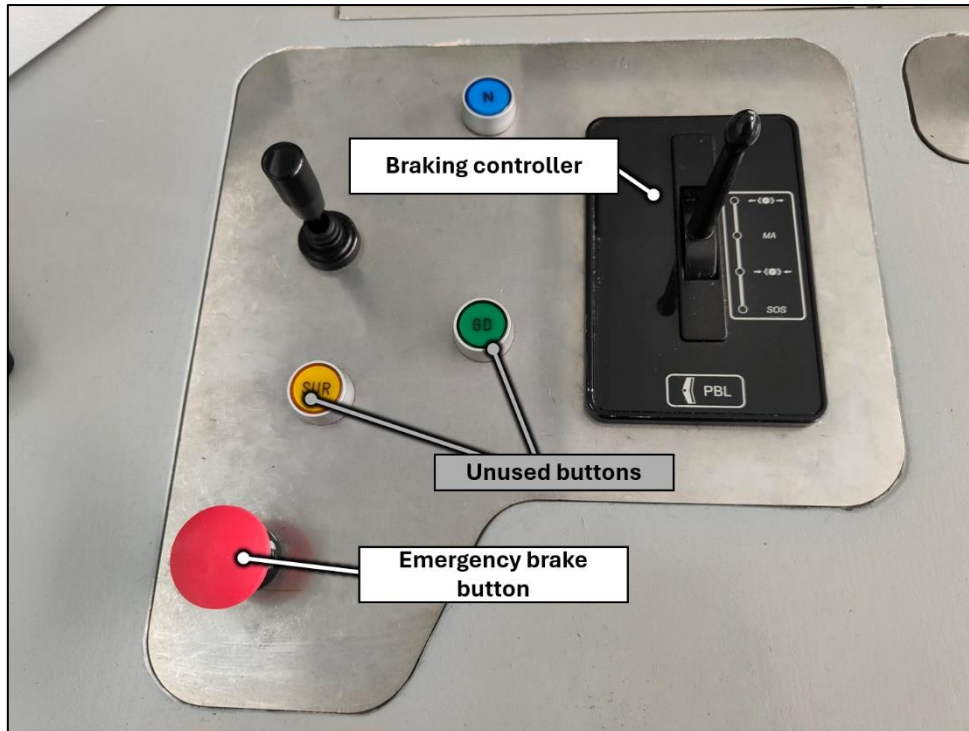


Figure 55 Commands on the left side of the remote driving platform

or buttons to control the opening and closing of doors. Most of the controllers that are not present on the remote driving desk can either be replaced by functions on the new driving virtual interfaces or were deemed not necessary in the context of the experiment. However, the absence of specific elements on the desk and on the virtual interfaces, such as for door control and monitoring, has been noticed by the participants (Section V.2.6). Finally, the traction and brake controllers are distinct, with the brake controller being on the left of the driving platform while the traction controller is on the right. The traction controller, however, is a model that appears in some locomotives that is able to provide both a tractive and braking effort. With this controller, the braking effort is commanded by pulling the controller towards the user while pushing it forward sends a traction command. In this remote driving platform, however, since the braking is controlled by the braking controller on the left side of the desk, the traction controller on the right was locked to only being able to send traction commands. The model of controllers, as well as their separation and position, was a design choice made for the TC-Rail project that has not been changed in this research project. As developed in Section V.2.6, some participants who had prior experience with similar controllers have found it confusing as well. Similarly, the main controllers for the driving activity are present on the platform, such as the braking and thrust controllers, but they remain extremely limited as the platform was missing nearly any controller that was not directly linked to controlling the speed of the train. While

they might not be essential for a simulation of the driving activity, this inevitably reduces the potential uses for the platform and may either confuse expert drivers who are looking for these elements. For example, the train starting procedure cannot be completely reproduced because of the lack of pantograph and door control, or the lack of communication interfaces with passengers or a supervising centre.

Remote driving desk: Virtual interfaces

The suggested virtual interfaces developed for these experiments have been mainly presented in Chapter IV with a few notable exceptions as there were elements designed specifically for this campaign alone. First, the simulator was different to that of the second experimental campaign, and the type of locomotive controlled in the driving phase of the experiment was different. Thus, the main informational interfaces for the driving activity, displayed on the wide middle screen, Screen 3 on Figure 53, were designed after the virtual interfaces of Regio2N locomotives. The objective was not to reproduce them exactly as they actually are but to provide a very faithful reproduction, with only some changes for the experiment and a few functionalities missing as they were not used. These elements are visible in Figure 56 where braking gauges and most pictograms were used only for this first scenario. On the left side of Figure 56, the pictograms, gauges and the KVB panel (“Contrôle de Vitesse par Balise”, a specific interface used for ATP and mentioned in Chapter I) are not from the Regio2N’s main interfaces and were added to match information from the simulated environment.

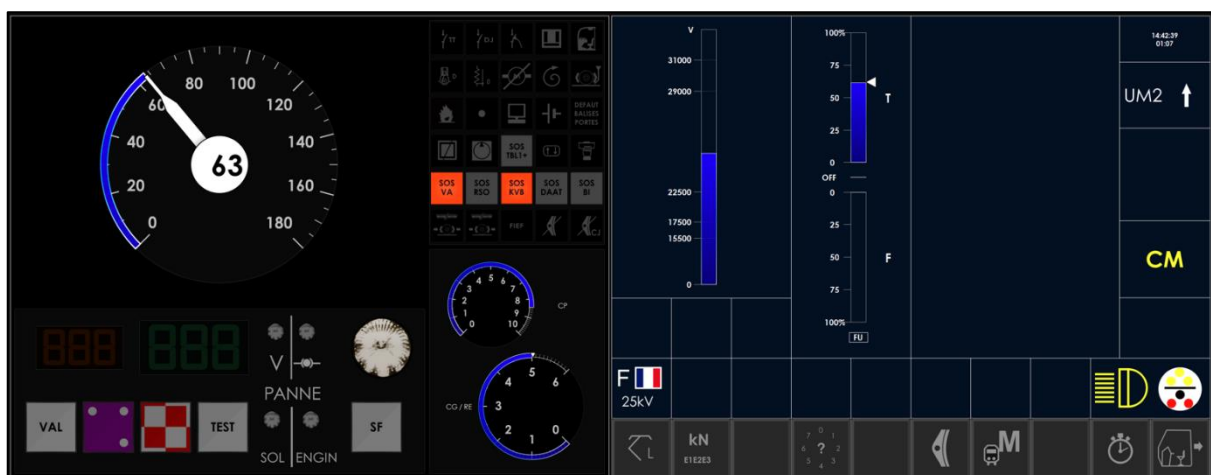


Figure 56 Driving information on the middle screen for the first experimental campaign

Then, in this scenario, the train is stationary and there has been a technical failure before the mission of the remote driver, while in autonomous mode, and the authority transfer process is simplified compared to the scenarios of the second campaign where the train can still be moving during the transfer. Thus, a particular attention was given to the starting phase. In this specific scenario, it was decided that the remote driver should test the controls of the remote driving desk (manipulators, buttons, etc.) and ensure that the traction and braking commands are correctly received by the train. This step, being a form of train preparation as defined in the activity, aims to verify the availability of the teleoperation system while enhancing the remote driver's trust in the platform.



Figure 57 Example of instructions before taking over control of the train

During this phase, the remote driver is explained that tests must be performed before getting control of the train and that actions on the platform will not yet be sent as commands to the train as it remains in autonomous mode. Figure 57 presents an example of the instruction panel that appears when the driver sends a TOR, asking to change to manual mode. These instruction panels are relatively verbose, as instructions are presented through text. This was important for the participants as they had not used the platform before and were unaware of this authority transfer process. It is, however, very likely that similar instructions in future interfaces will aim to be clearer and more concise, perhaps through easily recognisable figures, but users will have to be trained to use them beforehand.

Simulation environment: Train Simulator

To conclude the presentation of the driving platform, this part will present the simulator used in the study. The simulator is a key component of the study as it emulates most of the driving activity and provides the video rendering required for driving the train. In the TC-Rail project, when the remote driving desk was first used in 2020 (Paglia and Richard, 2021), the simulator was a two-part solution that combined a simulated model of a freight train and a video player linked to the model. The model would take command inputs from the desk and calculate the train dynamics and position. The player would then use a pre-recorded video reference of a train driving activity, to which the appropriate driving data were associated, and would adapt the playback speed to match the train speed from the model.

This solution, while useful in the context of that previous project, had multiple caveats. First, it requires good quality video footage with a relatively high framerate to avoid video stuttering when the simulator slows down the video. This happens when the train speed calculated by the model is much slower than that of the video reference. Then, this solution also requires a reliable driving model of the train used in the experiment, such as AGC or Regio2N passenger trains. As resources were limited, both of these elements could not be obtained in the timeframe of this research project and another solution was necessary.

The only other reliable solution was to use an already existing simulation platform where the model of an AGC train, a Regio2N train or another similar passenger train already exists. The first available solution, thanks to the resources from the UPHF LAMIH CNRS laboratory was to use their own train driving platform: PSCHITT-Rail intended specifically for railway research. This platform was used in the second experimental campaign where the ability to directly control the driving parameters and the ability to develop and emulate the automated driving system agent was more important than the realism of the passenger train driving environment. Indeed, the platform, presented in the next section for the second, offers a highly detailed driving model and provides tools to finely tune the experimentation environment. However, the model and the environment itself were, at the time of the experiment, limited to tramway trains. This means that both the visual rendering of the activity and the control interfaces on the PSCHITT-Rail simulator are catered towards tramway simulation. In this very experiment, the focus was less on the faithful rendering of the driving model and more on the feeling of expert driver participants in a semi-realistic visual environment. Their driving experience was key to evaluating interfaces solutions and exposing

their opinion on how they imagine the transition of control for train remote driving. Thus, a crucial criterion for the simulation environment was to present a faithful representation of a French mainline passenger train with its visual interfaces, as well as a proper train line with correct signalling.

The best simulators to meet these criteria would undoubtedly be official driving training simulators. These have been used for many years for driver trainings and use the most accurate driving models and visual interfaces to date as they are meant to faithfully prepare for actual train driving. However, these environments are reserved for training centres and cannot be adapted for research purposes. Furthermore, the needs of this research project do not justify, at this stage of development, the cost of employing such a solution. Thus, another solution was needed.

Finally, the choice was made to use the Train Simulator software, developed by Dovetail Games and that provides users with the opportunity to operate various types of locomotives on a range of different lines. Visuals from the software are presented in Figure 58. Unfortunately, while it is a much more affordable solution, its main purpose is to be a train simulation game, which is available on the Steam platform. This means that, although the game is known for its rather realistic portrayal of trains and landscapes, in addition a library of downloadable content featuring thousands of lines, locomotives and other railway assets, it remains first and foremost a game, with the main aim of offering users a recreational experience. As such, the software has not been developed for driving training or research. The driving model, for example, is not completely faithful and cannot perfectly reproduce the actual driving activity. The limitations of the platform are detailed further in the following section. Despite these limitations, Train Simulator has been a very useful solution as the environment proposed by the software has indeed proved to be quite complete and realistic. The software offers multiple tools to finely craft and edit lines and scenarios and there is a very active community that provides extremely detailed French lines including realistic landscapes, railway assets and faithful signalling. These were quite important for the needs of the experiment as the line's faithfulness and especially that of signalling was primordial to help construct and evaluate the participant's situation awareness.

In the experiment, a reproduction of the northern line, near Lille (France), was used, with an AGC train as the locomotive. Both were made and maintained by independent creators and are available on the Railsim-Fr website as of today. While the project was initially using



Figure 2 *Figure 58 Train Simulator displayed view of a French train line*

Regio2N trains as reference, especially for the design of virtual interfaces, the assets for these locomotives were not available at times. The choice was made to use the AGC locomotive, an older similar unit used in French regional routes (TER). The virtual interfaces used in the experiments, however, could not be remade to use AGC train interfaces because of both the limited timeframe and the available resources used as reference that was exclusively for Regio2N.

How the remote driving platform is used

The different elements of the remote driving platform are used together to emulate the driving activity but are each designed to be relatively independent. They are used together using intermediary communication programs. The interactions can be summarised as follows:

- A number of information can be acquired from the Train Simulation software in real time by reading its DLL (Dynamic-link library). The data that can be obtained from the program may differ depending on the assets used in the simulator, but they usually include most of the train dynamics (such as speed, tractive effort or position) and the state of most, if not all, buttons and visual indicators featured within the cabin. A specific python submodule of the driving platform has been developed to read from the library or write into it. The data is then sent to the platform's virtual interfaces program and translated into the appropriate data format.
- The virtual interfaces program updates its "model", which stores dynamic train data as the software reads new information. The model is then used to update the "view", the virtual displays such as text information, indicators, gauges and buttons.
- The user may then interact with the driving platform using either the virtual interface on tactile screens or the buttons and controllers on the driving desk itself.
- Input data from the desk is read by a Programmable Logic Controller (PLC) and transmitted towards the virtual interfaces program to update the command inputs state and to the Train Simulator communication submodule to interact with the simulator. For the experiment, the PLC was replaced by a Raspberry micro-computer because of a technical failure.

The interactions between the physical desk controllers, the virtual interfaces and the simulator are naturally transparent to the user. Using the platform requires setting up a scenario on the simulator. This is done by choosing the desired line from the assets and editing it to configure the chosen train asset, the starting position on the line and the destination serving as the scenario's completion objective. For example, in this experiment, the starting position was between two stations as the scenario was centred around taking-over control of the automated train following a system failure.

