

Article

Expected Challenges and Anticipated Benefits of Implementing Remote Train Control and Automatic Train Operation: A Tramway Case Study

Xavier Morin ^{1,*}, Nils O. E. Olsson ¹  and Albert Lau ² 
¹ Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway; nils.olsson@ntnu.no

² Department of Civil Engineering and Environmental Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway; albert.lau@ntnu.no

* Correspondence: xavier.morin@ntnu.no

Abstract: The digital transformation of the railway industry is necessary for addressing growing challenges and advancing its sustainable development. Digital technologies include Automatic Train Operation (ATO) and Remote Train Control (RTC), which offer opportunities to potentially optimize operations and enhance safety. Both technologies, however, could pose significant challenges that need to be addressed in order to capture the anticipated benefits in an urban public street environment. This study thus bridges the gap between theory and practice by exploring the projected benefits and challenges of implementing RTC and ATO through a case study of a European public transport operator deploying these technologies in tramway operations. Employing a case study methodology, the research draws on 44 semi-structured interviews with stakeholders from the operator and its supplier. The findings highlight significant anticipated benefits, including increased productivity, improved safety, and enhanced sustainability. Yet, prospective challenges such as regulatory hurdles, technical complexities, and organizational changes pose barriers to implementation. Key obstacles include ensuring robust connectivity, addressing cybersecurity concerns, and managing workforce transitions. This study underscores the importance of collaborative approaches, stakeholder engagement, and incremental deployment to mitigate risks and maximize the impact of automation technologies. By providing actionable insights into the practical adoption of RTC and ATO, this research supports the development of advanced urban transport systems.

Keywords: automatic train operation; remote train control; digitalization



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1. Introduction

This study aims to utilize the major opportunity offered by the digitalization and automation of rail operation illustrated by an empirical case study.

1.1. Background

The digitalization of railways is viewed as essential for their sustainable development and overcoming the sector's growing challenges [1,2]. Leveraging the digital transformation will enable railways to optimize operations, reduce energy consumption, enhance the passenger experience, and increase both the quantity and frequency of rail services [3]. According to Nold and Corman [4], the most notable advancements are anticipated in the field of automation. This field includes digital twin technology, which can automatically

monitor operations and help prevent accidents [5]. Digital twins thus enhance railway systems by providing a virtual representation of the rolling stock that supports automation and better decision making. It helps users understand the system and its environment more deeply, leading to better performance and safety [6].

Other advancements include Automatic Train Operation (ATO), which covers four levels of automation, known as Grades of Automation (GoA). GoA1 is manual operation with driver assistance, GoA2 automates movement but requires driver supervision, GoA3 allows the train to operate largely independently with a driver available for handling emergency situations, and GoA4 is fully autonomous with no driver needed for safe operations, and disruptions are managed remotely [7]. The ATO market is typically not identified as a single market in publicly available reliable statistics. ATO is frequently a part of newer metro investment projects.

Nold and Corman [4] report on railway experts' expectations for the railway market in 2050. They indicate that high levels of ATO have high potential and may be achieved on different time horizons, depending on the implementation approach. Sing et al. [8] list some challenges for ATO implementation. Many of these relate to needed investments, which also means a significant market potential for suppliers. As examples, they mention that the Positive Train Control (PTC) installation can cost USD 35,000 per locomotive, implying that the installation of ATO-related equipment is of a similar magnitude. The Norwegian Railway Directorate has published a conceptual evaluation of ATO implementation in Norway [9]. For full implementation of ATO on GoA3 or 4, they estimate cost at NOK 34.3 billion. The main cost element is infrastructure installations along the track, amounting to NOK 24 billion. The network is approximately 4200 km, indicating an investment need of NOK 5.7 million per km track for ATO to be used.

However, it is important to recognize that implementing ATO in an urban public street environment, like a city tram, may be overly ambitious at this stage. As a result, alternative approaches are being explored, including shared onboard control and Remote Train Control (RTC) [10].

Both ATO and RTC technologies hold significant potential for enhancing railway performance. ATO is expected to reduce accidents and improve overall safety, leading to lower operational costs for railway companies. It is also anticipated to decrease emissions while increasing passenger capacity, supporting environmental and transportation sustainability. As a result, railway services are likely to become more sustainable, reliable, robust, and efficient [7,11]. Meanwhile, RTC allows a remote operator to control and monitor rolling stock, interact with other remote agents, and maintain safety even in the face of operator errors, environmental challenges, or technical malfunctions [12].

Achieving automated functions in an urban public street setting presents challenges, including the need for organizational restructuring and addressing safety, technology, and communication concerns [13,14]. Also, while automation may reduce crew sizes, human staff may still be crucial for handling complex situations [15]. While preparing for higher levels of automation, misunderstanding the evolving role of different staff categories is a potential problem [16,17]. Organizations face further complexities as they undergo structural and cultural changes to integrate new technologies [8]. In the case of RTC, challenges include increased monotony for drivers, higher cognitive workload due to excessive information, and altered collaboration dynamics when working with machine agents [10,18,19].

Despite growing interest in RTC and ATO use cases, empirical case studies evaluating the expected benefits and challenges of these technologies in an urban public street context remain scarce. Most automation implementations occur in closed environments like metro systems, while research on ATO and RTC deployment in urban public street situations is

particularly limited. On that matter, Yin et al. [20] pointed out that future research in the domain should investigate the implementation of ATO in mainline railways, while Singh et al. [8] suggest that developing a cost–benefit model associated with ATO deployment will aid stakeholders make informed decisions regarding ATO projects. Gadmer et al. [10] also highlighted that human-centered approaches and methodologies for crafting assistance and collaboration within the domain of ATO and RTC are lacking in scientific research. Wang et al. [21] proposed to close the gap between theoretical research and actual implementation of automated transport, which this paper aims to do.

1.2. Aim and Research Contribution

The purpose of this research is to bridge the gap between theory and practice by exploring the benefits and challenges of implementing RTC and ATO in an urban public street environment (tramway) through a practical case study. By uncovering practical insights, this study aims to enhance the understanding of the potential barriers to adopting these technologies while highlighting their projected advantages. The findings provide guidance for overcoming implementation obstacles and maximizing the positives impact of RTC and ATO. This paper addresses the following research question: *What expected challenges can slow the realization of the anticipated benefits associated with the introduction of RTC and ATO in a Tramway system?*

The selection of RTC and ATO technologies is grounded in their relevance to addressing specific operational challenges in urban tramway systems. RTC enables precise remote control and monitoring of train operations, ensuring improved safety and operational efficiency, while ATO supports automation to enhance system reliability and performance. Together, these technologies are essential building blocks for advancing tramway automation in mixed-traffic environments.

This paper is organized as follows: Section 2 reviews the existing literature on digitalization in the railway industry, with a focus on identifying the key enablers and barriers to implementing digital technologies within the sector. This section also examines the benefits and challenges associated with RTC and ATO as highlighted in current research. Section 3 outlines the methodology employed in this study. Section 4 presents the findings. Sections 5 and 6 are dedicated to discussing these findings and drawing conclusions, respectively, summarizing the implications of the research and suggesting directions for future work.

2. Literature Review

This section will introduce literature on railway digitalization, followed by an overview of the studies assessing benefits and challenges of both RTC and ATO. The section will be concluded by an overview of the identified research gap.

2.1. Digitalization in the Railways

The environment, stakeholders, and organizational processes all play a central role in digitalizing the railway sector [22], thus reinforcing the relevance of analyzing digitalization in the railways as part of a sociotechnical system [23]. In this diverse stakeholder environment, due to the required expertise and preparedness of personnel, managerial factors have been identified as significant barriers to the adoption of digital technologies in the railway sector [24–26]. These barriers are related to the adoption and advancement of digital technologies that are reshaping work in organizations across areas from customer engagement to supply chain considerations. Notably, enhanced data accessibility enables more efficient use of rolling stock, with increasing integration of systems and subsystems across infrastructure, machinery, and vehicles. This interconnection turns the rolling stock

into a source of valuable insights on infrastructure status, while the infrastructure itself is equipped to monitor and diagnose the condition of the trains [27]. Data-driven operations are therefore raising new challenges such as an increased demand for digital literacy in railway organizations and developing the right technological infrastructure to capture and make use of the data [28]. These novel challenges can potentially limit or prevent the realization of the anticipated benefits of using digital technologies. Consequently, to reduce the impact of these challenges, railway organizations should map the expected benefits and their respective challenges.

