Tampere University

Nikoo Razavi

TECHNICAL CONSIDERATIONS IN HUMAN-CENTRED REMOTE OPERATION CENTRE FOR AUTOMATED PUBLIC TRANSPORT

Master thesis
Faculty of Built Environment
Examiner: Prof. Heikki Liimatainen
Markus Pöllänen, Lecturer
April 2025

ABSTRACT

Nikoo Razavi: Technical Considerations in a Human-Centred Remote Operation Centre for Automated Public Transport
Master thesis
Tampere University
Civil engineering (Sustainable transport)
April 2025

The integration of automated vehicles into urban environments is a global objective due to its potential economic and environmental benefits. However, technological limitations, safety concerns, and public scepticism pose significant barriers to widespread adoption. A transitional solution, already utilized in marine and military contexts, is remote operation. While this approach is still emerging for road-based automated vehicles, it presents an opportunity to bridge the gap between conventional driving and full autonomy. Finland's MetaCCAZE project is currently exploring the feasibility of remote operation in urban settings.

This research focuses on the critical factors influencing the establishment of a Remote Operation Centre (ROC) for automated public transport. A human-centred design approach is used to examine workplace conditions, operator requirements, and the technical challenges involved. Given the limited research in this area, the study seeks to assess feasibility, identify obstacles, and refine existing categorizations based on expert input.

Key challenges stem from the physical separation between the operator and the vehicle, requiring a reliable communication system and a robust IT infrastructure. Managing large volumes of data for situational awareness is crucial, with experts recommending visual, haptic, and auditory feedback mechanisms. Additionally, vehicle automation algorithms must dynamically adapt to changing traffic and environmental conditions.

Operators must be equipped to handle emergencies, manage complex traffic scenarios, and ensure route efficiency. A driver’s license is considered essential for understanding fundamental driving principles. Key responsibilities include monitoring vehicle status, conducting inspections, and intervening when necessary. Critical skills encompass multitasking, situational awareness, and rapid decision-making. Training, particularly simulator-based modules, is essential for preparing operators for cognitive demands. Experts suggest limiting shifts to 4–6 hours to mitigate overload, while AI assistance could enable a single operator to manage up to 40 vehicles under optimal conditions.

A significant gap in existing research relates to the maintenance requirements of remote operation centres. Additionally, situational awareness and network connectivity are interdependent, requiring further investigation to minimize negative impacts. While expert insights provide a foundation for operator training, standardized protocols must be developed.

This study contributes to the growing body of research on remote operation in automated urban vehicles, offering insights into its feasibility and challenges. By addressing technical, human, and operational factors, it aims to facilitate the successful implementation of remote operation as a steppingstone toward full autonomy in urban transport.

Keywords: Urban mobility, Human-centred remote operation centre, Remote operation, Intelligent transport systems, Human factor challenges, Smart mobility, Automated vehicles

USE OF AI IN THESIS

I have utilised AI tools in my thesis:

☐ No
☒ Yes

The AI tools utilised in my thesis and their purposes are described below:

Names and versions of AI tools: Copilot 2024

Purpose of using AI tools: Translating the Finnish traffic regulation to English

Sections where AI tools were used: In Theoretical background section 2.10 (Finnish regulation)

I acknowledge that I am fully responsible for the entire content of my thesis, including the parts generated by AI, and accept accountability for any violations of ethical standards in publications.

PREFACE

The motivation to write and research throughout this thesis was akin to the power of the One Ring—except this time, the power stemmed from curiosity.

First and foremost, I am grateful to **Professor Heikki Liimatainen**, who entrusted me with the Ring and allowed me to step into a land that was largely unknown to me, exploring its every corner with inquisitive wonder. Heikki gave me the wings to embark on this journey. I am gratefully indebted to my second supervisor **Markus Pöllänen** for his thoughtful and useful comments on this thesis.

I extend my heartfelt thanks to all those at **Transport Research Centre Verne**, who stood by me like the Fellowship of the Ring. Without their support, this journey would have been truly arduous, at times even impossible and utterly exhausting.

I would also like to express my sincere gratitude to the experts and professors who generously shared their time and insights, contributing to the survey and discussions that shaped this research. Their expertise and perspectives were invaluable in refining the direction of this work.

Finally, I am especially grateful to “**Amin**”, my husband, my own Samwise Gamgee, who believed in me when I struggled to believe in myself.

Tampere, 1 April 2025

Nikoo Razavi

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

ADS	Automated Driving System
ADS-DV	Automated Driving System-Dedicated Vehicles
AV	Automated Vehicle
HAV	Highly Automated Vehicles
HMI	Human-Machine Interaction/Interface
ODD	Operational Design Domain
PT	Public Transport
RA	Remote Assistant
RO	Remote Operation
ROC	Remote Operation Centre
SA	Situational Awareness
SAE	Society of Automative Engineers
UI	User Interface

1. INTRODUCTION

1.1 Background

Automation technologies have made significant strides and have the potential to reshape the future of road transport by 2035 (Li et al., 2024), yet there are situations where a vehicle's automation may fall short (Kettwich et al., 2021). Urban environments with mixed traffic present complex and rapidly changing conditions that challenge Highly Automated Vehicles (HAV) (Razavi & Sierpinski, 2024). Some of those challenges exceed the Operational Design Domain (ODD)—the specific conditions in which an Automated Vehicle (AV) can safely operate autonomously. Additionally, having a human onboard operator as a fallback is not mandatory for AVs operating at Level 4 automation according to the Society of Automotive Engineers (SAE) standards (SAE International, 2021).

Remote Operation (RO) by a human operator could offer a practical solution to enable automated driving without the exhaustive definition of every potential ODD required for fully automated Level 5 driving. Achieving full automation under these standards may be a lengthy process, if attainable at all. Within the framework of substitution models, RO serves as an alternative to the primary controller—in this case, the driving automation system (Shi & Frey, 2021).

The field of RO for automated Public Transport (PT) is still emerging and faces numerous challenges due to lack of study in this area (Gavanas, 2019). These include the necessity for detailed regulations, as well as operational and legal hurdles that could impede technology implementation. This study aims to explore the current landscape of RO for AVs. Employing the Delphi methodology, expert perspectives are gathered to assess the technical feasibility of this approach, focusing on a case study in Finland.

The field of RO in automated PT is still in its early stages. Especially in the fields of regulation, transport, and technical issues, numerous questions and ambiguities remain to be addressed. Even with the modern and advancing software and hardware currently available, there is still a gap in research regarding remotely operated AVs.

1.2 Objectives and research questions

The objective of the research is to investigate technical requirements and obstacles for a remote operating AVs, with an insight into public transport. Understanding the complexities involved in the phenomenon of remotely operating AVs, identifying the factors that may increase or reduce these complexities, as well as recognizing the effective existing standards and relevant regulations, and, more broadly, addressing the technical issues associated with this phenomenon, constitute the aim of this research.

RO in this thesis refers to a situation where a human operator controls or assists a vehicle from a location outside of the vehicle. This study aims to explore its technical and technological feasibility, as well as the workplace conditions and human-related factors that enhance its viability for operators.

Hence the main research question is:

How to set up a remote operation centre following the human-centred design process for automated public transport operations?

The main question is accompanied by the following four sub-questions, as outlined below:

Sub-question 1: *What are the functions of a remote operation centre?*
Sub-question 2: *What are the existing standards, regulations and guidelines?*
Sub-question 3: *What are the technical requirements and obstacles?*
Sub-question 4: *What are the tasks and skills of a remote operator?*

To achieve the objectives of this study and address the stated research questions, previous published articles will be reviewed to establish foundational concepts. Given the limited number of relevant studies, experts in the field will be consulted through questionnaires and interviews. A brief overview of the research methods employed in this study will be provided in Subsection 1.4, followed by a more detailed and comprehensive discussion in Chapter 3.

1.3 Scope of study

This thesis focuses on understanding the RO technology of AVs, with an emphasis on public transport. While this technology is not inherently new (Parr et al., 2024), there are limited studies in the context of road transport and public mobility.

After identifying the key factors influencing the success of this technology, the research will delve into the fundamental aspects of establishing a Remote Operation Centre (ROC). Due to the limited studies available in this field, a questionnaire will be designed and distributed among experts to gather data. The collected information will help identify the critical concerns and challenges associated with implementing this technology in real-world scenarios. It should be noted that some of the discussed factors may be presented in a broad and generalized manner, as each involves highly technical and complex engineering discussions that fall beyond the scope of this study.

The primary focus of this research is on the technical aspects of RO. Legal and social considerations will not be explored in depth. However, given the objectives of the MetaCCAZE project regarding green and connected mobility, relevant regulations in Finland will be considered, as Tampere is one of the trailblazer cities in the project.

The MetaCCAZE project aims to revolutionize urban mobility in European cities by integrating electric, automated, and connected solutions for both passengers and freight, making transport smarter, net-zero, and more efficient. In four trailblazer cities—Amsterdam, Munich, Limassol, and Tampere—MetaCCAZE tests and demonstrates shared, zero-emission mobility technologies, with successful solutions later implemented in six Follower Cities—Athens, Kraków, Gozo, Milan, Miskolc, and Poissy (Paris). To ensure alignment with citizens' needs, local co-creation activities will be organized. By accelerating the shift from conventional vehicles to smart, automated, and user-centred mobility systems, the project contributes to climate neutrality and strengthens the future of Europe's transport and energy sectors (MetaCCAZE, 2025).

Since different use cases may involve varying definitions and categorizations, one of the key aspects investigated in this study will be how different factor categories vary and to what extent regulations (in a summarized and generalized manner) influence this technology.

Another crucial aspect of this research is examining remote operators, including their training process, required skills, and existing operational guidelines. Additionally, the working environment in which these operators interact with AVs will be a focus throughout the study.

1.4 Overview of the research methodology

While various definitions of "research" may exist, it can generally be described as a systematic study aimed at acquiring useful knowledge on specific topics. Research serves as the foundation of human advancement, enabling society to overcome its limitations through curiosity-driven inquiry, systematic analysis, and an unwavering pursuit of understanding that shapes industries, philosophies, and civilizations (Swargiary, 2024).

The methods employed to address research questions can vary depending on the subject, nature, and specific requirements of the study (Saunders et al. 2019). To comprehensively address the research questions, three key data collection methods are employed:

1. Literature review: This provides a theoretical foundation by identifying existing research on RO technology and potential challenges in its implementation. However, literature alone may not capture real-world complexities.
2. Expert interviews: To bridge the gap between theory and practice, semi-structured interviews are conducted with experts in the field. These insights help refine the research focus and align it with epistemological and ontological considerations.
3. Delphi method and questionnaire: Given the complexity of RO technology, a structured Delphi study is used to gather expert opinions iteratively, ensuring the research findings are well-grounded in industry knowledge. This method reflects a pragmatic approach by emphasizing real-world relevance and consensus-building.

By integrating these methods, this study ensures a balanced approach between theoretical understanding and practical application. The research strategy aligns with case study and survey research methods, as data is gathered from both academic and industry experts. Furthermore, since the Delphi method involves iterative data collection over two rounds, the study follows a cross-sectional time frame. The research methodology and employed methods will be discussed in detail in Chapter 3.

1.5 Structure of the thesis

In this thesis, the theoretical background for remote operation (centre), remote operator, challenges of the technology and Finnish regulation related to remote operating AVs will be reviewed in Chapter 2. In Chapter 3, the methodology applied for reaching the answers to research questions will be deployed. Furthermore, the main framework for the application of Delphi method as well as interviews for gathering experts’ opinion about important parameters and obstacles of the phenomenon will be represented in this Chapter.

In Chapter 4, the analysis will be discussed based on the data and responses gathered from the interviews and survey, as well as the theoretical background presented in the previous chapters. In Chapter 5, a concise guideline for the implementation of a ROC will be presented in the form of a flowchart. Finally, in Chapter 6, the findings of the thesis will be summarized in the conclusion.

2. THEORETICAL BACKGROUND

This chapter reviews the existing literature on the recognition and history of RO technology. It then explores the relationship between ROs and driving. The chapter further discusses the various challenges associated with this technology, offering a closer look at the operations centre and the operators themselves. Finally, it examines the principles governing this technology, as well as the relevant regulations in Finland.

2.1 The necessity of remote operation

Continuous progress in technology related to AVs is increasingly making HAVs (SAE Level 5 of Driving Automation) on public roads a closer reality. Simultaneously, regulatory adjustments suggest that countries are preparing for a more significant presence of AVs, both for testing purposes and after-market use (Parr et al., 2024). As computing, sensing, and communication technologies continue to advance, they can enhance the capabilities of AVs. According to Tengilimoglu et al (2023), AVs are expected to perform better than humans, with a significantly reduced likelihood—or complete absence—of errors such as speeding, fatigue from long-distance driving, distraction, and similar issues. However, Smith (2012) claims that the integration of AV technologies with electronic communication systems will introduce additional challenges.

On the other hand, achieving full automation of driving tasks remains a distant goal as real-world driving environments are dynamic and complicated and include edge cases that HAVs cannot manage or resolve (Bengler et al., 2014).

Solutions are being explored to address the issue of disengagement from the Automated Driving System (ADS) in Level 5 vehicles, which can occur due to damage, unexpected operational conditions, or software failures, among other reasons (Parr et al., 2024). An interim solution to leverage today's advanced automation without compromising passenger safety is to outsource the operating task from the driver's onboard cabin to a higher-level entity (Goodall, 2020), such as an operation centre that can remotely control and command the vehicle when needed. These solutions are not solely proposed for the highest level of automation; some texts also mention that they are effective in reaching that level. According to Sheridan (1995) teleoperation (remote operation) is even considered as a prerequisite for the introduction of SAE Level 4 (L4).

RO, as of one solution, enables a human operator to assist an automated and connected vehicle from afar, has been suggested as a way to address the challenges of vehicle automation (Larsson et al., 2023).

To classify the various reasons for arriving at this interim solution, these can be grouped into the following four main categories:

1- Technical challenges and failures: such as navigating interactions with non-AVs (Bhavsar et al., 2017). In high-risk, safety-critical systems like transport, automation introduces new types of risks, such as system failures (software or hardware failures) and latency issues.

2- Society/Safety: Still, we are dealing with the concept of “Trust” in people's attitudes regarding AVs. Social influence has been recognized to be an imperative factor in determining user acceptance of automated vehicles (Kadylak et al., 2021; Sener et al., 2019). Studies are done regarding the importance of exploring user trust in automated vehicles in daily life circumstances. For instance, in a survey conducted by Li et al (2024) participants indicated not fully trust the L4 AV to disengage mentally from the driving loop completely and it also highlighted a significant need for the option and ability to communicate with remote drivers when necessary, which could potentially help them feel more at ease. According to interviewee I01, in a real situation in France, when a group of passengers in a stuck AV (trying to take a turn) felt relieved when they heard a human remote driver who assured them that he was aware of the situation and would handle it. This situation and other similar ones lead us to the statement by (Kadylak et al., 2021; Sener et al., 2019) regarding social influence which has been recognized to be an imperative factor in determining user acceptance of AVs.

3- Regulatory: There are still significant regulatory gaps regarding the testing and operation of AVs on public roads that must be addressed. Regulators should establish a set of operational scenarios and a variety of conditions under which AVs must be assessed, ensuring that public safety is not compromised by the introduction of these vehicles. For instance, issues related to weather conditions and sensor malfunctions due to debris need to be thoroughly examined (Claybrook & Kildare, 2018). Human monitoring can facilitate or fill some of those gaps.

4- Financial aspect: RO is claimed as a cost-saving solution. If AVs can monitor their driving environment and request assistance, when necessary, companies can employ teams of remote operators to minimize the number of drivers required to manage a fleet (Goodall, 2022). Moreover, Tener & Lanir, (2022) claim that it

> is not economically feasible for all AVs to have the best types of technologies and sensors. Hence, Ro can improve the situation in this matter.

On the other hand, according to the survey conducted by Li et al (2024), another reason for the usability of RO could be filling the transition period for even the users of Level 4 AVs and has the potential to address several challenges that are currently hindering the commercialization of AVs (Larsson et al., 2023). Some of the participants commented that using the AV’s menus and functions was somewhat challenging and that some time is needed to transition from traditional driving to AV driving. It seems that RO could be a good option for this time, and it is reasonable that Li et al. (2024) considers RO or teleoperation as the failsafe of Level 4 automated vehicles. Hence, it seems essential to delve in depth into the definitions and function of the concept.

2.2 History of remote operation

RO itself is not a novel concept: any operation of a system or machine from a distance falls within the realm of remote (or tele-) operation (Parr et al., 2024). The earliest significant example of RO is attributed to Nikola Tesla and his radio-controlled boat in 1898. During an Electrical exhibition at Madison Square Garden in New York City, Tesla demonstrated his invention, which he called a "teleautomaton." Utilizing a radio transmitter, he was able to remotely control a boat, which had a receiver that interpreted his commands. This event stands as one of the first instances of wireless RO (Thompson, 2015). This technology established the groundwork for numerous contemporary RO systems. Historically, before the advent of the Internet, numerous scientists, researchers, and companies endeavoured to develop RO systems where operators could interact with equipment from any location worldwide, regardless of time differences (Machotka et al., 2011).

The development of the first unmanned vehicles occurred in both Britain and the USA during World War I. In March 1917, Britain tested the Aerial Target, a small radio-controlled aircraft (Imperial War Museums, n.d.). In the United States, the Kettering Bug, an experimental unmanned aerial torpedo, was developed as a precursor to modern cruise missiles. This device could hit ground targets up to 75 miles (121 km) away from its launch point, traveling at speeds of 50 miles per hour (80 km/h). A successful test flight took place in October 1918. The Bug's expensive design and operation led Dr. Henry W. Walden to develop a rocket that could be controlled by a pilot using radio waves after launch (Cornelisse, 2002). ROs in aviation allow one air traffic controller (ATC-T) to manage several low-traffic airports simultaneously. This has improved operational efficiency by reducing the number of air traffic control officers (ATCOs) needed, as it minimizes traffic gaps. Remote ATC-T also facilitates easier adaptation to new technology and lowers maintenance costs compared to traditional ATC-Ts (Saab, n.d.).

In 2017, the maritime industry witnessed the demonstration of the world’s first remotely operated commercial vessel, the Svitzer Hermod, in Copenhagen Harbour, Denmark. This milestone was part of a collaboration between Rolls-Royce and global towage company Svitzer. From a Remote Operating Centre (ROC) at Svitzer’s headquarters, the vessel’s captain, stationed onshore, successfully maneuvered the ship by berthing it alongside the quay, un-docking, executing a 360° turn, and piloting it back to Svitzer HQ for another docking. The design of the ROC aimed to transform vessel control by focusing on practical input from experienced captains. Unlike traditional wheelhouse designs, the ROC positioned system components to optimize the captain's control and confidence. The goal was to establish a future-proof standard for remotely controlled vessels. Building on this, in 2021, Svitzer A/S, Kongsberg Maritime, and ABS joined forces to develop RECOTUG, the world’s first fully operational tugboat with complete RO capabilities (Safety4Sea Editorial Team, 2022). Autonomous ships hold the potential to reduce environmental impacts and enhance shipping efficiency. Additionally, with a shortage of seafarers, ROs enable an increase in the number of shipments that can be managed with the same number of crew members (MUNIN, 2016). Ideally, the ROC serves as a supervisory station for a fleet of vessels. Some noteworthy projects in the maritime sector are discussed in the following paragraph.

From 1982 to 1988, Japan undertook a project aimed at developing a highly reliable, intelligent, and automated operational system for maritime operations, with the ability to be remotely controlled from a shore-based control station. Meanwhile, South Korea began researching Unmanned Autonomous Surface Vessels (USVs) in 2011, focusing on their use for maritime surveys and surveillance. Some notable projects worth mentioning are the European MUNIN project (2012), REVOLT by DNV-GL (2013–2018), the AAWA project led by Rolls-Royce (2015), Lloyd’s Register Guidance (2016), and the MOL project for the Autonomous Ocean Transport System (2017) (Matikka, 2021).

From a road transport point of view, an automobile was first controlled via radio by an operator in a following vehicle in 1925 (The New York Times, 1925). A small fleet of dockless electric scooters in Atlanta in the United States are repositioned with the help of RO based in Mexico City (Korosec, 2020). According to Sheridan (1995) the traditional way of controlling or manually navigating a vehicle is changed with the European Community PROMETHEUS and DRIVE projects, the Japanese AMTICS and RACS projects, and the American IVHS, for intelligent vehicle highway systems. Thomas B. Sheridan, an American professor of mechanical engineering at the Massachusetts Institute of Technology has mentioned supervisory control in his article, which seems like a fundamental concept for what we today call RO and more precisely, remote assistance, which will be discussed in detail in the following subchapters. It's intriguing to note that he raised concerns at the time regarding whether control should be abruptly taken from the driver or transitioned gradually, allowing both the driver and the computer to operate simultaneously for a period. Additionally, he questioned when and under what conditions control should be returned to the driver. His concerns and worries are among the questions and foundations of RO in our world today (ASME, n.d.).

2.3 Automation and remote operation

According to Ginzburg et al (1966), there were instances where the human direction of mechanized production required additional specialized facilities. This led to the creation of machines designed to replace human physical labour in controlling and inspecting production processes. The field of engineering dealing with these methods and facilities for eliminating human labour in production process control and inspection is known as automation and RO. Specifically, automation involves control and inspection over relatively short distances, while RO involves carrying out similar functions over long distances, necessitating special methods. RO in transport and logistics is not entirely novel (Ginzburg et al., 1966). Many processes in modern industrial production and transport rely heavily on automation and RO.

Although the Automated Driving System (ADS) at level 5 is capable of operating the vehicle in any location and under all conditions (SAE International 2021a), no currently available automated vehicle is capable of functioning in every condition and environment (Goodall, 2020). During the initial adoption and integration phases of Level 4 and 5 AVs, there may arise scenarios where the vehicle faces challenges that its programming cannot adequately address (SAE International 2021a).

According to Neumeier et al (2019), the integration of highly automated driving features on public roads allows for distant human involvement in critical situations that the highly automated vehicle cannot manage independently. Kettwich et al (2021) suggest that teleoperation of vehicles offers a viable solution to harness the benefits of automated driving until fully automated vehicles (SAE Level 5) become feasible and safety and reliability are maintained through the oversight of a human operator remotely monitoring the vehicle and intervenes when disturbances exceed the automation's capabilities. Also Parr et al (2024) endorse that in situations where the ADS encounters challenges in handling a road scenario, there is a concept of employing an RO who can interact with the vehicle from a distant location to fill the gap. This RO plays a crucial role in supporting automated driving by ensuring the journey progresses smoothly when the AV technology struggles to identify and address issues.

Automation and RO systems are comprised of distinct components or fundamental units that are interconnected (Ginzburg et al., 1966), but in a general view, Goodall (2020) considers the RO feature present in many early ADS is the reliance on human input, as even the most advanced AVs occasionally require assistance in challenging driving conditions or during hardware or software malfunctions. To better understand the subject and the function of RO in AVs, it may be necessary to delve into the main activity itself, driving, and its connection with the remote operator. This is covered in the next subchapter.

2.4 Remote operation modes in driving

Driving can be understood through three levels of abstraction: strategic, tactical, and operational. The strategic level encompasses route planning, along with evaluating costs and risks. The tactical level, which is deliberate and intentional, involves decisions made by the driver in specific situations, like choosing the right moment to overtake another vehicle. The operational level executes the decisions from the tactical level, covering basic actions such as steering, accelerating, or braking (Michon, 1985).

SAE International (2021b) defines the driving task as, “all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints” (SAE International 2021b). Both definitions specify which components of the driving tasks correspond to each level of control. This encompasses subtasks related to lateral and longitudinal control, as well as tasks like object detection, recognition, classification, and response preparation, which lead to the execution of responses to objects and events, involving both operational and tactical efforts. Tasks performed by the driver vary in their cognitive demands due to their differing natures, and this principle also applies to ROs (Habibovic et al., 2020).

Depending on the scenario, the RO may need to perform all these tasks, as well as others not mentioned, when the ADS is unable to fulfil the dynamic driving task (DDT) as intended. In ROs, the mentioned three levels of abstraction (See Figure 1) can help explain the various modes in which the RO can function (Habibovic et al., 2020).

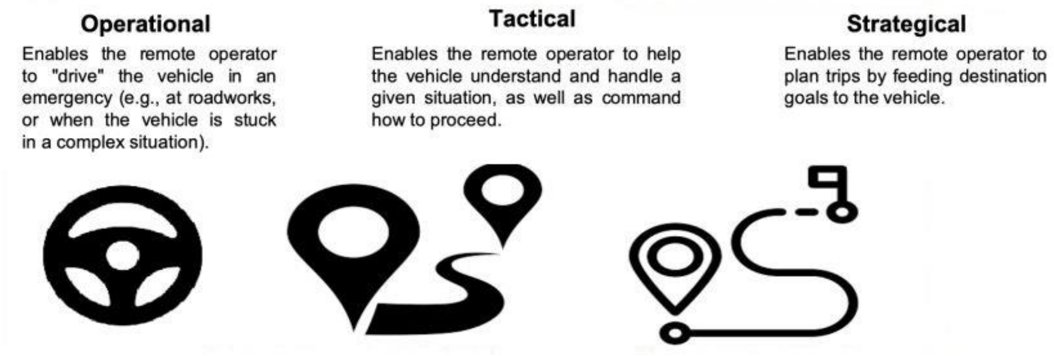

Figure 1: *A conceptual illustration of vehicle control across various levels (Habibovic et al., 2020)*

The effectiveness of RO will depend on numerous interconnected factors that are unique to the remote nature of the tasks (Habibovic et al., 2020). Currently, there is no universally agreed-upon definition of RO roles, and various authors propose differing approaches. One approach is to consider the types of control the operator might have. According to interviews conducted by the author (I02, I03 and I06) and also Goodall (2020), RO is generally categorized into two main forms. In the first form, the remote operator assists a stationary vehicle by identifying obstacles or planning a route around them. Here, the operator does not directly manage the vehicle's steering, acceleration, or braking but provides navigation instructions, which the vehicle's ADS then executes. This approach is commonly utilized when an automated vehicle encounters an unfamiliar work zone.

In the second form, the remote operator assumes direct control over the vehicle's steering, acceleration, and braking to perform the driving task. This method, referred to as remote driving, typically involves the use of computer setups equipped with steering wheels, pedals, and multiple monitors displaying live wide-angle camera feeds transmitted wirelessly from the vehicle. These two forms are often labelled as indirect and direct RO, according to expert terminology.

There are other perspectives and classifications as well, regarding the different modes of ROs, which branch out from the mentioned two main ones. The four-level approach offers a more thorough classification of RO, emphasizing a human-centred perspective (Parr et al., 2024) & (Aramrattana et al., 2024):

Remote Monitoring (RMo): Involves observing an AV, user status, and surrounding conditions remotely to collect data for identifying potential issues and supporting decision-making processes (Parr et al., 2024).

Remote Assistance (RA): Focuses on providing remote support or information to vehicle users or external agents, such as emergency responders or recovery teams. A remote operator offers tactical guidance in real time, which the vehicle processes and executes (Aramrattana et al., 2024).

Remote Management (RMa): Entails issuing commands to an AV remotely to initiate system actions when the vehicle is unable to operate independently. This function can be applied to individual vehicles, convoys, or entire fleets and often includes tasks like fleet management and dispatching (Parr et al., 2024).

Remote Driving (RD): Refers to taking direct control of the dynamic driving task (DDT) of an AV remotely, typically for a short duration, when other measures such as RA or RMa are inadequate to resolve the issue (Parr et al., 2024).

To better understand and determine which option is more suitable for different projects, it is necessary to familiarize ourselves with the challenges of implementing and executing RO (specifically in the context of driving and PT). In the following subchapter, we will address some of the most important challenges, although it cannot be claimed that this covers the entire issue.

2.5 Challenges of implementing remote operation in driving

Performing a complex task like RO in a dynamic driving environment requires a deeper and more precise understanding of its challenges and obstacles. The RO of road vehicles presents its own challenges, which are not only tied to the technology used but also to the human factors involved in the operation (Tener & Lanir, 2022). Depending on the perspective and discussion topic, authors have proposed different categorizations of challenges and obstacles in various articles, though these categorizations share commonalities. For instance, Aramrattana et al (2024) divided these issues into three categories, focusing more on remote assistance implementation: 1) Design of the RO workstation, 2) Human factors and Human-Machine Interaction (HMI), and 3) Design of AVs and HAVs.

On the other hand, another categorization appears bit broader. As Li et al (2024) states, we are dealing with three parties are involved in the teleoperation process (See figure 2).