V.2.3 Participants

To meet the needs of the experiment, it was necessary for participants to be or have been professional passenger train drivers. Thanks to the help of the "Club de Grande Vitesse Ferroviaire" (High Speed Railway Club), the project was able to invite and host eight former driving experts to take part in these experiments. The association brings together passionate

members who have been or still are involved in the world of railway transport and whose aim is to promote railway heritage and knowledge.

Among the 8 driving experts invited, two have been invited before the start of the experiment to provide their insight during the development phase and to help point-out potentially important mistakes on the simulator that could invalidate the experiments. Of all 6 participants, all were male, aged between 55 and 74 years old. One of them has been a train driver for about 8 years before moving to management. Others have been train drivers for about 20 to 31 years (mean: 27, standard deviation: 3.8). They all had experience with both freight train driving and passenger trains but no one had experience driving an AGC or Regio2N passenger train with their respective interfaces. Finally, for each but one driver, the only experience with train driving simulators was mostly limited to the simulators used in driver training. The remaining participant had also become an aircraft pilot and had experience with flight simulators, some of which being designed primarily for entertainment purposes, much like the simulation environment used in this experiment.

The limited number of participants means that the results of the study are not statistically significant to provide definitive answers to the issues raised above. However, given the lack of similar studies for railway remote driving and human-machine interfaces for train teleoperation, and the participation of expert professional drivers, this initial feedback can be used as a solid basis for adapting the knowledge model of the remote driving activity and formulating initial hypotheses about the proposed interfaces in terms of their ease of use, usefulness, and applicability. These discussions also allow us to project into the future, evaluate the needs anticipated by current drivers, systems, and interfaces that they would like to see developed or that they consider necessary, and to their reservations about the evolution of the activity.

V.2.4 Hypotheses and expected results

As stated in Section V.2.1, there were multiple objectives to this experiment. First, regarding the functional validation of the driving platform, it was expected to provide a relatively detailed, realistic, and intuitive simulation of the driving environment, both physically and virtually. However, due to limitations to this platform regarding the physical interface of the driving desk and the lack of a reliable train simulation model, this phase of experimentation was carried out with several biases. First, a questionnaire to assess the

participants' sense of presence was initially planned but was eventually abandoned as it was impossible to deviate from the highly experimental aspect of the simulation. In addition, the physical interfaces were presented to the participants, explaining their limitations. However, one of the initial hypotheses was that *the remote driving platform, although mostly intuitive, could confuse the participants* who might be looking for different controllers on the desk expect a specific behaviour from the train in the simulation. One objective of the test is to ensure the usability of a remote driving platform through the addition of intuitive interfaces adapted to the driver's needs. Feedback from users, whether they express concerns about the platform as presented, or when they find it intuitive and practical, will highlight the elements they consider most important.

It is worth pointing out that the participants in this test were all driving experts. Their knowledge of the activity is key in trying to identify what will be potentially valuable for the train remote driver's future activity, but it is not enough on its own to determine how the train remote driving platform should be. Indeed, the activity of a train driver and that of remote drivers are entirely different, and it is still difficult, if not impossible, to estimate the extent to which the two would converge in the future. Feedback from participants will help formulate hypotheses and recommendations for future interfaces, but these must also be compared with the needs highlighted by future analyses of the future train remote driving profession.

Among these hypotheses and considering the limitations that were presented in the previous part, as well as the lack of varied modalities to convey information, it was highly probable that part of the feedback from the participants would mirror what had previously been observed in the TC-Rail project (Paglia and Richard, 2021) where there were similar limitations. Especially, it is expected that participants will point out: *the lack of a realistic soundscape, thus drastically reducing their immersion as well as their ability to sense the train's behaviour and how it responds to commands; the overloading of the visual channel, or in general, the almost non-existent use of other means of transmitting information; and multiple important commands missing from the remote driving desk*. Although most of these observations are expected, they do not represent the real objective of this experiment. Indeed, these observations are mainly linked to the remote driving activity itself. However, the main aspect to be studied in these experiments is the ability of the remote driver to resume the driving activity with the remote driving platform. If they are indeed formulated by the participants, they could however help to confirm the observations already made by the TC-Rail project.

Although the visual interfaces for the transfer of authority seemed comprehensible during the internal functional validations, only the opinion of driving experts will be able to help formulate recommendations or point out major shortcomings. Thus, the objective here was not to test a specific hypothesis, beyond answering the question "can this interface help with the transfer of authority?", and then evaluate the participants and their behaviour with regard to this hypothesis. Rather, the aim is to give them the opportunity to freely express their appreciations and reservations regarding the physical and virtual interfaces. Consequently, the main hypothesis would be to consider that all interfaces presented in Sections IV.5.1 and V.2.2 are expected to provide a certain level of assistance for train remote driving. In particular, they are expected to help the human operator when resuming driving from the remote platform. The tests, for which the procedure is detailed in the next section, will then be used to test this assertion and, where appropriate, attempt to assess the extent to which these interfaces are deemed useful.

V.2.5 Testing procedure

Each test was carried out in three stages and lasting between one and a half and two hours in total. The procedure is resumed in Figure 59 along with a picture of the platform and the simulator used for the experiments.

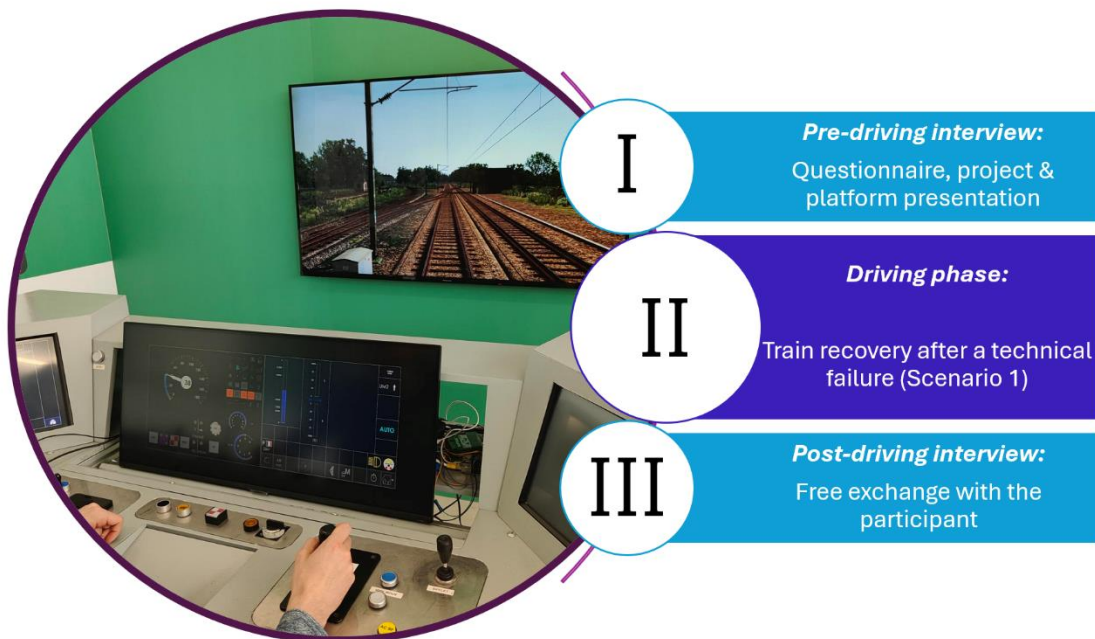


Figure 59 First experiment's procedure

The remote driving platform is located within Railenium's building. Each participant was welcomed and taken to the room where the platform was presented to them. The participants were then invited to the interview room away from the platform, where they were interviewed. They first introduced themselves, and the context of the study was presented to them. Then, they were asked to answer the following questions:

- What was your activity in relation to train driving? How long did you work in this capacity?
- What type of locomotives have you worked with?
- Have you ever used a simulator and under what circumstances?

The objective of these questions was to give the participants the opportunity to present themselves and to give an overview of their experience as a driver and their experience with specific types of locomotives. The objective of the last question was to identify participants who may have had more experience driving in a simulated environment. Indeed, being used to simulation may have affected their expectation of the simulated activity and the behaviour of the train model, especially if they used less realistic environments than train driver training simulators. The results of this first step were used to highlight similarities and disparities between participants to better understand the nature of the observed panel, as presented in the previous part.

The participants were then invited to freely discuss the project, present their concerns, their understanding of the subject and the involvement and role of human factors researchers. These exchanges gave the participants the opportunity to express their opinion freely on each aspect of the experiment, such as the relevancy of a train driving solution, their views on the future of railway activities, what they expect from interfaces in a potential situation of remote transfer of authority. Finally, to conclude the first stage of the test, the virtual interfaces of the train were presented to the participants through a slideshow featuring most indicators and functions from the cabin, such as speed gauges, warning indicators or the button used to initiate the take-over procedure. Then, the physical platform and all controllers were presented in detail. The objectives were both to confirm that participants could easily and intuitively understand the nature of each element (controllers or visual indicators) and to properly present them when they did not intuitively understand their meaning or purpose.

The second stage of the experiment was the driving phase. In this experiment, the focus was more on the needs and impressions of the human operator with regard to interfaces

and assistance systems before and during the transfer. As such, a scenario from the first use case, presented in Chapter IV, has been selected. In this scenario, that was presented to the participant at the beginning of the second stage, the train was performing the driving activity in a GoA3 level of automation without an on-board driving attendant, in accordance with the definitions of the driving modes defined in section II.3.2 of Chapter II. A technical failure of the obstacle detection from the automated system causes the train to initiate an emergency safety procedure and request a take-over from a human driver. The participant is asked to take control of the train through the remote driving platform, drive the train remotely towards the next station on the line to safely stop the train and evacuate passengers. During this stage, the participants are encouraged to express their feelings and observations on anything that could help meet the objectives of the experiment. This may include their vision of the interfaces and their usefulness, the ease of initiating the transfer process or the elements that they feel was most lacking.

Finally, the last stage of the test protocol was a final free exchange after the driving phase. The idea was to give participants the opportunity to complement their first ideas after having experienced the transfer of authority scenario.

V.2.6 Analysing results

This section will present and analyse the data collected from the experiment. The aim was to collect the participants' opinions, concerns, and ideas regarding the usability of the train remote driving platform, its physical and virtual interfaces, and what they feel must be explored and improved. The participants have thus been instructed to voice their thoughts regarding these aspects during the presentation of interfaces and the driving phase. To avoid leading them towards specific answers, no direct question was asked during the driving phase. Indeed, their immediate comments and reactions would thus reflect what stood out the most for them. In the final interview, however, participants were asked more directly ?? questions that aimed to complete their remarks during the previous phases and allow them to add more details to their observations. Due to the lack of a training scenario, as it was important to collect the participants thoughts during their first experience with the platform, and the lack of in-depths instructions beyond the simple mission objective (resuming the driving activity until the next station), participants could still ask questions during the driving phase regarding the use of specific interfaces or when they felt they were lacking information to make decisions.

Collecting participants' observations

Comments from participants have been grouped within different sub-categories, each being associated with a broader category. Figure (ref) presents the different categories and sub-categories as well as how many times all participants combined have made a comment or had a question regarding said category. Multiple observations related to a singular sub-category from a single participant were counted separately when they were made at different times and thus not considered a simple extension of the previous observation. The categories will be developed next, along with some specific observations from participants. Naturally, because the low number of participants, the maximum number of observations regarding each category remains correspondingly low. Similarly, because participants were not asked direct questions, the themes that emerge from their observations may differ greatly between one another. Indeed, because of the subjective nature of these observations and the low number of participants, some observations may only be brought up by a few of them, if not only one of them. On the other hand, some themes may be brought up by multiple or all participants, sometimes maybe more than once. While the latter case can help identify the needs and concerns that appear to be the most critical for driving experts, observations that have been brought up only once or twice among all participants must not be disregarded. Indeed, this information could still prove to be highly relevant, and the fact that it is less frequently noted can be explained by the reasons mentioned above. In particular, it can be linked to the size of the sample of participants, their differing experiences, or the potential biases related to the simulation, which can divert the attention of some participants from certain aspects of the experiment.

Analysing the collected data

This part will present all the topics that came up during the experiment, providing more details on the meaning of each category and what has been specifically pointed out by the participants. It is important to note that the categories in Figure 60 have not been ordered as they represent parts of the driving activity that are often quite unrelated, and any order of importance would be arbitrary.