2.2. Benefits and Challenges of Remote Train Control

RTC is recommended as a first step for the successful deployment of automated functions in an urban public street setting [12]. RTC allows a remote operator to monitor and manage rolling stock, interact with other remote agents, and maintain safety, even in the face of operator errors, environmental challenges, or technical problems [12]. Remote driving is also important in situations wherein it becomes necessary to assume control over an automated train, especially following a malfunction in ATO systems. Achieving RTC can therefore be seen as a requirement before ATO can be safely and fully implemented in an urban public street environment [29]. As outlined by Alsaba et al. [30], RTC currently has three main areas of application: (1) coordinating activities in the “last mile” between yards and client sites, reducing extended transport times and driver idle time; (2) managing technical routes between maintenance centers and stations to keep the infrastructure running smoothly; and (3) overseeing the recovery and retrieval of automated trains, whether operational or facing technical issues.

However, the introduction of RTC in railways comes with several challenges. Notably, it can exacerbate the monotony of train driving and negatively impact attention levels [18]. It also increases cognitive demands on operators due to the heavy reliance on information and visual data [10]. Collaboration between team members also shifts significantly when machines are integrated into the process, with the remote operator—physically distant from the train—facing challenges in gathering environmental information and making real-time decisions. Instead, they rely on an advisory system to collect, analyze, and provide predictive data about the driving process, which informs their actions [19]. This setup creates obstacles, including delays in signal recognition caused by system latency and engine response times, complicating data interpretation [31].

When implementing RTC, organizations must define clear protocols for determining when and how the authority for train control is transferred between different parties. This transition is a gradual process that involves thorough discussions with multiple stakeholders [10]. For example, in unexpected situations like evacuations, a driver may still need to perform physical tasks. The driver is then required to coordinate closely with traffic control to devise the most effective plan and transmit it clearly to passengers [15].

2.3. Benefits and Challenges of Automatic Train Operation

Introducing automated functions in an urban public street context is undertaken with the aim of capturing various anticipated benefits that range from improving passenger experience [32] to reducing energy consumption [33]. Both these benefits can be potentially attained by the envisaged reduction in the variability of driving patterns [32,34,35], which allows for smoother travels where sudden movements are considerably minimized [33] and consequently limits energy spending [34]. In terms of socioeconomic value, the introduction of ATO can significantly contribute to user convenience by addressing issues such as traffic and punctuality, both of which are critical factors in enhancing the overall passenger experience [13,20]. Punctuality is indeed projected to be improved with the deployment

of ATO [13,20]. Moreover, by reducing traffic and ensuring more reliable schedules, ATO systems can offer substantial socioeconomic benefits, leading to greater public satisfaction and increased usage of public transportation systems [32]. Other expected benefits of ATO include the potential optimization of operational efficiency through a better use of human resources and rolling stock, thus theoretically reducing cost [13,36,37]. Safety improvements are foreseen, since automation can reduce errors caused by human factors, such as distractions or fatigue [32,38,39].

ATO and RTC implementations are likely to be combined with several emerging technologies. Work is ongoing on using digital twin technology to support positioning support for ATO, and to some extent RTC [5,6,40]. Positioning using digital twin has advantages compared to GPS-based positioning, especially where satellite signal is difficult to obtain, such as in tunnels, but also for redundancy in general.

Nonetheless, attaining the desired levels of autonomy in an urban public street setting is met with several challenges, including both legal and technical hurdles [41]. From a legal perspective, the presence of pedestrians, cyclists, and motorists in the proximity of railway tracks underscores the imperative to establish suitable frameworks for ascertaining legal responsibilities in the event of accidents [42]. From a technical perspective, Powell et al. [13] showed that infrastructure enhancements could be necessary to accommodate the deployment of ATO.

Also, while the implementation of automated systems has the potential to reduce the size of the crew required for train operation, it has been recognized that human drivers play an indispensable role in train operations [16]. Their expertise extends beyond driving skills to encompass anticipatory abilities and the capacity to interpret complex situations. Misunderstandings regarding the evolving roles of drivers during the transition to automated operations can lead to safety and service quality issues [17]. The prospect of job displacement stemming from the deployment of automated trains also raises concerns about potential labor strikes by railroad unions. Managerial and organizational challenges when transitioning to RTC and ATO have been identified as underexplored in the academic literature [43].

2.4. Research Gap

The last section showed that the realization of the potential benefits of introducing RTC or ATO could be slowed by several challenges. The literature showed that anticipated benefits fall under three main categories: (1) productivity, (2) safety, and (3) sustainably, while the potential challenges also fall under three main categories: (1) legal, (2) technical, and (3) organizational. Despite these findings, much of the current research is based on theoretical models or simulation studies, with only a limited amount of empirical evidence stemming from real-world deployments. This highlights a gap in practical and theoretical research, emphasizing the need for studies focused on the actual implementation of RTC or ATO in an urban public street environment. The majority of ATO-related studies center on metro systems, leaving automation in mixed-traffic railways operating in an urban public street context, such as tramways, mostly unexplored.

The aim of this research is to bridge this gap by examining a practical case: the automation of a city tram network. This paper seeks to identify and map the expected challenges and anticipated benefits, ultimately offering a framework that can inform and guide future railway automation initiatives in an urban public street environment. By providing concrete insights, this research aims to address the current deficit in empirical literature. The research question guiding this study is as follows: *What expected challenges can slow the realization of the anticipated benefits associated with the introduction of RTC and ATO in a tramway?* To address this question, the research will first examine the challenges experienced by key stakeholders in implementing RTC and ATO, and

then explore the anticipated benefits of these technologies as perceived by them. The methodology adopted for achieving these objectives is detailed in the following section.

3. Methodology

This research is driven by the need to gain empirical insights into the projected challenges and anticipated benefits of implementing RTC and ATO in an urban public street environment. This study adopts a multi-stakeholder perspective to capture the diverse expectations, concerns, and perceived advantages associated with these technologies. By mapping these expectations from various stakeholder groups, this research aims to establish a foundational understanding that can guide future decision-making. This mapping will serve as a reference point for identifying knowledge gaps and acquiring further empirical and quantitative evidence to support informed policy development, technological adaptation, and strategic planning.

The grounded theory method, involving a single exploratory case study based on semi-structured interviews, was employed. It allows researchers to familiarize themselves with the context of the research [44] and case studies are particularly relevant when scarce information surrounds the phenomenon under study [45], i.e., deployment of RTC and ATO in an urban public street context. Employing grounded theory ensures that the evidence generated is rooted in the specific context of the case study, thus avoiding overly generalized conclusions [46].

The authors recognize that semi-structured interviews are inherently subject to biases from both interviewers and interviewees. To mitigate these limitations and enhance the reliability of the findings, this study includes 44 interviews spanning more than a dozen different roles across multiple organizations. This broad scope ensures the representation of various hierarchical levels and perspectives, allowing for a more nuanced and multidimensional understanding of the case under study. Thus, counteracting individual biases and providing a holistic depiction of the case [47,48].

3.1. Case Description

The criteria for the field selection were to identify an organization actively engaged in deploying RTC and ATO in an urban public street context within its operation. This case was made available by a public transport operator in a major European city which is currently introducing RTC and ATO in its tramway operations through interorganizational project-based activities with the supplier of the technology.

The publicly owned operator is responsible for operating and maintaining the public transportation system in the city. It has more than 3000 employees and transports around 220 million passengers each year across its network of trams, metro, and buses, with 52 million of those in the tramways. The operator is currently investigating the use of new technologies in tramway operation, which includes the implementation of RTC and then of ATO. By 2030, it aims to offer 100 million tram journeys. To do so, it has invested to acquire new tramways which are suitable for adding RTC and ATO components.

The project started in 2015 with the investment decision, which was followed by the prequalification of suppliers in 2016. Negotiations and officialization of contracts occurred in 2017–2018. The delivery and commissioning of new trams began in 2020, until mid 2025. Further tests are being carried out until 2026 with the supplier to explore how automated and semi-automated technology can best support passenger and drivers in the tramway experience. The project's goal is to create scalable automation that gives the opportunity to choose which tramway functions are to be automated or not, resulting in more efficient and punctual tramway operation. Testing is conducted inside a closed area and not yet out in traffic. The results of testing will determine which functions should be automated in

the depots and other closed area, before continuing with testing in the traffic. They plan to begin with RTC in closed environments like depots, where they will gather data and introduce GoA4 later on. Simultaneously, city-operated tramways are being equipped with sensors and cameras to collect data, enabling the implementation of certain automated functions at GoA2. Safety issues are a part of the project, including finding appropriate GoA levels depending of the type of traffic context and technological development, and possibly other issues such as regulations, public impression of safety, and automation.

The supplier of the tramway is a private multinational specialized in designing, manufacturing, and supplying railway vehicles and systems, including project management, system integration, and maintenance. During the testing of this project, the supplier is capturing high quality data and providing real-time information for the operator. It prepares a dataset for future use cases, which includes safety, predictive maintenance, passenger counting, energy consumption, and various automated or remotely control functions that have been developed in coordination with the operator. This project-based company is collaborating with the tramway operator to deploy RTC in the depots by May 2026 and ATO functions subsequently.