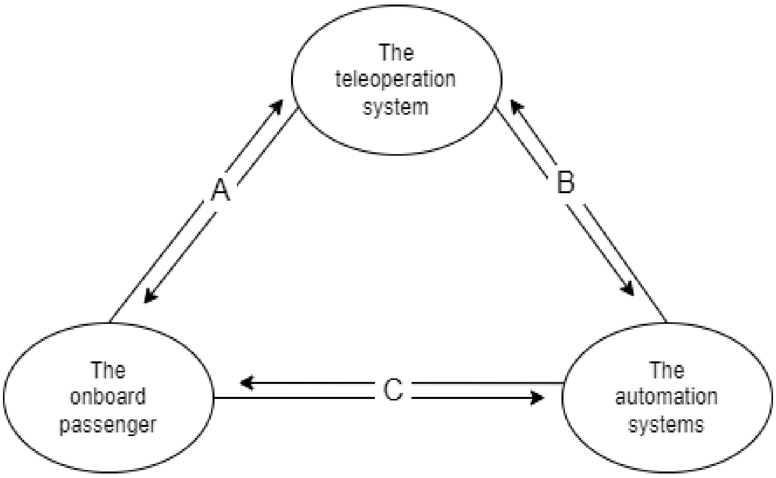

Figure 2: *Parties involved in teleoperation process (Designed by the author)*

In this categorization, which Li et al. (2024) refer to as a dynamic shared control scenario, the teleoperation system is specifically controlled by a remote driver. However, this concept is also applicable to RO. The complexity of the concept increases further when applied to PT, highlighting a critical limitation: the exclusion of the environment surrounding the AV, such as urban streets and other road users. Therefore, it may be beneficial to introduce a fourth entity into the framework while also refining the categorization to better align with RO, as illustrated in Figure 3. In the section related to the SAE guidelines (Subsection 2.9), this relationship will be explored in more details.

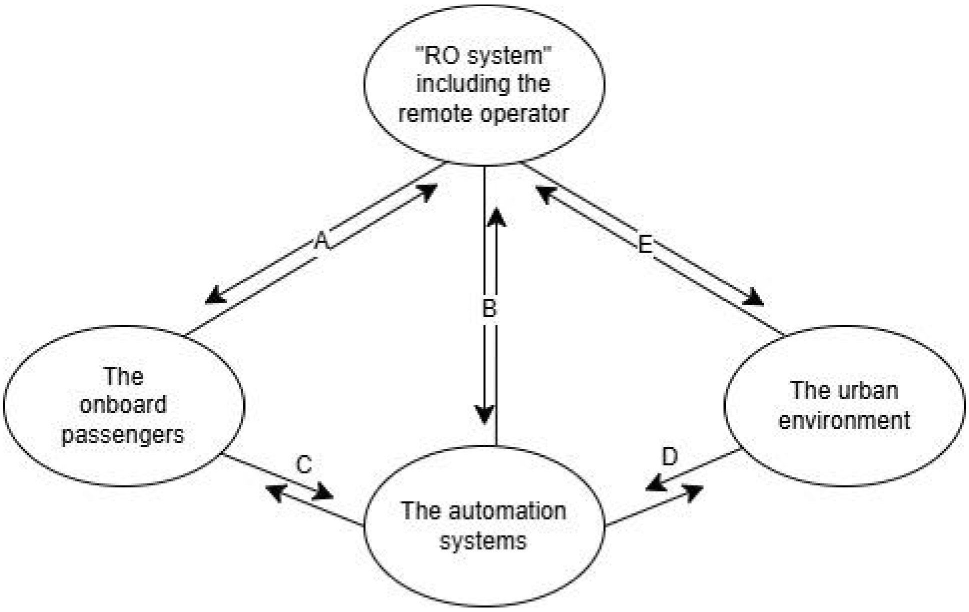

Figure 3: *Parties involved in RO process (Designed by the author)*

However, apart from the number and the parties themselves, it is also important to pay attention to the relationship between them, which is actually the basis for the emergence of many issues and challenges. In both figures 2 and 3, these relationships are indicated by the letters A, B, C, D and E. This does not necessarily mean that a challenge arising in the two-way relationship B has no interference with other relationships but for a better understanding of the probable origin, potential occurrence, and type of challenges as well as their effects and impact on other components and relationships, these distinctions seem helpful. Challenges and obstacles such as HMIs, latency, and Situational Awareness (SA) seem to more deal with B, while they are all about enhancing safety, trust, and people acceptance which also occurs in A, C, D and E.

According to a survey conducted by Li et al (2024), it was found that people tend to be more inclined towards automated systems in leisure and recreational activities. However, now that AVs are expected to become more prevalent and effective on urban and public streets, understanding these challenges seems more important than ever. In this section, several key factors that arise in relationship B will be introduced and explored as thoroughly as possible. In this thesis, the focus is more on the challenges that arise in the B relationship (mostly known as Human Factor Challenges) and other issues are outside the scope of it. However, ultimately, all these efforts aim to achieve stability and safety for all participants in the environment and eventually improve safety in the urban streets.

2.6 Human factor challenges

Design and implementation of RO of HAVs require integration of human and technological subsystems, and since HAVs are intricate systems, ensuring their safe and dependable deployment requires attention to software reliability, cybersecurity, and human factors (Andersson & Söderman, 2024). Their success additionally relies on gaining acceptance from operators, vehicle users, and other road users. Andersson & Söderman (2024) present a systemic perspective on RO, highlighting the interconnections among socio-technical factors such as control modes, vehicle capabilities, ODD, HMI, operator tasks and knowledge demands, as well as work organization, which collectively influence the constraints of operator tasks.

Although the challenges of operating a vehicle remotely are similar to those faced during in-vehicle driving (HF-IRADS, 2020), there are also challenges specific to remote tasks, which will be addressed separately. The following subsections discuss important challenges related to human factors, which are highlighted in most studies on ROs.

2.6.1 Human-machine interaction and feedback

Design and implementation of RO of HAVs require integration of human and technological subsystems (Andersson & Söderman, 2024) and in linking RO and HAV, special attention falls onto the Human-Machine Interaction (HMI) for RO (Schrank et al., 2024). HMI facilitates the human operator's engagement with the remote environment. A well-designed HMI should support effective task execution and enhance the operator's sense of telepresence (Hosseini & Lienkamp, 2016). HMI can be grouped from basic on-screen tables displaying sensor statuses (e.g., on a mobile phone or computer) to advanced outputs such as audiovisual feeds and haptic feedback systems (e.g., head-mounted devices, speakers, vibration, or torque simulation) (Amador et al., 2022).

A well-designed HMI and a carefully planned process for transitioning control — both taking and giving it up and potentially monitoring attention — would benefit the remote operator. A remote driver station and its HMI might incorporate additional functionalities different from those found in a contemporary driver's environment (HF-IRADS, 2020).

According to Griffin & Stanford University (2003), the level of HMI in teleoperation tasks is typically classified into three categories:

1. Direct control (or closed-loop control): refers to a teleoperation level where the operator continuously sends direct signals to maintain control over the remote system (similar to what is happening during remote driving).
2. Shared control: describes a level of HMI where both human input in programmed tasks and computer assistance in manually controlled operations are allowed (Salisbury, 1988).
3. Supervisory control: the machine performs the task independently, while the operator continuously monitors and makes iterative updates or adjustments to the program.

Schrank et al. (2024) discuss a concept known as the variant of RO, which is essential for identifying the appropriate components within the entire system. They explain that the HMI can differ significantly based on how RO is implemented. For example, in remote driving, the interface must include components that facilitate the execution of dynamic driving tasks, such as steering wheels, joysticks, or pedals (Direct control as mentioned). In contrast, RA does not require the remote operator to perform driving tasks but instead focuses on enabling them to rapidly and comprehensively evaluate the traffic conditions surrounding the supervised HAV (Schrank et al., 2024).

Now that we are familiar with the various levels of control in HMI, it is important to recognize the significance of feedback, as these feedback mechanisms become crucial in tasks like driving and according to Aramrattana et al. (2024) there exists a research gap in understanding the communication needs, patterns, and feedback mechanisms between actors in the traffic system to ensure the safe and efficient operation of a large number of vehicles. One such gap is the lack of insight into these interactions, particularly during adverse events such as network breakdowns, where recognizing interdependencies can significantly enhance the analysis of traffic system resilience. Addressing this issue can lead to more effective traffic management strategies, improving adaptability and robustness in dynamic and unpredictable conditions.

Feedback

The necessity of feedback is widely acknowledged, and its role in facilitating tasks for end-users has been well established (Renaud & Cooper, 2000). Various definitions of feedback have been proposed (Cerrato, 2002). If we seek a fundamental definition, *Merriam-Webster* (2024) describes feedback as:

- The return of part of a system’s output to its input, influencing its further operation.
- The process of relaying evaluative or corrective information about an action, event, or procedure back to its initial source or governing system.
- The term can also refer to the information being transmitted.

To simplify and summarize this concept, feedback can be understood as the way a system—such as the user interface of a ROC—responds to data and presents it in a form that is comprehensible to humans. Essentially, feedback focuses on the method and nature of interaction, the participants involved, their objectives, and the interface between humans and computers (Spink & Saracevic, 1998).

Feedback manifests in different forms depending on the context. In this thesis, key types of feedback will be discussed that were frequently mentioned in interviews (I05, I04) and survey responses, drawing from Kuchenbecker (2015).

1. **Haptic Feedback:** This type of feedback involves the use of tactile sensations—such as vibrations, applied forces, or texture simulations—to recreate the sense of touch. It is commonly found in various devices, including smartphones that vibrate for notifications and gaming controllers that provide force resistance during gameplay. By adding a physical dimension to interactions, haptic feedback enhances user experience and complements both visual and auditory cues.
2. **Audio Feedback:** This feedback mechanism relies on sound cues to inform users about their interactions with a system. For instance, the distinct clicking sound of a keyboard keypress reassures users that their input has been successfully

registered. Often combined with visual feedback, audio feedback improves engagement and accessibility, making interactions more intuitive. Regarding the importance of audio feedback in a ROC, Appendix A provides details.

3. **Visual Feedback:** Visual feedback uses graphical elements and animations to communicate information and confirm user actions. It ranges from basic indicators, like progress bars and checkmarks, to more advanced animations that replicate real-world interactions. This type of feedback is particularly crucial for touchscreen interfaces, where users rely on visual cues to navigate and interact with digital environments.

Another important type of feedback is force feedback, which is described by Iris Dynamics (n.d.) as: The replication of physical touch sensations within a virtual environment, such as virtual reality, is achieved through motorized movement or applied resistance. While many people associate force feedback with gaming peripherals like steering wheels, pedals, and flight simulator joysticks, its applications extend well beyond the gaming industry.

According to HF-IRADS (2020), incorporating force feedback alongside visual feedback in driving controls could enhance performance. This combination may provide the remote operator with a better understanding of the environment and its limitations, helping to prevent dangerous collisions. In terms of visual feedback, the display element in the HMI for remote operators is crucial. Unlike traditional vehicle-based HMIs, where the operator directly interacts with the vehicle’s environment, remote operators rely heavily on visual feedback to acquire information, interact with the system, and manage control, as they are distanced from the in-cab or driving environment (HF-IRADS, 2020).

The critical issue here is the number of visual feedback elements, which is particularly important for designing the remote operator's workspace. Displays can be categorized into two types: one set that shows the operator what is happening inside and around the vehicle, and another set that the operator uses to interact with the vehicle when the automated system requests assistance. However, to ensure optimal performance, it is important that the interfaces do not overload the operator with an excessive number of devices (such as displays and controls) that require high levels of cognitive and motor skills simultaneously (HF-IRADS, 2020).

The importance of information at this stage for selecting the type of feedback is clearly understandable. From an HMI and human factors perspective, challenges arise in choosing the feedback or information provided to the Remote Assistant (RA) (Amador et al., 2022). Additionally, HAVs must be equipped with appropriate sensors to transmit such information from the vehicle to the RA at the RO station. Several feedback modes and their combinations have been explored in RO stations, such as auditory feedback (Larsson et al., 2023), augmented reality (Bout et al., 2017), haptic feedback, motion feedback, steering force feedback (Zhao et al., 2024), and virtual reality. As Amador et al. (2022) claims, visual feedback alone may not be sufficient to create adequate SA for the remote operator; rather, a combination of various feedback methods is required. However, researchers have yet to reach a consensus on the appropriate amount and modes of feedback needed. Another crucial issue is how to link the SA of the remote operator and the AV, which will be further addressed in the next section but in brief it is good to know that most AVs are equipped with systems capable of detecting and identifying objects in their surroundings. Providing such information to the remote operator can potentially enhance SA (Aramrattana et al., 2024).

Overall, the efficiency and inefficiency of HMI act like two edges of a knife; just as it can facilitate the work of the remote operator, it is equally prone to significant problems and issues. This depends on numerous parameters and extensive studies.

2.6.2 Situational awareness

When it comes to the success of a RO project in any sector, one of the most critical and sensitive issues, and indeed a key factor for success, is Situational Awareness (SA). Considering the subject and aim of this research, SA in the context of driving operations is examined, including the conducting and supervising of these operations from a distance.

As stated by the Automated Vehicle Safety Consortium (2023), situational (or situation) awareness refers to the recognition of environmental elements, the understanding of their significance, and the anticipation of their future status.

According to Hosseini (2018) & HF-IRADS (2020), when a human operator remotely controls a vehicle, their SA is lower compared to controlling it from within the vehicle. In the context of RO, the operator has no sensory perception of the vehicle's body or its surrounding environment, and even if communication is established via cameras and various sensors, the operator may only have a limited sense and understanding of the conditions. This reduction in SA can impact the driving performance of the human operator. Therefore, it is essential to consider the cognitive limitations of the operator, particularly when working in high-risk environments such as urban areas, roads, and PT, as physical detachment from the vehicle may reduce the sense of urgency, which in certain situations could lead to negative consequences for the entire operation. Furthermore, potential ethical concerns arise from physical detachment from the vehicle and traffic conditions, meaning remote operators may lack empathy and sensitivity toward their surroundings, especially from the perspective of passengers in vehicles being remotely controlled (HF-IRADS, 2020). So, SA provides a suitable foundation and indeed a prerequisite for the process leading to correct decision-making for the remote operator, which can almost be said to be impossible without this foundation.

SA in tasks such as driving, particularly for an operator who is remote from the vehicle, is described through three levels, similar to an input-process-output model. At the first level, the operator perceives dynamic events in the environment, such as other vehicles present or infrastructure elements, and also pays attention to crucial situational elements like checking the speedometer or reading navigational data (Lindgren, 2009). At the next level, the operator uses the perceived information to comprehend the situation, which includes evaluating the importance of the received information in order to create an internal understanding. For example, this may involve noticing a warning signal from the engine and assessing the significance of the issue by combining it with the operator's prior knowledge (Endsley, 2016). At the final level, based on all the gathered and evaluated information from the previous two levels, the operator can predict future actions of elements in the environment, including the AV, passengers within the vehicle, and other elements in the environment, to identify potential conflicts. When these three levels are properly processed, the operator can make decisions about the appropriate actions to take. Therefore, these levels collectively form SA, which provides the necessary context and enables sufficient decision-making (Endsley, 2016; Lindgren, 2009).

Depending on the operator's decision and the goal they aim to achieve, the level of involvement in the SA levels will vary (Matthews & Beal, 2002). To better understand the three abstract levels in driving, as presented by Michon (1985) and related to SA—namely strategic, tactical, and operational driving—discussed in previous chapters. In strategic driving, there is a significant relationship with the second and third levels of SA, namely the comprehension of the current situation and environment, and projection. There is a minor connection with the first level, as the remote operator needs to monitor the environment to strategically plan future decisions. The next level of abstraction in driving, tactical driving, is mainly related to the first and second levels of SA because it involves understanding the situation and deciding if larger manoeuvres should be made. Since these two levels of SA involve perceiving and comprehending the situation for short-term decision-making, they are strongly interconnected. However, operational driving involves very small manoeuvres that do not require SA in comparison to the previous two levels. Nonetheless, some perception and understanding of the situation are still necessary, which is why operational driving has a weaker relationship with the first and second levels of SA (Matthews & Beal, 2002).

All the aforementioned points were an attempt to emphasize the significance of SA in remote projects, particularly in this study on the RO of AVs. However, other general insights have been discussed in the literature that may not align directly with the levels of SA but offer an interesting perspective on the subject. For instance, Papadimitriou et al. (2020) identifies the cause of insufficient SA in ROs as the detachment from the action, as the operator lacks an embodied sensation of the vehicle. Hence, sensors and cameras should be employed in a way that enriches the operator's bodily experience, enabling a more accurate and comprehensive understanding of the conditions to facilitate proper evaluation and decision-making.

Why is this issue important? Papadimitriou et al. (2020) further explains that physical detachment might reduce the sense of urgency in a situation, potentially leading to a lack of empathy towards the environment, including the people around the vehicle. This highlights the critical nature of the issue. It is not merely about driving and manoeuvring a vehicle but being present in a highly dynamic and human-centric environment that necessitates empathy with the surroundings.

Additionally, the importance of information comes into play. While data from cameras and sensors are crucial for improving SA, they may also lead to information overload (Papadimitriou et al., 2020). When operators experience this, assessing the situation becomes more challenging, rendering SA inadequate. Although the investigation of the quantity and validation of transmitted information goes beyond the scope of this study, understanding the necessity of a balance between providing essential information and avoiding information overload is vital. Papadimitriou (2020) points out that without this balance, *change blindness*—where significant changes in the scene go unnoticed due to visual perception being overly occupied—can occur. In ROs, this might happen when excessive continuous visual information is presented.

Given the absence of humans inside the vehicle, it is essential to understand what humans perceive and unconsciously attend to, as these factors are likely to be required in a ROC as well (Matthews & Beal, 2002). Mutzenich et al. (2021) emphasize this point, stating that AVs do not and will not perceive information in the same way humans do. Deciding which factors are important and how to consider them must be addressed beforehand. Moreover, they argue that individuals perceive different elements—some focus more on road infrastructure, while others pay more attention to road signs and traffic. This variability extends to how individuals construct SA, making it more challenging to define the requirements for remote operators to create and maintain SA (Mutzenich et al., 2021).

Understanding the factors that influence an operator's SA is itself a complex and in-depth subject. However, it is essential to recognize that the relationship between SA and other factors, which will be discussed in the following subsections, is not one-directional. Other elements can also impact the level and quality of SA. According to Schrank et al. (2024), all these aspects are interconnected. For example, the quantity and quality of information relayed from the traffic environment can significantly influence the remote operator's SA. This includes the restricted input received through sensory modalities (e.g., absence of force feedback), the clarity of the information (e.g., low-resolution video streams), and delays in data transmission, all of which may impact the operator’s ability to assess the situation effectively (Schrank et al., 2024). The also discuss the relationship between the HMI and SA, stating that an HMI, in order to ensure the safety of ROs, must be designed with the goal of enhancing SA.

2.6.3 Network and communication

One of the most important and technical aspects of implementing RO is Network and how the communication will be provided. In every interview conducted by the author with experts, network was described as a challenging issue. The presence, type, and stability of network are among the essential requirements and, in fact, serve as a foundational infrastructure for ROs.

Even if ROs are conducted by experts, poor communication can compromise task performance. Depending on the situation, different modes of communication may be required. For remote assistance, auditory communication might suffice and would demand relatively less bandwidth. For remote management, video connectivity will likely be necessary, potentially between the AV’s camera and the remote controller (HF-IRADS, 2020). Additionally, there will be a need to transmit diagnostic information about the vehicle to the remote workstation. While extremely low latency may not be a strict requirement, ensuring stable and reliable communication is likely to be critical in supporting human performance (HF-IRADS, 2020).

With remote driving, the situation becomes significantly more challenging. High-resolution video and audio feeds from the vehicle will likely be required, potentially in stereo. The greater the pixel resolution and field of view needed, the higher the demand for bandwidth and uninterrupted communication (HF-IRADS, 2020). Delays and jitter in communications also become critical concerns. For instance, if there is a one-second delay in the remote operator receiving the scene and an additional half-second delay in transmitting control commands to the vehicle, it would add 1.5 seconds to the typical one-second reaction time of a driver to an event (ibid.). Vehicle control would become erratic as delay could substantially increase risk in many situations. About fixed time lagging studies (e.g. Sheridan & Ferrell, 1963; Corde Lane et al., 2002) have shown that it can be an issue for RO. However, Davis et al. (2010) highlight that fluctuations in lag posed an even greater obstacle to effective performance in RO than the lag itself. This suggests that maintaining consistent transmission may be a fundamental necessity (HF-IRADS, 2020).

2.6.4 Latency

A crucial factor for secure and reliable driving is latency (Zulqarnain & Lee, 2021), also has a significant effect on driver performance (Goodall, 2020), and safely controlling the vehicle under latency is one of the main problems that have to be solved (Georg et al., 2020). When obtaining a driver's license, visiting a doctor and undergoing a check-up are done to ensure the physical and mental health of the applicant. The reasons for this check-up include vision health, hearing Health, coordination, balance and reaction time, and general health. The results indicate whether the person can control their movements and respond quickly in various situations (capable of making decision in real time). While the check-up focuses on the individual's fitness for driving, addressing aspects like co-ordination and reaction time, these factors (even indirectly) are important in understanding and managing latency issues in the broader context of driving safety.

To understand the factors contributing to latency and whether different types of latency exist, (Georg et al., 2020) identifies two primary aspects: roundtrip latency and maximum upload bandwidth. Latency primarily affects the controllability and safety of the vehicle, whereas upload bandwidth influences the amount of transmittable sensor data and, consequently, the operator's SA, as well as the operational costs of the entire system. In the context of RO, (Bachhuber & Steinbach, 2016) introduces two types of latency: sensor latency and actuator latency. Sensor latency refers to the time between the occurrence of an event in the vehicle's environment and its display on the operator's monitor (commonly referred to as "Glass-to-Glass" (G2G) latency) and the other refers to the time taken by the operator to process information, make a decision, and react to the situation.

Latency, Network and RO

There is limited research on latency requirements and bandwidth allocation for ROs. However, as noted by (Goodall, 2020), it is evident that latency in wireless networks varies over time and space. Saeed et al. (2019) presents a conservative estimate for the data requirements of remote driving, which includes a 3GPP estimate of the required upload rate of 20 Mbps with 99.999% reliability. He also notes that there are disagreements regarding the extent to which wireless networks can support remote driving. Furthermore, deploying 5G infrastructure to support remote driving across all roads may not be feasible due to the costs associated with fibre backhaul, signal interference, and limited upload capacity (Saeed et al., 2019).

The focus on upload capacity is due to the fact that ROs require the transmission of video or still images, audio, coordinates, and sensor data from vehicles to remote operators (Higgins, 2018). Based on the author's understanding from reviewing various articles and conducting interview with (I03), and as supported by the claim of Higgins (2018), a reasonable amount of latency is acceptable when the vehicle is theoretically positioned safely (Goodall, 2020) (SAE mentions this as Minimal Risk Condition (MRC)). Thus, it can be asserted that, given the current state of technology and wireless network, remote assistance is more feasible compared to remote driving. As remote driving requires substantial bandwidth over wireless networks to ensure reliable, low-latency, two-way communication between the vehicle and the remote operator (Goodall, 2020).

2.7 Remote operation centre

Designing a Remote operation Centre (ROC) -in some texts Remote Control Centre (RCC)- and defining its functions involves meeting several requirements. Initially, it is essential to specify the level of SA among ROC staff. According to Endsley (1995) framework, tasks involving direct control may emphasize perceptual SA, whereas supervisory roles often require higher-level comprehension and projection. Therefore, maintaining SA depends on the specific tasks performed by operators. Secondly, maintaining attention or vigilance is crucial in ROC operations (Merat et al., 2019)

Based on the design of the workstation and the tasks assigned to the remote operator, motion sickness could also be a concern, similar to experiences in driving simulators. Also, it is anticipated that instances of inattention and distraction may arise (HF-IRADS, 2020). Hence, as well as other parameters, such as workload, building cost and size of the operator's workstation should be considered (Wolf et al., 2024). Therefore, monitoring the remote operator may be necessary. In a control room setting, operators have the flexibility to move around, potentially not being at their workstation when needed for a call (HF-IRADS, 2020).

In addition to the technical concepts, Kettwich et al. (2021) designed a graphical User Interface (UI) for an RO workstation on six screens and an additional touchscreen. Three screens in the top row show video streams of the vehicle's surroundings. The other three screens below visualize an overview map, detailed vehicle information and the current disturbances. Moreover, the TS shows a bird's eye view map of the vehicle's immediate surroundings including the originally planned trajectory where the RO sets waypoints for path specification. It is assumed that the AV travels the route at its own velocity.

System design considerations should address how to effectively capture the operator's attention, allocate tasks among operators, and maintain their attentiveness. The transition of control between the system and operator, as well as between operators during breaks and shift changes, represents a critical phase with heightened risk of errors. Hence, changing operators should be meticulously planned and executed. Assessing the hand-over process and fostering collaboration between remote operators and local operators (those located inside or near the vehicle) could yield substantial benefits (HF-IRADS, 2020).

One highly challenging issue in the context of RO stations is whether they should be an exact replication of the current driver's environment or, conversely, introduce entirely new elements. As mentioned in (HF-IRADS, 2020), it is suggested that a RO station and its HMI might actually offer more functionalities and capabilities than what a modern-day driver has access to. Thus, it is possible for the station to be different from or go beyond the in-vehicle environment.

Overall, as HF-IRADS (2020) claims, best practices in operation centres are implemented through analysing the workflows of actual tasks and designing the ROC around those workflows and the human operator. In other words, an appropriate design is one that is user-centred, focusing on factors such as optimal seating distance, optimization of light and sound, effective information presentation, and task simplification to the greatest extent possible. However, there is no documentation regarding the maintenance of the ROC, and it is unknown as Lu et al. (2024) claims.

The interview results done by Klingberg (2023) indicate that remote operators primarily need information about automation failures and how to resolve them. Additionally, the findings support previous research that emphasizes the need for interactive interfaces to prevent passive monitoring, which can lead to out-of-the-loop problems. Recommendations for designing a ROC include integrating both verbal and digital communication capabilities and enabling collaboration both internally and externally. Lastly, the results highlight the importance of distinguishing between different modes of ROs within the ROC to clarify the responsible actor and prevent automation surprises.

2.8 Remote operator

Regarding the skills and knowledge required for remote operators of road-based AVs, there is a lack of comprehensive research. This study's methodology attempts to address this gap by posing relevant questions to experts. According to HF-IRADS (2020), remote operators are expected to undergo specific, targeted training. In cases where remote driving is required, it may even be necessary for these operators to hold a valid driving license corresponding to the vehicle category. The source also highlights other considerations, such as health checks, like sleep apnea screening, which could benefit remote operators, especially when they are involved in controlling public service vehicles. Depending on the type of support provided, operators may need training in the traffic regulations applicable to the roads where the vehicles operate. Moreover, the transfer of control between operators at national, regional, or provincial borders might also be necessary.

2.8.1 Challenges and responsibilities of remote operators

Both human remote operators and ADS possess their own intelligence and ability to act independently. Managing this automation, particularly when transitioning between vehicles with varying capabilities, is a key responsibility of remote operators. While ADS may encounter failures, basic vehicle safety systems such as Automatic Emergency Braking (AEB) or Electronic Stability Control (ESC) can also malfunction. Remote operators must be well-acquainted with the functionalities of these systems, and established procedures to address such failures can enhance ROs (HF-IRADS, 2020).

The HF-IRADS (2020) highlights two critical issues that are common in the work of remote operators:

1- Information overload:

Due to the diverse sensors in AVs, remote operators may receive significantly more information compared to onboard drivers. This challenge is further exacerbated if operators are responsible for managing multiple vehicles simultaneously. Replacing the physical sensory feedback of being in the vehicle with sensor data can result in excessive information, potentially impairing the operator's ability to accurately perceive the situation. This phenomenon, termed "change blindness," refers to the failure to detect significant changes in visual scenes. For instance, operators might miss critical scene changes if overwhelmed with information or engaged in continuous monitoring (HF-IRADS, 2020).

2- Operator fatigue:

Fatigue is a common issue among remote operators, and human error, inattention, and distraction are natural risks. Furthermore, motion sickness, similar to what occurs in driving simulators, might arise due to the design of the workspace and operator tasks. Despite prior mentions, the design of the operator’s workspace remains crucial given these challenges. For example, operators may have the freedom to move around and might not be physically present at their workstation when a critical alert arises. In such scenarios, system design must address questions such as how to capture operator attention, allocate tasks effectively, and ensure sustained focus and productivity (HF-IRADS, 2020).

On the other hand, Aramrattana et al (2024) raises two unresolved and significant research questions in their article, which are worth mentioning here.