The first category that appear in Figure 60 is “*Monitoring*”, that includes, among others, all aspects related to train and passenger supervision. As the study is focused on the transfer of authority, the monitoring of the environment during the activity is not included in this topic. Information gathering on the environment, however, will be part of the second

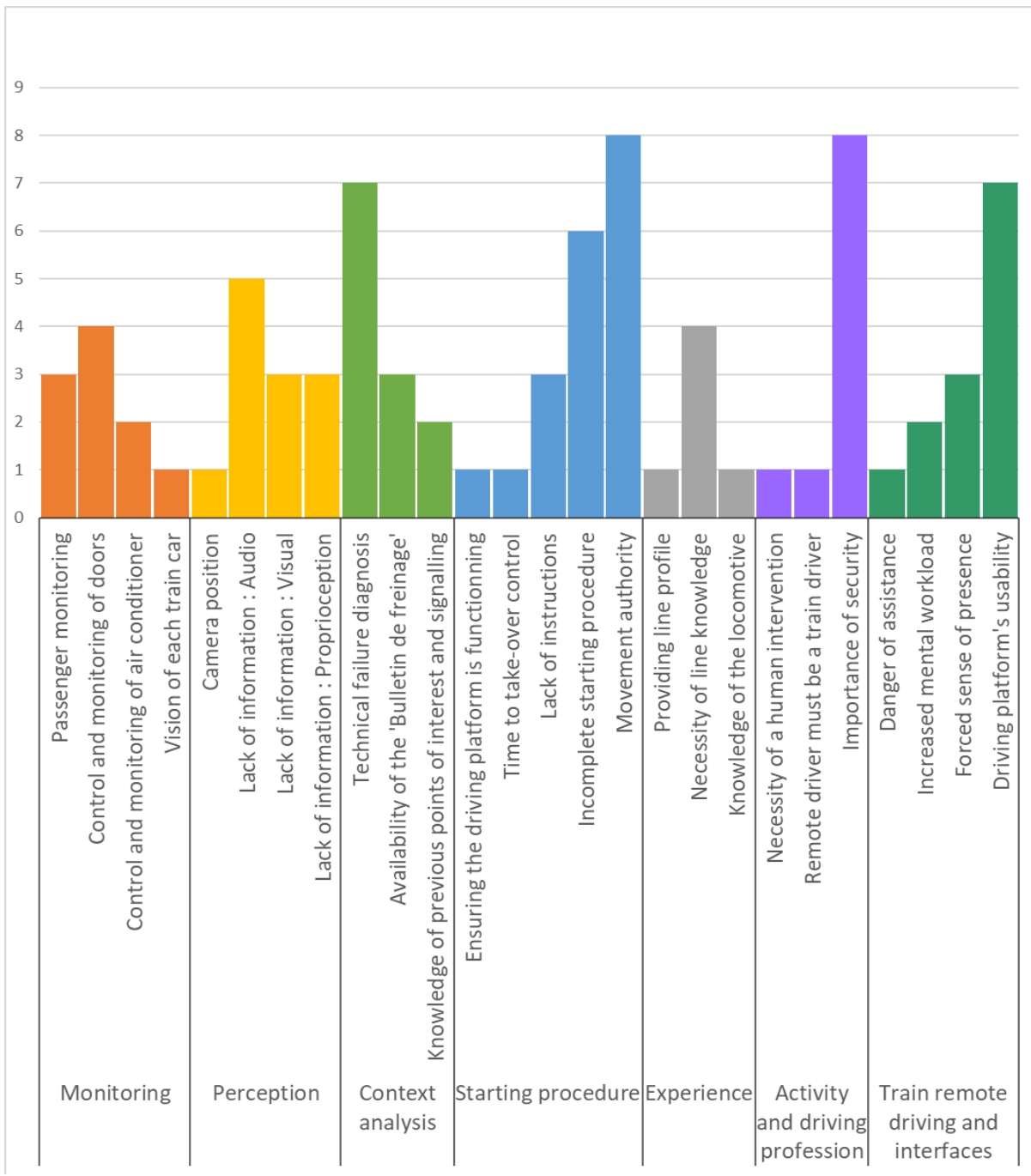


Figure 60 Cumulative participant observation for each subcategory

category. In this first category, the most common observations from half or more of participants were about *passenger monitoring* and the *control and monitoring of doors*. Specifically, they pointed out the importance to communicate with passengers while making sure they are safe and do not act dangerously. In the context of a stopped train, a participant pointed out an elevated risk of participants getting impatient and agitated. As a necessary safety procedure, the train driver must ensure that the doors are closed to prevent passengers from leaving the train in the middle of the track. It is thus not surprising that most participants would point out

the lack of information regarding the state of doors and the monitoring of passengers in real time. Similarly, two participants have mentioned the need to check the functioning of the air conditioner within the train, as it is not only important for passenger comfort while the train has stopped, but its absence can become a danger, especially during the hotter seasons.

The second category, “*Perception*”, includes all information gathering related observations. Specifically, they mostly involve the differences between information that can be perceived from within the train cabin and the remote environment. First, even if evaluating the remote driving activity was not the focus of the study, most participants have pointed out the sound provided by the platform in their observations. Unlike the experiments previously carried out in the TC-Rail project, Train Simulator was able to provide a relatively immersive soundscape and reproduces most sounds from the driving activity. This has been mostly appreciated by participants as most of their actions was linked with an appropriate audio cue. Among the most significant were the sound of the air escaping from air brakes, or that of the wheels when braking. Conversely, two participants have expressed that the sounds were unrealistic when expected sounds were absent from the simulations. Indeed, even if the sound restitution is quite important for the driver’s sense of presence, as pointed out by the TC-Rail project, this restitution must aim to be complete so as not to hinder the sense of presence. These observations were counted under the sub-category “*Lack of information: Audio*”. Similarly, under the categories “*Lack of information: Visual*” and “*Lack of information: Proprioception*” are all observations already pointed out by TC-Rail regarding the degradation of visual and kinaesthetic information. Finally, even if it had been pointed out by a single participant, the *camera position* is an interesting topic as there may still be some technical barriers regarding the placement of the camera and its protection for high-speed travels. Additionally, it raises the question of the number of cameras needed to provide the train’s view, a potential night vision, and to observe the rear and sides of the train. How many of these views are useful in the context of this use case and should be provided on the remote driving platform’s interfaces must still be evaluated and tested.

The following category, “*Context analysis*”, refers to the ability to understand the situation before the authority transfer using the interfaces from the train remote cabin’s interface. This includes getting information on the train, on the line, and on the itinerary. In the context of this study’s use case, the recovery of a train after a technical failure, the most important factor in this category, raised by all participants, is the need to be able to properly

identify the details of said technical failure (categorised under the “*technical failure diagnosis*” sub-category). Indeed, participants have all pointed out that interfaces provided during the experiment were insufficient to “understand the failure”. This need is most illustrated by the following statement by a participant: “When the driver takes over his train, he wants to know if the machine is working and what its restrictions are” (in French, “Quand le mécano reprend son train il veut savoir si la machine fonctionne et quelles sont ses restrictions.”). If the interfaces do not provide the necessary information to understand and diagnose the technical failure, the remote driver will be unable to ensure the safety of the driving activity and will not be able to proceed to the transfer procedure. In France, most of the information regarding the train, its size and composition, its weight, the number of cars as well as most details to calculate the parameters for braking are available in what is known as “braking bulletin” (“bulletin de freinage”). This “braking bulletin” is always available in French trains and participants have thus expressed the necessity for interfaces to provide it as well, or at the very least provide similar information before the transfer procedure. Finally, as explained in Section IV.5.2 of Chapter IV, one of the possible solutions to enhance the situation awareness of the remote driver prior to the transfer of authority was to give them information about the past. The goal is to allow the remote driver to easily figure out what happened in the activity before the train stopped by providing information on the previous points of interests, signals and the origin of technical failures. This timeline of events interface was also expected to allow the driver to play back a recording of the activity from each point of interest to help build situation awareness of the past. When presented to the first two train driving experts who helped correct the driving procedure and interfaces before the start of the experiment, they expressed their concerns regarding such interface. First, because of the limited timeframe available to recover the train activity, the ability to replay previous events from the activity seemed counter-productive and the information that could be obtained from such playbacks that was not already in the itinerary or the failure diagnosis was considered not worth spending the extra time looking into. This interface has thus been scrapped from the experiment but the concept has been presented to each participant. Two of them have confirmed the concerns raised by the driving experts who had helped previously (“*knowledge of previous points of interest and signalling*”). Specifically, one participant added that “The train driver doesn't care what happened before.”. According to that participant, the train driver in charge of recovering the train must only be able to assess the safety of passengers, the train's operating status and that of the remote driving system, then they must obtain the authorisation to start the driving activity

from an external authority. Perhaps this sort of interface could still be implemented in a way that could target more specifically the reason that lead the train to stop and request a takeover, such as the origin of a technical failure, or a more critical issue, such as an impact with an obstacle that would require on-board intervention.

Nevertheless, obtaining the “*movement authority*”, which is the permission for the train to move on the track, seemed to be by far among the main concerns for a train driver when taking over the driving activity. It had been pointed out by all participants, sometimes multiple times, as observed in Figure 60 in the “*Starting procedure*” category. It was the most frequent comment within the category but also among all observation, on par with the “*importance of safety*” in the activity category. This highlighted two points that had not been anticipated in the design of this scenario. First, especially following an incident, the remote driver in charge of the recovery will be in constant contact with a remote station such as a supervision or troubleshooting station. Perhaps the train remote driving platform itself will be integrated into one of these supervision centres, but the driver will be interacting with other agents at all times during the recovery. Almost all the participants mentioned the fact that they expected to have a telephone or radio to receive instructions and authorisations and were therefore surprised not to have access to one with the context of this scenario. Of course, these elements are very likely a more complete version of a driving platform. The second is the importance of the procedure itself in the driver’s activity. Indeed, it seems from these interviews that obtaining the movement authority was more important for the driver than being able to assess on their own the availability of the track and the state of previous or future signals. Extended to the rest of the activity, it appears that in most situations, train drivers will likely follow instructions before their own judgement. These points are illustrated by the observations regarding the “*lack of instructions*” sub-category, as participants had more freedom in their decision making for the transition of control and the driving phase of the experiment where they expected more and clearer instructions. Finally, while it has sometimes been implied as one of the missing aspects of the starting procedure, only one participant has specifically mentioned the time allocated for the recovery process. How long would it take for a remote driver to be assigned a train to recover and start the procedure and how long should said procedure last at maximum? These are questions to which answers remain uncertain. The driving experts who came to help for the experiment stated that, in France, when assisting a train after a breakdown, the driver and the breakdown assistance centre have about fifteen minutes to identify and resolve the issue. Once

this time has elapsed, help is immediately requested for the train for direct intervention. Until safety and security norms adapted to train teleoperation are properly defined, the project assumed that similar timeframes would apply to remote driving, especially for the recovery of passenger trains.

As participants were not asked direct questions, few participants have commented regarding the categories of “Experience” and “Activity / Driving profession”. The former includes statements relating to the drivers’ experience and knowledge regarding the train, the line or the activity itself. The latter, however, contains observations on the place of human operators and the role of the remote driver in a teleoperated activity. One question they had however, and that came up during the presentation of the platform, was on the nature of the “train remote driver” profession and whether they would also be or have been train drivers before. This question unfortunately remains without a clear answer and is beyond the scope of this project. It is worth noting, however, that the train driving experts interrogated believe a train remote driver must also have prior experience with regular train driving and must be experts with the trains they would recover remotely as well as the lines they would operate on. Most of these comments, however, were made after the driving phase, in the last interview with more direct questions aiming to complete observations from the participants or obtain their opinion on themes they did not mention before. The one topic that came out for every participant, is the “*importance of safety*” in the driving activity and how central safety is when making decisions. This illustrates how central the place of safety is in the railway activities as participants have all expressed concerns on the relevance of teleoperation for railway activities. Indeed, they believe that any change in the activity that might negatively affect the safety of the driving activity as it exists today is undesirable, even when such would happen indirectly or could also positively affect other aspects of the activity.

Finally, the last category “Train remote driving and interfaces” reflects the experts’ feelings regarding teleoperation during the driving phase opposed to their previously expressed apprehensions. It also represents observations made on the remote driving platform interfaces. First, all participants have expressed that the driving platform used in the experiment felt intuitive. This includes performing the driving tasks using the desk controllers, reading and using virtual interfaces as well as the relatively realistic feeling of driving the train from the simulator. While they have of course mentioned that the lack of audio or kinaesthetic information, this latter element was a rather surprising outcome, even with a non-professional

tool. Regarding the transfer of authority, the procedure itself was incomplete which had likely distracted the participants, as previously mentioned. Although, when asked about it after the driving session, they seemed to find using the virtual interfaces to get information on the train and communicate with the system for the transfer process relatively intuitive. Participants found that the process being quite verbose helped understand interactions with the system, but it might have been affected by their lack of prior experience with the platform and providing a lot of textual instructions during the take-over process could prove unfavourable in the future. Additionally, while the aim was not to evaluate the driving process, all of them were able to easily operate the train and perform the driving activity, moving the train until the next station, without prior experience with the simulator. Other observations in the categories were, however, more nuanced and negative. First, one participant had concerns regarding the use of too much assistance (“*danger of assistance*”) as it could harm the driver’s sense of presence in the activity. This is a known phenomenon, previously mentioned in Section II.4.2. Two participants observed a “*forced sense of presence*”, mentioned twice by one of them, along with an “*increased mental workload*”. When asked to elaborate on the subject, they explained it was difficult for them to mentally place themselves in the situation which was both distracting and tiring. It is very likely, however, that this feeling has been largely affected by the use of a simulator. The simulator, even if relatively realistic regarding the activity, was only able to provide a 3D generated view of the environment which reinforces the feeling of simulation, forcing the user to exert greater mental effort to imagine the corresponding real-life situation.

Using the insight from these exchanges

In conclusion, this analysis offers the perspective of train driving experts on the remote recovery of a train after a technical failure, which should help shape future designs of remote driving systems. These exchanges are extremely valuable to define and design user-centred systems and the feedback seem to be in line with most hypotheses. For example, addressing the absence of some sensory channels, such as audio and kinaesthetic information, will be a priority for the design of future interfaces. Innovative means to transform the data that can be acquired from the train cabin and transmitted it to the remote driver must be explored to enhance the readability of interfaces, the overall immersion for the driver and of course, their situation awareness.

A balance between providing assistance and avoiding over-reliance on said assistance is crucial, requiring future designs to favour systems that preserve the driver's sense of presence

and control when possible. The identified "forced sense of presence" during the experimentations and its associated mental workload underlines the necessity of implementing features that can alleviate the cognitive strain, especially in the context of remote driving. The participants' ability to easily operate the train without prior experience with the simulator suggests that, after a period of familiarisation and training, a versatile and general solution could be used and trusted by train drivers. Currently, however, driving experts seem to mostly express concerns regarding the overall safety of remote operations as they do not imagine the activity without a direct human intervention.