The case study is conducted in what can be described as a large city (between 2500,000 and 1 million). Using the terminology by Saidi et al. [49], the layout of the city in question can be described as having a circular core with radial connections out of the city.

3.2. Data Collection

Data collection occurred in two stages: the first stage in February 2024 with 25 semi-structured interviews with stakeholders working for the operator and the second stage in June 2024 with 19 interviews with stakeholders working for the supplier, for a total of 44 semi-structured interviews. Interviewees were approached by e-mail and most interviews were conducted in person, while some of them were conducted using the Microsoft Teams platform. The composition of the respondent pool was deliberately designed to ensure a diversity of perspectives, including technical experts, operations staff (e.g., drivers, controllers), and managerial roles (e.g., project leads, financial officers, and executives). While technical departments were more represented due to the nature of the project, efforts were made to include operational and strategic viewpoints, thus ensuring a balanced dataset. The participants' profiles are detailed in Table 1.

The interview guide was composed of 14 open questions to collect rich data while maintaining the flexibility necessary for exploratory research. Interviews lasted an average of 40 min. The interview guide explored participants' expected impact of RTC and ATO on their roles, and their perceptions on the benefits and challenges of using these technologies. Emphasis was placed on identifying potential advantages for the tramway system, as well as technical, operational, and managerial challenges, along with strategies to address stakeholder concerns, ensure smooth implementation, and foster acceptance. Selection for the interviewees was based on typical case sampling, to ensure that participants represented various groups and perspectives [50,51]. To mitigate potential bias from unequal representation across stakeholder groups, several measures were implemented during the selection of respondents and the analysis of their input. The data analysis process carefully considered respondents' organizational roles, enabling themes to be assessed and compared based on the interviewee's position. For instance, concerns from drivers, such as job security and safety, were contrasted with the efficiency and productivity-focused priorities of managers, allowing for the identification of both converging and diverging perspectives. Stakeholders were strategically selected to ensure a broad and balanced representation of experienced and influential voices within the industry, following best practices outlined by Forsythe et al. [52]. This selection provided diverse and experienced

opinions on the project [52]. The stakeholders were selected to ensure that the collected data represent broad, experienced, and influential opinions within the industry and specific efforts were made to balance the respondent pool by targeting underrepresented groups and avoiding overrepresentation of certain categories, ensuring the findings reflect diverse and well-rounded stakeholder perspectives [52]. The chosen professionals meet specific selection criteria relevant to the case under study [53], namely:

1. **Direct Involvement**—The individual must have hands-on experience or decision-making authority in tramway operations, automation, or policy development.
2. **Relevant Expertise**—The individual should possess technical, managerial, or operational knowledge relevant to RTC, ATO, and tramway systems.
3. **Experience Level**—A balance between senior experts and junior professionals to capture both strategic insights and day-to-day operational challenges.
4. **Role Diversity**—Ensuring representation across different hierarchical levels, from front-line workers to executives.
5. **Willingness to Participate**—The interviewees must be open to sharing insights and discussing potential challenges and opportunities.

The authors acknowledge that semi-structured interviews are inherently subject to biases and have addressed this through a robust selection and analysis process.

Table 1. Operator and supplier participants' profiles.

Stakeholder category	Operator	
	Responsibility	Level of ATO/RTC maturity
Drivers	Driver	Low
	Driver	Low
	Driver	Low
Senior managers	CEO	Medium
	CFO	Medium
	Safety and technical director	High
	Communication director	Medium
	IE manager	High
	Analyze manager	High
Project team	Technical engineer	High
	Safety manager	High
	RAMS engineer	High
	IT manager	High
	PMO	High
	Communication manager	Low
	Technical engineer	High
Managers	Innovation manager	High
	Department manager	Low
	Operation manager	Medium
	Traffic safety manager	High
	Engineering manager	Medium
	Technical manager	High

Table 1. *Cont.*

External	Transport coordination agency	Low
	Transport coordination agency	Medium
	Transport coordination agency	High
Supplier		
Stakeholder category	Responsability	Level of ATO/RTC maturity
Rolling Stock	Tramway Train Control Engineer	High
	Digitalization Innovation Program Manager	High
	Zero Emissions Innovation Program Manager	High
	Technical Project Managers Coordinator	High
	Tramway Architect Line Manager	Medium
	Tramway Product Line Manager	Medium
	Testing Manager	Medium
	Tramway Train Control Engineer	High
	Autonomous Tram Project Manager	Medium
Signalling	Autonomous Mobility Innovation Program Manager	High
	Main Line Project Manager	High
Research and Development	R&D Software Development	High
	Innovation Strategy	High
	R&D Communication & Cibersecurity manager	High
	R&D Communication & Cibersecurity	Medium
	R&D Modeling and AI	Medium
	Innovation Programs Manager	High
	Innovation Strategy	High
	R&D Communication & Cibersecurity	High

Following Sallnäs, Rogerson, and Santén [54] guidelines, this study adhered to rigorous evaluative standards to ensure the reliability and robustness of the findings [55]. Interviews were recorded, comprehensive notes were documented, and additional insights and clarifications were sought from participants [54]. Preliminary results were presented to both the operator and supplier. This step aimed to establish the validity of the findings by allowing key stakeholders to review and provide feedback on the interpretations. Presenting the findings also offered an opportunity to share recommendations that could guide further development in the project, fostering a collaborative approach to the implementation of the technologies. The data collection process was also systematically documented, detailing all points of contact, their timing, and key methodological decisions [54,56].

3.3. Data Analysis

Data analysis started with importing interviews transcriptions into Nvivo 15 software. NVivo is a software tool developed by QSR International [57] designed for qualitative data analysis, enabling researchers to systematically organize and interpret responses from interviews [58]. By importing qualitative data from external sources, NVivo facilitates the identification of key themes through a structured coding system using nodes—categories that help group and analyze related segments of text [58,59]. These nodes streamline the process of categorizing data, allowing researchers to allocate interview segments to specific themes and explore their interconnections [58,60]. NVivo enhances the applicability of qualitative research by offering an organized framework for data analysis [58,61].

The initial step in the analysis involved applying a combination of theory-driven template codes and inductive codes derived directly from the data [62]. This dual approach ensured a balance between pre-defined categories and emergent themes. Verbatim were first coded to highlight general keywords and trends. Data was thus organized to facilitate further analysis, which was achieved by narrowing the data into more precise themes as the coding progressed [63]. By following Gioia et al. [64] guidelines, data was first categorized into open codes. These open codes were then divided into two first-order categories: Remote Train Control and Automatic Train Operation. Afterwards, benefits and challenges for each of these categories were identified. Second-order categories of benefits (productivity, safety, sustainability) and challenges (legal, organizational, technical) were then developed to further refine the analysis. Additionally, each benefit or challenge category was linked to specific sub-challenges or sub-benefits, enabling a granular understanding of the issues.

As new inductive codes emerged during the analysis, previously coded transcripts were revisited and re-analyzed to ensure consistency with updated themes. A priori codes were treated with flexibility, allowing for modification or elimination when necessary, as dictated by the iterative analytical process [62]. Analyst triangulation was applied [50,54], with all three authors actively engaged in evaluating the data, interpreting the results, and collaboratively discussing the findings and conclusions [54]. Through this iterative and collaborative process, the analysis ensured that all codes—both deductive and inductive—aligned with the evolving insights and adequately represented the perspectives within the dataset. This systematic re-evaluation provided a robust foundation for drawing meaningful conclusions.

4. Results

This section presents the expected challenges and anticipated benefits of implementing Remote Train Control and Automatic Train Operation in an urban public street context, as expressed by professionals interviewed in this research. The findings reflect expert opinions and expectations rather than definitive outcomes, as the project is still ongoing. The goal is to map stakeholder expectations and gather initial evidence that will inform the development of quantifiable performance metrics. Perspectives from both the operator and the supplier are analyzed to identify key similarities and differences. All quotes included are directly sourced from the interviewees.

4.1. Challenges

Challenges for both RTC and ATO are categorized in three levels of challenges: (1) legal, (2) technical, and (3) organizational. From each of these levels, specific challenges are identified from both the operator and the supplier. Quotations, relevant stakeholder, and specific challenges are presented in tables.

4.1.1. RTC Challenges

Both the operator and supplier anticipate legal and regulatory challenges in adopting RTC, as shared by respondents. They expect the certification process to be slow due to strict requirements and the lack of railway-certified components. Professionals from both sides believe that extensive discussions with authorities and rigorous safety demonstrations will be necessary. To address this, the supplier is expected to assist the operator through a specialized department dedicated to securing homologations. Respondents suggest that testing in closed environments could help ensure compliance and build trust with regulators. Detailed data transcripts are presented in Table 2.