1. Assessing mental workload:

Determining the appropriate threshold for mental workload remains unclear. Although various biological measures, such as heart rate and eye movement, are commonly used for assessment, it is still unknown what constitutes an optimal workload level, influencing how long operators can work effectively each day.

2. Managing information volume:

Designing interfaces that provide sufficient information without increasing workload is critical. A well-designed UI should account for operator workload, ensuring tasks are completed without causing information overload (Aramrattana et al., 2024).

What is required to create a HMI that is both safe and user-friendly? (Aramrattana et al., 2024) addresses this question by emphasizing the importance of defining the tasks of remote operators systematically. Koskinen et al. (2024) recommend using Core Task Analysis as a systematic method to compile a comprehensive and structured list of remote operators’ tasks.

For instance, Aramrattana et al. (2024) identifies two examples of tasks that a remote operator can perform as follows:

1. Object categorization:

Remote operators can enhance ADS functionality by reclassifying specific objects detected near the vehicle. For example, a double-parked car may be mistakenly interpreted by the ADS as a car waiting in line, leading to an incorrect decision to wait behind it. A remote operator can reclassify the vehicle as an obstacle, enabling the ADS to take appropriate action.

2. Wayfinding**:**
   When road conditions are unclear, such as during construction, the ADS may become confused. In such cases, a remote operator can suggest an optimal route by manually placing waypoints on the map for the ADS to follow.

Monitoring highly automated road traffic can be considered a repetitive task. Hence, it is essential to diversify tasks and actively create opportunities for engagement to redirect attention, thereby helping to maintain or restore vigilance (Wickens et al., 2003).

It is also important to ensure an optimal task load. The frequency and diversity of tasks are critical, as well as the number of tasks that need attention at any given time. Both underloading and overloading can negatively impact task performance: underloading may lead to mind-wandering and reduced efficiency, while overloading can overwhelm operators. Therefore, a moderate level of task load is likely to yield the best performance. (Schrank & Kettwich, 2021).

According to the same source, a model is proposed outlining central and peripheral roles within the ROC. Each role involves distinct tasks that demand different skills and qualifications. This role model is developed from strategies for HMI in AVs for PT, systematic analysis of operations in PT control centres, and the collection and systematic categorization of use cases and scenarios in teleoperated driving.

Central Roles

In this section, three central roles are outlined:

1- Supervision of ROC: This role (mentioned as a Remote Coordinator (RC)) involves overseeing operations within the remote centre and ensuring the identification, resolution, and documentation of all incidents. It also includes monitoring automated driving operations and managing operational disruptions.

2- Direct Remote Driving Operations (RDO): This role entails the direct RO of AVs, utilizing a steering wheel for navigation and pedals for acceleration and braking.

3- Systematic fleet operations supervision: This role (mentioned as a Remote System Operator (RSO)) is responsible for configuring automation software for system components, analysing video footage, categorizing objects, and assisting RC in incident analysis.

The RC also adjusts routes based on traffic conditions in collaboration with other mobility operators to facilitate intermodal mobility and meet travel demands. For AV remote operators, the RC indirectly guides trajectories or sets waypoints linked to a trajectory, while direct driving tasks are assigned to the RDO. During emergencies, the RC handles emergency calls and supports on-site emergency service intervention, documenting incidents and their resolution.

Peripheral Roles

In addition to the primary roles within the ROC, several peripheral roles that are not immediately critical to the operation of AV teleoperation are conceivable. A Service Technician (ST) plays a crucial role in maintaining fleet operation beyond the RSO's scope, handling cases that cannot be resolved by the RSO. The ST's main responsibilities include diagnosing AV malfunctions, resolving issues, and manually guiding the AV to a safe stop or until automated driving can resume. Other roles indirectly involved in operating teleoperated AVs in PT include dispatchers who balance AV demand and supply, passenger service providers assisting travellers with special needs, cleaning and maintenance staff ensuring continuous AV fleet operability, and security personnel handling conflict resolution and vandalism prevention (Schrank & Kettwich, 2021).

The scope of the operator’s responsibilities or tasks plays a crucial role in determining the importance or the level of contribution of other system components. For instance, in relation to the discussion on variants in Section 2.6.1, Schrank et al. (2024) highlight that the design of the HMI is directly influenced by the tasks assigned to the remote operator.

2.8.2 Quantity of remote operators needed for an AV fleet

In most teleoperation applications, each remote vehicle is typically assigned one or more operators. However, in the RO of a fleet of ADS vehicles, the approach is designed so that a single operator can oversee and manage multiple vehicles simultaneously (HF-IRADS, 2020) as its sole cost benefit compared to a human driver in the vehicle comes from reduced wages through outsourcing (Goodall, 2020). Given the existing literature in this field, which is admittedly limited, there isn't a single method for determining the number of remote operators and the fleet they can manage or supervise. However, we've included two different approaches from two studies that used relatively equations. In the first case, Goodrich and Olsen considered this equation:

$FO = (NT+IT)/IT$

The interaction time (IT) refers to the duration that a remote operator spends actively engaged with the vehicle, while neglect time (NT) denotes the period during which the vehicle can function without requiring attention from the remote operator. These variables together define the fan-out (FO) as the equation.

While it appears straightforward for estimating how many vehicles a remote operator can handle, determining NT and IT is intricate. For example, IT depends on at least four factors: (1) monitoring and selecting vehicles, (2) switching contexts, (3) problem-solving, and (4) issuing commands (Goodrich & Olsen, 2003).

When ADS failures occur, the duration or onset of neglect time is unpredictable, turning interaction time into a random variable rather than something that can be scheduled. Moreover, neglect time for one vehicle may be influenced by others. For example, a thunderstorm could lead to simultaneous ADS failures across multiple vehicles. The more system-driven or beyond the operator's control the monitoring requests are, the more they overlap for different vehicles, which limits the operator's capacity to manage them all at once. This overlap restricts the number of vehicles a single operator can handle without risking neglect. Despite the computational complexity, the fan-out equation offers a valuable framework that illustrates how human factors and design choices impact the safety and efficiency of remotely operated fleets (HF-IRADS, 2020).

In the second study, Goodall (2020) uses queueing theory and explains how the number of remote operators required to manage a fleet of vehicles can be estimated. According to him, with knowing call volumes and call durations in a ROC, we can use the Erlang C formula to determine the required staffing levels to meet performance objectives and reduce caller wait times.

The Erlang C formula (Erlang, 1917):

$$P_C(m, a) = \left(\frac{a^m m}{m!(m-a)}\right) / \left(\sum_{i=0}^{m-1} \frac{a^i}{i!} + \frac{a^m m}{m!(m-a)}\right)$$

The result ($P_C(m, a)$) is the likelihood of an incoming request that cannot be instantly addressed, depending on the number of agents m and the request load a (Goodall, 2020). The load a is defined as the ratio of the average request rate per unit time λ to the average number of requests a single operator can handle per unit time μ.

$$a = \frac{\lambda}{\mu}$$

The request rate λ is determined by multiplying the takeover request rate of an ADS r_v by the total number of automated vehicles in the fleet n_v (Goodall, 2020).

$$\lambda = r_v n_v$$

Goodall attempted to derive equations for the variables either by using assumptions or by referring to other studies, and for some variables, he calculated values based on data provided by companies offering RO services. His aim was to arrive at a solution that specifically applies to the United States, as the data utilized pertain to states within this country. Table 1, extracted from Goodall's article, succinctly presents the variables:

Table 1: *Variables in Erlang C model. Source:(Goodall, 2020)*

Parameter	**Symbol**
Operators	M
ADS failure rate	r_v
Vehicles on road during shift peak hour	n_v
Request rate	λ
Service rate	μ
Requests (load)	a
Target failure rate	r_t
Remote operator missed call rate	P_c

Depending on the assumptions employed, the number of remote operators required can vary from as few as 24 to as many as 1.4 million (the required number of remote operators to oversee all driving activities in the United States, under the assumption that driving is fully automated). If AVs request assistance every 397 hours (equivalent to Waymo's 2018 disengagement rate), the entire traffic load could be managed with 4,074 operators (assuming one minute per request) or 37,538 operators (assuming ten minutes per request). The International Organization of Motor Vehicle Manufacturers reported approximately 289 million registered motor vehicles in the U.S. for 2020 (CEIC Data, n.d.), the year when Goodall wrote the paper.

During interviews with I04 and I06, Goodall's paper and the method he proposed for determining the number of operators were discussed. According to those currently working on RO projects, Goodall's approach is an interesting effort, and his calculation method is somewhat acceptable. However, the estimated number seems a bit “optimistic”, as the parameters considered are quite limited. In practice, many factors influence this number, and while the method might be somewhat accurate for the specific case study in the paper, it cannot necessarily be applied to different countries or used with the same formula.

The remaining subsections of this chapter examine the regulations and principles related to technology. However, before addressing these aspects, it is essential to highlight a crucial point regarding all the human factors discussed since the beginning of this chapter. According to Aramrattana et al. (2024), it is vital to consider these factors as an interconnected set rather than isolated components. In most cases research studies tend to examine individual aspects of the socio-technical environment that make up a RO system, rather than exploring the interconnections between its sub-systems (Aramrattana et al., 2024). In a nutshell, these factors highlight the necessity of an interdisciplinary approach to the design, assessment, and implementation of ROs.

Furthermore, as Aramrattana et al. (2024) states, regulations play a significant role in advancing this technology and legal considerations must be taken into account to ensure adherence to laws, regulations, and ethical standards.

2.9 Guidelines and best practice by SAE

This best practice by Automated Vehicle Safety Consortium (AVSC) provides guidelines that ADS manufacturers and researchers can use to understand the utility and functionality of RO. Regulators can also use these guidelines in rulemaking that applies to remote assistance for ADS. It aims to clarify and define concepts and, to some extent, tasks in the specialized field of RO to mitigate ambiguities and challenges in this domain. For instance, it has been stated that the ADS is designed to guide the vehicle into a Minimal Risk Condition (MRC) —identified as “triggers” within this best practice—, at which point it requests assistance from a remotely located human operator.

The European Union's ADS Type Approval regulation 2022/1426 refers to the term "remote intervention operator," which aligns closely with the definition of remote assistance in SAE J3016. According to the regulation, a "remote intervention operator" is a person located outside a fully automated vehicle who may perform tasks typically handled by an on-board operator, provided it is safe to do so. This operator does not drive the vehicle, and the ADS continues to perform the Dynamic Driving Task (DDT) (ECR, 2022). The primary focus across these definitions and classifications is to establish clear boundaries for RA and understand the nature and extent of support it provides. The overarching goal is to ensure that RA in ADS-equipped vehicles is safe, reliable, and efficient (AVSC, 2023).

Remote Operator: A human(s) who provides guidance and assistance to the ADS, passengers, and law enforcement. Remote operator can be thought of as combining the functions of RA, Customer Support, Authorities Interaction, and/or Remote Driving (RD).

There are variations and agreement in how RA is defined, particularly in terms of its scope and components which are mentioned as an appendix in the text of the practice but according to the main text the RA is a specific component within the broader context of ROs, which may encompass additional functions such as customer service, remote monitoring, and dispatching. A RAs may also perform other fleet operations functions (ibid.).

RA provides guidance and support to the ADS-Dedicated Vehicles (ADS-DV), enhancing its decision-making process, while RD is directly engaged in DDT and can take control of the vehicle and perform all DDT functions, similar to a conventional human driver.

In Figure 4, the components of RO are depicted, divided into two sections: one pertaining to remote interactions with the vehicle or fleet, and the other related to interactions with humans. Together, these sections encompass various functions, including remote driving, remote monitoring, and dispatch management. It is important to note that this set of guidelines focuses specifically on RA to the ADS, excluding remote driving, dispatch management, and remote assistance to human occupants or other road users.

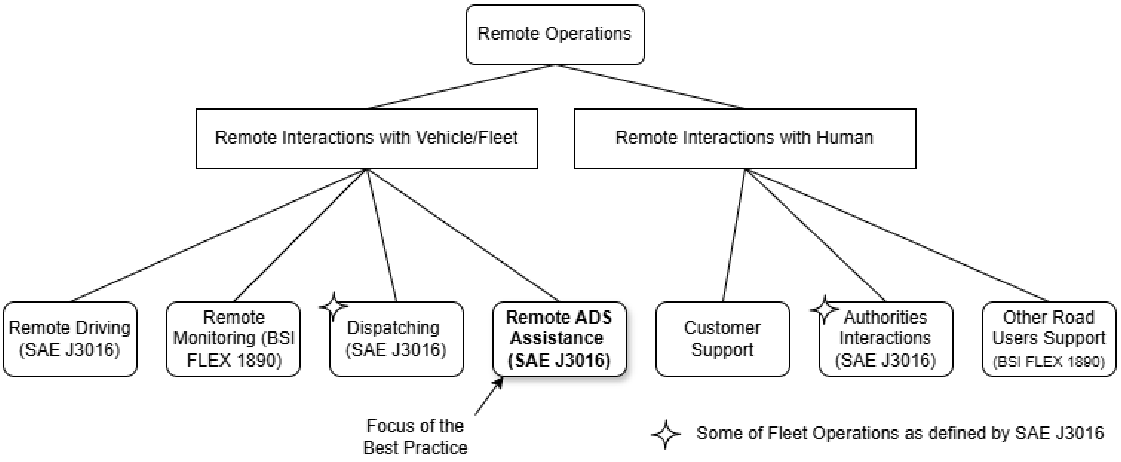

***Figure 4:** Components of RO (source: AVSC, 2023)*

RA is a critical component within the broader landscape of ROs. Functions of RA are often confused with remote driving. However, there is a clear distinction between the two. Unlike remote driving, **RA primarily serves to provide real-time guidance and information to an ADS-DV in specific scenarios without assuming direct control of the vehicle (i.e., without performing any part of the DDT)**.

The functions and tasks of RA primarily address the tactical behaviours of an ADS-DVs which lets executing its actions on the roadway when necessary and triggered. As the specific functions of RA continue to evolve, the practice does provide an exhaustive list of every function instead, it provides broad categories of types of assistance that might be provided to an ADS (See Table 2).

Table 2: *Tasks example involved in RA. Source: (AVSC, 2023)*

Example Function	Notes
Confirming or Changing Tactical Behaviour/Manoeuvre Plans	Tactical behaviours/manoeuvres are the near-term actions an ADS-DV intends to take. Manoeuvres are a subset of goal-oriented behaviours but are often more elemental actions. Behaviours often describe the high-level tasks and possible goal state. Examples of this function can include suggesting a lane change to the right lane, turning right at an intersection, or following the current lane. The ADS, not RA, performs the behaviour or manoeuvre.
Confirming or Changing Trajectory Plans	The trajectory plans define the specific path (often defined by waypoints) and associated speeds an ADS intends to follow. Changing trajectory plans could include defining a new trajectory from scratch, modifying an existing trajectory, or selecting from multiple candidate trajectories.
Confirming/Augmenting Object Classifications	Object classifications are usually derived from perception data and can provide context like the motion model (or other object properties) of a sensed object. Augmenting an object's classification (or assigning a classification to an unknown object) can often provide the ADS information it needs to proceed through a scenario. For example, an unknown moving object that is clearly—when the RA views the object—an empty plastic grocery bag flapping into the drivable area of a road could be reclassified to an overridable object.
Temporarily Modifying Specific Driving Policies	Temporary changes in driving policies are modifications to rules an ADS uses to make decisions. One example is when a human RA might modify a standard non-parking policy, allowing an ADS-DV to temporarily park to deliver packages or assisting passengers at a location not originally planned.
Temporarily Changing Zones	Marking an area as being a temporary keep-out zone ensures ADS operations remain clear of the area, even if, for example, the sensors don't detect anything unusual. Examples where temporary keep-out zones might be remotely assigned: wet concrete, temporary work zones (e.g., with thin wires/cables hanging in the vehicle's path), or an emergency responder scenario (e.g., with fire hoses crossing the road). Temporary keep-out zones could also be used to inform an ADS an entire street is impassable, forcing it to reroute. Marking an area as being a temporary free space tells the ADS that this area is safe to drive even if the sensors indicate otherwise. Some predefined reflections can be ignored, but others continue to inform safe path planning. Examples where temporary free space might be useful: grass growing into the road, small, low-hanging branches stretching over the street, or slotted metal grates that can look like an uneven surface to a lidar.

Some of these examples are already in use, while others may be implemented in the future.

According to the guideline, RA and RD play distinct roles in ADS-DV remote operations: RA offers guidance and support to the ADS-DV, improving its decision-making process, whereas RD is actively involved in DDT (e.g., supporting the vehicle’s operation outside of the ODD). Unlike RA, RD has the ability to take full control of the vehicle and carry out all DDT functions, much like a traditional human driver.

Below are some examples highlighting the differences across various components:

In terms of hardware, RA necessitates ADS-DVs to be outfitted with advanced sensors, cameras, telematics, and communication devices to enable real-time data transfer. In contrast, RD may require advanced redundant controls and actuators within the vehicle, along with high-definition cameras, to allow the remote driver to directly control steering, acceleration, braking, and other functions. Redundant safety mechanisms and fail-safe features are also crucial for ensuring safe operation (AVSC, 2023).

Regarding network infrastructure, communication systems facilitate real-time data exchange between the RA and the ADS-DV. While low latency is preferred for RA communications, it is not a strict requirement. However, RD communication systems demand a highly reliable and ultra-low-latency network to enable immediate response and direct control. This network should be supported by multi-modal (or multi-frequency band) communication and effective forward error correction techniques to minimize the delay between the remote operator's commands and the AV's actions (AVSC, 2023).

2.9.1 Training guidance for remote operator/assistant

In the guideline provided by SAE, a framework for the training that should be given to remote operators has been established, with the following categories considered:

1. Comprehensive Knowledge:

A remote operator must have a deep understanding of the operational aspects of ADS and the complexities of Remote Assistance (RA) interface systems.

2. Conceptual and Practical Training:

Operators should gain both conceptual understanding and practical experience regarding the functioning of ADS and RA interfaces.

3. Blended Training Process:

The training process should encompass foundational understanding to skillful execution and effective troubleshooting. This may involve a combination of self-guided learning and instructor-led activities.

4. Comprehensive Training Guidance:

The training must cover the full range of tasks that RAs are expected to perform, as well as all inputs they interact with during their operations.

5. Focus on ADS Behaviours and ODD:

Remote operators should develop the ability to understand the behaviours of ADS and elements of the ODD. This is crucial for effectively managing scenarios that exceed the ADS's design capabilities, such as novel or highly complex situations.

6. Awareness of Local Laws and Regulations:

Remote operators must be well-informed about the laws and regulations specific to the jurisdictions in which the ADS operates.

7. Specialized Training:

Specialized training can enable remote operators to enhance their efficiency in specific aspects of RA operations and develop expertise in particular skills.

Remote assistance is an integral part of a well-structured process that operates within a framework of decisions and rules, customized according to the developer and the ODD of the ADS. Figure 5 demonstrates a high-level process of implementing RA which includes 3 steps: 1: Vehicle data collection 2: Triggers for needing assistance 3: RA response.

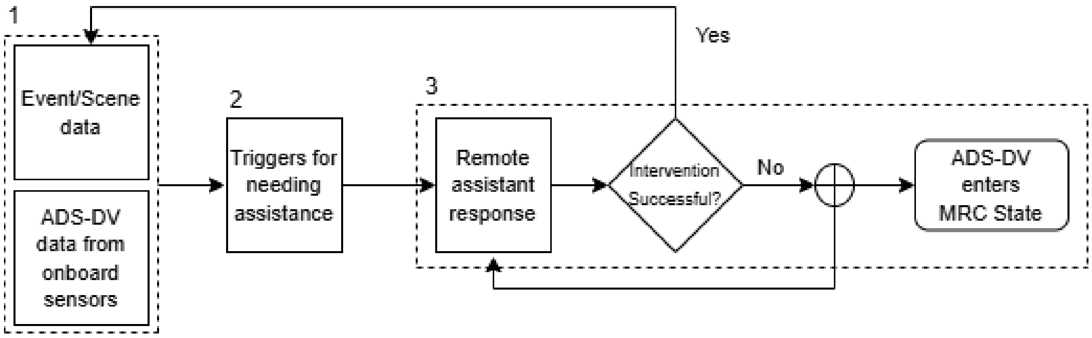

***Figure 5:** RA process flow (source: AVSC, 2023)*

In the first step the ADS RA system should enable the RA to access relevant time-stamped vehicle data, including sensor readings, telemetry, and system status. Triggers of step 2 may arise from ambiguous situations, for instance, novel road or environmental conditions, exceptionally complex manoeuvres, or encounters with obstacles that the ADS may not understand. In step 3, if the need for assistance is determined, the remote assistance system automatically provides all relevant information about the triggering event, the vehicle's state, status, and SA data to the RA who evaluates the information and formulates an appropriate response.

After providing guidance or forwarding the request, the RA may continue to actively monitor the scenario and assess the success of the assistance, depending on the scenario.

If the assistance proves unsuccessful and the issue cannot be resolved, the ADS-DV is guided to reach an MRC state, prioritizing safety, and minimizing risks.

2.10 Finnish regulation and legal aspect of remote operation

In the regulations related to the world of AVs, its various associated sections and subcategories, and the challenges arising from it, there are still many ambiguities and gaps, which some of them are mentioned by (Imai, 2019). With the addition of RO, it does not appear to simplify matters or reduce ambiguity or may even intensify it in some cases, as a third party is introduced into the whole process. Moreover, the legality of the RO of AVs has received little attention in the literature (Goodall, 2020).

Hopefully, Finland's goal is for the development of automation, as well as digitalization in general, to proceed from human-centred perspectives. In this subsection, the existing regulations related to RO in Finland will be reviewed. Whether we are in a situation where we can say that the existing regulations are helpful in optimizing the process of reaching RO or not, or even there is enough attentions for RO itself, is one of the goals of this section. The regulation points are taken from (Miettinen et al., 2024) which is in Finnish, and the translation was done using AI Copilot 2024 and the translation website (sanakirja.fi). After comparing the translations, the version that sounded more coherent and relevant to the previous texts was selected and incorporated into the thesis.

Previously, three main (and challenging) items for implementing the RO were introduced: the on-board passenger, the automation systems, and the RO system itself controlled by the remote operator (Figure 2). It seems that the overall perspective and legislative approach in Finnish traffic regulations (Miettinen et al., 2024) can be followed in a similar structure for better understanding, although not necessarily exactly. Since the regulations related to automation systems and AVs were beyond the scope of this thesis, the relevant parts to the (remote) driver and the remote management (its definition and its subsections) are considered.

1. Driver and automation

The Vienna Convention of 1968, also known as the International Road Traffic Convention, along with the 1949 Geneva Convention on Road Traffic, play a crucial role in standardizing traffic regulations for international travel. The Vienna Convention of 1968 has been incorporated into Finnish law through the Road Traffic Act (729/2018). According to these conventions, a vehicle must have a driver **inside** the vehicle. In 2021, an amend-

ment was made to the convention, introducing a new Article 34 bis, which reads as follows:
"The requirement that every moving vehicle or combination of vehicles must have a driver is considered fulfilled when the vehicle uses an ADS that:
(a) complies with national technical requirements and applicable international legal instruments concerning wheeled vehicles, equipment, and parts installed in or used on wheeled vehicles; and (b) conforms to national legislation regulating operations."

The amendment to the agreement came into effect in July 2022, enabling the development of regulations for traffic automation in member states. However, the explanatory memorandum of the amendment noted that the introduction of automated driving in Finland requires more detailed national-level regulation. The amendment did not change the fundamental requirement that a vehicle must have a person in charge who still has general responsibilities in case of AVs:

- Be aware of how to operate the automated vehicle,
- Be aware of their roles and responsibilities as a driver and a driver-in-readiness,
- Follow the vehicle's operational instructions,
- Respond correctly and promptly to vehicle alerts and requests,
- Be prepared and able to take dynamic control of the vehicle, when necessary,
- Refrain from interfering with the driving system in a manner that could create danger,
- The driver-in-readiness must be prepared to assume dynamic control of the vehicle if needed and possess the necessary driving license.

In the current state of Road Traffic Automation part, two use cases are distinguished: 1) vehicles with a responsible human inside who can take control of the vehicle if needed, and 2) remotely operated vehicles carrying passengers, goods, or empty. Vehicles in the second usage case are typically small buses or so-called robot taxis that operate on predefined routes or areas and are subject to remote control measures. The revised Road Traffic Act has been drafted with minimal barriers to automation in traffic, such as not requiring a driver to be present inside the vehicle. However, according to current interpretations, a vehicle with an ADS can be used if it is type approved.

In Finland, the national regulation concerning vehicle use in traffic is contained within the Road Traffic Act, while vehicle technical regulations are found in the Vehicle Act. Currently, the Road Traffic Act allows for the driver to be located outside the vehicle.

2. Remote management

Some automated vehicles will be subject to remote control. While these new concepts are generally not yet established at the international level, Finnish legislation has considered this issue. Although there are still ambiguities and unclear aspects in the regulations, the effort to prepare the groundwork and facilitate remote control in traffic is important.

The definitions of the automatic driving system and dynamic control come directly from the Vienna International Road Traffic Agreement.

- A driver in readiness refers to a natural person inside the vehicle who can either drive the vehicle themselves or transfer dynamic control to the automatic driving system.
- A provider of automated driving refers to an entity responsible for the movement of the vehicle on the road when the dynamic control is with the automatic driving system.
- Remote management refers to the remote control or remote assistance of the vehicle via telecommunication connections.
- An entity responsible for organizing remote management is referred to as a remote management provider.
- A natural person who performs remote management activities on behalf of the remote management provider is referred to as a remote management agent.

In 2021, a working group named GE.3/LIAV was established with the task of preparing a draft for a new international legal instrument regulating the use of automated vehicles on the road. Although the group's work has since slowed down, a preliminary draft of the legal instrument was completed in the spring of 2023. The preparation involved Finland, Germany, Greece, Luxembourg, the Netherlands, Poland, Portugal, Sweden, and the United Kingdom. Although GE.3/LIAV has not continued processing the draft, it remains a document that reflects the most advanced thinking at the international level regarding the use of automated vehicles in traffic (Miettinen et al., 2024).

The draft contains six chapters, and it does not differentiate between levels of automation. The fifth chapter of the draft addresses situations where the vehicle has no driver. Such vehicles must be subject to remote management. Remote management encompasses both remote assistance and remote driving. The key difference between these concepts is that in remote assistance, the dynamic control of the vehicle remains with the ADS at all times, whereas in remote driving, the dynamic control is with the remote driver. Remote driving can also apply to conventional vehicles that have been retrofitted with systems and devices enabling remote control.

In remote management, the vehicle must be subject to at least the following actions:

- General monitoring of the vehicle's status, including its location,
- General monitoring of the vehicle's interior,
- Procuring assistance when necessary and resolving technical issues,
- Communicating with authorities, first responders, and other road users.

Additionally, if the vehicle is transporting passengers, a two-way communication capability must exist between the passengers and the personnel managing the vehicle remotely.

The safety of operations primarily depends on the activities of the company organizing the operation, the Remote Management Provider. It is expected to create an organizational structure, accountability arrangements, and procedures to ensure the following:

- Ensuring the safety of remote management services, including the physical security of operation centres,
- Ensuring adequate communication links, cybersecurity, and system resilience in fault and disruption situations,
- Logging events related to remote management, including the ability to distinguish remote driving situations.
- Ensuring sufficient skills and training for remote management personnel,
- Ensuring adequate staffing and organizing work to reduce fatigue and promote concentration.

Remote Management Providers must also establish procedures that enable cooperation with authorities and emergency services in accident situations. This includes providing clear information on how to effectively contact the on-duty remote management personnel. Additionally, remote management services must provide competent authorities with necessary data from their systems for accident investigations.

Remote Management Agents must ensure they have the required training and qualifications for their role. They must continually maintain their physical and mental capabilities during their shifts. They must also understand the difference between remote assistance and remote driving, and what this difference means for their responsibilities and legal liabilities.

2-1- Licensing requirement for remote management service providers

Providing remote management services in Finland would require a license. Offering such services would necessitate either a notification to or a license application with the Finnish Transport and Communications Agency.

2-2- Responsible operator for the safe operation of automated vehicles in traffic

When a vehicle is no longer conventionally driven by a human driver who is responsible for its movement on the road, there needs to be a legal entity to whom liabilities can be attributed. However, there is no consensus on which entities can qualify or the process for identifying them.

The preliminary draft of the international instrument also refrains from defining operators but asserts that each automated vehicle must have an operator responsible for its behaviour on the road, identified through mechanisms established in each state.

2-3- General obligations of the operator of an automated vehicle

In the future, the role of the driver in ensuring road safety will be replaced by the role of organizations. However, the use of automated vehicles also requires a new set of skills from their operators. Responsibility will therefore continue to be required of individuals. There are certain aspects that are more important than the traditional role of the driver.