V.3 Second campaign: Testing the system's behaviour in situations of authority transfer

V.3.1 Objectives and context

The second campaign was carried out at the beginning of 2024. The aim of the first campaign was to understand the point of view of expert drivers during a remote recovery, in the context of the first scenario in Section IV.2.2. The aim of the second campaign was to test the second and third scenarios and the virtual interfaces for the transfer of authority. In these scenarios, the train is no longer stationary at the start of the mission because of a technical failure. Instead, the mission parameters simply accept that a portion of the line is already defined to not be suitable for autonomous driving, for reasons presented in Chapter IV. The other major difference with these scenarios is that they involve a change of authority while the train is still moving.

Unlike the first campaign, the participants were not expert drivers, and this time the tests focused more on the activity on the simulator and the experience of using the platform and its interfaces. While the Train Simulator software was used in the first campaign to provide a realistic environment for the train driver participants, this campaign exploits the potential of UPHF LAMIH CNRS's PSCHITT-Rail simulation platform. Despite providing a tramway environment which was not adapted for the first campaign, this simulator, is an advanced professional tool which offers precise control over the process. As a result, it was possible to develop and integrate the autonomous train control module as well as the decision model for changing modes, presented in Section IV.4.

Ultimately, the objective in this campaign was to validate the theoretical framework for the transfer process, as well as the usability, intuitiveness and usefulness of the virtual interfaces that were implemented.

V.3.2 Simulated environment: PSCHITT-Rail simulator

Briefly mentioned in the previous section, the PSCHITT-Rail platform, visible on Figure 61, is one configuration for the versatile experimental platform PSCHITT (Collaborative Simulation Platform Hybrid Intermodal in Land Transport) at LAMIH UMR CNRS 8201 and operational since 2016. The platform is made of a multi-axis mobile base for the simulation of movements and accelerations, along with numerous sensors. It can be configured for projects related to individuals with reduced mobility, aircraft seat movements, and railway operation, for which an entire tram cabin can be installed as seen in Figure 61.



Figure 61 PSCHITT-Rail platform for tramway/train simulation

In the case of this application, however, the physical platform was not used. Indeed, to simulate the context of teleoperation, the train remote driving platform from Figure 53 in Section V.2 was used to connect to the simulator. The simulated environment from the PSCHITT-Rail platform is the OKSimRail software suite from Oktal for tramway simulation. As explained in the previous chapter, tools for communicating with the simulator and the Simulink models of the autonomous train have been developed using the MQTT

communication protocol. Thanks to these tools, the train remote driving platform could be used to control a train on a railway line of over 16 kilometres. The behaviour of the train in autonomous mode is defined by a feedback loop that follows predefined speed instructions for this line.

V.3.3 Participants

Unlike the first experimental phase, the participants were not expert train drivers. First, the quite restrictive time constraints did not allow for the planning of a new recruitment session with either the French railway company SNCF or the CVGF association, which had previously helped us during the first campaign. If it had been possible, however, it is highly likely that the participation of expert drivers would have completed the study, that would still have involved non-drivers in parallel. Indeed, while the first campaign aimed to encourage dialogue with drivers and gather their opinions from their perspective, involving novice participants in the second campaign seemed favourable. First, the tramway environment might have greatly surprised and confused mainline train drivers. Similarly, it did not seem desirable to invite tramway drivers who would have recognised the environment and signalling but might not have understood the relation with the subject or teleoperation or might have interpreted the project objectives for their own activity. Thus, the decision was made to invite participants who had never driven a train and who had limited or no knowledge of this project while still being familiar with the railway environment. The objective of this latter point was to ensure that the participants had at least basic knowledge of the railway environment so they could more easily understand the driving phase and provide relevant insight when answering the questionnaire.

There were 9 total participants, 4 women and 5 men, between 25 to 41 years old (mean 28.8 and standard deviation 5.11). All participants were engineers or research engineers in the railway industry, although, as previously mentioned, they were not directly involved in the project or remote authority transfer issues. Among the 9 participants, 7 had previously been in a train cabin, and 4 had the opportunity to enter a cabin while the train was moving, notably as part of their professional activities. Only one participant reported having previously experienced a professional railway driving simulator, such as those used for training purposes. Others had either occasionally studied professional simulators in other fields such as automotive or maritime, or had at least some familiarity with non-professional virtual systems, especially from video games.

Finally, all participants had a car driving license (on average for 8.4 years, standard deviation 6.3). This was not a participation criterion for the study, and driving on the simulator is, of course, quite different from driving a car. Nevertheless, there may be specific habits acquired from their driving experience that could influence their decisions in this study when observing the environment or monitoring the speed for example.

V.3.4 Variables

Different configurations were to be tested in this experimental campaign. Since there were only nine participants in this second experimentation, only up to three binary variables could be controlled so each of the eight total configurations could be tested at least once, granted that no participant is excluded from the results. The three variables that were retained would modify the following: the amount of “time” allocated to the transfer process (which is actually linked to the length of the transfer area), the initial state of the train and the behaviour of the ADAS when a TOR is issued.

The first variable controls the length of the transition phase. Precisely, the variable does not modify the duration of the transfer itself, but it reduces the area in which the transfer can happen. According to the complete transfer process presented in Section IV.4.1 of the previous chapter for a transfer of authority while the moving train, a certain point on the line, known as the “transfer limit”, is defined as the last point where the train is authorised to operate under the origin driving mode. For example, for the third scenario, in Section IV.2.4, the autonomous train operates until a specific breaking point where a transfer of authority towards manual driving is required. The train remote driver enters the transfer process before the train reaches this limit to gather information and prepare for the upcoming transfer. The upcoming transfers and their exact position on the line can be anticipated from the assistance interfaces. In this experiment, if the remote driver initiates a transfer before reaching the transfer area, in orange crosshatched area in Figure 62, the ADAS will initially deny the transfer and explain that it is not the appropriate time. If, according to the negotiation process described in IV.4, the participant forces the transfer and the train changes the driving mode outside of the expected areas, an emergency procedure is activated. The participant is then only allowed to begin the transition during the allocated “transfer”, while the train is on the associated portion of the line.

Thus, the first experiment variable controls the length of the “transfer phase” area, specifically the distance between the beginning of the transfer area and the transfer limit. For the

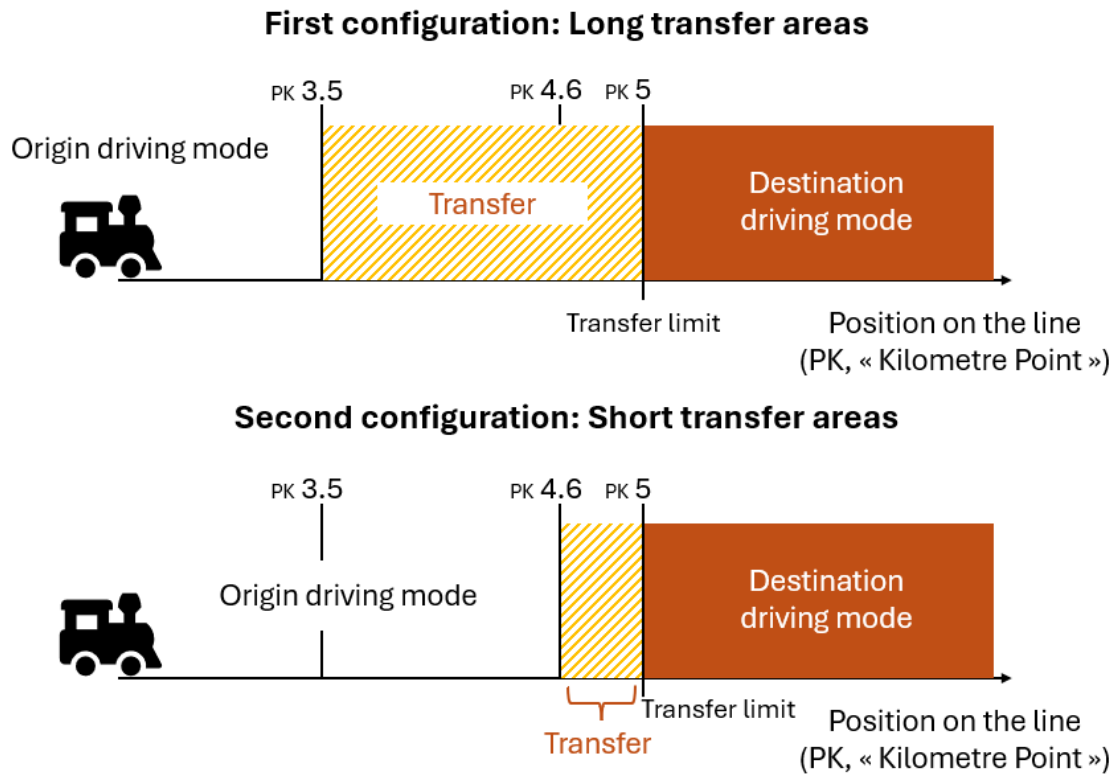


Figure 62 Variables for the second campaign: length of the transfer area

first half of participants, this transfer spanned over 1,5km before the “transfer limit”. For the rest of the panel, the transition could only be done up to 400m before the transfer limit. In a purely mainline railway context, these values can appear relatively small. In the PSCHITT-Rail simulator, the model is that of a tramway, which is much slower and lighter. In particular, in these experiments, train speed will be limited to 70km/h, with driving phases alternating between 20km/h, 50km/h and 70km/h. With such parameters, the train covers the 1.5km transfer zone between around 4.5 minutes and 1.3 minutes, leaving plenty of time for the transfer of authority. Indeed, when interactions with the ADAS are smooth, the transfer of authority is estimated to take from 5 to 10 seconds. This includes the TOR initiated from the screen or receiving a TOR from the train, waiting for the agents’ decisions and preparing the transition of control. Of course, this can greatly increase in case of conflicts or if an agent takes more time to process information, such as getting more information on why the train issued a TOR from the interfaces. With the second parameter of a transfer area of only 400m, the time for the transitions varies between about 1 minute for the lowest speeds to only about 21 seconds at higher speeds which is much more restrictive and likely well below what could be expected in real-life applications.

In the case of the experiment, if the participant respects the speed limits, transfers at relatively high speeds (50 to 70km/h) should only happen for the final transition from manual to autonomous, leading to the end of the driving phase (see part V.3.5).

Although they know that several transitions are expected in the driving phase, the participants were not aware of the length and location of transfer areas before the mission. As these were only displayed on the help interfaces, they cannot estimate the time necessary for upcoming transfers in advance. Thus, the objective of this first variable is to observe potential behaviour differences between participants when the transfer seems very short or when a lot of time is allocated. In particular, the aim is to observe whether, when the transfer area is large, participants will choose to wait for a more appropriate time before transferring or obtaining control of the train after they entered. It should be noted, however, that since the participants had not received any training beforehand, lacked train driving experience, and were relatively few, the results cannot be used as definitive conclusions.

Participant	Variable 1 Transition length	Variable 2 Initial train state	Variable 3 « Conflict »
<i>Participant n°1</i>	Long	Moving	None
<i>Participant n°2</i>	Short	Moving	None
<i>Participant n°3</i>	Long	Stopped	None
<i>Participant n°4</i>	Short	Stopped	None
<i>Participant n°5</i>	Long	Moving	One TOR refused
<i>Participant n°6</i>	Short	Moving	One TOR refused
<i>Participant n°7</i>	Long	Stopped	One TOR refused
<i>Participant n°8</i>	Short	Stopped	One TOR refused
<i>Participant n°9</i>	Long	Moving	None

Figure 63 Different variable configurations for each participant of the second experimental campaign

During the driving phase, all participants in this campaign would alternate between manual and autonomous driving phases, for a total of four transitions. The second variable controls the context of the first transition, to follow either the second or third scenario presented in Chapter IV, Section IV.2. With this configuration, the train was stationary at the beginning of

the driving session and the first take-over to manual driving was done while the train was stopped for half the participants. For the remaining participants, the train is moving autonomously at the beginning of the session and the transfer is done while the train is still moving. All following transfers, towards either autonomous driving or manual driving, are done while the train is moving. In all cases, the recovery of a moving train is tested in these experiments. However, as the participants have no prior experience with the simulator, the objective of this variable is to observe a possible difference in behaviour when a train is resumed while stationary or in motion, and to determine whether an initial when stopped influences a future transfer in motion. Finally, since there are multiple transfers during the experiment, another objective is to see how participants adapt and learn how to use the interfaces.

Finally, the last variable introduced an element of conflict in one of the transitions for half of the participants. During the last transfer to manual mode, which corresponds to the penultimate transition (see part V.3.5), the remote driver is expected to request the transfer to manual driving when they arrive in the appropriate area on the line, but the autonomous train indicates that it is busy and not ready to carry out the transfer and refuses. The driver can then accept the refusal and wait for the system to repeat the request itself or initiate the transfer again later. The driver can also refuse the system's decision and force the transfer. As it was not possible to simulate overly complicated events, this case results in a normal transfer to manual without any incident. The aim was to test, although on a rather small number of participants, the negotiation phase, and to observe how the participants use the information communicated by the system to make a decision.

Figure 63 presents the configurations for each of the participants. The three variables are named "variable 1", "variable 2" and "variable 3" respectively, in order of presentation.

V.3.5 Testing procedure

The campaign's procedure was relatively similar to the first one, and was also combined of three distinct phases that required filling a questionnaire, a driving phase, and completing final post-driving questionnaire. The full procedure is summarised in Figure 64 which also presents the platform being used during the experiment.