Table 2. Remote Train Control legal challenges.

Legal Challenges		
Supplier		
Example of Quotes	Stakeholder	Specific Challenge
<i>“Even if the tram is without passenger, with remote driving, the authorities are asking for a lot of explanation. Lots of administrative work to demonstrate that it’s going to be as safe as when we are operating a tram with drivers inside”</i>	Main line project manager	Obtaining authorization from local authorities to operate remote driving.
<i>“Regarding the homologation of the system for remote driving, all the computational hardware needs to be railway certified. For example, the cameras are industrial cameras, and they are not railway certified, but they currently offer the best resolution and latency.”</i>	Specialist in R&D modelling and AI	Obtaining the certification from railway authorities for equipment that is not specifically made for the railway.
Operator		
Example of Quotes	Stakeholder	Specific Challenge
<i>“Many parts of the equipment and sensors are not certified for the railway industry. It’s always an issue. We are working on it now, and we are in communication with the Ministry of Transport, as we are trying to get a new set of rules for trams.”</i>	Project manager	Obtaining the certification from railway authorities for equipment that is not specifically made for the railway.
<i>“We need to show that the technology is impacting the current licenses to be able to operate on the network. Some new operational measures are taking place, and they are shared with the railway authorities so they can be convinced that what we do is in control.”</i>	RAMS engineer on the project team	Obtaining authorization from local authorities to operate remote driving.

The expected technical challenges of RTC, as identified by respondents, primarily concern communication and connectivity between the tramway and control center to ensure real-time, low-latency image transmission. Specialists warn that delays could undermine trust in the system, while the operator stresses that robust connectivity is a top operational priority. Infrastructure modifications may be needed to address blind spots. Some challenges, like cybersecurity, overlap with ATO but are more pronounced in the latter and will be detailed in that section. Detailed data transcripts are presented in Table 3.

The anticipated organizational challenges, as identified by respondents, are more significant for the operator, as RTC alters internal processes, particularly for drivers. Transitioning to remote operation requires adjustments in training, operational rules, and depot protocols. Digitalizing a long-established system introduces risks, making worker involvement essential. Effective training, communication, and union collaboration are crucial to managing new responsibilities. Similar but more substantial challenges related to ATO will be addressed in the following section. Detailed data transcripts are presented in Table 4.

Table 3. Remote Train Control technical challenges.

Technical Challenges		
Supplier		
Example of Quotes	Stakeholder	Specific Challenge
<i>"We face some issues regarding communication because we are expecting real time communication as if you were in the tram. But the further you are, the bigger latency you will have. If you start having problems with the communication, you will lose trust in the system."</i>	Cybersecurity specialist	Communication and connectivity issues between the tramway and the control center to ensure that image projection is made in real time with no or minimal latency.
<i>"Having low delays is a must. You have to make sure that there is integrity to the signals you are reading."</i>	R&D specialist	Keeping delays to an acceptable threshold is essential to ensure the accuracy of the signals that are being received.
Operator		
Example of Quotes	Stakeholder	Specific Challenge
<i>"Connectivity with the trams is a top priority for us to have smooth operations"</i>	Project manager	Operations are dependent on good connectivity between the tramways and the control center.
<i>"We need to ensure that drivers don't have a blind area around the vehicles or things that the driver can't see. In the future, especially in depots or in particular areas with difficult visibility, this will need to be modified in some way."</i>	Technical engineer on the project team	Certain modifications to the infrastructure might be needed to ensure that the remote driver sees everything around the trams in specific areas.

Table 4. Remote Train Control organizational challenges.

Organizational Challenges		
Supplier		
Example of Quotes	Stakeholder	Specific Challenge
<i>"For us, it is not so different as with other innovation project. We do every innovation project with strong leadership and a plan. For the operator, it should be more of a change, as it will be changing the way that they work. There will be impacts on the workers, the drivers. They will drive differently, then transfer to a control center. So, there will be changes for the people and changes in operational rules."</i>	Innovation strategy manager	Organizational challenges are more pronounced on the operator side, since it directly impacts various stakeholders.
<i>"The operational protocols in the depots have to be updated in order to capture the benefits of the technology, because it will represent a complete change in the way of doing things."</i>	Communication and cyber security specialist	The technology will disrupt operational protocols in the depots, which will require adaptation from the operator.
<i>"The thing about remote driving is that it creates new processes in the organization and there can be difficulties to implement them with the workers unions. So, it should be introduced progressively with the workers and the unions."</i>	Communication and cybersecurity manager	Unions and workers need to be included in the transition process to ensure that they are on board with the new ways of working.
<i>"It is not only about the movement, but also about the quality of the experience for the remote driver. If it feels like the tram does not move or does not react in the same way that it does locally, we will get some difficulties."</i>	Communication and cybersecurity manager	The driving experience for the remote operator must be similar to driving a tramway.

Table 4. Cont.

Organizational Challenges		
Operator		
Example of Quotes	Stakeholder	Specific Challenge
<i>"We are digitalizing a 150-year-old mechanical institution and we've been driving and operating trams the same way for these 150 years, but now we want to remote control them from one place to another without disrupting the whole tram processes in the city."</i>	IT manager of the project team	The digitalization process entails a significant amount of complexity which translates into major changes in how the organization operates.
<i>"We need to start by educating those who works in these areas, because we need to have a new set of rules that includes extra barriers and detection. This must be in place before we can go to everyday use. So, it's a mix of safety barriers, as well as training and comprehension."</i>	Safety manager of the project team	The technology will disrupt operational protocols in the depots, which will require adaptation from the operator.
<i>"I think it's easier when you're in the tram to feel how it's behaving. If you get difficulties driving in snow, for example, you can feel how the tram is working, but you can't when you're sitting in a remote spot."</i>	Tram driver	The driving experience for the remote operator must be similar to driving a tramway.
<i>"The key here is to go together with the union all the way in the project. Keep them happy. Don't stop communicating with them. Have them along all the way."</i>	Senior communication director	Unions and workers need to be included in the transition process to ensure that they are on board with the new ways of working.

4.1.2. Automatic Train Operation Challenges

Both the operator and supplier highlight that, despite the technology being ready, slow legislative adaptation remains a major barrier. The operator expects regulatory approval to be lengthy and uncertain due to authorities' limited understanding of autonomous technology. Moreover, tramways are subjected to both road and rail authorities, consequently amplifying the legal constraints. The supplier echoes this concern, noting the lack of a standardized legal framework for certification. Issues like GDPR compliance and AI ethics further contribute to delays. Legal challenges are also tied to technical safety requirements, and both parties anticipate that regulatory frameworks must evolve for ATO deployment. Detailed data transcripts are presented in Table 5.

Respondents anticipate that challenges related to perception systems and AI will be closely tied to legal considerations. They expect that developing automated tramway systems will face significant technical hurdles, particularly in AI-based perception and cybersecurity. AI's unpredictability complicates safety validation, especially for vision-based systems, as these technologies are non-deterministic and constantly evolving. According to respondents, traditional validation methods may be insufficient for certifying AI safety. Cybersecurity is another key concern, with both operators and suppliers foreseeing risks related to hacking and data breaches. Ensuring system security while protecting passenger safety and privacy will require close collaboration among stakeholders. Detailed data transcripts are presented in Table 6.

Table 5. Automatic Train Operation legal challenges.

Legal Challenges		
Supplier		
Example of Quotes	Stakeholder	Specific Challenge
<i>“There is no legal framework to run autonomous vehicles. We will need to deal with this in the future and we will have to work closely with the authorities to define the milestones, but also regarding Artificial Intelligence and nondeterministic systems, how to validate that they are working properly and according to the regulations.”</i>	Autonomous Tram Project Manager	Defining a legal framework with the relevant authorities is difficult due to the complexity and the opacity of the technologies that are being used.
<i>“I’m thinking about the GDPR. We have issues regarding collecting data from the cameras in the public context. This data will be needed in the perception module for the autonomous movements. So, we need to develop mitigation measures for this issue.”</i>	R&D modeling and AI specialist	The ethical questions of data harvesting to develop the perception systems have not yet been answered and require the involvement of various stakeholders.
<i>“The main challenge will be how you can demonstrate that systems are safe enough to operate without a driver. So, it’s not really the technology per say, it’s more convincing people and showing that it’s safe and that there’s a standard. There is concern about the algorithms that are used that are based in AI.”</i>	Innovation strategy manager	Obtaining the certification for systems based on AI is an arduous process since it requires demonstrating its safety, while there is no standard for that.
Operator		
Example of Quotes	Stakeholder	Specific Challenge
<i>“The railway authorities, when it comes to autonomous technology, they have limited knowledge about this. So, they need to approve something they don’t really know about. Technically speaking, autonomous technology could be introduced almost immediately. It’s the legislation that is behind.”</i>	Project manager	Railway authorities do not have the required knowledge to legislate autonomous technology, which causes the laws to evolve slowly in comparison to the technology.
<i>“My primary concern is about the regulations. That sort of process takes a long time, and we are not quite sure how can we help the politicians and the authorities getting there faster. So that’s kind of a big worry.”</i>	Communication director	Legislative processes are lengthy, and the operator remains uncertain on how they can assist the policymakers and authorities in accelerating the processes.
<i>“I’m worried about the political part because there are laws and regulations that are not modern enough to receive that kind of technology. That might be a bottleneck for us to realize on the deliverables of this project.”</i>	IT manager of the project team	Unsuitable laws can slow down the implementation process and jeopardize the delivery of iterations.