Firstly, the user should have a clear understanding of the type of vehicle he is using. Is the vehicle equipped only with driver assistance systems, or is it equipped with an ADS. If the vehicle is equipped with an ADS, the user should know his role (driver on standby) when he has transferred dynamic control to the system and the responsibilities associated with that role. The user should become familiar with the vehicle's systems so that he or she understands what information and notifications the system provides or can provide, and when these notifications require a response. This is particularly true for vehicles with ADSs that generate transfer requests. The user should also have a general awareness of the limits of the environment in which the ADS is designed to operate, i.e. whether the journey ahead can be completed at all without the responsible person in the vehicle having to act as driver.

3. Remote operation of an automated vehicle

If there is no responsible person inside the vehicle, remote control measures must be applied to ensure traffic safety. Remote control refers to actions performed via telecommunication connections. Remote control can be divided into remote assistance and remote driving. Remote assistance applies only to automated vehicles, and the key point is that the dynamic control of the vehicle is always handled by the automatic driving system. Remote driving can also apply to conventional vehicles that have been retrofitted with remote driving enabling devices. In remote driving, the dynamic control of the vehicle is with the remote driver. If it is an automatic vehicle, dynamic control can sometimes also be with the automatic driving system, similar to how it can be with a driver inside the vehicle. In remote assistance, the person performing the remote control can manage multiple vehicles. The proposals do not prevent a monitor from being placed inside the vehicle if necessary.

At least the following remote-control measures should be applied to vehicles without a responsible person inside:

1. General monitoring of the vehicle, including information on the vehicle's location,
2. General monitoring of the vehicle's interior, passengers, and cargo, and
3. Obtaining and providing assistance in case of malfunctions and emergencies.

Information about the location of vehicles is often considered quite sensitive. However, for remotely controlled vehicles, it is a crucial safety factor. A situation where an automatic vehicle moves on the roadways with only passengers or cargo inside, without anyone being aware of its location, is not possible. For instance, passengers might include minors and the elderly, and in case assistance is needed, knowing the vehicle's location is essential. Additionally, remote assistance can include setting or changing strategic driving elements, such as the destination or an alternative route, or giving driving instructions to the automatic driving system, such as braking or avoiding an obstacle. In these situations, the remote controller does not directly brake or steer the vehicle longitudinally or laterally but can provide advice to the automatic driving system or confirm an action proposed by the driving system.

Furthermore, vehicles carrying passengers should be equipped with two-way communication devices that enable effective communication between the passengers and the remote controllers.

The automatic driving system must be capable of bringing the vehicle to a safe state, even for those automated vehicles under remote control. Both the passengers in the vehicle and the remote controllers should be able to initiate the function to bring the vehicle to a safe state when necessary (Minimal Risk Condition is mentioned before).

3-1- Remote operation service provider

In remote control operations, the safety of the service is heavily dependent on the company providing such services. While the actions of an individual employee are significant, ultimately, it comes down to the company’s safety culture and the tools it provides to its employees. Therefore, in Finland, remote control service providers would be required to obtain a license granted by the Transport and Communications Agency (Traficom).

The service provider must have the technical, financial, professional, and operational capabilities necessary to perform the task. Since there are currently no international standards or regulations that set specific requirements for this type of operation, the safety management system of the service provider plays a crucial role in ensuring safety. This system introduces a systematic approach to hazard identification and risk management, ensuring the effectiveness of control measures to mitigate identified hazards and risks. The safety management system, in essence, must guarantee the oversight and responsibility for all risks associated with the organization's operations.

Furthermore, the safety management system should emphasize supervision at all organizational levels, the assignment of responsibilities within the organization, the continuous improvement of the safety management system, and the active involvement of employees in decision-making processes related to the management system.

The safety management system must also be documented in written form. The CEO or another individual in a senior authoritative position within the service provider’s organization holds the responsibility for the effective implementation and maintenance of the safety management system.

Regarding financial capabilities, the service provider must possess sufficient financial solvency, enabling an assessment—based on known factors—that the organization can meet its actual and anticipated obligations and commitments for at least one year. Additionally, to support its operations, the service provider must maintain adequate liability insurance or equivalent arrangements.

3-2- Ensuring operational safety, communication connections, and information security

Since RO generally occurs beyond visual line of sight and relies on telecommunication connections, ensuring the quality of these connections is crucial for safety. Therefore, at this stage, Finland would require RO services to be provided from a RO service provider. Additionally, it would be required that the ROC is located within Finland.

Along with sufficient telecommunication connections, these requirements ensure that the service provider can manage access control and other physical security measures at the ROC and adequately supervise the activities of its employees. This also ensures that the authorities can exercise their inspection rights.

3-3- Requirements for RO service providers

The service provider would be required to ensure the existence of sufficiently reliable and fast communication connections relative to the quality of operations. Additionally, they must take necessary precautions to secure communication connections in case of malfunctions and disruptions. Attention must also be given to positioning technologies. Latency must be considered, and it is especially important in remote driving where latency has a significant impact.

The service provider must ensure the information security of their services. They are required to promptly notify the Transport and Communications Agency of any significant information security incident affecting their systems that could pose a significant danger to traffic safety.

The service provider would also be obligated to have contingency plans in place.

3-4- Practical arrangements related to the safety of RO services

As previously mentioned, the safety of ROs largely depends on how securely the service provider can organize these functions. In Finland, in addition to the previously mentioned requirements, general obligations would be included in the regulations that the service provider must consider in their safety management system. Therefore, the RO service provider must ensure that the equipment and workstations intended for remote control are appropriate, considering the quality of operations. The provider must also organize work in such a way that shifts and breaks maintain the alertness of personnel performing remote control tasks. Additionally, the provider must ensure that individuals performing remote control are continually physically and mentally capable of safely performing their duties.

Individuals engaged in remote control must have the necessary professional skills and have completed the required training. As of now, there are no national or international regulations, standards, or even guidelines related to the qualifications and training of personnel. Therefore, the RO service provider's safety management system must establish internal criteria for the necessary skills and training required for operations. The provider must also monitor that the personnel meet these requirements.

3-5- Requirements for individuals performing RO services

At a regulatory level, individuals performing remote control services would be required to be at least of legal age and possess a valid driver's license. The driver's license requirement ensures that the individual is knowledgeable about traffic rules. In their safety management system, the RO service provider may set even stricter requirements, such as requiring the individual to hold a driver's license corresponding to the type of vehicle they are remotely controlling.

Additionally, individuals performing remote control services would need to be suitable for the task based on their health status. They would also be required to have sufficient language skills to understand and communicate effectively in the languages used in the service offerings. Furthermore, they must have completed the necessary training required by the RO service provider.

Individuals performing remote control tasks must ensure that they are constantly physically and mentally capable of safely performing their duties. This includes managing factors like fatigue and monotony through regular breaks, for example.

3-6- Remote operated vehicles

In the remote management of AVs, the focus of the penalty system also lies within the operations of businesses. Similarly, for remotely controlled AVs, actual violations of traffic rules generally fall under the responsibility of the ADS provider, as such an operator must be present for remotely controlled vehicles as well. Ensuring the safety of remote management operations primarily depends on the actions of the business operator, i.e., the remote management service provider. Penalties in this regard could include administrative coercive measures, administrative fines, and criminal sanctions targeting the organization.

Individuals involved in remote management would not be held criminally liable for traffic violations committed by the vehicle when the dynamic control of the vehicle is under the automatic driving system. However, certain actions could still lead to criminal liability. An example of such a situation would be consuming intoxicating substances, which renders the remote operator incapable of physically or mentally performing their duties. Regarding RO, traffic fines are indeed applicable, but the liability of a remote driver for traffic offenses committed by the vehicle may need to be restricted compared to a "conventional" driver, given that the ability of a remote driver to safely operate the vehicle remotely largely depends on the framework provided by their employer for carrying out their work.

The development of national and international regulations and subordinate norms regarding remote control services still requires time. Therefore, there may be a need the Traficom to issue specific regulations concerning certain aspects related to the safe implementation of RO services.

2.11 Alignment and adequacy of Finnish regulation with best practice and guidelines by SAE

The SAE is a global association related to the automotive and vehicle industries (SAE, n.d.). As stated in its published guideline (see Subsection 2.9), it aims to provide a suitable framework for policymakers regarding RO. During discussions with experts conducted by the author of this thesis, it was highlighted that policymakers often lack sufficient knowledge about the technical aspects of AVs and related issues. This issue served as a motivation to examine the alignment between the guidelines published by SAE and the latest version of regulations concerning the use of AVs in Finland.

A review of Finland’s latest traffic regulations reveals their comprehensive nature, aiming to cover most modern technologies and relevant aspects and the groundwork and facilitate remote control in traffic is done well. While many countries have yet to officially recognize remote operators—creating legal barriers to RO projects—this issue has been addressed in Finland. The regulations allow a driver to monitor or even control a vehicle from outside the vehicle itself. Additionally, efforts have been made to clearly distinguish between different entities involved, such as the driver, the RO service provider, the vehicle manufacturer, and others, defining their respective responsibilities and duties. No significant legal obstacles to implementing RO projects appear to be present.

The first noticeable issue is the use of different terms to refer to the same concept. What is identified as *Remote Operation* or *Remote Assistance* in the guideline is referred to as *Remote Management* in Finland's regulations. However, this terminology is not entirely consistent. In some instances, *Management* is also referred to as *Assistance*, and the terminology shifts depending on the context. While some of these variations may stem from translation differences, the key issue is that no specific categorization regarding the different types of remote vehicle control has been established. Ultimately, it appears that there is not notable distinction between *Remote Driving* and a scenario where the operator does not control the vehicle in real time.

When clear boundaries in definitions are lacking, it inevitably affects the distinction of responsibilities. In the event of an issue, this ambiguity can create a legal gap in assessing the situation.

The guideline provides a detailed classification of different levels of automation, whereas Finland's regulations do not introduce or reference any such categorization. Instead, they only mention type approval. However, according to the guideline, one of the most critical aspects of defining the responsibilities of a remote operator is understanding the scope of automation—specifically, the extent to which the remote operator should influence this scope.

Perhaps for these very reasons, Finland’s regulations take a highly general approach when outlining the responsibilities of *Remote Management*. The duties are described only at a fundamental level, focusing on basic priorities rather than providing detailed guidelines.

Similar to the published guideline, Finland’s regulations attempt to consider the remote operator’s interaction with both AVs and other road users. However, certain situations and definitions receive minimal attention.

One of the most underdefined aspects is the concept of *triggers* or *Minimal Risk Conditions*, as outlined in the guideline. There is little detail on when a vehicle should request assistance, which institutions are deemed suitable and qualified to oversee AV projects, the specific responsibilities of automated systems, and the structure and content of operator training. These gaps highlight areas where further clarification is needed.

Finland’s regulations state that the only requirements for becoming an operator are holding a valid driver’s license and meeting the legal age requirement. In contrast, the guideline specifies additional training parameters and educational content for operators.

It is commendable that Finland’s regulations address workplace conditions for operators, including aspects such as cybersecurity, fatigue, and workload. However, they do not specify how networks should be established or how to equip the operator’s workspace with a reliable communication infrastructure to enhance SA. Additionally, there is a significant legal gap concerning the HMI.

While the regulations acknowledge the existence of each component involved, they remain at a highly general level. For instance, they do not define the minimum requirements for an interface, nor do they specify the essential elements needed to ensure a remote operator’s baseline SA. Similarly, there are no clear criteria for the companies responsible for providing network connectivity and communication infrastructure.

3. METHODOLOGY

According to Walliman (2020) a research study is not merely based on the collection of facts or information without a clear purpose. Following Saunders' definition of research and its nature (Saunders et al., 2019), this thesis aims to achieve its objective—answering the questions posed at the beginning of the study—by systematically gathering and interpreting data. Saunders states the Research design is a framework for choosing specific methods of data collection and data analysis.

Saunders et al. (2019) present the 'Research Onion Model,' which provides a systematic framework for developing the research methodology in a dissertation or thesis. It provides a helpful framework for selecting the right research philosophy and creating an effective strategy. The model is made up of six layers, with each layer representing a specific aspect of the research process. To establish a robust research methodology, academic research begins with formulating research questions and objectives. This is followed by a series of decisions regarding the research philosophy, approach, and overall design, which includes methodological choices, research strategy, time horizon, as well as data collection and analysis. Each layer of the research process is interconnected and dependent on the others. In essence, the selected research philosophy shapes the approach, which subsequently influences the methodological choices, strategy, time frame, and methods for data collection and analysis (Saunders et al., 2019). Figure 6 illustrates what Saunders has described as the different layers of a research study.

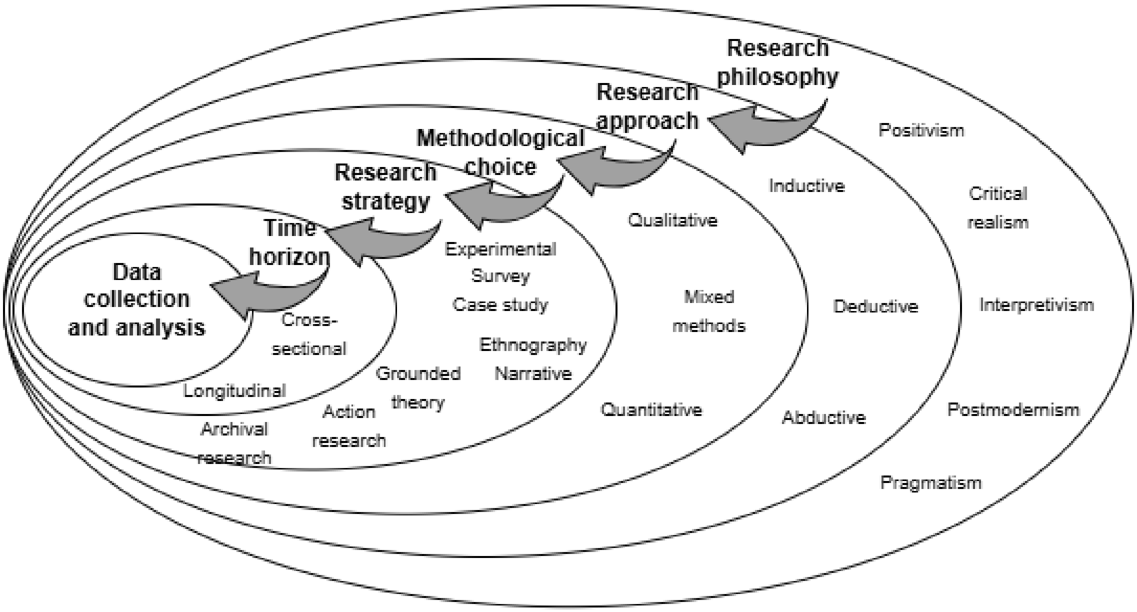

Figure 6: *The Research Onion of Mark Saunders (Saunders et al., 2019)*

Based on the process followed in writing this thesis, the layers of “Research Onion” model are as follows:

1. Research Philosophy:

What Saunders et al (2019) refers to as research methodology is, a system of beliefs and assumptions about the expansion and advancement of knowledge, which can be specific to a particular field. Moreover, research philosophy defines the worldview within which research is conducted.

This study is initiated around a central research question, aiming to gather insights and practical solutions that contribute to the improvement or advancement of RO technology as well as the establishment of a control room centre. It inherently incorporates a pragmatic emphasis on practical outcomes.

Considering Saunders’s definition of pragmatism—describing it as an effort to reconcile objectivism and subjectivism, facts and values, rigorous and precise knowledge, and diverse contextual experiences—it can be argued that this study aligns with this philosophical approach (Saunders et al., 2019). This alignment is reflected in how theories, concepts, ideas, hypotheses, and research findings are not merely considered in abstract terms but are analyzed in relation to their function as tools for thought and action, along with their practical implications in specific contexts.

According to Brannen (2017), Epistemological assumptions are established upon the understanding of the nature of knowledge; they connect to human knowledge and are gained through the empathic understanding of the participant’s subjective lived realities, and understandings. Aside that, Ontology, as Saunders wrote in his book, refers to assumptions about the nature of reality and Axiology refers to the role of values and ethics (Saunders et al., 2019). The ontology of this research involves contemplating the reality of RO technology and its operational centre. In terms of epistemology, this technology has been approached through logic and reasoning.

Finally, it should be noted that the axiology of the obtained data is evaluated based on its alignment with real-world experiences and the consensus of experts on a particular issue or challenge. Additionally, efforts have been made to acknowledge the innovative perspectives of specialists.

2. Research Approach: Since the research is based on previous articles and frameworks were extracted for the study, it follows a deductive approach. Induction has also been employed, as interviews, the Delphi method, and questionnaires have contributed to discovering new patterns and perspectives.

3. Methodological Choice: This is a multi-method research study because both qualitative interviews and, to some extent, quantitative methods have been employed (some questions can be analysed quantitatively, and for those questions, descriptive quantitative analysis will be presented. For other questions, qualitative methods will be used for analysis.). The Delphi method, applied to this thesis, is considered a structured technique for collecting expert opinions and is one of the qualitative methods.
4. Research Strategy: The research strategy aligns more with case study or survey research methods, as the data has been collected from industry and academic experts.
5. Research Timeline: The data has been collected in two rounds of the Delphi method, using different sets of questions from the same experts. Despite the iterative nature of the method, the time frame is considered cross-sectional.
6. Data Collection: literature review, interviews, Delphi method (questionnaires). Data analysis: The interviews have been coded and content analysed, thus qualitative analysis has been used.

Despite the limited research directly related to the primary research question presented at the beginning of this thesis, relevant insights could be drawn from similar studies in the field of AVs in aerospace and maritime domains. This is because RO technology, along with the presence of a station where a human operator controls and assists the process, is a common feature in these domains as well. Consequently, while general knowledge from these studies could be leveraged, it was necessary to refine and, if needed, adjust the findings based on input from experts specializing in road-based AVs.

Therefore, the literature review incorporated existing studies that examined technological challenges in a broader sense. The subsequent step involved refining these challenges specifically for automated road vehicles, ensuring that only issues aligned with the research objectives were included. To identify and validate research gaps, collaboration with academic and industry experts was deemed essential. This approach facilitated the formulation of relevant research questions and the identification of potential answers. Given that some of these experts had conducted studies in recent years, they were invited for interviews to assess whether the challenges they had previously identified remained relevant despite technological advancements.

The insights gained through these interviews were instrumental in shaping the research methodology itself, as expert perspectives played a crucial role in advancing the thesis.

Notably, some industry professionals preferred brief online interviews over participating in detailed surveys or providing written responses. During these interviews, numerous concepts and underlying "whys" were discussed, necessitating a structured framework (like a survey) to systematically address them. The list of interviewees is included in Appendix B.

Moreover, the nature of this research is complex and forward-looking, requiring the convergence of perspectives from experts with diverse viewpoints. RO is not merely a transport issue; it is a technology that intersects with multiple engineering, scientific, and practical disciplines. As a result, it is inherently an interdisciplinary topic that demands analysis from various academic fields.

Additionally, the regulatory and policy landscape surrounding this technology varies across countries, making it valuable to engage experts from different regions. It is important to note that even within a single country, different cities may adopt distinct approaches to this technology. Taking all these factors into account, the Delphi method was identified as a suitable approach for gaining deeper insights and reducing some of the uncertainties associated with this research.

Two rounds of the Delphi study were conducted to comprehensively address the research questions and accommodate the researcher’s curiosity, which at times extended beyond the predefined inquiries. The goal was to synthesize expert opinions and extract meaningful insights. The questionnaires for both rounds are included in Appendix C.

Regarding the data analysis, throughout the thesis, the data collected through interviews or questionnaires were qualitative in nature. These data were compared with the literature review, which also focused on qualitative data, in sections where relevant. The structure of the questions and analysis followed the organization of the literature review, grounded in previous research. During the coding process, responses were categorized into various themes (e.g., HMI), and some of the coding also addressed specific research questions, linking responses to their corresponding questions.

For questions such as rankings or multiple-choice questions, the most frequent response was considered the consensus among experts. In open-ended questions, all responses were reviewed and coded according to the identified themes, although not all responses directly addressed the specific questions posed in the questionnaire. For instance, in network-related questions, some responses referenced latency or communication, which was expected due to the interdisciplinary nature of the technology. Nevertheless, clear answers were required for each section, and coding helped to define boundaries, making the results more readable and comprehensible. Any contradictory or supporting sources from the literature were cited where appropriate.

3.1 Delphi method

The Delphi method, developed by the RAND Corporation in the 1950s, is a research approach designed to gather expert opinions on complex research issues for which precise information is unavailable (Linstone & Turoff, 2011). The method focuses on systematically structuring group communication processes to reach a consensus among experts. Expert opinions are typically collected through multiple rounds of detailed questionnaires, generating both qualitative and quantitative data for analysis. The results from each round inform the design and content of subsequent questionnaires, continuing this process until the group's opinion stabilizes (Gupta & Clarke, 1996 & Linstone & Turoff, 2011).

For this thesis, after studying and gathering relevant information from various articles and identifying challenging issues or research gaps, questions were designed for the survey. During the interviews with experts, the questions were updated and then sent to the experts in two rounds, collected, and finally analysed.

According to the methodology employed in this research, two rounds of surveys were conducted: the first in September 2024 and the second in November 2024. Each round featured a distinct set of questions, and both surveys are included in Appendix B. The variation in questions was informed by insights gained from the first round and the identification of gaps between these insights and the overarching research questions. Consequently, no technical questions were repeated, and efforts were made to address all aspects of the research questions across both rounds.

Furthermore, throughout the process of writing the thesis, interviews were conducted with professors and specialists from various regions of the world. In certain cases, their responses and key points raised during the interviews have been referenced, especially in relation to specific topics. Since the interviews did not follow a standardized set of questions, not all aspects discussed in the interviews were used to inform the survey questions.

In total, 78 questions were included in the surveys, divided into distinct sections based on specific topics or issues. This structure allowed experts to respond to the sections where they felt they had the most expertise. The surveys were distributed to 60 experts, who were also given the flexibility to forward the surveys to colleagues they believed might possess greater expertise in specific areas. To better understand the respondents' qualifications, both rounds included a question asking about their years of experience and the fields in which they felt most knowledgeable (Professional Background). This information was used to identify areas with the greatest potential for generating valuable insights for the future research.

All procedures were conducted in compliance with GDPR regulations, and consent was obtained from all participants. The GDPR consent question was the first and the only mandatory one in both rounds.

In first round, 53 questions were included, and responses were collected from 39 participants, consisting of 22 fully completed surveys and 17 partially completed ones. However, after a detailed review of the responses, 8 participants were excluded due to having left all questions unanswered. As a result, the data from 31 participants were analysed in Round 1. In both rounds, not all questions were answered to the same extent, as participants were given the freedom to select topics in which they had greater expertise.

In second round, based on the results and issues that emerged from the first round, most of the questions were related to the remote operator, the operator's work environment, and the progress of the process. This is due to the noticeable knowledge gap in these areas. The questionnaires were sent to 60 experts in this round, with 31 individuals responding. However, 11 of them submitted the questionnaire without providing any answers. As a result, these responses were completely excluded from the analysis, and the remaining 20 responses were evaluated.

Among the participants, 6 were researchers (road safety specialists or Ph.D. holders), 3 were project managers, 7 were consultants, and 4 were professors. Overall, the average experience across all participants was more than 11 years in their respective fields.

4. DATA ANALYSIS

According to the methodology explained in chapter 3, two rounds of surveys were conducted. The analyses of rounds one and two are detailed in subchapters 4.1 and 4.2.

4.1 Analysis of first round

Based on the experts' professional backgrounds or current roles, the participants were categorized into three groups. Additionally, a question was included to determine whether they had been involved in a remotely operated project. This information served as a basis for understanding the strengths and weaknesses of such projects, which were further explored in subsequent questions. Table 3 provides an overview of the initial information about the respondents.

Table 3: *Overview of respondents' initial information*

Professional backgrounds or current role	Number of people	Years of experience on average	involved in a project concerning the RO of AVs	Not involved
Leadership and Management	8	14.25	22	9
Academic and Research	15	8.06		
Consultants, Technical and Engineering people	8	9.5		
Total	31	10.03 (Average in total)		

According to the table, there are three distinct groups, presenting the potential to receive different responses from the academic and industry sectors. Twenty-two respondents have been involved in a RO project, and their perspectives on its strengths and weaknesses could provide insights that reflect real-world scenarios. Regarding the strengths, the experts' key points can be categorized into three main groups:

1. Transport Issues: Traditional driving methods and their consequences have occasionally led to challenges. Experts, considering certain potentials of RO, suggest that this technology could help address some of these issues. For example, RO has the potential to resolve challenges related to last-mile and first-mile solutions.

2. Safety and Advancement: RO can enhance safety in automated transport by helping identify weaknesses in self-driving systems, leading to improvements and further advancements.
3. Reduced Workforce Dependency: The adoption of RO can decrease the number of individuals directly involved in transport through driving, thereby reducing workforce dependency in the sector.

Other strengths highlighted by participants include addressing research gaps, identifying real-world challenges, and uncovering legal and regulatory shortcomings in the AV sector. As a result of these strengths, RO can provide a safer pathway for advancing AVs, facilitating their more effective integration into urban environments.

However, the weaknesses of this technology, as pointed out by participants, are primarily related to communication and technical challenges. Key concerns include operators' limited SA and potentially inaccurate perception of the vehicle's real environment, the overall technical complexity of RO for operators, network disruptions leading to latency issues, sensor errors, and system-originated failures within AVs. These factors collectively represent the main weaknesses identified in RO projects.

4.1.1 Current state of technology

According to NASA (2024) the Technology Readiness Level (TRL) scale is used to assess or represent the development maturity of a specific technology. It consists of nine levels:

TRL 1: Observation of basic principles

TRL 2: Formulation of the technology concept

TRL 3: Experimental demonstration of the concept

TRL 4: Validation of the technology in a laboratory setting

TRL 5: Validation of the technology in a relevant environment (for key enabling technologies, this means an industrially relevant environment)

TRL 6: Demonstration of the technology in a relevant environment (industrially relevant for key enabling technologies)

TRL 7: Demonstration of a system prototype in an operational environment

TRL 8: Completion and qualification of the system

TRL 9: Proven functionality of the actual system in an operational setting (for key enabling technologies, this could involve competitive manufacturing or deployment in space).

Considering the scope of the projects in which the participants were involved, along with an assessment of the current state of technology and the strengths and weaknesses of RO, the participants estimated the Technology Readiness Level (TRL) of this technology to be 5.43.

Speaking of technology, it is essential to understand the relative importance of each technological subcomponent. According to the respondents, the following factors were identified based on their importance for the success of a RO project.

1. Communication and Network
2. Latency
3. HMI and SA
4. Remote operator capability
5. ROC (Work environment)

Additionally, respondents had the option to suggest other relevant parameters. Among the aspects mentioned were automated system algorithms and the technology related to sensors.

In the literature review, the importance of HMI, network and communication, workplace, and latency was discussed. However, due to the scope and focus of this study, sensors, automated system algorithms, and their complexities were not addressed.

The significance of these factors is highly interdependent. This interdependence is evident not only throughout the interviews but also across responses to all questionnaire items. Despite the categorization of different sections and the formulation of distinct questions for each area (e.g., network, HMI, etc.), experts frequently mentioned other sections in their responses. The phrase “This also depends on the network/HMI/operator tasks/etc.” was repeatedly mentioned.

This suggests that the segmentation of topics is merely a superficial structuring intended to facilitate a clearer understanding of the overall issue, and the technological parameters involved. However, in practice, these components are highly interconnected, and their significance or level of reliance is often influenced by one another.

For instance, as stated by Interviewee I01, network speed is a critical factor in RO. However, depending on the specific tasks assigned to the operator, even lower network speeds might be sufficient.

However, similar to the literature review, where each component was examined separately, the issues in this chapter have also been categorized into distinct sub-sections for readability. Nonetheless, these aspects are not entirely independent and may overlap across different sub-sections.

4.1.2 Network

The most challenging aspect of RO in PT is network reliability. This is crucial because low-latency communication and high bandwidth are essential for real-time control of AVs, and any disruption or delay can jeopardize both safety and operational efficiency. Irregular network coverage, especially in urban or rural areas, presents significant challenges in maintaining a stable connection between the vehicle and the remote operator, creating a critical barrier to the successful implementation of RO systems. The network connection must be reliable to ensure real-time SA when necessary. ROs require high bandwidth, and as the number of vehicles increases, network reliability decreases. Even with advanced 5G networks, there may still be slight but critical delays in data transmission between the vehicle and the operator. In fast-paced and unpredictable environments like urban PT, these small delays can lead to slower responses to potential hazards, increasing the risk of accidents.