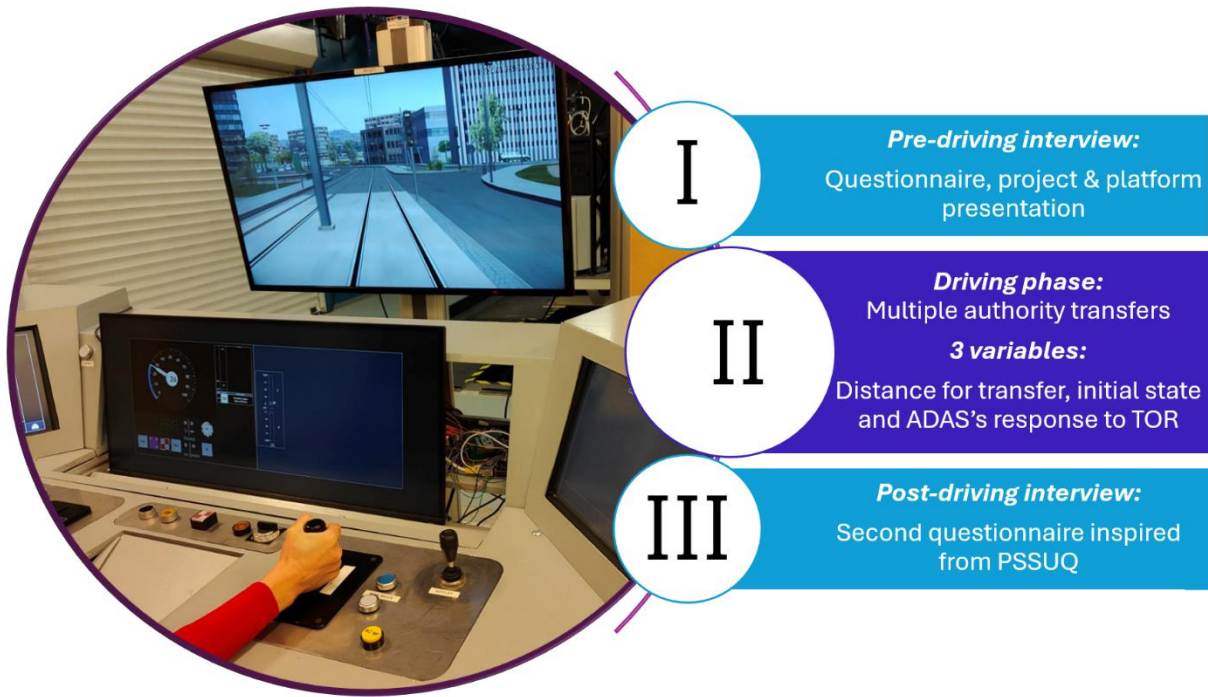


Figure 64 Second experiment's procedure

First questionnaire

The purpose of the first questionnaire was to assess the user's experience with simulators and virtual environments. The actual questionnaire, in French as presented to the participants, is available as Appendix 2. The questionnaire included questions such as:

- Have you ever been in a train cabin? If yes, in what context and how many times?
- Have you ever used or studied a professional railway driving simulator?
- Have you ever used a non-railway virtual driving environment that is not a professional simulator (video game, etc.)?

The second part of the questionnaire had broader questions on automation and teleoperation:

- Have you ever studied or interacted with automated driving systems or teleoperated systems?
- As a user, what aspects of transport automation do you find most beneficial?
- What are your main concerns regarding transport automation or remote control?

The first question of the second part aims to find out the experience the participant may have with the subject of the research project. The other two aim to identify the users' appreciation of these new technologies and potential biases they may have.

Driving phase

After they had filled the first questionnaire, the platform was presented to the participants along with the objective of their mission as a remote train driver. The context of the mission was explained to all participants, corresponding to the previously defined scenarios. They are informed that they must take or release control of the train in specific portions of the line, indicated by the virtual interfaces. They are also informed that the system may not always request a transition itself and are shown how to initiate the transfer request themselves. For all participants, when reaching the area for the first two transitions (with the

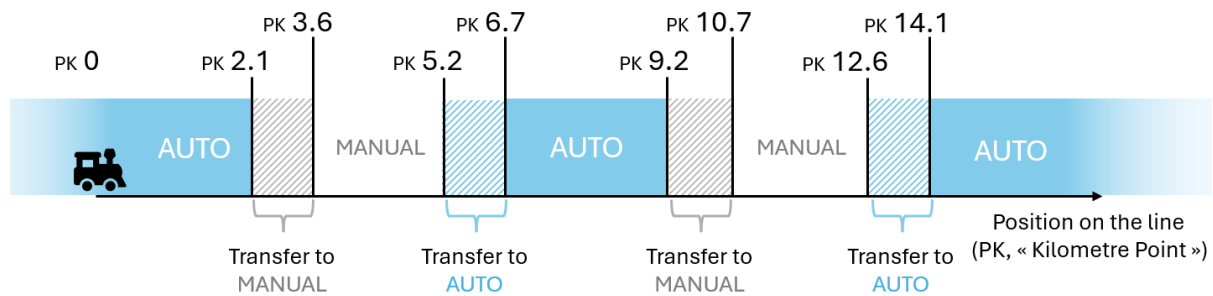


Figure 65 Example of a driving phase for the second experimental campaign in context of “long” transfer areas

exception of the first in scenarios where the train is stationary at the beginning of the activity), the autonomous system initiates a transfer request, which is displayed on the assistance interfaces on the remote driving desk. All following transitions require the participant to use the appropriate button on the interface to ask for a driving mode change.

The driving phase for all participants is composed of four total transitions from autonomous driving to manual, and from manual driving to autonomous, as presented in Figure 65. According to the configuration presented in Figure 63 of part V.3.4, the first “autonomous” phase may be skipped and the length of transfer areas can be reduced from 1.5km to only 0.4km. Overall, following the speed instructions and scheduled transfers, the driving phase takes around 25 minutes and covers slightly over 15 km.

Second questionnaire

The driving phase is followed by a second questionnaire, available as Appendix 3. The aim of the questionnaire is to evaluate the overall experience of the driving phase and the different interfaces. To this end, two possible questionnaires were selected to be the basis for this experiment. The first was John Brooke’s standardised and very popular System Usability

8. « De manière générale, les informations fournies (telles les informations de conduite et les messages à l'écran) étaient claires. »

"Overall, the information given (such as driving information and on-screen messages) was clear."

<p><i>Strongly disagree</i></p> <p>Fortement en désaccord</p>						<p><i>Strongly agree</i></p> <p>Tout à fait d'accord</p>
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Figure 66 Answering the post-study questionnaire from the second experimental campaign

Scale (SUS) (Brooke, 2013). The questionnaire, since it was made publicly available in 1986, has been a reliable tool to assess how people perceive the usability of a system. After evaluation, however, the questionnaire chosen was IBM's Post-Study System Usability Questionnaire (PSSUQ) (Lewis, 1995) which specifically targets studies where participants are questioned after testing a computerised system. A general version of the PSSUQ is also defined, that does not necessarily target post-study evaluations, and is known as the Computer System Usability Questionnaire (CSUQ). According to (Lewis, 2018), the results obtained from the SUS or the CSUQ should not be marginally different, so the PSSUQ, being similar and targeted for a post-study questionnaire, appeared as a good basis evaluations of the user interfaces developed for the experiment. The questionnaire was, however, not used as defined in (Lewis, 1995). A French version of the CSUQ has been suggested in (Gronier and Johannsen, 2022) and was used as basis for Appendix 3. The questions, in French, were used as a base for this questionnaire, only slightly readapted for a post-study questionnaire to like the PSSUQ with some questions changed to match the objectives of the study. For example, the question *"The system gives error messages that clearly tell me how to fix problems."* in the original questionnaire was changed to *"Les messages d'erreur et indications sur les interfaces m'ont clairement indiqué les problèmes et comment les résoudre."* (in English: *"Error messages and indications on interfaces have clearly shown me the problems and how to solve them."*).

Similarly, the question *"I believe I became productive quickly using this system."* was removed from the questionnaire as it did not apply for this study. Each question is a statement to which participants rate whether they "strongly agree" or "strongly disagree" by ticking a box, as shown in Figure 66. Unlike the original PSSUQ questionnaire, the participants had to choose from a 6-point Likert Scale (7 points in the original questionnaire). This choice encourages the participants to decide whether they actually agree or disagree with the

statement, even if only slightly, eliminating neutral answers. Usually, these questionnaires are used to calculate an overall level of usability for the system. The answer from the questionnaire can thus be linked to a score between 0 (when the user strongly disagrees with the statement) and 5 (when the user strongly agrees with the statement). In the original PSSUQ, each statement can be associated with one of the following scale: system usefulness (SYSUSE), information quality (INFOQUAL), and interface quality (INTERQUAL) (Gronier and Johannsen, 2022; Lewis, 1995). However, since the objective is to evaluate the physical and virtual interfaces of the remote driving platform, the “SYSUSE” category may overlap with the “INTERQUAL” scale. When interpreting answers, the two categories have been combined together under a new common scale “interface usefulness” (INTERUSE).

Sub-scale	Question statements	
INTERUSE	Q1	"Overall, I am satisfied with how easy it is to use interfaces."
	Q2	"Using the system interfaces was straightforward and effortless."
	Q3	"I was able to rapidly accomplish the scenario objectives using these interfaces."
	Q4	"I felt comfortable using the interfaces."
	Q5	"I quickly learned to use the interfaces efficiently."
	Q11	"The aesthetics of the system interfaces were pleasant."
	Q12	"I liked using the interfaces of this system."
	Q13	"This system had all the features and capabilities that I expected it to have."
INFOQUAL	Q6	"When I made a mistake using the interfaces, I was able to recover easily and quickly."
	Q7	"Error messages and prompts on the interfaces clearly indicated the issues and how to resolve them."
	Q8	"Overall, the information provided (such as driving parameters and on-screen messages) was clear."
	Q9	"It was easy to find the information I needed."
	Q10	"The organisation of information on the screens was clear."
Overall appreciation	Q14	"Overall, I have been satisfied with these interfaces."

Figure 67 Question statements from the post-study questionnaire and their respective category

In the context of this study, however, the experimental nature of the interfaces proposed induces obligatory biases when interpreting the answers from the questionnaires. Indeed, as some interfaces and visuals are not yet complete and can be rather minimal in comparison with industrialised systems, their evaluation may be negatively affected. Furthermore, the absence and modification of certain questions can influence the level of reliability of this questionnaire when compared to that defined by (Gronier and Johannsen, 2022). Nonetheless, this questionnaire also allows participants to express their feedback through a comment space. Given the small number of participants, these responses may be more detailed and meaningful than the arbitrary score from the answers to each question, but both can be used, especially when combined together, to formulate hypotheses regarding interfaces and to understand the opinions and needs of users for future applications. Figure 67 presents all questions adapted from the PSSUQ in English with their respective categories.

To complete this post-study questionnaire, another section was added to the questionnaire where participants could give their opinion on more general questions such as "*If you encountered difficulties, do you think they were related to the way the interfaces were designed, a lack of information, or other factors?*" as well as questions that targets specific steps of the driving phase such as "*During transition of control process, how did you perceive the interface's communication regarding the current state of the system and the train's level of autonomy? Did you feel that you had a clear and precise understanding of the situation to make decisions?*". Finally, some questions also asked the participant to express ideas and axes of improvement for future interfaces, if they had any.

V.3.6 Analysing results

Before presenting and interpreting the answers to this questionnaire that followed the driving phase, the events of the driving phase can be analysed first. Indeed, several interesting behaviours regarding the use of interfaces were observed.

Driving phase

The first notable element is that, although participants were informed that the system might ask for a transition of control every time, and although buttons to initiate the transfer were presented to them, most were relatively surprised that the system did not initiate the TOR to change the driving mode after the initial transitions. This can likely be explained by the lack



Figure 68 Remote driving platform in use: TOR from the virtual interfaces

of experience with the platform. Indeed, since participants were asked to evaluate the intuitiveness of the interfaces and their ability to learn how to use it, they did not have opportunity to use it before. Having to learn how to use each of the physical interface and virtual, even when rather minimalistic for the activity, while focusing on the train require a lot of concentration. Thus, before using the platform at least once with a proper scenario, it can be relatively easy to forget some parameters of the mission and their role as train remote drivers in this experimental scenario. Notably, the fact that their role also involves initiating a TOR when necessary and not always following the system's decisions. However, this illustrates the potential effects of over-reliance on assistance technologies. Without a good understanding of the system and its limitations, users can easily become inattentive to the tasks they also need to perform, relying instead on the system's assistance. When the system asked for a transfer, participants were immediately guided towards the assistance interface and could quickly accept the transfer. However, when reaching the first transfer zone where the system does not initiate the transfer itself, three participants (participants 1, 2 and 9) did not send a TOR, causing the train to cross the transfer limit point and causing an emergency stop procedure. Regarding other participants, although surprised by the system's lack of request after the first two transitions,

they were able to initiate the transfer via the interface after waiting a few more seconds (about 3 to 5 as illustrated below in Figure 69). Figure 68 presents an example of the ADAS screen communicating with a participant to initiate a transfer of authority.

The second interesting behaviour observed concerns how quickly participants accepted or initialised these transfers. Regarding the previous point, despite occasional initial misunderstandings due to a lack of experience with the system, participants quickly understood how to use the interfaces. Consequently, even after failing the third transition, which required the driver to initiate the TOR, all following transitions were successfully and rapidly completed. Participants had understood the system's functioning and the mission's constraints. However, all but one participant completed these interactions as quickly as possible. Indeed, disregarding the first "tricky" transition that required a driver's action, 8 out of all participants initiated the transfers immediately as the train entered the transfer zone, often without considering external conditions on the line. While there were no specific traps in the scenario or simulated dangers during this driving phase, it nonetheless highlights a potential issue when using these interfaces. The rapid learning curve is a very positive aspect and they could prove highly useful for enhancing situation awareness, especially as professional remote drivers will have undergone extensive training to use these systems. Unfortunately, while presenting the interfaces without prior training allows studying their intuitiveness and the how easy participants learn to use them, it also implies certain biases and shortcomings due to the lack of experience. Indeed, almost half of the participants (four out of nine) indicated that they were worried about missing the transitions, and that they would sometimes "panic" when entering a transfer area, forcing the transition as soon as possible without worrying about the state of the process.