Respondents believe that the operator’s current structure, designed for routine operations, may lack the agility needed for innovation projects like autonomous tramways. They highlight that senior management will need to provide clear direction and embrace change management to align the workforce with new technologies. It is expected that automation will reduce the need for drivers, raising concerns about job security and requiring retraining efforts and union negotiations. Ensuring that employees feel secure and involved in the transition is seen as critical to success. The supplier acknowledges these expected changes for the operator but does not foresee significant organizational shifts on their side. Detailed data transcript are presented in Table 7.

Table 6. Automatic Train Operation technical challenges.

Technical Challenges		
Supplier		
Example of Quotes	Stakeholder	Specific Challenge
<i>"We have to highlight the AI challenge. In this case, we are including something that is not deterministic. This is something that we are installing that you don't know the final conclusion that the system is going to take. It can come to a different conclusion depending on the environment, but that tram is having 200 people on board. It's something that we need to think about and it's a very important technical challenge."</i>	Autonomous tramway project manager	The decisions taken by a non-deterministic AI system are difficult to explain and understand, which can cause some safety concerns and issues.
<i>"Handling a process that is based in artificial vision from a safety point of view is quite different from the safety critical processes that we know. We know well from railway signaling, but these are deterministic solutions, so now its very different. The validation is challenging, proving that a system based on neural networks is safe enough 99.9999% of the time."</i>	Innovation strategy specialist	Validating autonomous systems poses novel challenges, since they are based on neural networks and the margin for error is very low.
<i>With AI, you cannot make a complete validation as the standard ask from. We have to find new way to demonstrate the safety of these kinds of systems. AI and artificial vision are progressing very, very fast and we have to take advantages of these things, but from a safety point of view it's a major challenge."</i>	Autonomous mobility program manager	Certifying the safety of AI and artificial vision remains to be done, which creates uncertainty since the technology is developing fast.
<i>"We have to integrate this with the existing IT infrastructure and share robust cyber security. So, it's not just the integration, but also structuring that sharing responsibilities for cyber security."</i>	Main line project manager	The operator and the supplier need to cooperate regarding cybersecurity concerns, which is a novel challenge in the railways.
Operator		
Example of Quotes	Stakeholder	Specific Challenge
<i>"I expect issues with the complexity of setting up the brain of the tram. The programming of the brain itself, I would expect that to be the most challenging part of the technological side."</i>	Safety and technical director	Developing the neural network for the autonomous system poses a major technological challenge.
<i>"Cyber security is a growing concern. We cannot be behind those who try to do harm. We have to be on the ball, be careful and be sure we're on top of our game. This is how we get the quality and the safety."</i>	Safety manager on the project team	Assuring the security of the network is crucial for the operator, as it needs to be better than the potential infiltrators.
<i>"On the technical side, one of the main problems is if someone get access to the infrastructure, if criminals wanted to make a mess, they could potentially hack into the system and take control of the tram."</i>	IT manager on the project team	Ensuring the security of the network is crucial for the operator, as it needs to be better than the potential infiltrators.

Table 7. Automatic Train Operation organizational challenges.

Organizational Challenges		
Supplier		
Example of Quotes	Stakeholder	Specific Challenge
<i>“For us, I don’t expect a big change in our way or working. It’s on the operator perspective that I think they will face more changes. With a reduction of the number of drivers needed, there could be some cases with the unions.”</i>	R&D specialist	The operator will need to negotiate and discuss with unions regarding workforce displacement resulting from the implementation of autonomous functions.
<i>With autonomous vehicles, the operator will have to change their way of thinking. For instance, how to reorganize the drivers’ responsibilities to focus on other aspects like efficiency?”</i>	Digital innovation program manager	The operator will need to negotiate and discuss with unions regarding workforce displacement resulting from the implementation of autonomous functions.
Operator		
Example of Quotes	Stakeholder	Specific Challenge
<i>“It’s difficult to work within the organization with development projects such as this one. We don’t have the procedures or ways of working that allows us to make fast decisions and this type of project needs fast decisions. The organization is set up for regular operations of vehicles, so we are not used to that.”</i>	Technical engineer on the project team	The organization is used to manage daily operations and needs to adapt in order to deliver a fast-paced project like this one.
<i>“I think its seldom the technology that is the problem, it could be management where the problems are, because you need to continuously solved them.”</i>	Innovation engineer	Managerial considerations are identified as a potential challenge since they continuously arise and thus necessitate continuous change management.
<i>“We need top level management to go in front and be very clear at speaking the directions where the organization is going. It’s quite hard, but I think that’s the way to go. There is no other way.”</i>	Communication director	Strong strategic alignment and leadership is needed from senior management.

4.2. Anticipated Benefits

Anticipated benefits of RTC are divided into two categories: (1) productivity and (2) safety. Benefits of ATO are divided in three categories: (1) productivity, (2) safety, and (3) sustainability. From each of these categories, specific benefits are identified from both the operator and the supplier. Quotations from relevant stakeholders and specific benefits are presented in tables.

4.2.1. Remote Train Control Benefits

Respondents expect that RTC has the potential to enhance productivity by optimizing human resource usage, particularly for drivers, and streamlining operations. They suggest that RTC will allow drivers to complete tasks more efficiently by enabling remote management of functions like train startup and depot movements. It is expected that this remote handling will reduce physical labor, simplify fleet maintenance, and ensure tramways are ready for service upon driver arrival. Both operators and suppliers believe these improvements will lower operational costs by minimizing walking time, shunting logistics, and unnecessary workload. While workforce reduction is not the goal, savings are anticipated through better time management and operational efficiency rather than staff cuts. Detailed data transcripts are presented in Table 8.

Table 8. Remote Train Control productivity benefits.

Productivity		
Supplier		
Example of Quotes	Stakeholder	Specific Benefit
<i>"I think that drivers will be equipped to make more operations in less time. It will be easier for them to handle the daily tasks. If they have a certain number of movements to do, they will do it faster because they don't have to switch from trains to trains."</i>	Specialist in R&D communication and cybersecurity	The switch from drivers to operators will make it possible to use human resources more efficiently, as they will be able to complete more tasks in a shorter amount of time.
<i>It will be very beneficial not to have drivers in the depots to move the trams. In terms of time and availability of the trams, it will be quite easy to move trams from one side to another side of the depot to prepare them to go into service. All the tests and preparations will be done remotely. It's going to be much easier."</i>	Tramway control engineer	Remote control of the tramway ensures a better availability of the fleet, and therefore makes it possible to run more tramways on the tracks. This translates into a better use of the rolling stock.
<i>'For the operator, it will reduce cost, not the actual staff cost, but the cost that can be committed from losing time depot moves or in network protocols that are quite standard."</i>	Specialist in R&D modeling and AI	An increase in productivity translates into cost savings for the operator.
Operator		
Example of Quotes	Stakeholder	Specific Challenge
<i>"In the depots, it's all about optimizing our productivity. We want that when a driver arrives the tram is ready with the report, and he can just start doing the route."</i>	RAMS engineer	By remotely preparing the tramways, the operator optimizes the use of the rolling stock and increases its productivity.
<i>"It will be much easier to handle a tram from on site to off site and vice versa. I think it will take a lot of unnecessary workloads off the personnel; some physical labor will be removed. It will be easier to maintain the fleet"</i>	Driver	The workload of drivers will be reduced by the introduction of RTC, which will allow for a better use of their time on more valuable activities.
<i>"If you don't need logistics personnel for shunting and other depot activities, you can actually cut costs immensely."</i>	Chief Financial Officer	An increase in productivity translates into cost savings for the operator.