Under current circumstances, potential solutions include network challenges must be carefully addressed to enable the safe and efficient implementation of RO systems. Maintenance teams should be available online 24/7 to monitor and resolve any issues with systems, networks, or vehicle fleets.

4.1.3 Latency

According to the literature review, as Zulqarnain (2021) stated that latency is a crucial factor for secure and reliable driving. Experts believe that the way this issue can impact the performance and safety of RO in AVs is as follows:

Initially, there is a consensus on the critical importance of this issue. However, it is later discussed that the impact of latency depends on the type of RO and the specific tasks assigned to the remote operator.

For instance, in remote driving (which is dependent on continuous monitoring), even the slightest delay can compromise both safety and performance, potentially leading to operational disruptions and accidents. In contrast, in remote assisting, due to the nature of the remote operator's involvement and responsibilities, latency is more manageable—even a 3G internet connection can be sufficient. This perspective was also confirmed in an interview with I05.

A key factor here is having a fail-safe strategy, ensuring that in the event of communication disruptions or latency issues, the vehicle does not experience operational failures, and the operator does not lose SA or control of the car. For example, an expert in the survey stated:

"The safety-critical functionalities must be built into the vehicle, so the latency is not as critical as often perceived."

An interesting viewpoint—mentioned by only a few but also highlighted in interviews (I01 and I04) with RO companies—is the importance of **learning how to cope with latency** rather than solely trying to eliminate it. Discussions with project leaders emphasized that a crucial skill for operators is developing the ability to adapt to latency and fully understanding the difference between operating a vehicle remotely and being physically inside it.

The following issues and consequences related to latency were identified by Delphi survey respondents:

- Security risks and delayed responses
- Loss of SA
- Unseen future and difficulty in predicting upcoming events
- Moving obstacles and their positions when the operator lacks full visibility of the vehicle and its surroundings (e.g., the position of passengers inside the car)
- Real-time decision-making challenges
- Loss of vehicle control, reduced precision, and decreased operational efficiency:

Latency forces remote operators to adopt more conservative driving strategies, which in turn reduces the vehicle’s performance and responsiveness, ultimately affecting the overall efficiency of the service.

Experts have proposed both software-based and hardware-based solutions to address and mitigate latency challenges:

The primary focus in software is on data management and transmission optimization. Video data is inherently heavy, so data compression (e.g., compressing video feeds for remote driving) can help reduce latency. In critical situations, only essential data—such as bounding boxes highlighting key factors—could be transmitted. This is also aligned with Kim's findings in his article related to remote sensing area (Kim et al., 2025). Bounding boxes are commonly used in computer vision systems and deep learning for object detection and tracking. These boxes are designed to define the position and dimensions of a subject without delving into excessive detail. For example, in object detection, a bounding box can be drawn around a specific object (such as a person, car, animal, etc.) to allow the system to identify and track it (Goodfellow et al., 2016).

Here, bounding boxes refer to data that help highlight key factors in a particular context (such as images or videos) without addressing other details, thereby reducing the data volume and emphasizing the most relevant information.

In other words, local perception processing can be performed within the vehicle, and only the necessary route-related information is sent to the remote operator. Hardware and network solutions are listed below:

Redundant network infrastructure: Establishing multiple dynamic connection options, such as satellite and Wi-Fi, can enhance connectivity. However, these technologies are still in their early stages, and cellular network coverage and performance remain the primary limitations.

Virtual simulators: Using virtual environment simulators at the operator's station to predict the vehicle's path can help manage latency during high-traffic situations.

Real-time network monitoring and seamless switching: A system capable of predicting network congestion in real-time and automatically switching to a lower-latency network without disruption can be highly effective.

Proactive intervention detection: Systems that anticipate potential remote operator interventions early can provide more time for SA before critical input is required.

Increased processing power and speed: Improving computing capabilities clearly enhances performance.

Reducing physical distance between the remote operator and the AV: Placing operators closer to the vehicle and using the most direct data transmission routes (e.g., avoiding satellite relays) can significantly reduce latency.

4.1.4 HMI and SA

The essential features of an effective HMI for Remote Operators of AVs, according to experts, include the following, which depend on the type of operation the remote operator is involved in, whether it is supervised or unsupervised automation:

- **Methods for achieving SA and minimal control**: Depending on the technical maturity of the ADS system and its alignment with the ODD, remote driving may or may not be required; this should be tested.
- **Real-time data visualization**: It should include visualizations of data such as video, maps, and sensor data to ensure SA.
- **Intuitive and responsive controls**: Quick decision-making, real-time data visualization, high-definition video with low latency, clear feedback on vehicle status, and integrated communication tools, especially for emergencies, are essential. This should be supported by clear warning systems that alert operators to potential hazards.
- **Compatibility with various levels of automation**: The interface should allow operators to switch between manual and automated modes based on needs.
- **Multitasking support**: It should support multitasking to manage multiple vehicles and provide an ergonomic design to reduce operator fatigue.
- **Communication features**: The system should enable interaction with passengers or emergency responders to ensure smooth operations.
- **Immersive experience**: The interface should offer a fully immersive environment for the remote operator, creating a "workspace" similar to the real-world context.
- **Emergency communication**: The ability for the RO to communicate with emergency responders via voice or video calls.
- **Data without unnecessary overload**: All necessary information should be provided without overwhelming the operator, based on empirically validated design guidelines and task dependencies.
- **360-degree visibility and support for autonomous decision-making**: The HMI should provide complete SA to the RO. The multisensory feedback, 360 visibility, and immersion can all work together if they're tailored carefully to provide context-sensitive information. That way, the user gets the richness of the experience, but it doesn’t cross into overload territory.

- **AI-driven traffic control equivalent**: The AI should be scalable, meaning it should not require a 1:1 RO/vehicle model.
- **Multisensory feedback**: This includes visual, auditory, and haptic feedback, such as 360-degree cameras (with depth information when possible), haptic feedback simulating motion (curves, acceleration/braking, underground simulation with accelerometers and motion platforms), force feedback in the steering wheel, and stereo sound for environmental awareness. It may also simulate external lighting conditions (day/night). The underground or subterranean simulation typically refers to virtual or physical models designed to replicate underground environments, conditions, or activities. These simulations are commonly utilized for training, research, and analysis across various fields (Jeong & Lee, 2024).
- **Interface design for inactive RO**: For inactive ROs, the interface should be simple and display only the most critical information. For active ROs, more detailed information should be shown to help the operator make the best decision possible. Ultimately, RO is entirely related to SA, decision-making, and driving behaviour.
- **Providing sensory data**: The HMI must provide sufficient sensory data to the RO to build and maintain SA. This will vary depending on the use case and should be tested by the RO organization.
- **User-centred design**: The interface should be designed with the user in mind and follow relevant ISO standards. It should be optimized for the RO to accurately and quickly understand traffic conditions and provide useful feedback to the AV.
- **Logical and clear physical control interface**: The control interface should be intuitive and unambiguous.

Earlier, we discussed the importance of SA and the impact of factors such as networking, communication, and the HMI. Based on the opinions of experts and specialists, the order of importance of these factors in terms of their challenges is as follows:

1. HMI
2. Feedback Modes
3. Network and Communication

4.1.5 Transport infrastructure and integration

Regarding the existing transport infrastructure and its level of support for RO, responses to this question were mixed. Out of 20 responses, there was a neutral stance, meaning that while infrastructure is helpful in some aspects, it falls short in others. On a scale from 1 to 5—where 1 indicates no support and 5 indicates full support—opinions varied. Figure 7 indicates the responses to the question.

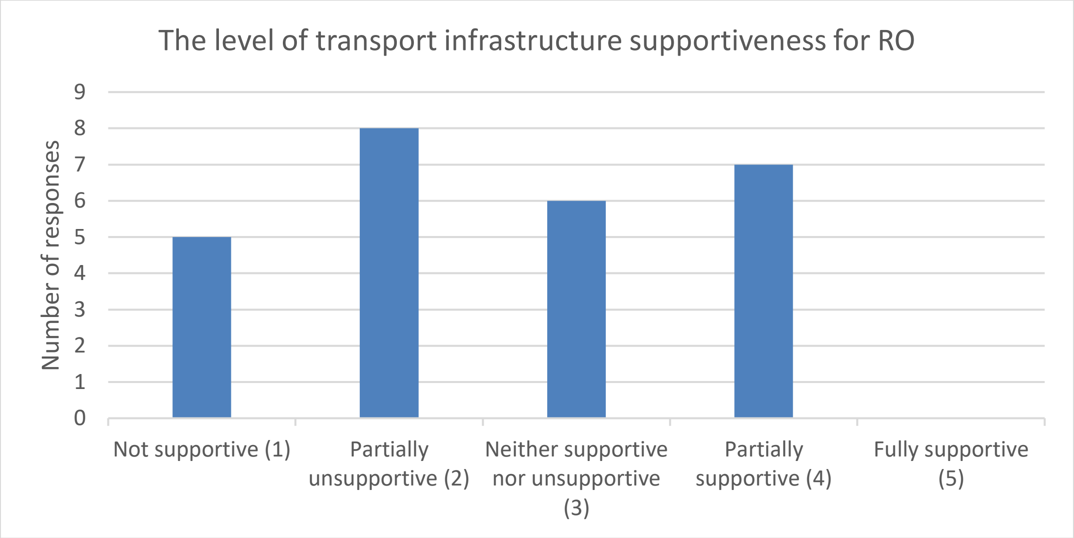

***Figure 7:** Respondents' views in Delphi on the supportiveness of transport infrastructure for RO*

Experts believe that to improve alignment between infrastructure and RO, greater use of digital infrastructure along roads could reduce the need for remote operators to rely solely on their direct visual feed. This could include providing digital information on speed limits, traffic lights, and other relevant data. In challenging locations like tunnels, additional communication infrastructure could be implemented.

Traffic management organizations already use multiple cameras for monitoring, so providing remote operators with access to these camera feeds could offer external views of situations. Urban environments are not always fully adapted to support AV operations, particularly in terms of integration with traffic management systems and physical infrastructure such as road signs and signals, which are not yet optimized for automated navigation.

Edge computing nodes, V2X communication systems, and the implementation of intelligent transport systems—including smart traffic lights, CCTV cameras, LiDAR on roads, cloud infrastructure, centralized control centres, and smart road infrastructure—could significantly improve the responsiveness and reliability of remote-operated vehicles.

However, implementing these systems requires substantial investment and long development timelines. Therefore, it would be more practical to begin with major urban highways.

It is also important to note that the feasibility of these improvements depends heavily on the specific country where the RO project is being implemented. In countries with poor infrastructure for vehicles a lot of upgrades need to be made for ROs to be even demonstrated let alone fully functioning. As a low-cost solution in these countries, promoting more orderly parking can be mentioned, as it helps reduce obstructions and improves visibility.

The role of RO in facilitating the integration of AVs into PT can take various forms. From the perspective of integrating automated PT systems, remote operators can and should act as fleet managers, ensuring that vehicles operate according to schedule as part of the PT network.

Remote operator systems can enhance flexibility, safety, and efficiency. These systems enable the expansion of AV services to underserved or hard-to-reach areas by providing human oversight in complex environments where full automation may struggle. This includes locations with limited or no PT, improved accessibility for elderly and disabled individuals, and addressing shortages of bus drivers or trained personnel. Additionally, RO enhances safety by allowing real-time intervention in challenging situations such as adverse weather conditions or road construction, ensuring smoother and more reliable operations. Furthermore, RO systems help AVs integrate seamlessly with existing transport networks by coordinating with other transport modes and adhering to schedules. They also provide emergency support and passenger assistance, improving the reliability and user experience of automated PT services. By separating vehicle management from driving tasks, they can further increase fleet efficiency.

Implementing this system will reduce labour costs and improve operational efficiency, allowing transport agencies to allocate resources more effectively. Additionally, RO systems can collect valuable data on passenger patterns and system performance, which can inform future transport planning and infrastructure improvements.

From another perspective, current AVs are not yet fully equipped to handle many of the unique challenges that arise in highly dynamic urban environments like London. When unexpected situations occur, remote operators can provide immediate support and contribute to the ongoing learning and adaptation of AVs.

However, the integration of RO into PT is not without its challenges, most of which are technical in nature and require further advancements to ensure seamless implementation.

One of the major challenges is ensuring a reliable, low-latency connection between AVs and remote operators, as unstable network coverage in urban or rural areas can introduce delays that compromise both safety and performance. Additionally, scalability of RO systems presents a significant challenge, as managing a large fleet of AVs at a citywide level requires complex infrastructure and coordination to handle multiple vehicles simultaneously. Ensuring that RO systems can function seamlessly across different environments while also addressing cybersecurity threats and data privacy concerns adds another layer of complexity. Furthermore, technical compatibility with existing transport systems—such as traffic management and scheduling—creates integration hurdles that must be resolved to enable smooth and efficient operations.

Beyond the technical aspects, environmental factors, public adoption, and interactions with other road users also pose challenges, many of which are still far from being fully addressed. Another critical issue relates to business models. While the initial investment costs are high, operational costs can be comparable to or even lower than those of traditional driving, making long-term viability a key consideration.

Regarding public willingness to adopt RO, the questionnaire included a key question: Does RO have the potential to establish or enhance trust between the public and AVs? In response, 22 participants believed that it indeed has this potential, while only 2 participants expressed a negative opinion (Figure 8).

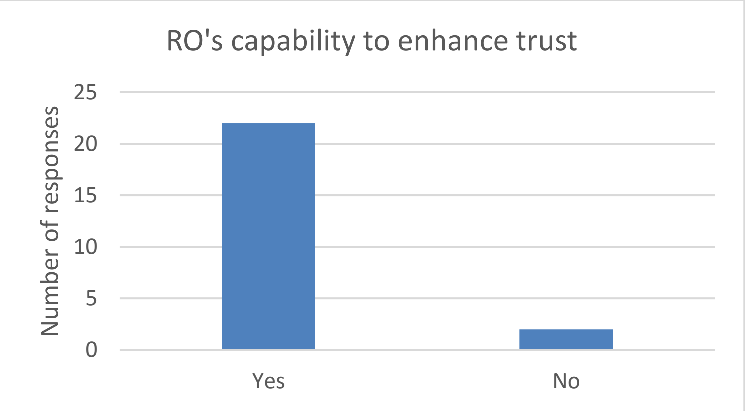

Figure 8: *Responses to RO can enhance trust between the public and AVs*

4.1.6 Safety issues

The main safety concerns related to remote operators of AVs, according to the participants in the survey, largely revolve around what we call technical issues. These include delays and communication instability, which lead to delayed SA and decision-making by the operator, ultimately affecting their ability to respond appropriately to what is happening.

One of the key concerns is network reliability and communication delays, as disruptions or delays in communication between the vehicle and the remote operator can hinder timely intervention, increasing the risk of accidents. Additionally, operator fatigue and high cognitive load, especially when managing multiple vehicles, can result in slower reactions or mistakes. Cybersecurity is another critical issue, as vulnerabilities in the system could lead to unauthorized control or data breaches, compromising vehicle safety. Finally, uncertainty regarding responsibility in emergency situations could cause confusion over which party—the remote operator or the AV—should be responsible for critical decisions, complicating response times and legal accountability. Can a bus full of passengers trust a remote operator managing a vehicle who is fully detached from the consequences of his/her actions, such as making a mistake? In fact, all of these factors—those that could lead to an accident or create dangerous situations for passengers—must be carefully considered. Addressing these challenges is crucial for the safe and successful deployment of RO systems in AVs.

In response to the question of how to mitigate or manage safety concerns, three main categories can be identified:

Through technology: Safety concerns can be reduced through a combination of technological advancements and policy measures. From a technological standpoint, vehicle-to-vehicle communication can help minimize the need for real-time communication. Improving network infrastructure, such as expanding 5G coverage and utilizing edge computing, can reduce delays and ensure a more reliable connection between the AV and the remote operator. Implementing strong cybersecurity protocols, including encryption and multi-layered defences, can protect the system against cyber-attacks. Additionally, developing advanced monitoring systems that track operator fatigue and implementing AI-based assistance can help reduce cognitive load and improve decision-making.

From a **policy perspective**, basic service level standards need to be established. Currently, we do not fully know where remote operators are physically located or how many are working at any given time. Clear regulations should define the responsibilities and obligations in emergency situations, ensuring that both the AV system and the ROs are evaluated according to specific safety standards. Regular inspections and certifications for RO systems, along with operator training and workload limitations, can further strengthen safety and trust in the system. By addressing both technological and policy concerns, these risks can be minimized, ensuring the safe integration of RO systems in AVs.

Efficient operator training: Specific occupational safety requirements for remote operators are crucial for ensuring safe operation.

Regarding the reliability of RO systems in different environmental and traffic conditions, key performance indicators (KPIs) are certainly involved, and experts believe these depend on the project's scope. Advanced sensing technologies, including a combination of cameras, radar, and LiDAR, provide redundancy, ensuring the vehicle can accurately perceive its surroundings in all weather conditions (e.g., snow, rain) and lighting. Strong communication networks, such as 5G and edge computing, along with network redundancy, help maintain low-latency, reliable communication between the AV and the remote operator, even in areas with poor coverage. AI-based decision support can enhance real-time decision-making and predict potential risks, allowing the system to dynamically react to changing conditions. Vehicles should also have adaptive features like traction control and dynamic route planning for safe movement in low visibility or heavy traffic conditions. Furthermore, continuous monitoring and diagnostics of the RO system ensure that potential issues are identified early, enabling timely intervention and improving overall reliability.

For communication, traffic and environmental conditions will impact network reliability (in terms of congestion, delays, etc.), and efforts to shift toward full autonomy instead of remote assistance may worsen the situation. Therefore, RO should focus more on remote assistance than on full remote driving. By integrating these technological advancements, RO systems can operate safely and efficiently in various environments and traffic scenarios.

What backup systems or safety measures should be implemented to manage potential system failures in ROs? Firstly, a critical communication network redundancy is essential, utilizing multiple channels such as 5G, 4G, Wi-Fi, and satellite to ensure a continuous connection even if one network fails. Local control backup mechanisms should also be available, ensuring that the vehicle can switch to a pre-programmed safe mode, such as stopping or pulling over, if communication with the remote operator is lost. Collision avoidance systems in vehicles are necessary to prevent collisions with other objects when the remote operator makes an error or communication is lost. Additionally, onboard decision-making systems, supported by AI, can act as a secondary layer of control, enabling the AV to perform safety manoeuvres or basic navigation automatically if remote control is unavailable.

Furthermore, continuous monitoring of system health; redundant control units on both the remote operator side and the AV side; and problem detection can notify the operator of potential issues and allow them to take preventive actions. Active safety systems and obstacle detection/avoidance that are always active can ensure the vehicle's ability to return to a safe position without requiring input. Manual override options for passengers or local authorities can provide an additional safety layer, allowing intervention in emergency situations. These combined safety measures ensure that potential failures are effectively managed, risks are minimized, and operational safety is maintained.

4.1.7 Remote operator

During sessions with experts and companies involved in RO projects, it was raised that many questions regarding the remote operator remain unanswered, particularly concerning the skills required, certifications, and training needed for the role. This prompted questions to be posed in the first round, and based on the results from that round, the topic of the remote operator was explored in more detail during the second round.

Initially, the question of whether a remote operator should work individually or as part of a team was discussed. According to experts, this depends on the context—specifically, the scale of the work and the responsibilities of the operator. However, the number of responses favouring teamwork over individual work was higher, indicating that RO is generally a team-based effort rather than an individual task. As for the skills or certifications that RAs should possess, the following list is arranged in order of importance:

1. Having a driving license
2. Familiarity with HMI systems and feedback
3. Knowledge of autonomy system
4. Stress management and situational empathy

It is also worth mentioning that high intelligence, task-switching ability, awareness of "road skills," and sufficient real-world driving experience are among the key factors highlighted by experts. The online sessions held by the author of this research included experts from around the world and various countries. One issue that seems to distinguish some experts' opinions on remote operators and their qualifications is their educational background. Some believe that having an engineering degree is essential for a remote operator, whereas, in the academic world and among many industry experts, this is seen as less important. They argue that certification should be considered a priority, while holding an engineering degree may not even be considered essential, even in the top 30 priorities.

In terms of distinguishing between the tasks of a remote operator and an assistant: experts believe that RAs should be familiar with the operational processes of AVs. This includes understanding sensor processes, HMI, and navigation in order to provide effective guidance. They should also be trained in emergency protocols for manual control or intervention in case of system failure.

• Additionally, RAs must know how to communicate with passengers, law enforcement, and traffic authorities while ensuring compliance with safety regulations and RO procedures.

The question of who could potentially be suitable for RA roles is also debated. Based on the results from the first round, experts pointed to the following groups and their strengths:

- **Professional drivers**: They have good knowledge of traffic laws and vehicle behaviour in traffic.
- **Gamers**: They are skilled at using complex interfaces and multitasking. Younger individuals may have more openness to this technology, but they must gain a proper understanding of real-world driving, as driving experience on the road is crucial for understanding the risks.
- **IT professionals and systems engineers**: Due to their expertise in automation systems and troubleshooting, they could be valuable candidates, along with individuals skilled in solving problems related to computer systems and related technologies.
- **Control room operators or dispatchers**: These individuals have experience monitoring and managing ROs.
- **Psychologists and engineers**: At the initial hiring stage, the presence of psychologists and engineers to assist in system design and analysing user needs is extremely helpful.
- **Experienced drivers who are no longer able to drive**: For example, a truck driver who cannot drive due to being in a wheelchair could work as a remote operator.

In the research literature, we also encountered challenges regarding the workload of the remote operator. During the first round, experts identified the following issues in order of importance:

1. Mental workload
2. Network reliability
3. Situation awareness
4. Sufficient information
5. Motion sickness

Regarding the operator's workload and how to measure or manage it, nearly 85% of experts agreed with the idea of using biological measurements (such as heart rate and eye movement) to assess mental workload, citing the following reasons:

- Monitoring the driver is necessary, especially when the type of work is entirely new. Studying the stress and workload of remote operators is valuable.
- Stress can be monitored through Electrodermal Activity (EDA); allowing self-determined breaks; EEG studies.
- It can be used to determine when the remote operator is unable to perform the task correctly. However, it must be ensured that these measurements are not used for any other purposes (concerns related to privacy).
- Biological measurements should be aligned with SA and decision-making during remote operator tasks.

Opposing opinions:

- These measurements have little value in everyday operations.
- If the ADS is active, the workload is low.

An important point here is understanding what factors might hinder or impede the training of remote operators. These factors are listed in order of importance:

- Complexity of the overall process
- Topics that need to be taught (what topics and under what platform) – as it is a new subject
- Laws (In a separate question, 75% of experts believe that laws can facilitate remote operators training)

- High training costs

Regarding laws and educational content, some experts believe that it is crucial to know exactly what requirements operators must adhere to, in order to standardize the training. Laws can facilitate remote operator training by establishing clear standards and guidelines for certification, educational content, and operational procedures—provided these laws align with the tasks. A good example in the aerospace industry is how the FAA and EASA train people to fly aircraft, operate drones, etc. Remote operators should receive training that includes technical understanding of vehicle systems, operational protocols, SA, effective communication skills, adherence to laws, simulation exercises for hands-on experience, and cybersecurity awareness in order to manage AVs effectively.

The duration and frequency of training for remote operators should depend on the complexity of the systems they manage, as well as their job responsibilities. Initial training may take several weeks and cover topics such as system operations, emergency protocols, and HMI. Additionally, ongoing practical exercises, such as periodic simulations, should be included in the training program to maintain the operators' skills and readiness for real-world scenarios. Considering the factors mentioned, it seems difficult to propose a specific timeframe for operator training. However, most experts agree that regular refresher courses, perhaps every six months, are essential to keep operators updated on new technologies, software updates, and safety procedures.

Among the topics remote operators should be trained on, HMI is of great importance. The depth of training in this area depends on how intuitive the UI is. The less intuitive the interface, the more training is required. Specific HMI elements that require intensive training include real-time data visualization tools such as sensor feeds and live video displays, as operators must quickly interpret this data for decision-making. Warning systems and notifications also need focused training so that operators can prioritize important alerts and respond under pressure. Moreover, manual control interfaces for remote driving require practice to ensure smooth and precise vehicle control during manual interventions. Operators must learn to interpret multiple real-time camera angles and sensor data simultaneously to maintain their SA.

However, there are experts who believe that the HMI should be like a regular car, so no special training would be necessary, or that the HMI system should be self-explanatory.

Regarding remote operator's tasks, if we were to prioritize the tasks of a remote operator, experts would rank them as follows:

- **Ensuring operational safety** and monitoring the safety of passengers, pedestrians, and other road users, intervening when necessary.
- **Maintaining SA** and retaining control of the vehicle, either autonomously or manually, in unforeseen circumstances.
- The need to question the desired level of automation (checking the health status of AV systems and related diagnostics).
- **Troubleshooting in specific cases** and addressing limitations within the ODD.
- Continuous monitoring of the vehicle's telemetry (such as battery levels, temperature, and mechanical components) to prevent critical failures. If a system fault is detected, the operator must prioritize diagnosing the issue, mitigating any immediate risks, and coordinating repairs or recovery.
- **Guiding the vehicle** in the event of a problem or when the ODD boundary is exceeded.

Based on the results derived from the RO technology in PT, where experts were asked to rate it from 1 to 5 (1 being impractical and 5 being highly practical), this technology is considered highly practical, and experts are generally optimistic about its implementation. Figure 9 shows the result of the ranking question about practicality of RO technology in PT.

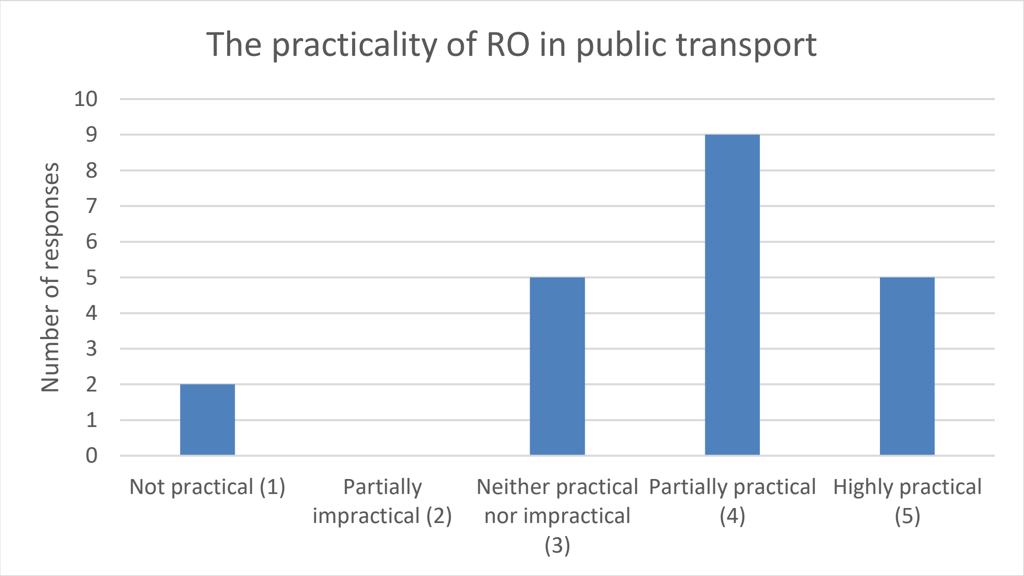

Figure 9: *The result of the ranking question about practicality of RO in PT*

As important as the capabilities of the remote operator are, the design, location and work environment are equally a concern for experts. In the second round, more questions were raised regarding the work environment. However, based on the information obtained from the responses in the first round, 90% of experts believe that the ROC should be located within the country where the project is to be implemented, rather than outside of it.

4.1.8 Regulatory and legal considerations

As mentioned in the literature, laws related to ROs are still in their early stages, and research in this area is quite immature (Goodall, 2020).

Experts' views on the challenges or regulatory gaps in adopting ROs for AVs will naturally differ by country. For example, in Finland, it has been stated that currently, there is no gap in the acceptance of ROs for AVs. However, at this point, traffic safety responsibility for AVs still lies with the remote operator. This situation is expected to change with new laws.

In general, the adoption of ROs for AVs faces several legal and regulatory challenges. One of the main issues is the lack of clarity regarding responsibility and accountability in case of accidents, as it is often unclear whether the remote operator, the vehicle manufacturer, or the automated system provider is responsible. Data privacy and security are also concerns, especially given the reliance on real-time data transmission, and evolving laws on how sensitive information should be managed.

Regulatory differences across jurisdictions further complicate the widespread use of AVs and remote operators, as laws concerning AVs and RO differ widely between regions. Remote operators are in a regulatory grey area in nearly all countries. There are no specific laws concerning remote operators. Additionally, there are no global standards for certifying remote operators, safety protocols, or communication systems, leading to ambiguity.