Regarding the change of behaviour between driving phases, after the transition, one participant was not quite sure what to do during the automated driving phase and kept hands on manipulators, worried about the train speeding or having an emergency. In this scenario, participants were informed that the train was supposed to be independent in autonomous mode and that they were only supposed to react to TOR or initiate them. Other participants let go of the manipulators relatively quickly after switching to autonomous mode. Of course, this scenario implies that users remain aware of upcoming transfers, as several occur during the scenario, and must therefore remain aware of the activity. This not exactly equivalent to a GoA3 level where the driver may not be present in the cab to supervise the driving activity. In

this experiment, this is due to the current lack of means to inform the driver of upcoming events, either from the system, or externally by supervision for example. The activity is not considered GoA2 either, as the user's responsibility is not involved during autonomous phases. Thus, this state may be a little confusing for participants to identify the limits of the autonomous system's use case in autonomous driving mode.

Figure 69 above summarises the driving phase for each participant, indicating the time in seconds to complete each transfer while specifying situations where the train has passed the transfer area without changing mode, leading to an emergency stop. The durations are calculated starting from the moment the train enters the transfer area and the end of the mode change. Once validated by the system and the participant, a transition always lasts around 15

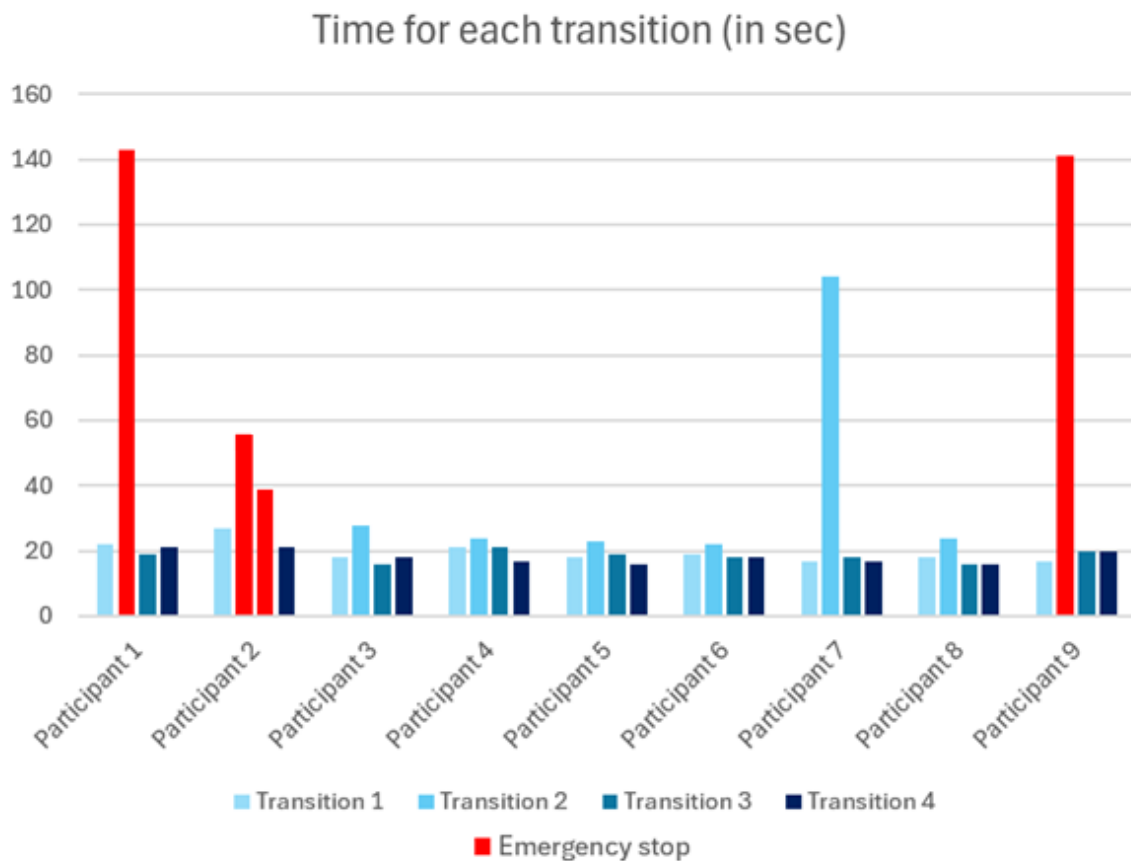


Figure 69 Recorded transitions duration for each participants

seconds, the difference with the recorded values therefore represents the time taken to interact with the interfaces and validate the transfer. Because of the different initial parameters and with only nine participants, comparing the exact duration of the transitions is not completely relevant in itself. However, they do illustrate the various observations made above.

Regardless of the initial conditions, when the transitions are carried out successfully and as soon as the train enters the transfer zone, they take around 20 seconds to complete (min: 16, max: 22). For all participants, the first transition was requested by the ADAS itself, and each of them quickly identified the information and validated the transfer. For all subsequent transitions, the participants themselves had to issue the TOR. For participants 4 to 7, the system would initially deny the second TOR (Figure 63) so they had to either force the transition or wait for a later time for the system to send another request. For all participants, the transition was either a few seconds longer, illustrating the fact they were waiting for another system request before issuing the TOR themselves, or much longer such as participants 1, 2, 7 and 9. For participant 7, this longer time did not lead to an emergency stop, they are actually the only participant who did not immediately force the transition after the ADAS' refusal. When questioned about it after the driving phase, the participant revealed that they did not understand the system's message initially but still chose to wait as the train was going over a bridge and thought it was not a great time to change the driving mode. Participants 4, 5 and 6 had similar response times to participants 3 and 8 for this second TOR despite the additional step where the system refuses the transition. As the interface immediately suggests forcing the TOR as a potential solution, these participants chose this option immediately to conduct the transfer. The actual delay between asking for a TOR and forcing seemed to be only about one second, suggesting they did not completely understand that the system was not behaving normally, especially since it was their first manual TOR. There were not enough participants to properly estimate whether the interface was unclear or these participants just accepted too fast, especially since they had no experience. It is however likely that the information could have been displayed more clearly, accentuating that this behaviour from the system (refusing the TOR) was not expected. For participant 1, 2 and 9, this led to an emergency stop as they had not initially understood that they may have to initiate the transfer themselves. Participant 2 also missed the third transition for the same reason. Compared to the second transition for participants 1 and 9 who lasted more than two minutes (about 140 seconds), the second and third transitions for participant 2 only lasted about 56 seconds and 39 seconds respectively because the transfer areas were reduced to only 400m (Figure 63). Whether they had an emergency stop or not, all participants then learned to anticipate the transition from the interfaces and were ready to initiate the transfer as soon as the train entered the transfer area. Thus, for all participants, the last transition lasted about the same time as the first that was requested by the train.

Participants' answers to the questionnaire

As explained above, the final questionnaire of this experiment has two components, a general appreciation evaluation, and a space for discussion. For each question, participants could tick a box depending on how they agree with the question statement. This answer is translated into a score between 0 to 5. This part will present a general overview of the questionnaire's answers before analysing the actual verbatim from participants' comments.

Overall, almost all participants indicated that they enjoyed using the simulator, and appreciated the various interfaces. Figure 70 presents the score given by each participant for each of the thirteen first questions as a box plot. For each question, the diagram displays answers to the questionnaires, as well as the minimum scores given, the two quartiles and the median value with an orange line. With the exception of a few more critical responses, that will be analysed separately, the majority of the scores given for all questions is 4 or 5, indicating that participants tended to agree strongly with each of the statements in Figure 67.

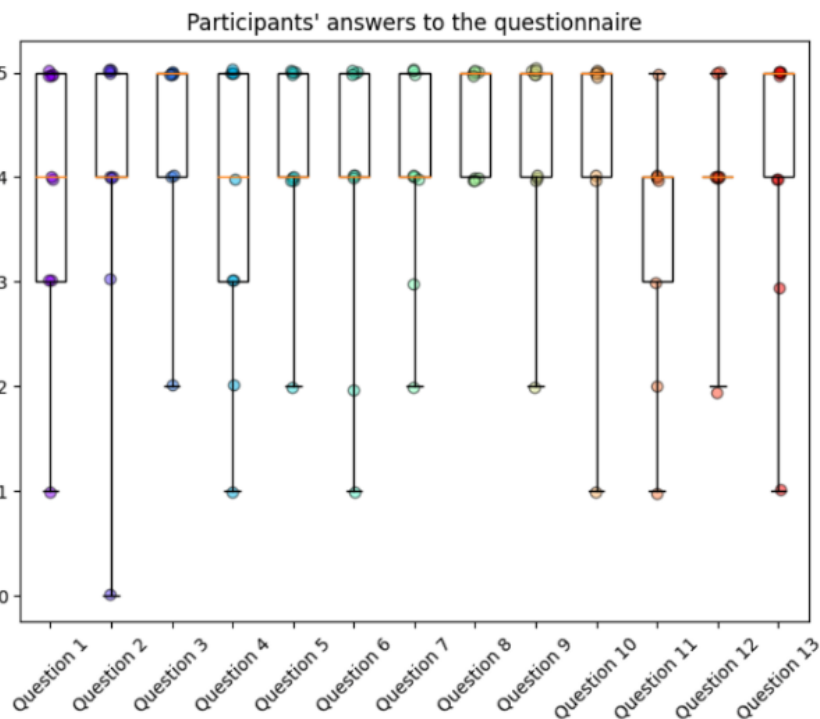


Figure 70 Distribution of participants' responses to the second questionnaire of the second experimental campaign.

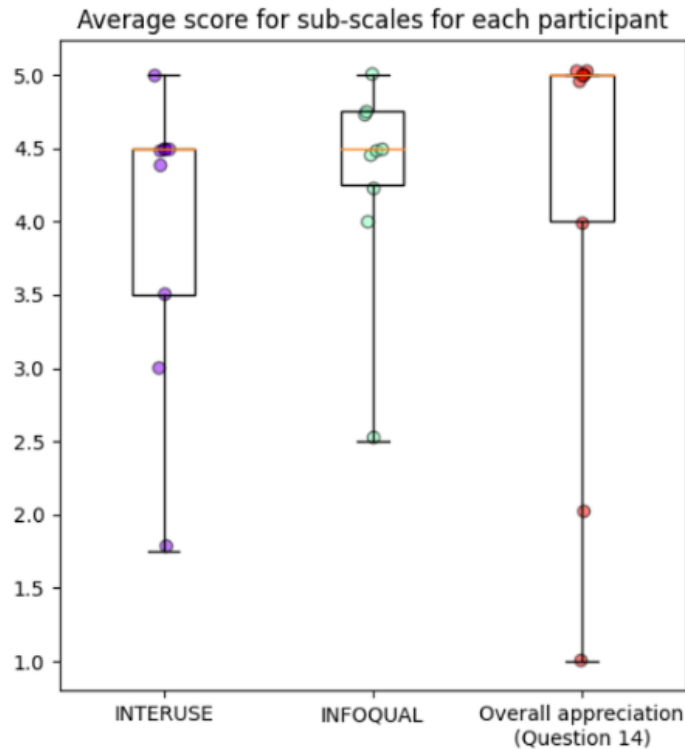


Figure 71 Average score for participants' responses to the second questionnaire, according to the defined subscales

Figure 71 presents the average scores for the two subscales defined previously, INTERUSE for the interface quality and usability (questions 1-5 and 11-13), and INFOQUAL for the quality of the displayed information (questions 6-10). The figure also presents the answers to the 14th question on the overall appreciation of the platform (see Figure 67) to which most participant answered they strongly agree with “being satisfied with the interfaces”. In average, the INTERUSE scale got a score of 3.96 with a standard deviation of 0.97 and a median of 4.5. The INFOQUAL scale got an average score of 4.31 with a standard deviation of 0.70 and a median of 4.5. The questions take the form of positive statements, such as "It was easy to find the information I needed". A score of 3 corresponds to a slight appreciation of the elements being studied, a score of 4 to a good appreciation, and a maximum score of 5 indicates that the participant totally agrees with the statement. Thus, the average and median scores for both the INTERUSE and INFOQUAL categories seem to indicate that participants quite strongly appreciated the presented interfaces and the quality of the displayed information in the context of their mission in the experiment. These results are very promising and confirm the general observations made during the driving phase. Indeed, even with very little knowledge of the system, the virtual and physical interfaces were appreciated and helped the

participants to achieve the objectives of the scenario. The authority transfer phases, the current driving mode and the state of transitions were clearly presented.

However, these results must be set against a few important factors. First there were only nine participants and there were not driving experts, so they might minimise the impact of certain factors or problems. It is thus significant conclusions cannot be made from this panel only. Then, the mission context, the various transition phases and the simulated environment in general remained relatively simple compared to actual train driving. As a result, participants were able to concentrate more easily on the proposed interfaces, providing the main manipulators and information for train control, and assistance when changing driving modes. And finally, the differences between each score from "strongly disagree" to "strongly agree" in the questionnaire may be vague and participants may interpret them differently. In particular, when they relatively agree with a response, it may be easier to tick closer to "strongly agree", and they may be less likely to choose a lower score unless they have an actual strong disagreement, giving greater weight to lower scores. (Joshi et al., 2015) suggests that when using a questionnaire using a Likert-scale, it is important to determine whether the points on the scale are equivalent and equidistant. For example, is a 4 closer to a 5 (strongly agree) than a 1 is to a 0 (strongly disagree)? In the case of this study, this is not perfectly defined, but the main objective of the questionnaire is to get a general opinion of the participants' appreciation of interfaces, which appears to be largely positive for this experiment.