Respondents believe that the use of RTC can potentially reduce accidents and enhance safety for both employees and passengers, a key priority for the operator. Many depot accidents result from human errors, which RTC can address by enabling more precise parking and smarter facility use. Outside depots, RTC acts as an assistance tool, providing alerts about nearby obstacles to aid in better situational judgment and collision prevention. The operator notes that RTC assists with maneuvering in tight spaces and poor weather conditions, enhancing overall safety. Additionally, it offers the benefit of operating in safer, more comfortable conditions. ATO is also expected to improve safety, and while these enhancements are similar, they are more pronounced and will be detailed in their respective subsection. Detailed data transcripts are presented in Table 9.

Table 9. Remote Train Control safety benefits.

Safety		
Supplier		
Example of Quotes	Stakeholder	Specific Benefit
<i>“With remote driving, I think the first benefit will be safety, for everybody.”</i>	Autonomous Mobility Innovation Program Manager	The reduction in accidents will be beneficial for the drivers, as well as for the passengers.
Operator		
Example of Quotes	Stakeholder	Specific Benefit
<i>“We will have less accidents in the depots and now we have a lot of them because we don’t have enough space to park properly, but with remote driving we will have more precision, and we can use the facilities in a smarter way.”</i>	Communication director	Remote control of the tramway will result in less accidents for the employees and drivers inside the depots.
<i>“For me, as a driver, I can be somewhere that is actually warm and safe, because driving trams are dangerous.”</i>	Driver	The driving experience will be much better, being safer and more comfortable for the drivers.

4.2.2. Expected Automatic Train Operation Benefits

Respondents foresee that autonomous functions could enhance productivity by optimizing track and vehicle usage, enabling more efficient tram operations. They suggest that the automation of repetitive tasks could free operators for other duties, reducing labor costs and improving efficiency. In controlled environments like depots, autonomous functions are expected to handle certain movements, which could be beneficial given the declining interest in driving roles. While the current focus is on closed areas, it is believed that autonomous systems may eventually surpass human drivers in crowded environments by processing more variables simultaneously. However, fully automated tramways in open spaces remain a long-term goal. In the meantime, respondents suggest that driver advisory systems using sensors and machine learning could enhance situational awareness and assist with navigation. Detailed data transcript are presented in Table 10.

Respondents project that autonomous functions will enhance urban safety by improving hazard detection and emergency response. Perception systems are expected to reduce human-related accidents by preventing attention lapses and ensuring consistent safety standards. By compensating for driver limitations, this technology could act as an additional security layer in mixed traffic conditions. Detailed data transcripts are presented in Table 11.

Respondents believe that autonomous tramway functions can potentially improve sustainability by optimizing acceleration, braking, and energy use. Smoother driving patterns are expected to enhance passenger comfort, punctuality, and reliability, encouraging public transport adoption. Reduced energy consumption and noise pollution align with urban sustainability goals, contributing to a more efficient and livable city. Detailed data transcript are presented in Table 12.

Table 10. Automatic Train Operation productivity benefits.

Productivity		
Supplier		
Example of Quotes	Stakeholder	Specific Benefit
<i>“With autonomous functions you include more vehicles on the same line so that trains can operate closer. So, you are increasing the efficiency of the transport system.”</i>	Head of innovation strategy	The introduction of ATO allows for a better utilization of the rolling stock, therefore optimizing operational productivity.
<i>“I think there are some movements that can be done completely automatically for this use case, because these are places that are completely controlled. So, this could be useful, since we have less people interested in driving the trams, it’s better to put them in places where they actually have to drive and let autonomous driving for the depots and shunting maneuvers.”</i>	Program manager of autonomous mobility innovation	By automizing repetitive movements, drivers are freed from less valuable tasks and can be reallocated to other activities, which enhance productivity.
<i>“With this technology, the operator is going to be more efficient in its operations since autonomous functions will replace some movements that are very repetitive and for them it will be beneficial because they can spend time on another task. It will increase operational efficiency and while reducing labor cost.”</i>	Specialist for R&D modeling and AI	The increase in productivity that is allowed by both the optimization of resources and rolling stock will translate into cost savings for the operator.
Operator		
Example of Quotes	Stakeholder	Specific Benefit
<i>“We would actually be able to improve the availability of our fleet since the technology would be able to work as the best driver in the world.”</i>	Safety and technical director	The introduction of ATO allows for a better utilization of the rolling stock, therefore optimizing operational productivity.
<i>“The trams will be equipped with radars, lidars and separate cameras for the perception systems. They’re going to collect a huge amount of data that we’re going to be put into a cloud solution and do some machine learning so the tram at some point can be kind of more self-aware. I think that we can have driver assistance first, where the tram can identify running pedestrians, bikes scooters or other vehicles and send signals to the driver.”</i>	IT manager on the project team	By combining human capabilities with an advisory system based on machine learning, the driver is better equipped to realize their daily tasks, which translates into a better use of human resources and increased productivity.

Table 11. Automatic Train Operation safety benefits.

Safety		
Supplier		
Example of Quotes	Stakeholder	Specific Benefit
<i>“The safety of the people around the tram is very important. Having a product that can recognize situations and then react with an emergency break or other functions will probably save a lot of lives in an urban context.”</i>	Tramway architect line manager	The perception systems that will be equipped on the tramway will help the driver in situations in which it is usually impossible for a human to react.

Table 11. Cont.

Safety		
Supplier		
Example of Quotes	Stakeholder	Specific Benefit
<i>“We installed a collision detection warning system. So if the driver gets distract for whatever reasons, which causes a lot of accidents, that should be completely solved since the system will act before the driver.”</i>	Innovation program manager	Autonomous functions should considerably reduce or eliminate human-related accidents caused by the drivers.
<i>“The main benefit is having an extra security layer. The perception system that we are installing will be used for warning or helping the driver in situation that are coming so fast that he just cannot see. So this will help driver reduce accidents.</i>	Specialist in R&D communication and cybersecurity	The perception systems that will be equipped on the tramway will help the driver in situations in which it is usually impossible for a human to react.
<i>“It’s very easy to distract a human. If you see a ball for example, maybe you focus on the ball and you don’t see the child that runs across the street. The machine always looks everywhere and has more than two eyes. It’s never tired and when you sit in a driver set for hours its impossible not to be tired.</i>	Tramway control engineer	Autonomous functions should considerably reduce or eliminate human-related accidents caused by the drivers.
Operator		
Example of Quotes	Stakeholder	Specific Benefit
<i>“Often when the tram drives in the city center, it will hit a parked car because it’s not properly parked. Depending on the driver, they might not be able to catch that. The perception system will be able to estimate free space and generate warnings to the drivers, which will prevent a lot of collisions.</i>	RAMS engineer on the project team	The perception systems will reduce the variability in driving patterns that is caused by having different drivers, which will improve safety.
<i>“The autonomous functions will first be there to assist the drivers. The technology will help the driver in situation in which the human eye cannot see. So, I really believe that it will have a positive impact on safety.”</i>	Senior engineer	The perception systems that will be equipped on the tramway will help the driver in situations in which it is usually impossible for a human to react.
<i>“The technology will prevent some of the human errors in traffic. We have a lot of collisions with passing car as we drive all the time in mixed traffic. This means that we will have less damages to the cars, more safety for the passengers, and especially for the people outside of the tram.</i>	Technical engineer	Autonomous functions should considerably reduce or eliminate human-related accidents caused by the drivers or other people.
<i>“I would expect our incident rate conflict with other vehicles and pedestrians would be reduced significantly. Also impacts with parked objects would be reduced significantly.</i>	Safety and technical director	Operations will be much safer due to a reduction in incidents.

Table 12. Automatic Train Operation sustainability benefits.