Ultimately, infrastructure readiness, such as 5G networks, is crucial, but is often overlooked in current legal frameworks, creating challenges for the reliability and safety of RO systems. Addressing these gaps is vital for widespread implementation.

In the United States, there are limited laws for RO. Some states mandate it for driverless vehicle testing, but there is very little legislation on how it should work in practice. Therefore, greater clarity in this area would be very helpful, whether through standardization, regulation, or increased transparency from developers.

The legal and regulatory challenges in adopting AVs with remote operators include the lack of standard safety laws, unclear liabilities in the event of accidents, concerns over data privacy, and insufficient frameworks for certification and testing of ROs in different jurisdictions, which creates governance gaps and public trust issues. There is no law for certifying remote operators, and current road traffic laws are based on the behaviour of an individual "driver," with no framework addressing the concept of a vehicle being controlled by a "team" of operators. There are also no safety standards for communication systems and infrastructure necessary to support RO.

To address these regulatory challenges, experts recommend conducting research to establish supportive and enabling laws. There is a need for a coordinated, systematic effort from policymakers at both national and international levels to create meaningful legislation. Additionally, testing in real-world environments will help identify gaps in the law and determine actionable steps. Governments and industry stakeholders must collaborate to establish standard safety and legal frameworks, clear data privacy and cybersecurity laws, thorough testing and certification processes, and policies adaptable to evolving RO technologies across regions.

In summary, the key issues to be considered include:

- Clarifying responsibilities and accountability.
- Establishing data privacy and security standards.
- Harmonizing regulations across jurisdictions (international collaboration for developing necessary standards and regulations; ensuring regulations are adapted to each country; cooperation between regulatory bodies, industry, and potential large-scale users).
- Setting operational standards and certifications.
- Improving infrastructure for RO systems.
- Implementing trial programs and regulatory testing environments.

However, there are disagreements about the approach to legislation. For instance, some believe that regulations should be a national competence, meaning each country should create its own set of RO laws. Countries such as France and Germany, for example, have their own unique laws regarding ROs. The ideal scenario is that these regulations be harmonized at the UNECE (United Nations Economic Commission for Europe) level and then transmitted to countries through the European Union. There is a need for significant interdisciplinary dialogue between vehicle industry regulators, transport and communications authorities, car manufacturers, road authorities, and technology developers to define the responsibility of each party in RO regulations. However, currently, there is not even effective dialogue between national road authorities and vehicle regulators.

To facilitate the development of clear and transparent laws, the following standards, according to experts, could be helpful in aligning with RO systems:

- SAE International's Levels of Automation
- General Data Protection Regulation (GDPR) for data privacy
- NHTSA AV Guidelines (U.S.)
- Federal Communications Commission (FCC) and European Telecommunications Standards Institute (ETSI)
- And local vehicular communication regulations

Some have also stated that the standards are sometimes vague and too industry-centric, and that it would be better to identify legal gaps and create appropriate regulatory frameworks through real-world testing.

4.1.9 Social impact

The social impact of RO technology on the public and the workforce may seem somewhat outside the focus of this research, but the reality is that the author's effort to conduct a comprehensive study led to questions being raised based on curiosity. As Aramarattana et al. (2024) state, in addition to technical factors such as software reliability, cybersecurity, and human factors, the success of the system also depends on user acceptance from operators, vehicle users, and other road users.

This phenomenon will undoubtedly have a mix of positive and negative impacts, as highlighted by some of the responses received:

• There are threats to job sustainability among current PT operators, especially drivers. When AVs are discussed, bus driver jobs will be replaced by remote operators, and the displaced individuals will need new job opportunities. Job losses will be significant, which could lead to protests. We've already seen instances where vehicles have been damaged or tricked by traffic cones.

• The social impact of RO of AVs on the public could be mixed. On the one hand, this technology provides greater access to PT, especially in underserved areas, improving mobility for the elderly, disabled individuals, and rural populations. On the other hand, the displacement of traditional driving jobs may create concerns about job losses in the transport sector, leading to economic insecurity for the affected workers.

- If RO is used more widely, naturally, the demand for remote operators will grow, thus having a positive impact on the workforce. For example, truck drivers could have a regular 9-to-5 job without needing to sleep in the truck on the road. Additionally, it could create a "home office for everyone" model, including truck drivers, bus drivers, excavator operators, agricultural equipment operators, etc.

- The social integration of people who are marginalized (those with limited financial means) could increase. More people could enter the workforce, including those who, due to personal factors, cannot drive a truck. Driving puts a lot of pressure on family life, and being able to stay home every night would undoubtedly make a difference.

- The social impact of RO of AVs includes increased mobility and accessibility but could lead to job displacement, requiring retraining for tech-focused jobs and changes in urban landscapes.

- This will significantly impact property prices. People will be willing to live farther away from their workplaces.

- People will initially be cautious and uncomfortable, like with any other innovation, but will eventually understand the benefits for themselves and society (cheaper travel at times and places where it is truly needed). This technology will enable people to perform other, more productive tasks and will address the driver shortage challenge.

- Public transport operators worldwide have long struggled with driver shortages due to the demands and working conditions. RO could reduce costs for operators and enable fleet management with fewer staff members. As a result, some of the savings could be transferred to the workforce, making PT a more attractive employer.

- For industries where there are significant health or safety risks for drivers, such as mining or construction, RO offers considerable benefits. However, for safer industries where human interaction plays an important role in service delivery, such as PT, while technological advancements may make it feasible to implement automated PT systems with RO support, it is likely that this will have significant social costs, particularly for the elderly and those who are uncomfortable or unable to use digital services. We have already seen changes such as the introduction of "ATMs" and automated ticketing machines that replace human jobs, significantly reducing the human interaction previously required for such transactions. While these changes undoubtedly have a positive impact on "shareholder value," they will have a significant negative effect on social cohesion, well-being, and access to services for those who cannot access these dehumanized systems. The widespread introduction of automated services will likely have a severe negative impact on communities that are already underserved by PT, i.e., those in rural or low-income areas, as budgets shift towards expensive, technology-dependent automated services. These services will also likely have less flexibility than those managed by human drivers, which will be especially important when disruptions occur due to climate changes.

To maximize the positive role of this technology or to mitigate its negative consequences, experts suggest organizing and training workers in the AV and RO industries. To ensure positive social outcomes, actions such as retraining and upskilling programs for displaced workers could be implemented to help them transition to new roles, such as remote operators or in technology sectors. Public awareness campaigns that highlight the safety and accessibility benefits of RO systems could also build public trust and acceptance of the technology. Moreover, ensuring equitable access to AV services, particularly in low-income or rural areas, will help maximize the social benefits of this innovation. Additionally, including and possibly prioritizing social groups that were previously not considered part of the regular workforce for these vehicles—such as wheelchair users, young people who prefer to drive "real" vehicles instead of playing simulation games, or forklift drivers who now have the option to work from home—will also contribute to the broader positive impact.

4.1.10 Timeline and feasibility

Based on current global technology, experts have estimated that the implementation of an RO project in a fully live and urban environment could take anywhere between one to fifteen years. The timeline depends on factors such as the country where the project is to be carried out, the scale of the project, and the degree of autonomy of the vehicles. From the responses, a summary can be made as follows:

- **Now**: Demonstrations and small-scale local deployment (e.g., Cruise, Waymo, etc.).
- **5 years**: National deployment for a limited range of services (e.g., taxis for specific routes, but available in every city within a particular country).
- **10-15 years**: National deployment for broader services (e.g., all urban bus services in a specific country operated with AVs).
- **International/Everywhere**: RO used on every road in every country worldwide with automated services, though this may never happen.

For Finland, one expert, considering all these factors, believes that even within a year, a medium-scale project could be fully feasible, and the regulations are supportive, as discussed in the context of Finnish regulations in the literature review.

The stages that experts see as necessary to achieve this feasibility in the near future, given that remote operators are still in relatively early stages of technological maturity, involve a set of issues that are outlined below:

1. **Infrastructure Development**: Vehicle-to-infrastructure communication (V2X), cloud infrastructure, and the establishment and widespread expansion of robust 5G networks and edge computing systems to support low-latency communications between AVs and remote operators are essential.
2. **Technology Maturity**: Continuous progress in AI technologies, sensors, and cybersecurity is vital to ensure safe, reliable, and secure ROs. According to Lu et al. (2024) the monitoring system integrates artificial intelligence and video analytics technologies to automatically gather background computer data and make informed decisions.
3. **Public Acceptance**: Building trust through education and showcasing the safety and benefits of remote operator systems in PT will be crucial for broad acceptance.
4. **Development of Comprehensive Regulations for Safety and Privacy**.
5. **Field Trials in Mixed Traffic**.

Some experts also emphasize the importance of regulations in this process. In other words, they state that while the foundational technology for remote operators is ready, legislation and policy still have a long way to go.

Given that one of the issues raised was public acceptance, during the meetings and surveys, the question was posed: how can the understanding and public acceptance of AVs with ROs be improved, and what educational or awareness programs would be appropriate for informing and engaging the public?

In this regard, informing the public about the presence of remote operators, ensuring well-established communications, and running educational campaigns that highlight the safety, efficiency, and advantages of the technology—such as reduced accidents and expanded access to transport—are seen as crucial actions to positively influence public acceptance. Furthermore, transparency in how systems work (explaining potential weaknesses and how they've been mitigated), including clear communication about safety features and cybersecurity measures, and providing a "face" to the vehicles (such as showing pedestrians that the vehicle is being remotely controlled and perhaps displaying video feedback from the operator) could help build trust.

Regarding educational programs, pilot programs that allow people to experience the technology firsthand, accompanied by positive media coverage and proven safety records, will play an important role in widespread adoption. Additionally, educational initiatives in schools that familiarize students with the technology, along with online courses and webinars for a broader audience, can help dispel misconceptions about AVs. Collaborating with local governments and running media campaigns that highlight the safety features, real-world applications, and transport benefits of these systems can provide more information to the public, thus increasing trust and acceptance.

4.2 Analysis of second round

According to the noticeable knowledge gap perceived in the first round regarding the remote operators' workplace and their skills, most of the questions in the second round focused on the remote operator, their work environment, and the progress of the process.

4.2.1 Remote operator

Regarding the remote operator and the skills that should be prioritized, the following were ranked by experts in order of importance:

1. Driving skills
2. Technical expertise and interpersonal skills (operator and passengers)
3. High ability in processing large amounts of information and focussed attention
4. Decision-making under pressure
5. Troubleshooting
6. Specific training for RO (awareness of the limitations of the sensors, knowledge of how to react to unexpected/emergency situations,
7. Traffic and road behaviour knowledge

Another issue raised in some responses during the first round, and discussed in the regulations of various countries, is the allocation of responsibilities between two parties: the provider of the AV and the remote operator. Experts have different views on this matter, but their opinions can be categorized into four general groups:

The first group views these two parties as representing two sides of a company: one as the seller and the other, the remote operator, as the customer and recipient of after-sales services. For example, it has been suggested that in this case, a ticketing system with a guaranteed response time could be implemented to ensure that the remote operator receives a solution or action within a specified time frame. The company would also be responsible for ensuring that any hardware or software issues with the vehicle are addressed in a timely manner.

The second group believes in a form of collaboration between the two parties, which may vary depending on the commitments and policies of each company. Clear agreements on the responsibilities and tasks to be performed are essential. Additionally, communication with the vehicle systems is necessary to ensure safety and guidance during operations.

The third group views the responsibilities as completely separate due to the differences in roles, and somewhat similar to the current system. They argue that most responsibilities should lie with the company. In this case, the operator would simply have a supervisory role, ensuring that the vehicle follows the correct path. This is similar to any other vehicle, where, in addition to checking fluid levels, you would not expect the driver to perform tasks like adjusting the engine settings or calibrating the spark plugs.

The fourth group believes that this issue depends heavily on the level of technology used in the vehicle's construction. However, they still maintain that the company must ensure proper communication between the vehicle and the ROC and be aware of the defined limitations and ODD. In contrast, the operator would be responsible for addressing any urgent issues that may arise during the vehicle's operation. For instance:

1. Ensuring that remote operator settings are functioning properly – daily checks by the operator (generally based on a checklist).
2. Ensuring protective measures against delays – the company’s responsibility.
3. Training operators (procedures for taking control, preventive takeover based on conditions, etc.) – the company’s responsibility.

Due to the varying opinions regarding the responsibilities of the operator, there are also different views on the appropriate number of hours for a shift. In fact, more experts believed that a shift should last longer than 4 hours than those who felt that this duration was adequate, though it was noted that this depends greatly on the operator's specific duties. The ideal shift length mentioned ranged from 4 to 6 hours.

More than half of the specialists believed that the importance of the operator’s workload, as opposed to fatigue and monotony, as well as factors stemming from the work itself, such as motion sickness, was greater. Addressing these concerns ensures that the operator feels more comfortable and engaged and nearly all the experts who participated in the survey agreed that "It makes a difference if remote operators had automated assistance." (Yes: 19, No: 1).

To clarify the matter of operator workload, several questions were posed in the questionnaire. Experts identified traffic density, route complexity, and time of day as key factors in determining the number of AVs a remote operator can effectively monitor, depending on situational factors.

Regarding the training of operators, 85 percent of experts believe that simulators are effective in the training and practice phase for operators.

4.2.2 Quantity of vehicles per remote operator

One of the issues that has attracted the attention of many specialists and even non-specialists in the world of RO is the number of vehicles that a single operator can manage, assist, guide, or supervise (Literature review: (Goodall, 2020)). However, all specialists agree that currently, there is no unique number that can be definitively stated (it can only be roughly estimated, though many consider this unrealistic). But there are several limiting factors that must be considered. These limiting factors for the number of AVs a remote operator can supervise have been ranked in order of importance by experts, assuming that the vehicle is a standard level 4 vehicle according to SAE definitions:

1. Reliability of communication between AVs and the operator
2. The operator's ability to respond to emergency situations
3. Real-time monitoring of the environment surrounding each AV
4. Traffic and environmental conditions

However, without taking pre-determined conditions into account and in a general sense, the number of vehicles that a remote operator should control depends on the operator’s specific duties, the type of supervision, the level of automation, the number of interventions (which itself depends on factors such as the maturity of the automated driving algorithms, weather/road conditions, traffic complexity at specific points, etc.), the operator’s experience, and the performance and safety level of the AV technology. 90% of specialists believe that having automated assistance would greatly help the operator.

In general, considering all the stated limitations, the number of vehicles that specialists believe is manageable by a remote operator ranges between 3 to 10 vehicles, with automated assistance potentially increasing this number to up to 40 vehicles. As Veitch & Andreas Alsos (2022) mentioned, the rapid advancement of AI technology underscores the need for a systems perspective, as AI is expected to become an increasingly integrated component of future RO work systems.

Ultimately, the maximum number of vehicles assigned to a remote operator should be dynamically managed. For example, in real-time monitoring scenarios, it might be possible for an operator to oversee up to ten AVs for RA. However, if an emergency situation requires direct remote control of one vehicle, the remaining nine vehicles should be reassigned to other operators until the driving task is completed.

A similar approach is used in decision-making for time-sensitive situations. For instance, if an AV halts due to a misdiagnosed object in a turn at an intersection and another vehicle in the same category faces a similar issue simultaneously, the system must be equipped to manage such overload situations. This requires cooperation between remote operators to ensure that issues are resolved efficiently without compromising safety or operational effectiveness.

However, some specialists working in the industry hold a view that might seem different at first glance: they believe the question should be about how many vehicles are operating within an ODD and how many remote operators are required, as there is no need to assign fixed vehicles to a specific operator. Remote support events should be managed in a queue based on the First-In-First-Out principle.

Still, in terms of what measures could make this management and supervision easier for operators, the respondents highlighted the following:

- Having a system that provides alerts to operators, such as weather conditions, heavy traffic, potential collisions, etc., allowing them to focus more effectively in abnormal conditions.
- A real-time 360-degree view = visual data should be precise, focused, and accessible.
- Prioritizing supervision based on specific parameters.
- Using a combination of advanced technologies, optimized processes, and ergonomic design. The goal is to increase SA, reduce cognitive load, and enable timely responses to critical events.
- A system that takes factors like route complexity, traffic congestion, and special passenger needs (e.g., vulnerable individuals) into account should determine how each AV is monitored. This system should be flexible and able to adapt to the AV environment in real-time.

- Requests for assistance from AVs should be automatically tagged based on their time sensitivity and risk level. When a high-priority vehicle requests help, the operator should already be aware of its status and ready to respond promptly. While high-risk situations occur less frequently among lower-priority vehicles, any requests at this level should be quickly referred to the most experienced operators.

4.2.3 ROC (workstation)

A workstation is a crucial tool for developing and maintaining a comprehensive understanding of the status of AV fleets in their respective environments. This station plays a key role in communication and executing actions that impact the vehicles and passengers. Given this central role, the design of the workstation is one of the fundamental principles to ensure safe and efficient ROs.

Research in simulated environments, such as experiments conducted by German Aerospace centre (DLR), as well as the creation of independent test environments, demonstrates that workstation performance is highly dependent on the precise definition of tasks and the manner of interactions. Similar to any ergonomic workspace, it should be designed in a way that focuses on critical tasks, such as safely navigating traffic.

To achieve this goal, workstations should be tested through iterative design processes with a focus on the remote operator. These tests should include evaluations of cognitive load, SA (both subjective and objective), performance, and user satisfaction. It is important that these evaluations are not limited to the initial design stages but also include long-term field tests in real-world conditions to ensure that the workstation remains effective and reliable under continuous use. This approach helps optimize the design so that operators can maintain their performance and safety over time.

Essential features, design, and key elements in evaluating the workstation:

- The hardware, operating system, and software of the workstation should be highly reliable for ROs and facilitate continuous operation.
- These capabilities should extend to the IT infrastructure, including networks. The Quality of Service (QoS) should be equivalent to that of IT server systems.
- The workstation should not be designed to overly resemble traditional driving. In traditional driving, tactile (haptic) feedback is converted into information, which is then visually confirmed. However, in RO, a set of cameras can be used to detect objects and inform the operator without the need to convert this data into tactile feedback. This type of driving should be designed with its own set of tools.
- Ergonomic settings

- The ability for the operator to adjust window content and tool positions
- Ability to quickly create SA
- Design tailored to the type of RO; for example, the needs for remote driving with customer assistance differ, and this difference should be reflected in the design of functionality and interactions.
- Free of distractions
- Large monitors to track journeys and a system that provides live feedback
- Highly suitable UI, especially when switching between different vehicles
- Software that prioritizes and categorizes information so the operator can focus on critical situations while avoiding irrelevant data
- A comfortable yet stimulating workspace to maintain alertness
- Prevention of operator fatigue or confusion
- Providing relevant information without creating unnecessary cognitive overload

According to the results from the first round of questionnaires, specialists believe that the remote operator's workstation should be located in the same country where the project is being implemented. In this round, the question arose regarding the ideal distance between the workstation and the vehicle. It seems that most concerns relate to network delay, language, country regulations, and regional traffic culture, and there are no other major limitations preventing the project from being carried out.

In this round, specialists have added that if the network is reliable and delay issues can be managed or resolved, depending on the operator's task:

- For remote teleoperation, the operator centre should be very close.
- For remote assistance, being in the same country is sufficient.
- For remote monitoring, it can be anywhere in the world.
- Proximity should be determined based on operational needs and infrastructure, usually within the same region or area.
- The physical proximity of the remote operator to the vehicle should not be of major importance, except when local awareness and familiarity with the environment are critical.
- It depends on the network connection and understanding of traffic conditions (for example, an Austrian operator is likely to provide quality service in Germany, but it might be more challenging in Hungary).

UI emerged as a critical factor during expert interviews (I02, I05), where specialists consistently emphasized its importance. As a result, a questionnaire was designed to assess the relative significance of the following UI elements in a remote operator workstation. The findings ranked them as follows:

- The ability to simultaneously view the interior and exterior of the vehicle
- The UI software of the workstation
- Steering controls and pedals
- The number of display screens

This ranking reinforces the key themes addressed throughout this research. The first and last elements pertain to the operator's SA, the second represents HMI, and the third relates to feedback and the execution of operator decisions.

One major concern among experts regarding ROCs is the volume of data transmission between the control centre and the vehicle. This concern is reflected in the responses to a question about whether all information received by the remote operator must be presented in an intuitive (instinctive) manner. While 57% of respondents answered affirmatively, the remaining 43% disagreed, citing the increasing data transmission load as a key issue.

A proposed solution to this challenge is the categorization of intuitive information. While the system should be designed to be instinctive, it should not rely solely on video feeds. Instead, incorporating haptic (tactile) and auditory feedback in certain scenarios may help mitigate the issue to some extent.

4.2.4 Improvement scenarios

In the first round, some experts proposed solutions or potentials to improve technical issues. In the second round, these solutions were presented to the respondents for prioritization, as shown in Table 4 in the next page.

***Table 4:** Technical issues and potential solutions for them*

Technical Issues	**Potentials or Solutions**
Latency	Dedicated network for ROC Edge computing Predictive algorithms Adaptive compression techniques
Situational Awareness	stable network 5 g 360-degree display Intuitive data display Auditory and Haptic Feedback: Feedback for pedals and steering. Predictive Analytics: Predictive analytics not only complement video feeds and 360-degree views but also provide advanced insights that raw visual data alone cannot offer. This includes identifying patterns or anomalies that may indicate potential hazards, such as a pedestrian stepping onto the road.
HMI	Self-explanatory HMI design Intuitive data display HMI optimized for passive RO Adaptive design covers a wide range of scenarios, from routine monitoring to high-stress emergencies. As a versatile solution, it enhances operator performance while reducing cognitive load.
AVs Faults	Detection of sensor-related problems Identification of software issues Blind spot detection (Sensors) Identification of complex software issues (e.g., "spaghetti" bugs)

Based on the interviews conducted with I01 and I04, it should be noted that not every ROC is expected to possess all these items at a high level of technology. However, having a fail-safe strategy is crucial. In other words, even if a component of the system lacks highly advanced technology, both the operator and the center should still be capable of managing emergency situations.

4.2.5 Remote operation in public transport

According to I03, the primary positive impact of remote operator technology on PT systems is economic, as it can reduce the number of required on-board drivers. Additionally, it enhances safety by minimizing human error through automation. Regarding the choice of vehicle type, experts consider shuttles to be the most suitable option, followed by automated taxis, which are seen as a better choice than automated buses.

Moreover, 76 percent of respondents agree that RO technology has the potential to encourage more people to use PT in the future.

Supporters argue that knowing they can speak to a real person at the push of a button provides a sense of reassurance that many users currently lack in PT systems. They also believe that people may place greater trust in a system under human supervision rather than relying solely on AVs. This could help overcome key barriers and enhance user experience by:

- Improving safety and reliability
- Increasing accessibility

Evidence of this can be seen in how companies like Waymo and Cruise incorporate RO into their automated taxi services. The availability of RO can help alleviate people's fear of entering an unfamiliar vehicle, such as a self-driving taxi or shuttle.

Opponents, on the other hand, acknowledge that while people generally prefer human support and may feel more comfortable knowing that a remote operator is overseeing the vehicle, they question how much this factor would truly drive PT adoption. They argue that this largely depends on the service provider rather than the presence of remote control. Additionally, they believe that accessibility and convenience are the primary reasons people choose PT, regardless of how the vehicles are operated. Those who do not currently use PT are unlikely to start using it simply because of RO.

However, they note that if Mobility as a Service (MaaS) continues to evolve, it could encourage people to adopt automated taxis as part of their transport choices.

Regarding the most critical parameters in the initial phases of remote operating AVs in PT (with support from a RA and existing technology), the following items are ranked by importance:"

1. Predefined route
2. Simplicity and functionality of the HMI
3. Redundant network for the ROC
4. Passenger connectivity to the ROC
5. Ergonomic workplace

4.2.6 Future developments and research

Advancements in various technological fields will undoubtedly support RO. But what foreseeable and plausible advancements can we expect in the real world? According to the survey participants, discussing this topic is somewhat challenging, as more driverless tests need to be conducted and analysed. However, at present, some of the comments are presented below:

- The adoption of 5G networks for low-latency communication
- AI advancements that improve autonomous decision-making and transitions between remote and self-driving modes,
- Edge computing will enhance responsiveness by processing data locally, while innovations in sensor fusion will improve environmental awareness.
- Breakthroughs in cybersecurity will be crucial to protect RO systems from potential cyber threats, ensuring safe and reliable ROs.
- Millimetre wave for local communications at high speeds
- Improved sensor technologies (like LIDAR and computer vision) for enhanced environmental perception
- Innovative HMIs that facilitate effective remote control and SA.

On the other hand, another perspective suggests that we do not need technological breakthroughs; rather, we need continuous, incremental improvements to existing systems and integration.

There is a general consensus on the need for further research in RO, with particular emphasis on the following aspects:

1. Since RO is a complex system with multiple interdependencies, pursuing a systemic approach is key in advancing RO systems.
2. Developing an understanding of the factors that affect SA for RO
3. Developing an understanding of the skills and character traits that make a person a good remote operator.
4. Network reliability
5. Onboard fault detection technologies
6. Developing an understanding of the factors that enhance HMI

5. GUIDELINES FOR SETTING UP A ROC

A systematic approach

The establishment of a ROC requires several stages to be completed to ensure an optimal and efficient setup. Based on the comprehensive studies, interviews, and analysis of questionnaire responses conducted in this thesis, which address the central question of establishing a ROC based on human-centred design for AVs in PT, it can be argued that setting up a ROC is akin to assembling a complex puzzle with many interrelated components. If these components are not placed correctly, the expected efficiency may not be achieved. This is because no element within this system exists in isolation or without interconnection with the rest; each part can influence the effectiveness or sufficiency of others.

In essence, setting up a ROC can be compared to the act of driving itself. Just as one cannot disregard the near-simultaneous coordination of a driver's hands, feet, focus, and vision when operating a non-AV, a ROC must account for all essential components. If, in some cases, a certain function—such as a driver's hand performing the role of their foot in vehicle navigation—is required, the necessary tools must be provided to facilitate this adaptation. This issue must be explicitly considered, as neglecting certain aspects or functions in the design of the centre could compromise its effectiveness. Since the primary objective of the centre is to ensure the secure and uninterrupted flow of operations, no critical functionalities should be overlooked or omitted.

Given the high number of factors that must be considered for the successful establishment of a ROC, a flowchart is provided (See Figure 10) to facilitate a logical and structured approach and as an attempt to answer the main thesis question. While not all suggested components may be relevant to every project, the overall framework follows the outlined methodology.

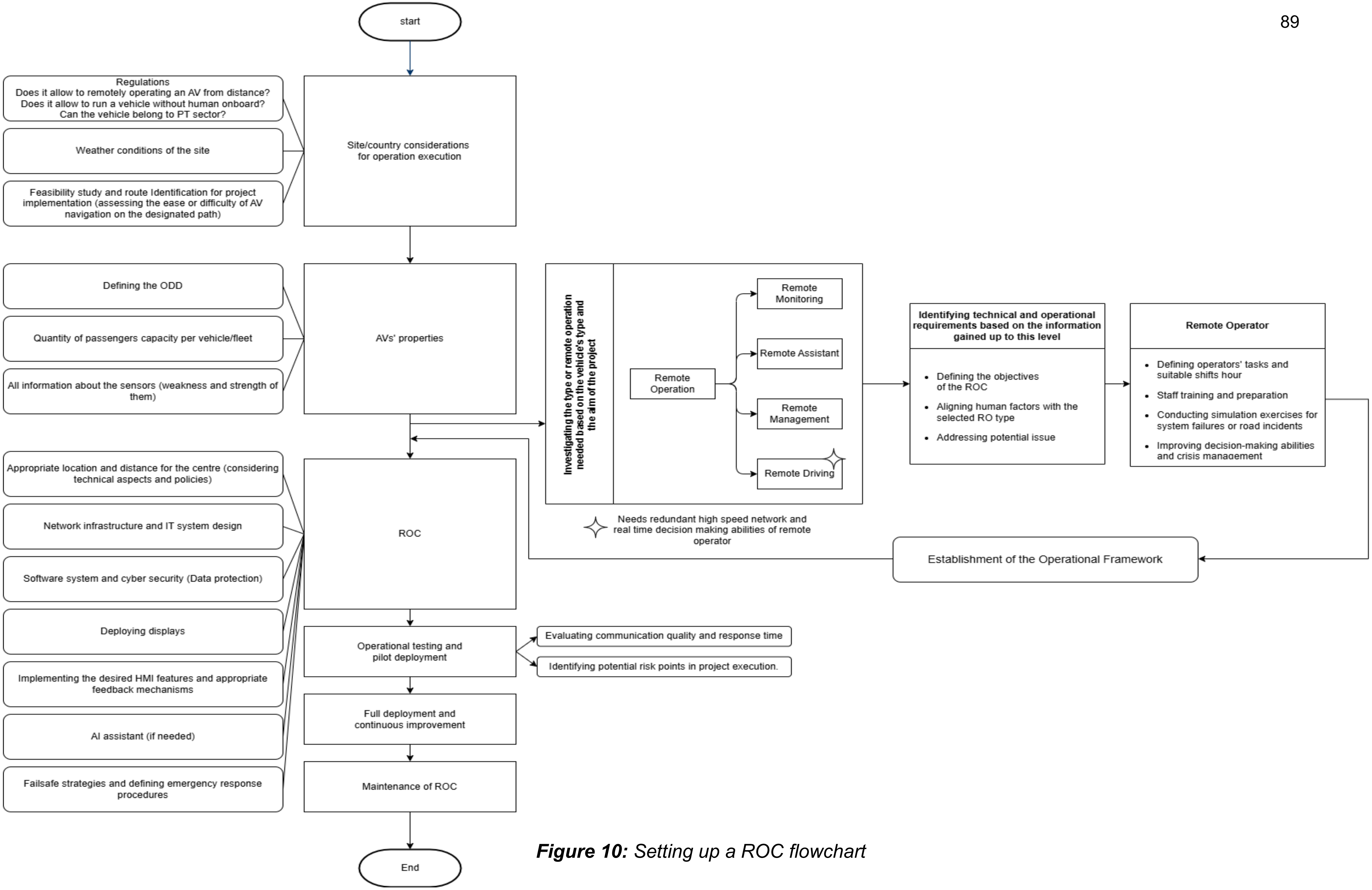

Figure 10: *Setting up a ROC flowchart*

Each sub-section of this flowchart can expand into dozens—or even more—checklist items or be further divided into subcategories that break down the overall concept into varying levels of detail. However, this requires expertise in the relevant field. For instance, in data protection or facilitating its transfer, multiple methods exist, and numerous factors must be considered.