How should the lowest scores be interpreted? To understand the participants' feedback, whether positive or negative, and to encourage them to elaborate on their answers to the questionnaire, a comment section was provided for each question. This part will now analyse the content of these comments to highlight the main feedback from participants, the most appreciated elements of the driving session, and of course the main criticisms. Overall, participants rarely added comments when they indicated that they "strongly agree" with the question, which was most answers. However, they all elaborated on their answer whenever they felt it was necessary. This analysis will mostly focus on the general opinion, while specific and unique comments from individual participants may be excluded if it is more linked to personal taste, such as on the use of a specific colour. Nevertheless, they will be kept and may contribute to future studies. The main comments that will be used to identify improvement axes are the following.

First, all the participants mentioned the difference in information between the autonomous mode and the manual mode, specifically the "lack of information in autonomous mode". This choice aimed to highlight the difference between automation levels and to separate the modes where the remote driver does not need to actively monitor the driving activity. Of course, in the context of the experimental study, the participants had to remain aware of the process to anticipate future transfers and they could feel a potential lack of important information to monitor the activity, even when it was not necessary. Notably, one participant mentioned a "constant feeling of not doing everything that was required". For example, during the first transition when the system does not request the transfer itself, the participant indicated that they knew they could use the interface to initiate the transfer, but that they were not sure they were "allowed" to do so. Once the transfer had been initiated, however, and when in manual driving mode, all participants indicated that they had the necessary information for the activity, at least in the context of this experiment.

Among the missing information in autonomous mode, however, one that was noticed by all participants, and which negatively affected their ability to prepare for a transfer to manual driving, is the lack of speed limitation information. Indeed, autonomous mode interfaces did not display current speed limitations or those to come, unlike interfaces in manual mode do, as presented in IV.5.1. Having no prior knowledge of the line, participants could not anticipate future changes of instructions. Overall, most participants did not really understand why interfaces differ between modes and change after the transition. For example, originally, the change between the horizontal scrolling line profile in autonomous mode (Figure 49 in Section IV.5.1) and the vertical scrolling interface (Figure 50 in Section IV.5.1) was intended to help distinguish between driving modes, offering a longer view of the line in autonomous mode, and bringing the main information closer to the centre of the screens in manual mode. It appears that this could be more confusing than helpful to users. Following studies may explore what formalism is more desirable, and to what extent it could be improved and implemented in the future.

Although they were not variables of the experiment, some participants also mentioned the latency as an issue during the driving phase. Latency from the commands, exchanges between the simulator and the driving platform and until the video feedback was approximately of 2 to 3 seconds. Although in a simulated environment, where the transmission of information could have been simplified and optimised, this latency was intentionally maintained for all

participants to simulate a remote driving situation where this remains of the technical barriers of teleoperation.

Another participant suggests further areas of improvement that are interesting. Despite being mentioned by only one participant, they are in line with the previously identified and anticipated needs from Chapters II, III, and IV. In the comments, the participant noted that their attention was often diverted from the track to the interfaces, which is both distracting while driving and could also become tiring. This observation supports the need to avoid overloading the visual channel. The same participant also suggested using other means of communication, such as haptic feedback or auditory cues. In addition, mainly for assistance interfaces during transfers of authority, the participant suggested that the text could sometimes be replaced by symbols, particularly when time is limited. They wrote that "the text is too long to read" or that it is not always easy to understand quickly. For example, the participant (participant 7 previously mentioned) did not understand the system's message when it refused the transition, which was one of the variables in the scenario (Figure 63), and simply waited to initiate the transition at a later time.

Finally, the rest of the comments from participants was mostly positive and it reflects the answers to questions which got relatively high scores. In particular, participants mostly highlight that the state of the train before and during transfers of authority is always very clearly understandable from interfaces. One participant specifically appreciates the minimalism of the information, ("just the necessary information with a simple yet eloquent design"). However, as previously mentioned, while this is helpful to focus on the objectives of this experimental campaign, it is still hard to determine how easily it can be integrated to more complete and interfaces for actual train driving, but they can offer ideas to rethink how virtual interfaces could be implemented and improved for train remote driving in general, to be more readable and efficient. Another participant also expressed not being comfortable during the first transfers. Indeed, while all physical and virtual interfaces were relatively intuitive, they still required, because of the lack of prior experience, a short adaptation period during initial transitions of control. This should be easily addressed by training future remote drivers to use the remote driving platform. Similarly, the change of authority could happen through different sub-levels of automation and authority to guide the operator progressively towards the destination authority.

V.4 Conclusion

Despite a number of challenges, two separate experimental campaigns have been successfully set up. The aim was to provide a functional validation of the implemented systems and interfaces presented in the previous chapter while testing their usability and desirability in the form of an exchange centred around the experience of the human operator. To this end, the first campaign benefited from the help of expert train drivers who were able to share their experience and their suggestions for the future needs of the activity. The drivers were able to take part in the simulated remote recovery of an autonomous train after a technical failure, using a simulated environment. The main objective of this first campaign was to encourage exchanges with drivers in immersive conditions. Their experience is key to improve the understanding of the activity as well as current and future needs. Of course, the major evolutions of the activity, such as the rise of automated driving systems and train remote control, can be a source of concern for today's drivers, both in terms of safety and social constraints. However, these open discussions are crucial to ensuring that these changes happen alongside drivers, centred around their best interests. This first campaign has been highly instructive and helped identify major needs for remote train recovery, particularly in terms of immersion and sense of presence for the human operator, and helped understand the future challenges to improve trust in future train remote driving applications. Notably, these exchanges with expert drivers gave multiple insights on what information drivers expect the most when taking over the control of a train. Participants emphasised how getting external “movement authority” was more important to them than trusting their own judgement, at least in most cases. They also expressed how important the safety of the passengers, as well as that of the train and the infrastructure, and how they expect the remote driving platform to be able to monitor and interact directly with passengers. Nevertheless, they also expressed multiple concerns on the viability of remote driving and train automation, which further accentuates the need to provide reliable systems and interfaces, and to create and maintain a high level of trust in their use.

To evaluate the physical and virtual interfaces suggested in the previous chapter, a second experimental campaign was carried out with nine engineers working in railway. This time, the experiment was based on the other two scenarios from Chapter IV which involved authority transfers of with a moving train. While it is still not entirely clear in what context

such ongoing authority transfers would be applied, this scenario provides an opportunity to observe the most difficult transition context for the driver. Indeed, the remote driver must carry out the transfer in a limited timeframe while building and maintaining situation awareness of the activity. Before and during the transfer, they must know the state of the system, as well as their own authority and his responsibilities while being able to interact with other agents, such as the automated train. General interfaces have been implemented, notably to help anticipate, prepare, and monitor transitions. Overall, the feedback from the participants of this campaign was very favourable and the interfaces seem promising. Among the takeaways, once again, is the importance of offering interfaces that are both comprehensive and concise, so as not to overload the remote driver's mental workload. To achieve this, it is crucial to develop multimodal interfaces that do not rely solely on visual information. Despite their lack of experience with the platform, the participants were guided through the remote driving and authority transfer phases and could quickly acquire sufficient knowledge to carry out the task assigned to them and understand the authority transfer process. It is thus possible that, with the right training, teleoperation systems could be used by new remote drivers who had never driven a train on-board. In particular, if these remote-control platforms promote interoperability and enable potentially different trains to be driven using the same interfaces and formalisms. On the other hand, the experiments were based on simulated and relatively simple situations, and it is still highly likely that a great experience or knowledge base of in-cabin driving will still be required to be able to deal with all potential situations.

From the positive outcomes in these experimentations, however, these interfaces can serve as a valuable basis for the design of future interfaces for train teleoperation in general, and to assist with the authority transfer process in perhaps even more challenging conditions. Of course, the following studies must also define more precisely the short and long term use cases for the teleoperation of an autonomous train along with the possibility of transferring control of a moving train between agents. Similarly, more attention must be paid to the remote driver's job, their role, capacities, and the possible future organisation of their profession.

Ultimately, to overcome the many remaining challenges, this first basis of knowledge can be used as part of an iterative design approach that emphasises user feedback loops and collaboration between system designers, human factors specialists and railway and train driving experts. Integrating these considerations means that future designs could not only meet

current challenges, but they may also adapt prospectively to future needs, preferences, and safety considerations regarding rail teleoperation, with a focus on human-centred principles.

CONCLUSION

To what extent can an agent take over, share or hand over the control and authority during the train driving activity with an autonomous train and from a remote station? What are the limits of such applications, and what can be done to support the remote driver during authority transfers?

To find answers to these questions, the three main axes of the thesis were explored separately: i) transport automation, ii) teleoperation and iii) transfers of authority. The literature study on transport automation and railway automation helped characterise the current understanding of the “autonomous train” and anticipate the limits and future needs of such systems in terms of human factors. Train remote driving, on the other hand, allows a train driver to intervene on a train without being directly on board. Initially, the development of railway automation could appear to partially contradict with the simultaneous development of train remote driving. Indeed, by definition, the automation of an activity tends to minimise the need for human intervention or even aims to become completely independent from it while teleoperation maintains the human activity as much as possible, even if it happens outside its initial environment. However, the two themes are not mutually exclusive and the main goal of this thesis is of course to study the possibility for teleoperation to complement the use cases of the autonomous train. Nonetheless, this separation implies that systems designed for train automation, centred on a computerised mode of operation, and systems designed for teleoperation by a human driver present major differences in their roles, design, and their ability to interact with a human operator.

Given the relatively recent state of research for automation and teleoperation for mainline rail transport, this thesis is quite prospective in nature and many barriers remain to be overcome. Regarding the deployment of autonomous trains, for example, the technologies are not yet, if ever, able to respond to the full complexity of situations encountered in open world railway operations, or may not comply to the strict constraints of railway safety standards. The goal of the TASV project, within which this thesis is being carried out, is to contribute in making these technologies a reality for the future of rail transport in France. Similarly, train teleoperation faces major challenges in terms of technological constraints, for remote transmission or safety, and human factors, as the driver's activity is greatly affected from being separated from the train. In particular, transmitting information from the train to the remote driving station results in an inevitable loss and degradation of information and reduced perception relative to several sensory channels compared with in-cab activity. Additionally,

train remote driving leads to a reduced sense of presence and the remote driver has a more limited knowledge of the process in general, especially in the context of a remote recovery of the activity, where the remote driver has limited initial information on the process before the transfer. This authority transfer phase corresponds to the third axis explored in this thesis. The study of authority transfers thus corresponds both to changes in driving mode, between manual driving by the human operator and autonomous driving by the technical system, and the transition between automation and teleoperation in general, while considering the difficulties that are specific to each. From the analysis of these three axes, general problematics for this thesis were extracted. What is the place of teleoperation, when performed by a human operator, in the activity of the autonomous train? How can and should the autonomous train communicate with the remote driver to enable remote authority transfers? And finally, what assistance systems and interfaces in general can help the remote driver to build and maintain situation awareness so authority transfers can take place?

The role of teleoperation for the autonomous train is already suggested by the postulate of the study, which accepts train remote driving as a potential means for a human intervention on an autonomous train when no human agent is present on board. The objective is to find answers to the current limits of train automation and deal with situations where autonomous operation without human expertise would not be completely possible. In the thesis, two situations were imagined. The first is following a technical failure in the autonomous system, such as the failure of an obstacle detection module, that would make autonomous driving impossible for safety reasons but would not prevent teleoperation. The other hypothesis suggests that, initially and for various potential factors such as to comply with safety standards, the infrastructure of the rail network might not allow fully autonomous operation throughout a whole itinerary or might be temporarily unavailable in a portion of the line. Thus, regular and predictable remotely operated recoveries of the activity could allow the autonomous train to keep operating on these lines. Similarly, a human expertise could become punctually necessary, such as to assist and confirm the detection of an obstacle by a previous train on the line for example. The usual definitions of Grades of Automation (GoA) exclude teleoperation, and present the human operator either directly in the cab to control the train, or away from it. To connect teleoperation and autonomous applications, new, more open GoA definitions have been proposed in the thesis, to include train remote control and focus definitions on agent authority.

Then, to contribute to making remote authority transfers possible, this study proposes a human-centred approach, through the application of a multi-agent cooperation model and the study of the technical system through its interactions with humans. In railway transport, as in other technological fields, the main considerations in the research and development of advanced systems, such as teleoperation or automation, are usually more focused on the technical challenges and the progress of technologies. Indeed, it is these areas of research and engineering, which include for example automation, safety or AI, that have led to advances in technology, equipment and infrastructure, and to the development of advanced computerised driving systems. However, the use of these technologies is usually still linked to a human activity, and their developments must therefore be carried out in a way that takes into account the needs and the constraints specific to this human activity, to guarantee a cooperative environment adapted to all. This desire to put or maintain the “human” at the heart of technical system design, supported by the study of human factors and human-machine cooperation, is now gradually being adopted in various fields such as production, robotics and transport. In mainline railway transport, these questions are still fairly recent and this thesis also aims to contribute to their integration into the design of future systems. In the proposed cooperation model, the interactions between three agents are studied. The train remote driver, who is the human operator, interacts with the autonomous train, the technical system for which the ability to cooperate with the remote driver must be identified and developed. Finally, to facilitate communication between these agents and help the human operator in their activity, as well as to help build situation awareness and engage in an authority transfer, a third agent is considered, an Advanced Driver Assistance System (ADAS) located with the human operator within the train remote driving station. The ADAS must be able to communicate both with the autonomous train and the remote driver, to support the exchanges between the agents, and use the interfaces of the remote driving platform to assist the operator in understanding and analysing the process and in making decisions.