Sustainability		
Supplier		
Example of Quotes	Stakeholder	Specific Benefit
<i>“Algorithms will be able to uniformize and optimize driving patterns, so it won’t accelerate or break so hard, which will account for a better passenger comfort”.</i>	Head of innovation strategy	By eliminating the variability in driving patterns, the tramway will run smoother, which will result in an improved passenger experience.
<i>“It will enhance the overall quality of the service. We want to have a better service for the cities and for the passengers. We want to make it less noisy, less problematic, less accidents. It fits within our sustainability road map.”</i>	Autonomous tram project manager	Cities will benefit from the autonomous system, as it will improve the quality of life due to a better and more reliable offer of public transport.
<i>“With an autonomous system, we will be able to better adapt to the demand and offer of public transport and it’s going to bring more value for people. It’s going to be beneficial for society as a whole.</i>	Autonomous Mobility Innovation Program Manager	Cities will benefit from the autonomous system, as it will improve the quality of life due to a better and more reliable offer of public transport.
<i>“The operator will definitely see some benefits in terms of energy efficiency, since it can be driven by some algorithms. It will result in less energy consumption and just an overall more energy efficient driving.”</i>	Innovation Program Manager	Energy consumption will be reduced due to autonomous functions, which improves the sustainability of the tramways.
<i>“It will provide a more consistent and dependable service for the passengers.”</i>	Testing manager	By eliminating the variability in driving patterns, tramways will be more punctual and reliable, which improves the service for the passenger.
<i>“By reducing the human factor in driving we ensure that we are improving the times between different stops and making operations more punctual. This is good for passenger perception.”</i>	Tramway product line manager	By eliminating the variability in driving patterns, tramways will be more punctual and reliable, which improves the service for the passenger.
Operator		
Example of Quotes	Stakeholder	Specific Benefit
<i>“By having a more standardized product, we will be able to provide a better experience for passengers, because now some will have smooth travel while other will experience it a bit rough. And with standardized driving we will cut energy consumption by a lot.”</i>	IT manager	By eliminating the variability in driving patterns, the tramway will run smoother, which will result in an improved passenger experience and reduced consumption of energy.
<i>“It will increase our efficiency, both at the stations and give a better flow in traffic. The issue today is some drivers are driving like this and some drivers are driving like that; everybody drives their way. So we could reduce the variation in driving and uniformize the driving patterns, which basically means smoother and better operations.</i>	Data analytics manager	By eliminating the variability in driving patterns, tramways will be more punctual and reliable, which improves the service for the passenger.

Table 12. Cont.

Sustainability		
Operator		
Example of Quotes	Stakeholder	Specific Benefit
<i>“Another issue that we have is energy consumption, which is really dependent on the drivers. So now with autonomous functions we are aiming at reducing the consumption of electricity and power for the trams.”</i>	Project manager on the project team	Energy consumption will be reduced due to autonomous functions, which improves the sustainability of the tramways.
<i>“I think that the autonomous technology will make the city more attractive and more livable. It will create holistic aspects when it comes to tram transportation, because as more trams will be running it enhances the city integration. It creates value from better space usage and more commercial activity”</i>	CFO	Cities will benefit from the autonomous system, as it will improve the quality of life due to a better and more reliable offer of public transport.
<i>“Autonomous trams are going to be better at driving. In a way that reduces energy consumption, but also eliminates various driving style that may be problematic, which can create lower customer experience.”</i>	External	By eliminating the variability in driving patterns, the tramway will run smoother, which will result in an improved passenger experience and reduced consumption of energy.

5. Discussion

This section will first outline the answer to the research question. Then, it will address the theoretical and practical contributions.

5.1. Addressing the Research Question—Expected Challenges That Can Slow the Realization of the Anticipated Benefits Associated with the Introduction of RTC and ATO in a Tramway System

This paper explores the expected challenges that could hinder the realization of the anticipated benefits associated with the introduction of RTC and ATO in an urban public street environment through a tramway case study, highlighting their interdependencies. Figures 1 and 2 illustrate the interconnected challenges and benefits of implementing RTC and ATO in an urban public street environment. Red arrows depict negative influences, showing how challenges hinder operational improvements, while green arrows highlight the positive impacts of addressing these challenges. The figures emphasize the importance of a holistic approach, as the cascading effects of overlapping challenges significantly influence productivity, safety, and sustainability outcomes.

For RTC, the potential organizational challenges are intertwined: (1) retraining human resources and (2) adapting operational protocols in depots. If these issues remain unresolved, they could diminish key benefits, such as reducing drivers' walking time and increasing fleet availability. Disruptions to operational protocols may constrain the operator's ability to remotely prepare trams, thereby undermining expected productivity gains.

Expected legal challenges further amplify these organizational hurdles, underscoring their interconnected nature. Updating depot protocols hinges on obtaining the necessary authorization for RTC operations, linking legal and organizational constraints. Securing certification for non-railway usage directly affects the operator's capacity to transition drivers to a remote-control center, which limits both productivity and safety improvements. These legal considerations ultimately impede the realization of benefits across multiple domains.

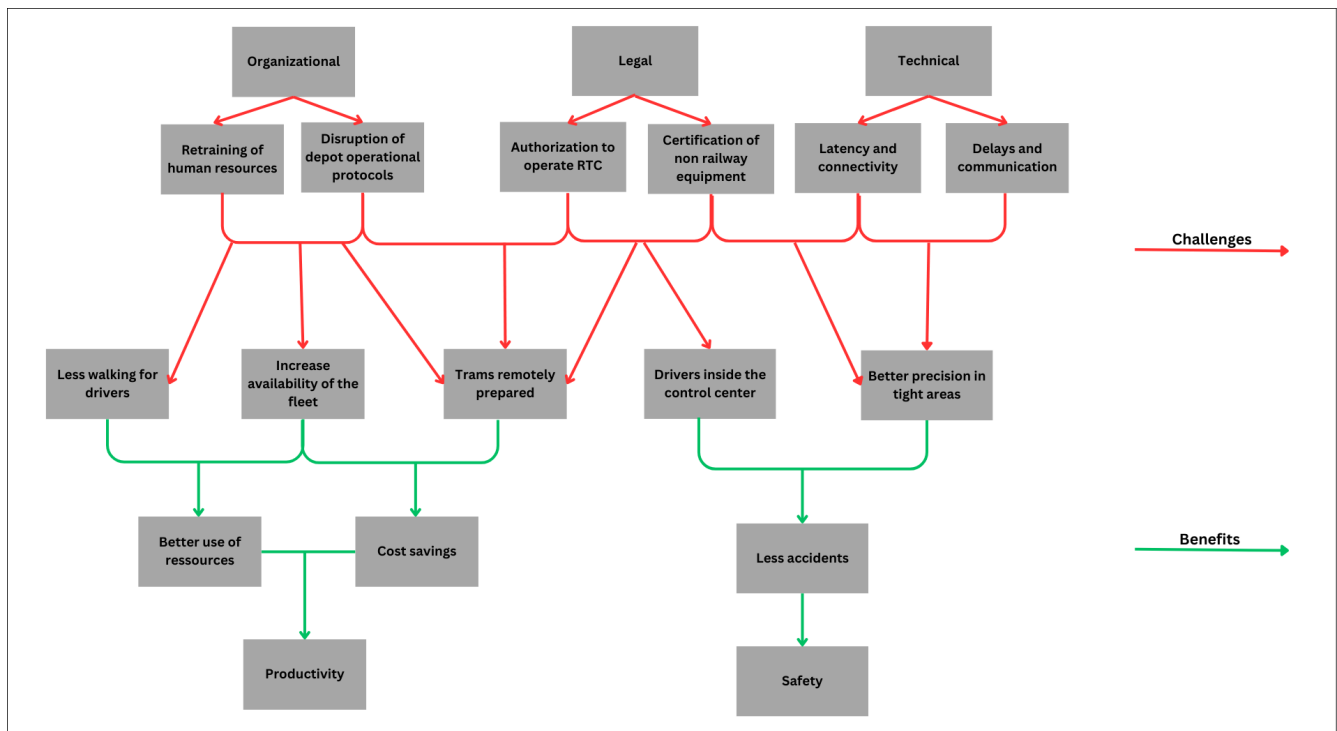


Figure 1. Illustration of possible relation between challenges and benefits for Remote Train Control.