Establishing a well-equipped and suitable environment for ROs is inherently a collaborative effort, drawing on expertise from various disciplines. The precise nature of the operation itself serves as the unifying factor, enabling experts to propose tailored solutions within their respective domains to support the mission effectively.

From addressing the main question of this thesis, it can be concluded that a ROC serves several critical functions in ensuring the safe and efficient management of AV fleets. One of its primary roles is maintaining SA among remote operators. Depending on their tasks, operators may need to focus on different levels of SA, whether through direct control or supervisory oversight. Effective workstation design and information presentation play a key role in keeping operators attentive and preventing distractions or inattention, which can lead to out-of-the-loop issues.

Monitoring and supervision are essential aspects of an ROC, as remote operators must track AV fleets, identify automation failures, and assist in problem resolution. To support this, the ROC should provide a highly reliable IT infrastructure, ensuring seamless data transmission and minimizing network delays. Communication and collaboration are also fundamental, with digital and verbal communication tools facilitating coordination between remote and local operators.

Beyond monitoring, an ROC enables different levels of remote intervention, including teleoperation, remote assistance, and general oversight. The level of involvement depends on network reliability and operational needs. For instance, direct teleoperation requires proximity between the ROC and the vehicles, whereas remote assistance and monitoring can be managed from greater distances, even across different countries.

A well-designed workstation is crucial for the effectiveness of the ROC. It should be ergonomically optimized, allowing operators to adjust UI elements, minimize distractions, and access large monitors for tracking journeys in real time. The interface should be intuitive, prioritizing and categorizing information to prevent cognitive overload. Additionally, ensuring a stimulating yet comfortable workspace is necessary to keep operators alert while preventing fatigue.

The transition of control between operators and the system, as well as between different remote operators, is another critical function of an ROC. These transitions must be carefully planned to minimize errors and ensure a seamless handover process. Testing and evaluation of the workstation design are essential to achieving this goal. Iterative design processes, cognitive load assessments, and real-world field tests help refine the system, ensuring that operators can maintain high performance over time. Hence, a ROC must be built around user-centred principles, focusing on workflow efficiency, effective information presentation, and an optimized environment to support operators in their tasks. By addressing these elements, the ROC ensures reliable oversight, swift decision-making, and enhanced operational safety for AV fleets.

The second sub-question of this thesis, which addresses existing standards, regulations, and guidelines, will be answered by examining the diverse and jurisdictionally varied standards, regulations, and guidelines surrounding ROs in the context of AVs. One key framework comes from SAE International’s Levels of Automation, which categorizes different levels of vehicle automation, providing clarity on the capabilities of automated driving systems (ADS). Additionally, the General Data Protection Regulation (GDPR) addresses data privacy concerns, ensuring that sensitive information transmitted during ROs is properly secured. In the U.S., the NHTSA AV Guidelines offer some regulatory direction on automated vehicle operations, although they do not provide specific regulations for remote operators.

Telecommunication regulations, such as those from the Federal Communications Commission (FCC) in the U.S. and the European Telecommunications Standards Institute (ETSI), help regulate the communication systems essential for RO, ensuring reliability and security in these interactions. On the international stage, the Vienna Convention on Road Traffic (1968) and the Geneva Convention on Road Traffic (1949) originally required vehicles to have a driver present, but recent amendments, particularly in 2021, allow for ADS-equipped vehicles to operate without a driver as long as they meet national and international standards. In Finland, national regulations, including the Road Traffic Act and the Vehicle Act, permit the use of remote operators, providing definitions and frameworks for terms like "driver-in-readiness" and "remote management."

While these standards provide a foundation, there are still gaps, particularly in the certification of remote operators, clarity around liability in the event of accidents, and standardized communication systems. To address these issues, experts call for further research, real-world testing, and international collaboration to create more effective and comprehensive legal frameworks that can accommodate the evolving nature of ROs in AVs.

The technical requirements and challenges discussed throughout the thesis include key factors such as HMI, appropriate feedback mechanisms, network infrastructure, latency, SA, workstation design for an efficient ROC, and the capabilities of remote operators.

The final sub-question of the thesis addresses concerns regarding remote operators, who are responsible for overseeing the safe operation of ADS and ensuring the smooth functioning of AVs. Their tasks include managing transitions between vehicles with varying automation levels, troubleshooting system failures, and ensuring the safety of passengers and others on the road. They also reclassify objects detected by ADS, such as identifying a double-parked car as an obstacle, and suggest optimal routes when road conditions are unclear.

A key challenge for remote operators is managing information overload, especially when overseeing multiple vehicles. They must process vast amounts of sensor data while maintaining situational awareness and avoiding issues like "change blindness." Operators also continuously monitor the vehicle's telemetry, ensuring that critical systems like battery levels and mechanical components are functioning properly. In the event of a system fault, they must diagnose the issue and coordinate repairs or recovery.

Remote operators may directly control the vehicle, using steering and pedals, or guide it indirectly by adjusting waypoints. They also manage fleet operations, analysing video footage, categorizing objects, and addressing operational disruptions. Communication with passengers, law enforcement, and other authorities is also part of their role, particularly during emergencies.

The skills required for remote operators include a strong understanding of driving principles, technical knowledge of ADS and HMI systems, and the ability to multitask and make quick decisions under pressure. They must also have strong problem-solving skills and be able to maintain focus during long shifts. Training for remote operators is extensive, covering vehicle systems, emergency protocols, and communication skills, with regular refresher courses to keep up with new technologies and safety procedures.

6. CONCLUSION

ROs have the potential to serve as a bridge between traditional driving and streets dominated by HAVs. They can also play a crucial role in strengthening public trust in automated systems while ensuring that safety remains a top priority during the transitional phase, as the technology continues to evolve.

This study examines the establishment of a ROC for the deployment of automated PT, focusing on human-centred design principles and usability evaluation.

The complexity of ROs, particularly in PT, arises from the integration of human factors with technology. Since human operators are central to ROs, their interaction with machines and other street elements introduces unique challenges. The most significant of these challenges include HMI, latency, SA, operator training, and task management.

Based on the analyses conducted in this research, the design and implementation of an efficient ROC for automated PT must effectively incorporate a human-centred approach. The design should prioritize ergonomic features and workstation usability to reduce cognitive load, enhance SA, and provide an intuitive and responsive user interface for operators. The ROC must be designed to perform critical tasks, minimize distractions, and support the needs of both vehicle operators and passengers. The usability of the ROC system should be tested in real-world conditions to ensure its effectiveness in continuous operations, especially considering the real-time demands placed on remote operators.

The ROC has several key responsibilities, including monitoring the status of AVs, ensuring proper communication between vehicles and remote operators, managing emergency interventions, and assisting in vehicle operations when necessary. The centre should also handle real-time monitoring, prioritize supervisory tasks, and issue alerts regarding weather conditions, traffic, or potential collisions. Furthermore, the ROC ensures that operators are trained for emergency scenarios and that automated support systems are in place to manage vehicle fleets. The ROC should function dynamically, reallocating vehicle control during emergencies to maintain operational safety.

Currently, there are few standardized regulations regarding the number of vehicles a single remote operator can manage. However, existing standards can be adapted for harmonization. Ideally, regulations should be coordinated at the UNECE level and then implemented across various countries through the European Union. Establishing clear responsibilities for each stakeholder in ROC regulations requires interdisciplinary discussions between automotive regulatory bodies, transport and communication authorities, vehicle manufacturers, infrastructure agencies, and technology developers.

The quality and reliability of network communications between AVs and the ROC are of utmost importance. Experts emphasize that network latency, regional traffic cultures, and local regulations must be considered and addressed. Since ROs aim to enhance the efficiency of automated PT—where fewer operators oversee multiple AVs—high-quality, reliable communication is essential. However, achieving this level of connectivity may not be feasible in all locations. Therefore, a fundamental requirement is to have a fail-safe strategy, ensuring that in the event of communication disruptions or latency issues, vehicles do not experience operational failures and operators do not lose SA or control over the vehicles. Additionally, integrating AI assistance can facilitate ROs when necessary.

The physical proximity of the ROC to the vehicles also plays a significant role. In RA scenarios, a shorter physical distance is required (emphasizing the need for the centre to be located in the country where the project is implemented). However, for remote driving (or teleoperation), operators must be much closer to the operational area to minimize potential latency issues.

The key technical requirements for an ROC include a reliable communication system that ensures continuous data exchange between automated vehicles and operators. This system must be supported by a robust IT infrastructure to maintain service quality and security for ROs. Hardware, software, and network systems should be highly stable to facilitate seamless operations.

One of the primary challenges is data transmission, particularly due to the large volume of information required to maintain SA. Experts suggest that a combination of visual, haptic, and auditory feedback can help mitigate these challenges. Furthermore, the maturity of vehicle automation algorithms and their ability to adapt to varying traffic and environmental conditions must be considered. Addressing these challenges is crucial to ensuring smooth real-world operations.

Experts stress the importance of an operator’s ability to respond to emergencies, traffic conditions, route complexity, and the level of vehicle automation. A remote operator is responsible for overseeing multiple AVs, ensuring their safe and efficient operation. However, before assuming this role, an operator must have a thorough understanding of driving and possess the necessary driving skills—thus, a driver’s license is a fundamental requirement.

The operator's duties include conducting daily inspections, monitoring vehicle status, and intervening in emergency situations. Essential skills for remote operators include:

1. A strong understanding of vehicle functions
2. The ability to monitor multiple vehicles simultaneously
3. The capability to react quickly to unforeseen circumstances or emergencies

Experts highlight the importance of training programs, including simulator-based training, to help operators practice different scenarios. The ideal shift length for remote operators is estimated to be between 4 to 6 hours, given the high cognitive demands of the role.

Additionally, automated assistance can significantly reduce operator workload, allowing them to supervise a greater number of vehicles. Experts suggest that under normal conditions, a single operator can manage 3 to 10 vehicles, but with AI-assisted operations, this number could increase to as many as 40 vehicles.

Limitations of the thesis and future research directions

This study encompassed a broad scope, and it is advisable to conduct more detailed investigations tailored to each specific region or country where RO projects are to be implemented. Such research should align with the legal frameworks of the respective regions to ensure that experts can provide well-informed and confident assessments.

A significant challenge encountered during this research was the scarcity of academic literature specifically addressing the RO of automated urban vehicles. Consequently, studies on RO in maritime and military contexts were consulted to provide a conceptual foundation. To access more specialized and potentially less accessible sources, initial consultations were conducted with academic experts, followed by engagement with industry professionals.

Interviews with industry specialists and professionals revealed varying perspectives. Representatives from companies involved in RO projects generally responded positively to discussions on the topic, demonstrating a willingness to participate in interviews and share insights. Conversely, engineers and specialists working in sensor related technology and software development for AVs expressed concerns that RO might hinder the advancement of automated systems. Their responses often indicated resistance and unconstructive criticism, reflecting a preference for full automation over intermediary RO solutions.

Despite these reservations, RO remains a mutually beneficial technology, as emphasized in the introduction of this study. It contributes to the advancement of vehicular automation while enhancing safety for other road users. Additionally, it serves as a transitional solution, bridging the gap until fully AVs can be seamlessly integrated into urban environments and mobility. Overlooking this intermediary phase will not necessarily expedite the achievement of full autonomy.

A notable obstacle in conducting this research was the reluctance of large-scale RO companies to collaborate with academia. Many declined interview requests and hesitated to disclose critical information that could aid in evaluating key operational parameters. A pertinent example is the challenge of estimating the number of vehicles that can be managed by a single operator. Regardless of the formulas applied—such as those referenced in Section 2.8.2—assumptions had to be made due to the industry's unwillingness to share empirical data. This issue was also underscored in Goodall’s paper as well.

The development of research questionnaires presented additional challenges. Despite efforts to ensure comprehensiveness, some questions deviated from the primary research objectives outlined at the beginning of this study. This deviation stemmed from extensive literature review, which sometimes prioritized the broader field of AVs rather than the specific subject of RO.

Challenges such as public trust in AVs and the complexities of self-driving technology’s hardware and software led to the inclusion of supplementary questions. The researcher’s curiosity and recognition of the relevance of these complexities to RO contributed to their retention. While this approach was not entirely misguided, the resulting questionnaire was excessively lengthy. One participant notably remarked:

"Stating that this questionnaire takes 40 minutes to complete is extremely optimistic!"

For the second iteration of the questionnaire, efforts were made to focus on the core research questions and to address areas that had been overlooked or evaded in the initial round. Although some questions appeared repetitive, rewording them facilitated the extraction of expert insights. However, the questionnaires could have been better balanced in terms of complexity and respondent burden. Non-technical questions, which were somewhat peripheral to the study’s primary focus, should have been limited or omitted altogether.

Nevertheless, the analysis remained aligned with established research categorizations. Organizing the collected data using the Delphi method proved challenging, yet meticulous efforts were made to present a coherent narrative that adhered to the study's research framework while maintaining an integrated perspective on the interconnected issues.

A key finding of this research is that the term "remote operation" encompasses a wide range of applications. Establishing a functional ROCs requires a clear definition of the specific type or subcategory of RO being implemented, along with the determination of relevant technical parameters and performance expectations for both the centre and its operators. However, the maintenance and long-term management of such centres remain poorly explored, presenting a potential avenue for future research.

Another critical knowledge gap concerns SA for operators controlling vehicles in highly congested urban environments. The optimal configuration of network architecture, HMI, and system latency remains uncertain. Achieving a balance between these components necessitates extensive research, particularly given that ROCs are expected to be cost-effective rather than reliant on prohibitively expensive, state-of-the-art solutions. The design and efficacy of HMI and display systems, which convey critical information to operators, represent an entire field of study requiring further investigation. A fundamental question is how to present information in a manner that maximizes data transmission efficiency while minimizing cognitive load. Both hands-on and hands-off interface designs warrant consideration.

Additionally, the spatial and ergonomic design of ROCs remains an area requiring further study. The objective is to create an optimized working environment that enhances SA and improves operator decision-making. Operator training also remains underexplored, particularly in the context of managing urban road vehicles. The precise skill set required for remote operators is still unclear, with expert opinions diverging considerably. Moreover, future research in this area must account for the regulatory requirements specific to each country where RO projects are deployed.

Finally, an essential avenue for future research is the integration of RO technologies with national legal frameworks—and vice versa. Examining how traffic regulations can accommodate RO and facilitate the establishment of operational centres is crucial for the successful implementation of this technology. Identifying regulatory barriers and supportive legal mechanisms will be instrumental in shaping the future of remote vehicular operations.

REFERENCES

Amador, O., Aramrattana, M., & Vinel, A. (2022). A Survey on Remote Operation of Road Vehicles. *IEEE Access*, *10*, 130135–130154. https://doi.org/10.1109/ACCESS.2022.3229168

Andersson, J., & Söderman, M. (2024). *Navigating the challenges of remote operations of automated road vehicles: A socio-technical perspective*. Intelligent Human Systems Integration (IHSI 2024) Integrating People and Intelligent Systems. https://doi.org/10.54941/ahfe1004466

Aramrattana, M., Schrank, A., Andersson, J., Zhao, L., Hermann, D., Mharolkar, S., Vanzura, M., Habibovic, A., & Oehl, M. (2024). A Roadmap Towards Remote Assistance: Outcomes from Multidisciplinary Workshop at the 2023 Intelligent Vehicles Symposium. In C. Stephanidis, M. Antona, S. Ntoa, & G. Salvendy (Eds.), *HCI International 2024 Posters* (Vol. 2118, pp. 175–185). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-61963-2_16

ASME, n.d. Rufus Oldenburger Medal. [online] Available at: https://www.asme.org/about-asme/honors-awards/achievement-awards/rufus-oldenburger-medal [Accessed 8 October 2024].

Automated Vehicle Safety Consortium. 2023. AVSC Best Practice for ADS Remote Assistance Use Case. SAE Industry Technologies Consortia.

Bachhuber, C., & Steinbach, E. (2016). A system for high precision glass-to-glass delay measurements in video communication. *2016 IEEE International Conference on Image Processing (ICIP)*, 2132–2136. https://doi.org/10.1109/ICIP.2016.7532735

Bengler, K., Dietmayer, K., Farber, B., Maurer, M., Stiller, C., & Winner, H. (2014). Three Decades of Driver Assistance Systems: Review and Future Perspectives. *IEEE Intelligent Transportation Systems Magazine*, *6*(4), 6–22. https://doi.org/10.1109/MITS.2014.2336271

Bhavsar, P., Das, P., Paugh, M., Dey, K., & Chowdhury, M. (2017). Risk Analysis of Autonomous Vehicles in Mixed Traffic Streams. *Transportation Research Record: Journal of the Transportation Research Board*, *2625*(1), 51–61. https://doi.org/10.3141/2625-06

Bout, M., Brenden, A. P., Klingegård, M., Habibovic, A., & Böckle, M.-P. (2017). A Head-Mounted Display to Support Teleoperations of Shared Automated Vehicles. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, 62–66. https://doi.org/10.1145/3131726.3131758

Brannen, J. (Ed.). (2017). *Mixing Methods: Qualitative and quantitative research* (1st ed.). Routledge. https://doi.org/10.4324/9781315248813

Burova, A., Mäkelä, J., Keskinen, T., Kallioniemi, P., Ronkainen, K., & Turunen, M. (2024). The Role of Audio Feedback and Gamification Elements for Remote Boom Operation. *Multimodal Technologies and Interaction*, *8*(8), 69. https://doi.org/10.3390/mti8080069

CEIC Data (n.d.) 'United States Motor Vehicle Registered', CEIC Data. Available at: https://www.ceicdata.com/en/indicator/united-states/motor-vehicle-registered (Accessed: 24 February 2025).

Cerrato, L. (2002). A comparison between feedback strategies in human-to-human and human-machine communication. *7th International Conference on Spoken Language Processing (ICSLP 2002)*, 557–560. https://doi.org/10.21437/ICSLP.2002-191

Claybrook, J., & Kildare, S. (2018). Autonomous vehicles: No driver…no regulation? *Science*, *361*(6397), 36–37. https://doi.org/10.1126/science.aau2715

Corde Lane, J., Carignan, C. R., Sullivan, B. R., Akin, D. L., Hunt, T., & Cohen, R. (2002). Effects of time delay on telerobotic control of neutral buoyancy vehicles. *Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292)*, *3*, 2874–2879. https://doi.org/10.1109/ROBOT.2002.1013668

Cornelisse, D. G. (2002). *Splendid vision, unswerving purpose: Developing air power for the United States Air Force during the first century of powered flight*. History Office, Aeronautical Systems Center, Air Force Materiel Command [u.a.].

Davis, J., Smyth, C. and McDowell, K. (2010). The effects of time lag on driving performance and a possible mitigation. IEEE Transactions on Robotics 26(3): 590-593.

De Barros, P. G., & Lindeman, R. W. (2013). Performance effects of multi-sensory displays in virtual teleoperation environments. *Proceedings of the 1st Symposium on Spatial User Interaction*, 41–48. https://doi.org/10.1145/2491367.2491371

Endsley, M. R. (1995). Measurement of Situation Awareness in Dynamic Systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *37*(1), 65–84. https://doi.org/10.1518/001872095779049499

Endsley, M. R. (2016). *Designing for Situation Awareness: An Approach to User-Centered Design, Second Edition* (0 ed.). CRC Press. https://doi.org/10.1201/b11371

Erlang, A. K. (1917). Solution of Some Problems in the Theory of Probabilities of Significance in Automatic Telephone Exchanges. *Post Office Electrical Engineer's Journal*, *10*, 189–197.

European Commission Regulation (EU) (2022). 2022/1426 of the European Parliament and of the Council of 6 July 2022 on artificial intelligence and repealing Regulation (EC) No. 2272/2006 (Artificial Intelligence Act). *Official Journal of the European Union*, L 227, 1–44. https://eur-lex.europa.eu/legalcontent/EN/TXT/PDF/?uri=CELEX:32022R1426.

Gavanas, N. (2019). Autonomous Road Vehicles: Challenges for Urban Planning in European Cities. *Urban Science*, *3*(2), 61. https://doi.org/10.3390/urbansci3020061

Georg, J.-M., Feiler, J., Hoffmann, S., & Diermeyer, F. (2020). Sensor and Actuator Latency during Teleoperation of Automated Vehicles. *2020 IEEE Intelligent Vehicles Symposium (IV)*, 760–766. https://doi.org/10.1109/IV47402.2020.9304802

Ginzburg, S. A., Lekhtman, I. Y., & Malov, V. S. (1966). *Fundamentals of Automation and Remote Control: International Series of Monographs in Automation and Automatic Control*. Elsevier Science.

Goodall, N. (2020). Non-technological challenges for the remote operation of automated vehicles. *Transportation Research Part A: Policy and Practice*, *142*, 14–26. https://doi.org/10.1016/j.tra.2020.09.024

Goodfellow, I., Bengio, Y., & Courville, A. (2016). *Deep learning*. The MIT press.

Goodrich, M. A., & Olsen, D. R. (2003). Seven principles of efficient human robot interaction. *SMC'03 Conference Proceedings. 2003 IEEE International Conference on Systems, Man and Cybernetics. Conference Theme - System Security and Assurance (Cat. No.03CH37483)*, *4*, 3942–3948. https://doi.org/10.1109/ICSMC.2003.1244504

Griffin, W. B. & Stanford University. Department of Mechanical Engineering. (2003). *Shared Control for Dexterous Telemanipulation with Haptic Feedback*. Stanford University. https://books.google.de/books?id=UWwTPQAACAAJ

Gupta, U. G., & Clarke, R. E. (1996a). Theory and applications of the Delphi technique: A bibliography (1975–1994). *Technological Forecasting and Social Change*, *53*(2), 185–211. https://doi.org/10.1016/S0040-1625(96)00094-7

Gupta, U. G., & Clarke, R. E. (1996b). Theory and applications of the Delphi technique: A bibliography (1975–1994). *Technological Forecasting and Social Change*, *53*(2), 185–211. https://doi.org/10.1016/S0040-1625(96)00094-7

Habibovic, A., Andersson, J., Castor, M., Meiby, L., & Rizgary, D. (2020). Human factors related to remote control of automated heavy vehicles. *SAFER Vehicle and Traffic Safety Centre, Sweden*, 44.

HF-IRADS. (2020). *Human factors challenges of remote support and control. A position paper from HF-IRADS, Informal document submitted to UNECE GRVA-07-65 [Online]*. https://unece.org/fileadmin/DAM/trans/doc/2020/wp29grva/GRVA-07-65e.pdf

Higgins, T. (2018, June 5). Driverless Cars Still Handled by Humans—From Afar. *The Wall Streer Journal*. https://www.wsj.com/articles/who-does-a-driverless-car-call-when-it-needs-help-a-human-1528191000

Hosseini, A. (2018). *Conception of Advanced Driver Assistance Systems for Precise and Safe Control of Teleoperated Road Vehicles in Urban Environments* [Doctrol thesis]. Technical University of Munich.

Hosseini, A., & Lienkamp, M. (2016). Enhancing telepresence during the teleoperation of road vehicles using HMD-based mixed reality. *2016 IEEE Intelligent Vehicles Symposium (IV)*, 1366–1373. https://doi.org/10.1109/IVS.2016.7535568

Imai, T. (2019). Legal regulation of autonomous driving technology: Current conditions and issues in Japan. *IATSS Research*, *43*(4), 263–267. https://doi.org/10.1016/j.iatssr.2019.11.009

Imperial War Museums. (n.d.). A brief history of drones. Imperial War Museums. Retrieved July 8, 2024, from https://www.iwm.org.uk/history/a-brief-history-of-drones

Iris Dynamics (n.d.) What is force feedback: explained. Available at: https://irisdynamics.com/articles/what-is-force-feedback (Accessed: 10 February 2025).

Jeong, S., & Lee, D. (2024). Driving Behavior Characteristics of Merging Sections in the Urban Underground Road Junction: A Driving Simulator Study. *Applied Sciences*, *14*(14), 6247. https://doi.org/10.3390/app14146247

Kadylak, T., Cotten, S. R., & Fennell, C. (2021). Willingness to Use Automated Vehicles: Results From a Large and Diverse Sample of U.S. Older Adults. *Gerontology and Geriatric Medicine*, *7*, 2333721420987335. https://doi.org/10.1177/2333721420987335

Kettwich, C., Schrank, A., & Oehl, M. (2021). Teleoperation of Highly Automated Vehicles in Public Transport: User-Centered Design of a Human-Machine Interface for Remote-Operation and Its Expert Usability Evaluation. *Multimodal Technologies and Interaction*, *5*(5), 26. https://doi.org/10.3390/mti5050026

Kettwich, C., Schrank, A., Avsar, H., & Oehl, M. (2021). What if the Automation Fails? – A Classification of Scenarios in Teleoperated Driving. *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 92–96. https://doi.org/10.1145/3473682.3480271

Kim, Y., Kim, S., & Jeon, M. (2025). NBBOX: Noisy Bounding Box Improves Remote Sensing Object Detection. *IEEE Geoscience and Remote Sensing Letters*, *22*, 1–5. https://doi.org/10.1109/LGRS.2025.3527712

Klingberg, L. (2023). *The future of Remote Operations for Autonomous Vehicles*. Linköping University.

Korosec, K. (2020, May 20). Remote operators in Mexico are driving scooters to riders in this Atlanta suburb. *TechCrunch*. https://techcrunch.com/2020/05/20/remote-operators-in-mexico-are-driving-scooters-to-riders-in-this-atlanta-suburb/

Koskinen, H., Schrank, A., Lehtonen, E., & Oehl, M. (2024). Analyzing the Remote Operation Task to Support Highly Automated Vehicles – Suggesting the Core Task Analysis to Ensure the Human-Centered Design of the Remote Operation Station. In H. Krömker (Ed.), *HCI in Mobility, Transport, and Automotive Systems* (Vol. 14732, pp. 145–156). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-60477-5_11

Kuchenbecker, K. J. (2015). Surgeons and non-surgeons prefer haptic feedback of instrument vibrations during robotic surgery. *Surgical Endoscopy*, *29*(10), 2970–2983. https://doi.org/10.1007/s00464-014-4030-8

Larsson, P., De Souza, J. B. R., & Begnert, J. (2023). An Auditory Display for Remote Road Vehicle Operation That Increases Awareness and Presence. *Proceedings of the 28th International Conference on Auditory Display (ICAD2023)*, 113–120. https://doi.org/10.21785/icad2023.8296

Li, S., Zhang, Y., Blythe, P., Edwards, S., & Ji, Y. (2024). Remote driving as the Failsafe: Qualitative investigation of Users' perceptions and requirements towards the 5G-enabled Level 4 automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour*, *100*, 211–230. https://doi.org/10.1016/j.trf.2023.11.018

Lindgren, A. (2009). *Driving safe in the future: HMI for integrated advanced driver assistance systems*. Chalmers tekniska högskola.