Several physical and virtual interfaces were explored and developed for the thesis. In addition to providing the essential driving information required for teleoperation, they aim to help remote drivers to immerse themselves quickly in the remote activity when they were initially "out of the loop", not being on board and potentially not knowing the mission before the transfer is assigned. The interfaces help follow the process of transfer of authority, and the changes in role, and therefore in responsibility, for the remote driver and the autonomous

system. Two separate experimental campaigns have been carried out to evaluate the usability and relevance of these interfaces and to complement the understanding of future needs. Through these two experiments, interfaces and remote transfers were tested in several situations in line with the different hypothetical scenarios of such a takeover, as imagined in the defined use cases. The first is to take over and hand over control of a stationary train, which is likely the simplest and safest context for teleoperation, but which lengthens the transition phases considerably and, if frequent, may not be beneficial compared to keeping a driver on board. Alternatively, transfers were tested while the train was still running, in an attempt to optimise transfer times when possible. This option probably is the one that highlights the most the challenges of remote transfers for the human operator and could, after identifying the situations in which this would be applicable, become a major use case for sharing the activity between an autonomous train and a remote driver.

Ultimately, what can be taken from this study, which explores both very broad general concepts and very specific scenarios and use cases, focusing specifically on the authority transfer process?

In order to overcome the general limitations of teleoperation, both the literature review and the experiments pointed out that it is crucial to be able to transmit to the remote driving station all the essential information needed to drive the train (vision of the environment, train dynamics, controller status, etc.) while taking care not to overload the visual channel. This, as highlighted by the experiments, is important to reduce the mental workload that results from overusing visual information, and to benefit from other means of communication, such as sound information and sensory feedback that can efficiently complement visual information. As the interface elements used in the experiments were mainly visual, the train driving experts who took part mentioned a very reduced sense of presence and the participants in general tended to confirm that it was difficult to make effective use of many visual virtual interfaces, such as the train's view on screens, general driving interfaces, assistance tools such as the dynamic track profile, and messages from the assistance system and the train when a transfer of authority was initiated. Regarding the transmission of information, among the various challenges related to human factors and the needs of the remote driver one to enable the transfers, extracted from the literature review and the activity, was the need for the driver to build appropriated situation awareness. In fact, in the most restrictive cases, when the remote driver must prepare for an upcoming transfer, they may know nothing about the activity, apart

perhaps from the general context of the mission that would be communicated before connecting to the train via the remote driving station. The interfaces must therefore help the user, in a limited time, become aware of the process' current state along with past events, and to anticipate future events, including upcoming authority transfers.

Finally, regarding the autonomous train, even when it is operating in nominal mode in a highly or completely autonomous way and without human presence, if the activity allows for the possibility of a transfer towards teleoperation, it is essential to be able to communicate effectively with a human operator. For the transfer of authority, the operator must build situation awareness before it is initiated, then know the system's capabilities and level of authority at all times during the transfer, in order to monitor the process and their own authority. The remote driver's experience with the remote driving platform and the rules for transfers defined for the activity help determine how the process evolves, but it must also be completed by all the information that the autonomous system is able to communicate. To implement this for the study, an architecture of the authority transfer process for the autonomous train has been defined and proposed in the thesis. This model presents general states, such as the driving modes corresponding to manual driving GoA1 and autonomous driving GoA3, of the autonomous system and their sub-states in the form of a state chart. The transfer process, which starts and evolves from interactions between agents and determines the final state of the system, is broken down into the various transitions in the chart. The purpose of the transfer assistance interfaces proposed and evaluated in the experiments was to help the remote driver integrate the process before entering the activity, respond to transfer requests, or initiate the process directly while guiding them through the various states. After the experiments, feedback from the participants was positive as these interfaces were considered relatively relevant and seemed to help participants during changes in driving mode.

What can be done now to pursue the study of all these problematics and build the future of cooperation with the autonomous train through teleoperation?

While these final lines are written, a few remotely driven train demonstrators have already seen the light of day in France (Masson et al., 2022), in other European countries (SBB/CFF/FFS, 2024) and beyond. Several other projects including train remote driving have surfaced such as SNCF's TELLi (Berdal et al., 2023) and other technological advances in railway and automation are constantly being made. In order to continue the studies carried out in this thesis and integrate them into this ongoing development, the analysis of the major

aspects of the subject will have to be revisited and completed, and the proposed methods challenged if necessary. Finally, it will be necessary to reproduce the experimental phases, attempting to overcome the limitations of these tests with a protocol that includes more participants, both driving experts and non-experts, with more advanced automated trains capacities including the integration of newer technologies. In particular, these experiments could be extended to test different configurations for assistance systems and interfaces that could incorporate other communication formalisms and exploit other means of transmitting information. For example, to avoid overloading the visual channel with interfaces, several alternatives can be evaluated, such as the use of alerts and sound signals to draw attention to a specific interface, perhaps taking advantage of the sound spatialisation, or to transmit information directly, such as a TOR or status updates when changing states in the transfer process. Interfaces using perceptive capacities linked to kinaesthesia could also be studied, as these channels of perception are generally unexploited once in a remote environment, with the possible exception of simple proprioception when using physical manipulators. Therefore, researchers studying human-machine interfaces for the future of rail transport and remote driving could consider and study the possibility of using haptic manipulators with force feedback and interfaces with tactile or vibratory feedback, and even to explore the use of mobile platforms to help reconstruct certain information such as acceleration.

The cooperation model presented in this paper has served both as a framework for defining the agents in the study with their interactions, and as a basis for developing the authority transfer process and the associated exchanges via the interfaces. Being constantly evolving, this model must also be revisited and completed in subsequent studies, adapting it to other scenarios of the activity and extending it to include other agents such as supervision centres. Notably, (Gadmer et al., 2021; Pacaux-Lemoine and Crévits, 2010) recommend that the cooperation model should be used within a design loop in which the study of the system and human factors help develop interfaces that are then tested in experimental phases. Following these tests, the new information obtained, together with an update of the state of the art and general knowledge relating to the activity, completes the initial studies in a new design phase, which will use the newly enriched cooperation model. Both design and experimental phases will alternate continuously to always reflect the current model of understanding of the activity and human factors and support the design of industrialised systems. As a first step, this study has laid the foundations of Human-Machine Cooperation (HMC) adapted to the thesis'

subject to extract the main needs specific to the project. To go even further, with increased understanding of the activity, the system and its interactions with human operators, particularly in new design phases of the loop, (Gadmer et al., 2021; Pacaux-Lemoine et al., 2015) suggest a tool to complete the cooperation model in the form of a grid to support a finer breakdown of the Know-How and Know-How-to-Cooperate of agents and of how they use the Common Work Space to complement their capabilities when cooperating. Using this tool, however, requires exploring very precise interactions between agents to be exhaustive and is recommended when a broader model of the process has already been established and with a clearly defined scope to not become an overwhelming and possibly infinite task. Other methods can also be used to complement this study or in conjunction with other studies using HMC. For example, Railenium also uses the "Cognitive Work Analysis" (CWA), as introduced by Rasmussen (Rasmussen, 1997; Rasmussen et al., 1994) a formative analysis method to establish the limits of a system through its constraints rather than describing the observed activity (Berdal, 2022; Pacaux-Lemoine et al., 2022).

Finally, to conclude this overview of perspectives following this study on train teleoperation and remote transfers with the autonomous train, it is worth thinking of the future use cases of teleoperation and automation in rail transport. Although this study has provided some answers as to the role of teleoperation for future autonomous trains, the assumptions of the thesis remain hypotheses. In fact, this study, carried out by the TASV project, which has led to the design of a technical demonstrator for an autonomous passenger train, assumes that highly automated trains and remote-controlled systems are already operational, and that these systems operate in a similar way to the current train driving activity. However, the future development of technologies, infrastructures and safety standards is likely to drastically change the activity and potential use cases of teleoperation and autonomous trains, and potential scenarios for remote takeovers must be reassessed throughout the design of these trains and will evolve concurrently. Consequently, the future role of the remote driver profession and its organisation must be continuously reevaluated. Will it be, as in this study, similar to the profession of a train driver, although carried out remotely through teleoperation, meaning that the remote driver manually controls a single train and assume responsibility for the activity like a train driver within a cab? On the other hand, following the example of less open environments such as the metro or aviation, will remote train control be delegated to autonomous train supervisory stations, whose role would be to monitor several itineraries and trains while taking

relatively long-term decisions, at tactical or strategic levels? Could the two activities be linked? This would allow, for example, a supervisory agent who is already monitoring one or more trains to take part in the driving activity from a teleoperation station, thus benefiting from a higher level of situation awareness in the mission when compared to the hypothesis of the thesis and the TASV project (Brandenburger, 2022; Brandenburger and Naumann, 2018). Will it be possible for these future professions to be performed by new “remote drivers” who have no prior experience of driving a train in a cab? While current driving experts seem to agree that this experience is essential, it is difficult to take a position on the prerequisites for what will effectively be a completely new profession. To what extent and for how long will the train remote driver profession still be necessary, while research and development of autonomous trains is rapidly advancing? And finally, how can we, as researchers and industrial engineers, support future human operators who will be interacting with the trains of tomorrow throughout all these changes? The future actors of rail transport will have to explore and answer these questions. In its own scale, this thesis aims to contribute to this development and encourage future research and industrial projects to keep including human factors at the centre of their studies when working on the systems humans will use tomorrow.

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APPENDIX

1. Autonomous system's state diagram in MATLAB Simulink

2. Pre-driving questionnaire in the experimental campaign

Entretien de pré-conduite

Nom :	Prénom :
Âge :	Sexe :
Etes-vous : Gaucher(e) / Droitier(e)	
Niveau d'étude :	Profession :

Expérience de conduite

1. Etes-vous déjà monté à bord d'une cabine de train à l'arrêt ? Si oui, dans quel contexte et combien de fois ?

2. Etes-vous déjà monté à bord d'une cabine de train en marche ? Si oui, dans quel contexte et combien de fois ?

3. Avez-vous déjà utilisé ou étudié un simulateur de conduite professionnel non ferroviaire (automobile, aviation, etc.) ? Si oui, dans quel contexte et combien de fois ?

3. Post-driving questionnaire in the experimental campaign

Entretien post-conduite

Nom :

Prénom :

Questionnaire de satisfaction et d'utilisabilité

Veillez indiquer dans quelle mesure vous êtes d'accord avec les propositions suivantes en cochant les cases correspondantes. Celles-ci représentent votre opinion entre « Fortement en désaccord » (la plus à gauche) et « Tout à fait d'accord » (la plus à droite).

Ce questionnaire vous demandera de juger votre appréciation de l'utilisation des interfaces utilisées lors de la phase de conduite. Le terme interface fait référence aux éléments physiques du pupitre (manipulateurs, etc.) et leur disposition ainsi qu'aux écrans et éléments virtuels qui y sont affichés.

Enfin, si besoin, vous pouvez ajouter un commentaire pour développer votre opinion.

1. « De manière générale, je suis satisfait(e) de la facilité d'utilisation de ces interfaces. »

Fortement en désaccord

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Tout à fait d'accord

Commentaire :

2. « Utiliser les interfaces du système était direct et sans effort excessif. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

3. « J'ai pu accomplir rapidement les objectifs du scénario grâce à ces interfaces. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

4. « Je me sentais à l'aise pour utiliser les interfaces. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

5. « J'ai rapidement appris à utiliser efficacement les interfaces. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

6. « Lorsque j'ai commis une erreur en utilisant les interfaces, j'ai pu me corriger facilement et rapidement. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

7. « Les messages d'erreur et indications sur les interfaces m'ont clairement indiqué les problèmes et comment les résoudre. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

3

8. « De manière générale, les informations fournies (telles les informations de conduite et les messages à l'écran) étaient claires. »

Fortement en désaccord

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Tout à fait d'accord

Commentaire :

9. « Les informations dont j'avais besoin étaient facile à trouver. »

Fortement en désaccord

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Tout à fait d'accord

Commentaire :

10. « L'organisation des informations sur les écrans de l'interface était claire. »

Fortement en désaccord

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Tout à fait d'accord

Commentaire :

11. « L'esthétique des interfaces de ce système était agréable. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

12. « J'ai eu plaisir à utiliser les interfaces de ce système. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

13. « Ce système possédait toutes les fonctionnalités et capacités que j'en attendais. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

14. « De manière générale, j'ai été satisfait(e) de ces interfaces. »

**Fortement en
désaccord**

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**Tout à fait
d'accord**

Commentaire :

Questionnaire général : Impressions et suggestions

Afin de compléter vos réponses aux questions précédentes, cette partie vous invite à répondre de façon libre aux questions suivantes :

15. Comment les interfaces vous ont-elles aidé à comprendre l'activité, le comportement du train et son environnement avant la reprise à distance, durant celle-ci et pendant la conduite à distance ?

16. Avez-vous rencontré des moments de confusion ou d'incertitude concernant l'état du train ou de son environnement, en particulier avant la reprise à distance ?
17. Quels aspects des interfaces ont rendu la téléconduite ou la reprise à distance plus simple ou difficile pour vous ?
18. Pendant le processus de transfert de contrôle, comment avez-vous perçu la communication de l'interface concernant l'état actuel du système et le niveau d'autonomie du train ? Avez-vous ressenti que vous aviez une compréhension claire et précise de la situation pour prendre des décisions ?
19. Si vous avez rencontré des difficultés, pensez-vous qu'elles étaient liées à la manière dont les interfaces étaient conçues, à un manque d'informations, ou à d'autres facteurs ?

20. Quelles améliorations pourraient être apportées aux interfaces pour aider à prendre des décisions et comprendre le processus de reprise à distance ?

21. Enfin, avez-vous des idées sur la manière dont les informations pourraient être mieux présentées ou organisées sur les interfaces pour vous aider à comprendre la situation ?