Linstone, H. A., & Turoff, M. (2011). Delphi: A brief look backward and forward. *Technological Forecasting and Social Change*, *78*(9), 1712–1719. https://doi.org/10.1016/j.techfore.2010.09.011

Lu, H., Zhang, Y., & Liu, Y. (2024). Research on Key Technologies of Remote Operation and Maintenance System for Substation Automation Equipment. *Applied Mathematics and Nonlinear Sciences*, *9*(1), 20242187. https://doi.org/10.2478/amns-2024-2187

Machotka, J., Nafalski, A., & Nedic, Z. (n.d.). *The history of developments of Remote experiments* [Doctoral dissertation].

Matikka, K. (2021, April 28). *Evolution of autonomous maritime operations driven by automation technology and digitalisati*on. Elomatic. https://www.elomatic.com/evolution-of-autonomous-maritime-operations-driven-by-automation-technology-and-digitalisation/

Matthews, M. D., & Beal, S. A. (2002). A Field Test of Two Methods for Assessing Infantry Situation Awareness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *46*(3), 352–356. https://doi.org/10.1177/154193120204600329

Merat, N., Seppelt, B., Louw, T., Engström, J., Lee, J. D., Johansson, E., Green, C. A., Katazaki, S., Monk, C., Itoh, M., McGehee, D., Sunda, T., Unoura, K., Victor, T., Schieben, A., & Keinath, A. (2019). The “Out-of-the-Loop” concept in automated driving: Proposed definition, measures and implications. *Cognition, Technology & Work*, *21*(1), 87–98. https://doi.org/10.1007/s10111-018-0525-8

Merriam-Webster (2024) Feedback. Merriam-Webster Dictionary. Available at: https://www.merriam-webster.com/dictionary/feedback (Accessed: 11 February 2025).

MetaCCAZE (2025) metaCCAZE Project – Revolutionising Mobility in European Cities. Available at: https://www.metaccaze-project.eu/ (Accessed: 20 March 2025).

Michon, J. A. (1985). A Critical View of Driver Behavior Models: What Do We Know, What Should We Do? In L. Evans & R. C. Schwing (Eds.), *Human Behavior and Traffic Safety* (pp. 485–524). Springer US. https://doi.org/10.1007/978-1-4613-2173-6_19

Miettinen, K., Riihelä, A., & Suomento, J. (2024). *TIELIIKENTEEN AUTOMAATION EDELLYTTÄMÄT LAINSÄÄDÄNTÖ_MUUTOKSET SUOMESSA*. Liikenne Ja Viestintäministeriö Kommunikationsministeriet.

MUNIN. (2016). Research in Maritime Autnomous Systems. Project Results and Technology Potentials. http://www.unmanned-ship.org/munin/wp-content/uploads/2016/02/MUNIN-finalbrochure.pdf

Mutzenich, C., Durant, S., Helman, S., & Dalton, P. (2021). Updating our understanding of situation awareness in relation to remote operators of autonomous vehicles. *Cognitive Research: Principles and Implications*, *6*(1), 9. https://doi.org/10.1186/s41235-021-00271-8

Nash, E. B., Edwards, G. W., Thompson, J. A., & Barfield, W. (2000). A Review of Presence and Performance in Virtual Environments. *International Journal of Human-Computer Interaction*, *12*(1), 1–41. https://doi.org/10.1207/S15327590IJHC1201_1

Neumeier, S., Wintersberger, P., Frison, A.-K., Becher, A., Facchi, C., & Riener, A. (2019). Teleoperation: The Holy Grail to Solve Problems of Automated Driving? Sure, but Latency Matters. *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 186–197. https://doi.org/10.1145/3342197.3344534

Papadimitriou, E., Schneider, C., Aguinaga Tello, J., Damen, W., Lomba Vrouenraets, M., & Ten Broeke, A. (2020). Transport safety and human factors in the era of automation: What can transport modes learn from each other? *Accident Analysis & Prevention*, *144*, 105656. https://doi.org/10.1016/j.aap.2020.105656

Parr, H., Harvey, C., Burnett, G., & Sharples, S. (2024). Investigating levels of remote operation in high-level on-road autonomous vehicles using operator sequence diagrams. *Cognition, Technology & Work*, *26*(2), 207–223. https://doi.org/10.1007/s10111-024-00762-w

Razavi, N., & Sierpinski, G. (2024). An attempt to determine the impact of the implementation of autonomous vehicles on a larger scale on the planning of city transport systems. *Journal of Sustainable Development of Transport and Logistics*, *9*(1), 96–120. https://doi.org/10.14254/jsdtl.2024.9-1.8

Renaud, K., & Cooper, R. (2000). Feedback inhuman-computer interaction-characteristics andrecommendations. *South African ComputerJournal*, *2000*(26), 105–114.

Saab. (n.d.). Saab Digital Air Traffic Solutions. Retrieved May 5, 2024, from https://www.saab.com/sites/saab-digital-air-traffic-solutions

SAE (n.d.) SAE International. Available at: https://www.sae.org/ (Accessed: 29 October 2024).

SAE, Society of Automotive Engineers. (2021a) Taxonomy and Definitions for Terms Related to Driving Automation Systems for on-Road Motor Vehicles; SAE: Washington, DC, USA, 2021, https://www.sae.org/standards/content/ j3016_202104/

SAE International (2021b) SAE levels of driving Automation™ Refined for Clarity and International Audience. SAE Int Retrieved 02/10/2022 from https://www.sae.org/blog/sae-j3016-update

Saeed, U., Hamalainen, J., Garcia-Lozano, M., & David Gonzalez, G. (2019). On the Feasibility of Remote Driving Application over Dense 5G Roadside Networks. *2019 16th International Symposium on Wireless Communication Systems (ISWCS)*, 271–276. https://doi.org/10.1109/ISWCS.2019.8877213

Safety4Sea Editorial Team. (2022, September 5). *Remote ship operations paving the way for autonomous shipping.* SAFETY4SEA. https://safety4sea.com/cm-remote-ship-operations-paving-the-way-for-autonomous-shipping/

Salisbury, K. (1988). Issues in human/computer control of dexterous remote hands. *IEEE Transactions on Aerospace and Electronic Systems*, *24*(5), 591–596. https://doi.org/10.1109/7.9687

Saunders, M., Thornhill, A., & Lewis, P. (2019). *Research methods for business students* (Eigth Edition). Pearson.

Schrank, A., & Kettwich, C. (2021, October). *ROLES IN THE TELEOPERATION OF HIGHLY AUTOMATED VEHICLES IN PUBLIC TRANSPORT*. The 7th Humanist Conference, Rhodes Island, Greece. https://www.researchgate.net/publication/356944935_Roles_in_the_Teleoperation_of_Highly_Automated_Vehicles_in_Public_Transport?enrichId=rgreq-b3056216e6ce5f53ee7fc8509e39e503-XXX&enrichSource=Y292ZXJQYWdlOzM1Njk0NDkzNTtBUzoxMTQ4NzY0ODY1NzI0NDE3QDE2NTA4OTgyOTUyOTI%3D&el=1_x_2

Schrank, A., Merat, N., Oehl, M., & Wu, Y. (2024). Human Factors Considerations of Remote Operation Supporting Level 4 Automation. In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation 11* (pp. 111–125). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-67466-2_11

Sener, I. N., Zmud, J., & Williams, T. (2019). Measures of baseline intent to use automated vehicles: A case study of Texas cities. *Transportation Research Part F: Traffic Psychology and Behaviour*, *62*, 66–77. https://doi.org/10.1016/j.trf.2018.12.014

Sheridan, T. B. (1995). Teleoperation, telerobotics and telepresence: A progress report. *Control Engineering Practice*, *3*(2), 205–214. https://doi.org/10.1016/0967-0661(94)00078-U

Sheridan, T. B., & Ferrell, W. R. (1963). Remote Manipulative Control with Transmission Delay. *IEEE Transactions on Human Factors in Electronics*, *HFE-4*(1), 25–29. https://doi.org/10.1109/THFE.1963.231283

Shi, E., & Frey, A. T. (2021). Theoretical Substitution Model for Teleoperation. In T. Bertram (Ed.), *Automatisiertes Fahren 2021* (pp. 69–81). Springer Fachmedien Wiesbaden.

Smith, B. W. (2012). Automated Vehicles are Probably Legal in the United States. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2303904

Spink, A., & Saracevic, T. (1998). Human-computer interaction in information retrieval: Nature and manifestations of feedback. *Interacting with Computers*, *10*(3), 249–267. https://doi.org/10.1016/S0953-5438(98)00009-5

Swargiary, K. (2024). *RESEARCH METHODOLOGIES*. SCHOLARS' PRESS.

Tener, F., & Lanir, J. (2022). Driving from a Distance: Challenges and Guidelines for Autonomous Vehicle Teleoperation Interfaces. *CHI Conference on Human Factors in Computing Systems*, 1–13. https://doi.org/10.1145/3491102.3501827

Tengilimoglu, O., Carsten, O., & Wadud, Z. (2023). Implications of automated vehicles for physical road environment: A comprehensive review. *Transportation Research Part E: Logistics and Transportation Review*, *169*, 102989. https://doi.org/10.1016/j.tre.2022.102989

The New York Times. (1925, July 28). *Radio-driven auto runs down escort; Wireless directs test car in traffic. The New York Times.* https://www.nytimes.com/1925/07/28/archives/radio-driven-auto-runs-down-escort-wireless-directs-test-car-in.html

Thompson, K. M. (2015). *I, Robot: Nikola Tesla's Telautomaton*. UNIVERSITY OF CALIFORNIA.

Veitch, E., & Andreas Alsos, O. (2022). A systematic review of human-AI interaction in autonomous ship systems. *Safety Science*, *152*, 105778. https://doi.org/10.1016/j.ssci.2022.105778

Walliman, N. (2020). *Your research project: Designing, planning, and getting started* (Fourth edition). SAGE.

Wickens, C. D., Goh, J., Helleberg, J., Horrey, W. J., & Talleur, D. A. (2003). Attentional Models of Multitask Pilot Performance Using Advanced Display Technology. *Human Factors: The*

Journal of the Human Factors and Ergonomics Society, *45*(3), 360–380. https://doi.org/10.1518/hfes.45.3.360.27250

Wolf, M.-M., Taupitz, R., & Diermeyer, F. (2024). *Should Teleoperation Be like Driving in a Car? Comparison of Teleoperation HMIs* (Version 2). arXiv. https://doi.org/10.48550/ARXIV.2404.13697

Zhao, L., Nybacka, M., Drugge, L., Rothhämel, M., Habibovic, A., & Hvitfeldt, H. (2024). The Influence of Motion-Cueing, Sound and Vibration Feedback on Driving Behavior and Experience—A Virtual Teleoperation Experiment. *IEEE Transactions on Intelligent Transportation Systems*, *25*(8), 9797–9809. https://doi.org/10.1109/TITS.2024.3353465

Zulqarnain, S. Q., & Lee, S. (2021). Selecting Remote Driving Locations for Latency Sensitive Reliable Tele-Operation. *Applied Sciences*, *11*(21), 9799. https://doi.org/10.3390/app11219799

APPENDIX A

The importance of auditory feedback in ROC

Subsection 2.6.1 covered the types of feedback, while this appendix briefly highlights the importance of audio cues, in particular. When driving and navigating through the city, we rely on nearly all our senses. This should encourage us to incorporate these senses into remote operation stations as well. In a ROC, where visual cues are typically transmitted monoscopically through a camera-display system and physical motion is absent, and it is not essential to receive all information through visual platforms (Larsson et al., 2023), the sound produced by the vehicle’s movement can become crucial for the operator to enhance SA (Burova et al., 2024) and a sense of speed judgment and presence - the sensation of “being there” (Nash et al., 2000). Moreover, according to interviews with (I02, I04 and I06), remote operators do not need to obtain all necessary information from the vehicles visually. Incorporating other methods could help reduce their workload. According to (Larsson et al., 2023) auditory displays can enhance the experience of remote vehicle operators in various ways across different scenarios and applications. Enhanced sound assists users in identifying surrounding objects, determining their locations (perception), and understanding their movement patterns (comprehension). Additionally, propulsion sounds provide insight into the vehicle's speed, enabling operators to anticipate how nearby objects are moving relative to the remote vehicle through the use of augmented audio cues. (De Barros & Lindeman, 2013) conducted a study reviewing the role of multisensory feedback in virtual teleoperation environments. Their findings suggest that auditory feedback improves immersion and concentration on tasks while also enhancing the perception of distances between the robot and its virtual surroundings.

Although the legal framework for ROCs is still being developed, it can be anticipated that certain sounds typically found in manually driven vehicles will also be required in ROs. Additionally, sounds like turn indicators or parking assistance alerts might be included to help convey the vehicle's status and/or enhance the operator's performance (Larsson et al., 2023).

APPENDIX B

List of interviewees

The table 7 shows the list of interviewees whose information is used for this thesis:

Table 5: *List of interviewees*

Interviewee's code	Country	Role or perfection	Organization	Expertise
I01	Israel	Industry	Ottopia	Head of Strategy
I02	Germany	Industry	Mercedes-Benz AG	Manager of Function and Software Development
I03	USA	Academic	Virginia Transport Research Council	Senior Research Scientist
I04	Germany	Industry	Easymile	Data analyser
I05	France	Academic	Opal-RT (Paris)	Embedded Systems & Software Development
I06	Sweden	Industry	Einride	Intelligent movement expert

APPENDIX C

In this appendix, the surveys from two rounds are included in the order they were conducted.

Questions of round One

There are 54 questions in this survey.

Information for participants:

The purpose of this survey is to identify the most critical technical aspects and challenges related to the remote operation of AVs in PT sector. The questions have been designed to gather insights into various areas of this technology, and your responses will help us understand the key factors influencing successful remote operations.

Each section of the survey is organized by topic, with the questions grouped into independent categories. This means you can respond to each section based on your area of expertise without needing to address unrelated topics. Your input on the other sections is still highly valuable.

Based on the responses we receive in this survey; we will conduct a second round of the survey later in the autumn. The follow-up survey will delve deeper into the issues identified in this round, and we would greatly appreciate your participation once again.

If you have any questions at this stage or have any technical difficulties with the survey, please contact: nikoo.razavi@tuni.fi

The survey is completely voluntary, and you have the right to withdraw at any time.

Thank you for your time and valuable contributions to this research.

List of acronyms:

Automated Vehicles: **AVs**

Remote Operation: **RO** (According to SAE: guidance and assistance to the ADS, passengers, and law enforcement is provided in remote operation). Remote operator can be thought of as combining the functions of Remote Assistant, Customer Support, Authorities Interaction, and/or Remote Driving.

Remote Assistant: **RA** (Based on the SAE definitions, RA provides guidance and support to the ADS dedicated vehicles, enhancing its decision-making process)

Technology Readiness Level: **TRL** (A method for estimating the maturity of technologies during the acquisition phase of a program. TRLs are based on a scale from 1 to 9 with 9 being the most mature technology (Wikipedia).)

***Table 6:** First round's questions*

GDPR: I agree to the use of the answers as stated in the privacy statement.

☐ I accept.

Professional Background		Please briefly describe your current role and the number of years of experience you have in the field of AVs: ……………………………………………………………………… ……………………………………………………………………… ……………………………………………………………………… Have you been involved in any projects concerning the RO of AVs? Yes☐ No☐ If yes, please write one strength and one weakness identified in the project. Strength: ……………………….. Weakness: ………………………..
Current State of Technology	**Technological Assessment**	How would you rate the following technologies in terms of their importance to the success of RO systems? (on a scale of 1 to 5, where 1 is 'Not Critical' and 5 is 'Extremely Critical) Sensors ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Communication and Network ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Remote Operator Capabilities ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Other ☐ (please specify): ………………… What is the current Technology Readiness Level (TRL) of RO technology for AVs? Rating: ……………….
	Latency and Communication	What are the existing challenges associated with latency in RO systems? Please rank them in order of importance. 1. ………………… 2. ………………… 3. ………………… How do latency issues impact the safety and performance of remotely operated AVs? (Please elaborate) …………………………………………… What are the possible solutions to reduce latency and guarantee real-time communication between the vehicle and the remote operator? (Please elaborate) ……………………………………………

Infrastructure and Integration	**Infrastructure suitability**	How well does the current transport infrastructure support the RO of AV? (Scale: 1 = Not Supportive, 2 = Partially unsupportive, 3= Neither supportive nor unsupportive, 4 = Partially supportive, 5 = Fully supportive) ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Are there any modifications or upgrades to the infrastructure that could facilitate ROs? (Please elaborate) ……………………………………………
	Integration with Current Systems	What role RO systems can play to be effectively integrated into the existing public transport networks? (Please elaborate) …………………………………………… What are the main technical challenges in this integration? (Please elaborate) ……………………………………………
Safety and Reliability	**Safety concerns**	Does RO of AVs have the potential to increase trust between passengers? Yes☐ No☐ What are the primary safety issues associated with ROs of AVs? (Please elaborate) …………………………………………… How can these safety concerns be mitigated? (Please specify if technological or policy measures are preferred) ……………………………………………
	Reliability of systems	What measures can ensure the reliability of RO systems across different environmental and traffic conditions? (Please elaborate) …………………………………………… What backup systems or fail-safes should be implemented to manage potential system failures in ROs? (Please elaborate) …………………………………………… Should RO of AV more be performed as a teamwork or as an individual task? Teamwork ☐ Individual Task ☐ Depends on Context☐ (please elaborate): ……………………
Human-Machine Interaction (HMI)	**HMI design**	What are the essential features of an effective HMI for the RO of AVs? (Please elaborate) …………………………………………… How can the HMI be designed to provide remote operators with comprehensive situational awareness and control? (Please elaborate) ……………………………………………
Regulatory and Legal	**Regulatory Challenges**	What are the regulatory and legal challenges or gaps in adopting RO of AVs? (Please elaborate) ……………………………………………

		What steps should be taken to address these regulatory challenges? (Please elaborate) ……………………………………………
	Compliance with Standards	Which existing standards and regulations should RO systems comply with? (Please specify) ……………………………………………
Economic and Social Impact	**Economic Benefits and Drawbacks**	What are the potential economic benefits and drawbacks of implementing RO of AVs in public transport? (Please elaborate) …………………………………………… How can the economic viability of such systems be ensured? (Please elaborate) ……………………………………………
	Social Impact	How do you foresee the social impact of this technology on the general public and the workforce? (Please elaborate) …………………………………………… What measures can be taken to ensure positive social outcomes? (Please elaborate) ……………………………………………
Timeline and Feasibility		Based on current trends and developments, what is your estimated timeline for the feasibility of RO of AVs in public transport? Estimated Timeline: …………………… What milestones need to be achieved to reach this feasibility? (Please elaborate) ……………………………………………
Research and Development Needs		What areas of research and development are most critical to advancing the feasibility of RO systems? (Please elaborate) …………………………………………… Are there specific technological breakthroughs or innovations that you anticipate being pivotal? (Please elaborate) ……………………………………………
Additional Considerations	**Public Perception and Acceptance**	How can public perception and acceptance of remote-operated AVs be improved? (Please elaborate) …………………………………………… What educational or outreach programs would you suggest informing and engaging the public? (Please elaborate) ……………………………………………
	Data management	How would you rate the following challenges related to ROs? (On a scale of 1 to 5, where 1 is 'Not Challenging' and 5 is 'Extremely Challenging') Data Exchanging ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Cyber security ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Amount of Data ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Other ☐ (please specify): …………………
Remote operator		Are biological measurements (e.g., heart rate and eye movements of the remote operator or RA, which are typically used for mental workload assessment) helpful? Yes ☐ No ☐

		Please elaborate on your answer: …………………………………………… On a scale of 1 to 5, where 1 is 'Not Important' and 5 is 'Extremely Important,' how would you rate the importance of the following criteria for selecting remote operators? Knowledge of the autonomy system ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Having a driving license ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Being an engineer ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Familiarity with HMI systems and feedback ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 If there are other criteria to consider, please specify: …………………………………………… Which operating processes do RAs need to know? (Please elaborate) …………………………………………… Additionally, for selecting RAs, from which groups should they be recruited (e.g., drivers, gamers)? (Please elaborate) …………………………………………… How would you rate the following challenges for the remote operator? (On a scale of 1 to 5, where 1 is 'Not Challenging' and 5 is 'Extremely Challenging') Sufficient Information ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Mental Workload ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Motion Sickness ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Workload ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Data Amount and Information ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Other ☐ (please specify): ………………….
	Training	What are the barriers to training remote operators? Law ☐ Education content ☐ Complexity ☐ Other (please specify): …………………. ☐ Can regulations facilitate the training? Yes☐ No☐ If yes, what kind of regulations? (Please elaborate) …………………………………………… How long and frequent training is required? (Please elaborate) …………………………………………… What kind of training should be provided to remote operators to ensure they can effectively manage the AVs? (Please elaborate) …………………………………………… Are there specific HMI elements that require more intensive training or user familiarization? (Please elaborate) ……………………………………………
RO centre/location		Should the RO centre be located inside the country in which AVs are operating or outside? Yes ☐ No ☐

Situational awareness	How would you rate the following aspects of situational awareness in ROs? (On a scale of 1 to 5, where 1 is 'Not Challenging' and 5 is 'Extremely Challenging') Network ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Communication ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Feedback Modes ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 HMI ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Other ☐ (please specify): ………………….
Evaluation	What are the priorities of a RO's tasks? (Please elaborate) …………………………………………… How would you rate the practicality of RO in public transport? (On a scale of 1 to 5, where 1 is 'Not Practical' and 5 is 'Highly Practical') ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 How would you rate the challenges of implementing ROs in public transport? (On a scale of 1 to 5, where 1 is 'Not Challenging' and 5 is 'Extremely Challenging') ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 On a scale of 1 to 5, where 1 is 'Not Significant' and 5 is 'Extremely Significant,' how would you rate the significance of the following barriers to RO in public transport? Regulations ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Technology and Sensors ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Technical Issues ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Network ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Weather Conditions (e.g., heavy snow, rain) ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Other ☐ (please specify): …………………. Which of the above barriers is the most challenging aspect of RO in public transport? And why? (Please elaborate) …………………………………………… Reason: …………………………………………… What do you consider to be the most positive or efficient aspect of RO in road transport? Economy ☐ Acceptance of people ☐ Other (please specify): …………………. ☐

Questions of round Two

There are 24 questions in this survey.

Information for participants:

The purpose of this survey is to identify the most critical technical aspects and challenges related to the remote operation of Automated Vehicles (AVs) in public transport sector. The first round was held during 14th to 31st October and the results related to this round's questions are attached to the survey.

Each section of the survey is organized by topic, with the questions grouped into independent categories. This means you can respond to each section based on your area of expertise without needing to address unrelated topics. Your input on the other sections is still highly valuable.

The questions have been designed to gather insights into different areas of this technology, and your responses will help us understand the key factors influencing successful remote operations. For this round, we consider areas which were more controversial in round 1 or those were neglected or has the room to be considered more.

If you have any questions at this stage or have any technical difficulties with the survey, please contact: nikoo.razavi@tuni.fi

The survey is completely voluntary, and you have the right to withdraw at any time.

Thank you for your time and valuable contributions to this research.

List of acronyms:

Automated Vehicles: **AVs**

Remote Operation: **RO** (According to SAE: guidance and assistance to the ADS, passengers, and law enforcement is provided in remote operation). Remote operator can be thought of as combining the functions of Remote Assistant, Customer Support, Authorities Interaction, and/or Remote Driving.

Remote Assistant: **RA** (Based on the SAE definitions, RA provides guidance and support to the ADS dedicated vehicles, enhancing its decision-making process)

Public Transport: **PT**

Human-Machine Interaction: **HMI** (Is defined as interaction between human operators and devices in a complex world through multiple interfaces.)

Remote Operation centre: **ROC**

Table 7: *Second round's questions*

GDPR: I agree to the use of the answers as stated in the privacy statement. ☐ I accept.

Remote Operator	1. Please rank these aspects regarding a remote operator's expertise in order of importance: ☐ Driving skills

	☐ Technical expertise ☐ Interpersonal skills (Operator & passengers) ☐ Other (please specify): ……….. 2. In general (not for daily tasks), how would you allocate technical responsibilities between the remote operator and the company providing the AV? Please elaborate: ……………………….. 3. What do you think is an appropriate length for a single shift for a remote operator? ☐ less than 4 hours ☐ 4 hours ☐ other (please specify) …………… 4. Based on the findings from the round 1 analysis, which indicate that most experts view the remote operator role as a collaborative, team-oriented process, which of the following aspects is the most important for supporting the operator's well-being? ☐ Workload ☐ Division of tasks ☐ Motion sickness ☐ Monotonous ☐ Other (please specify): …………………….. 5. Would it make a difference if remote operators had automated assistance (e.g. predictive monitoring tools, alerts etc.) to help manage multiple AVs more effectively? ☐ Yes ☐ No ☐ Other (Please specify): …………… 6. If the number of shuttles a remote operator monitors at one time were to be adjusted based on situational factors, please rank the following factors in order of importance. ☐ Time of day ☐ Traffic density ☐ The complexity of the route ☐ Other (please specify): …………………… 7. Please rank the factors that limit the number of AVs a single operator oversees. ☐ Real-time monitoring of each AV's surroundings ☐ The operator's ability to respond to emergencies ☐ Communication reliability between the AVs and the operator ☐ Traffic and environmental conditions 8. How many AVs a single remote operator should monitor at one time to ensure safe operation? Please elaborate: …… 9. What is the safest way for operators to monitor multiple AVs at once? Please elaborate: ……
Workstation	10. How would you assess the functionality of the workstation for the remote operator, and how important do you consider it to be? (Please elaborate): ……………………………………. 11. How far should the remote workstation be located from the vehicle? (The round 1 results indicate that the ROC should be within the same country.) ☐ So close that if there was a need, remote operator can reach out the vehicle ☐ Not very close, but within the same city ☐ Within the same district ☐ Other (please specify): …………………… 12. How would you rank the importance of the following elements for the workstation user interface (UI) for a remote operator? Please arrange them in order of importance. ☐ Number of screens ☐ Ability to view the vehicle's external environment

	☐ Ability to view both the inside and outside of the vehicle ☐ Steering wheel and pedals ☐ Workstation UI software
Process and Progress	13. Which option would you prefer to implement in the first phase of a remote operator project concerning PT? ☐ Automated Taxis ☐ Automated Shuttles ☐ Automated Buses 14. Should all the data in the workstation (HMI) be intuitive (Video base data)? ☐ Yes ☐ No ☐ Other (Please specify) 15. Which of the following options (scenarios) do you believe offers the best potential for network and latency improvement? Please rank the options from most to least important. ☐ Edge computing ☐ Dedicated network for ROC ☐ 5G network exclusively for ROC ☐ Other (please specify): __________ 16. Please rank the following options (scenarios) based on their potential to improve situational awareness. ☐ Intuitive data display (Video base) ☐ Stable 5G network ☐ 360-degree view of the environment ☐ Other (please specify): __________ 17. Please rank the following options (scenarios) based on their potential to improve the HMI. ☐ Intuitive data display ☐ Self-explanatory HMI design ☐ HMI optimized for passive RO ☐ Other (please specify): __________ 18. Please rate the following areas in which a remote operator could help improve AV technologies: ☐ Blind spot detection ☐ Identification of software issues ☐ Detection of sensor-related problems ☐ Identification of complex software issues (e.g., "spaghetti" bugs) 19. Please rank the following options regarding the most helpful in the initial phases of operating AVs in the PT sector, with support from a RA and existing technology. ☐ Predefined route ☐ Workstation located near the vehicle ☐ User-friendly HMI ☐ 5G network ☐ Other (please specify): __________ 20. Do you believe that simulators can aid in learning and practicing the RO of AVs? ☐ Yes ☐ No ☐ Other (please specify): __________ 21. How much time delay/latency would be considered acceptable between the remote operator's commands and the AV's response in critical situations? ☐ No noticeable delay ☐ Up to 1 second ☐ Up to 3 seconds ☐ More than 3 seconds

	22. Please rank these environmental factors that might challenge a remote operator’s situational awareness. ☐ Low lighting or weather conditions like fog or rain ☐ Limited camera angles or sensor blind spots ☐ Time delay in communication or data transmission ☐ Distractions in a ROC ☐ Other (please specify) 23. Will the RO of AVs be capable of encouraging more people to use PT in the future? ☐ Yes ☐ No ☐ Other (Please specify) 24. Would the passenger feel safer knowing that an AV can be remotely stopped or redirected by a human operator in case of an emergency? How should training for remote operators differ between managing automated vessels and automated vehicles (AVs), and what specific skills or tools do you think are essential in one field that may be less crucial in the other? Please elaborate