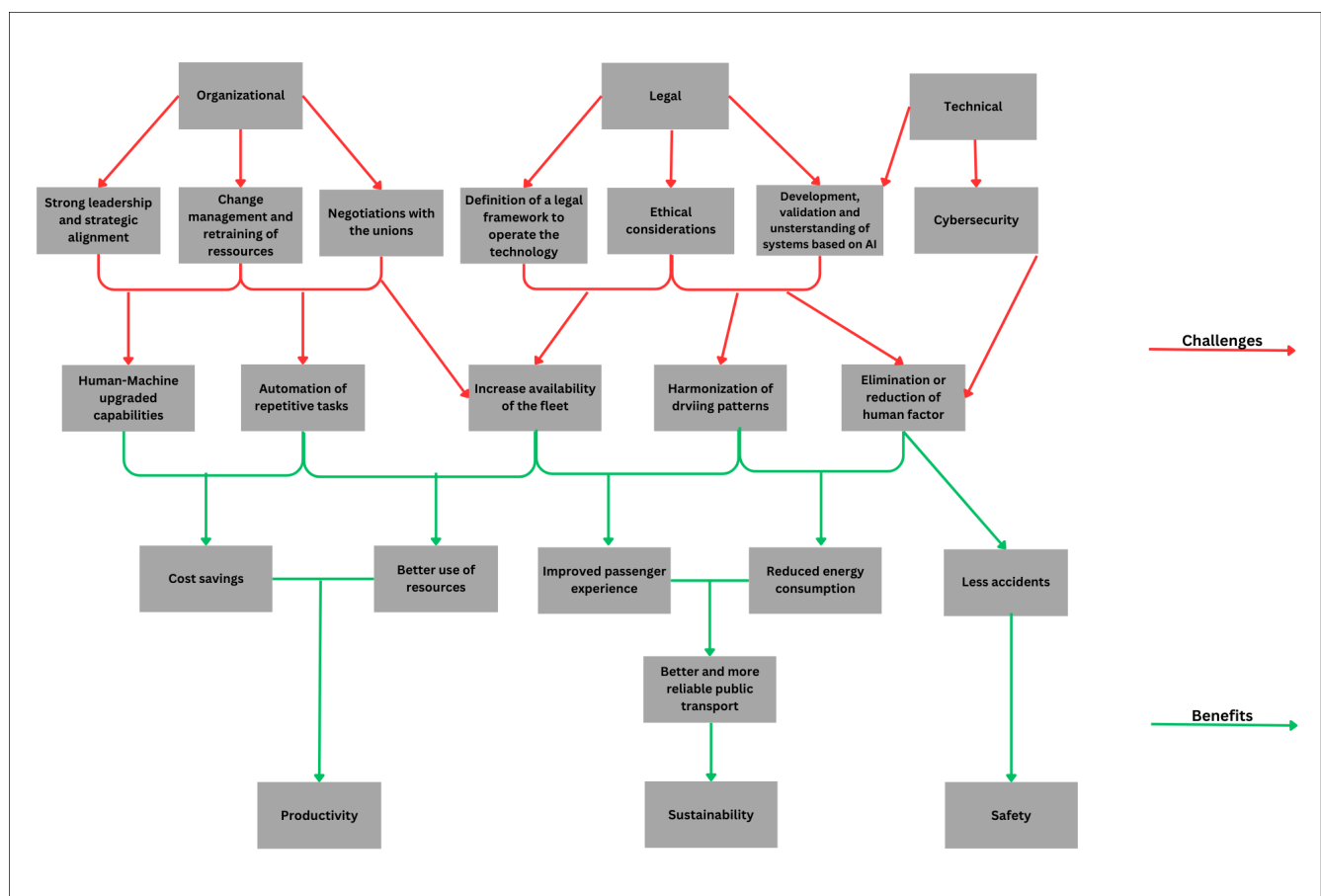


Figure 2. Illustration of possible relation between challenges and benefits of Automatic Train Operation.

Technical challenges, such as latency and connectivity issues with the tramways, compound these difficulties. These problems can undermine the anticipated precision in tighter operational areas, which is necessary for safety gains. As shown in Figure 1, the intricate relationships among these organizational, legal, and technical challenges impacts productivity and safety.

For ATO, the projected organizational challenges are threefold: (1) the need for strong leadership and strategic alignment, (2) change management and retraining of resources, and (3) acceptance of employees and employee representatives. These challenges are interconnected and collectively slow the integration of human–machine interfaces and the automation of repetitive tasks, reducing potential productivity gains. This slowdown also limits the reduction in accidents, thereby undermining safety improvements. Additionally, challenges related to union negotiations and resource retraining constrain the operator’s ability to enhance fleet availability, which negatively affects the passenger experience. As a result, organizational challenges impede productivity, sustainability, and safety benefits.

The foreseen legal challenges introduce further complexity, as they are linked with organizational and technical concerns. These include the following: (1) establishing a legal framework for operating the technology, (2) addressing ethical considerations for data collection and analysis, and (3) developing, validating, and understanding AI-based systems. Without a robust legal framework, the operator cannot fully utilize the technology in urban public street areas, hindering fleet availability and harmonization of driving patterns. Ethical constraints on data usage limit opportunities for both the supplier and operator to advance the technology, while challenges in creating effective AI-based perception systems hinder the ability to reduce human error. These legal barriers thus impact productivity, sustainability, and safety gains.

The envisioned technical challenges, such as validating and understanding AI-driven systems, are inherently tied to legal constraints. Cybersecurity further complicates these technical hurdles, presenting safety risks that ripple across operational and legal domains. As illustrated in Figure 2, the interconnected nature of these challenges affects the realization of productivity, sustainability, and safety benefits.

Figures 1 and 2 illustrate the interconnected nature of the expected challenges and anticipated benefits associated with the implementation of RTC and ATO in an urban public street environment. The three challenge categories—organizational, legal, and technical—each influences various aspects of implementation. Red arrows indicate negative influences, showing how challenges can create obstacles in achieving operational improvements, while green arrows represent positive impacts, highlighting the benefits that emerge as these challenges are addressed.

For instance, organizational challenges such as leadership alignment, change management, and union negotiations are necessary steps to enable human–machine collaboration and automation of repetitive tasks. These, in turn, lead to cost savings, better resource utilization, and ultimately, greater productivity. Similarly, legal and ethical considerations, along with defining an appropriate regulatory framework, affect the availability of fleets and harmonization of driving patterns, which can contribute to improved passenger experience, sustainability, and safety. On the technical side, overcoming challenges related to cybersecurity and AI system validation is critical to reducing reliance on human operators, potentially leading to fewer accidents and enhanced system reliability.

In summary, the interconnectedness of challenges and benefits emphasizes the need for a holistic approach when deploying the technologies. Addressing these challenges in isolation could overlook their broader implications on the system, while a comprehensive perspective ensures that potential benefits are maximized through strategic management of the obstacles. Indeed, the overlapping challenges create cascading effects, collectively

limiting the ability to achieve the intended productivity, safety, and sustainability improvements. The theoretical and practical implications of these findings will be discussed in the next subsections, while Table 13 summarizes the answer to the research question.

Table 13. Summary of findings.

Challenges		
Organizational	Legal	Technical
Strong leadership and strategic alignment	Definition of a legal framework	Development of AI systems
Change management and retraining of resources	Ethical considerations	Cybersecurity
Negotiations with unions	Validation of AI systems	Latency and connectivity
Benefits		
Productivity	Sustainability	Safety
Cost saving	Improved passenger experience	Reduced accidents
Better use of resources	Reduced energy consumption	Better precision

5.2. Theoretical Contributions

This paper builds upon established theoretical foundations while contributing to their further development. It provides a concrete example supporting Nemtanu and Marino's [22] assertion that organizational processes are pivotal to the digitalization of the railway sector. Specifically, this study demonstrates how organizational challenges can hinder an operator's ability to fully realize the anticipated benefits, underscoring the importance of addressing these challenges early in the digitalization process. Moreover, it reinforces the understanding of railways as being part of a sociotechnical system [23]. By highlighting how managerial barriers—such as personnel retraining, change management, leadership alignment, and workforce displacement requiring union negotiations—affect the adoption of digital technologies, this research deepens insights provided by earlier studies [24–26].

In the case of RTC, this research validates the three primary areas of application identified by Alsaba et al. [30] while enriching the discussion by detailing specific advantages, such as improved resource utilization and enhanced fleet availability. By leveraging RTC, operators can optimize depot management, enabling a more efficient allocation of both human and rolling stock, which directly contributes to increased productivity. The research also highlights how RTC can enhance operational safety by minimizing the physical presence of drivers in hazardous areas and allowing for remote oversight of tram operations. Unlike much of the existing literature, which predominantly focuses on conceptual research, this study offers novel insights by providing clear, practical examples of RTC use cases. By demonstrating tangible applications and benefits, this research bridges the gap between theory and practice. This study thus provides a more nuanced understanding of RTC's multifaceted benefits, demonstrating its potential to drive significant advancements in productivity, safety, and overall performance within the railway sector.

With regard to the challenges, this paper extends the work of Gadmer et al. [10] by offering evidence that underscores the necessity of redefining operational protocols when implementing RTC. Specifically, it highlights the need for drivers to undergo specialized training to address the issues identified by Anceaux et al. [18], such as adapting to new control systems and responding to unexpected operational scenarios. This research delves

into previously underexplored challenges associated with RTC, particularly legal and technical considerations. These include the establishment of regulatory frameworks for RTC operations, ethical issues surrounding data collection and usage, and technical hurdles like system latency and cybersecurity risks. To the best of the authors' knowledge, these aspects have received limited attention in the academic literature, making this study a valuable contribution to the field.

In the case of ATO, this study provides empirical evidence of its potential wide-ranging benefits in an urban public street setting. While previous studies primarily relied on simulations or conceptual analyses, this research delivers new theoretical contributions grounded in real-world data from a case study. This empirical approach offers practical insights into how ATO operates in actual conditions, bridging the gap between theoretical predictions and practical implementation.

The findings demonstrate that ATO is expected to reduce variability in driving patterns, leading to lower energy consumption and advancing sustainability goals. This research further highlights how the transition to ATO can potentially enhance passenger experience by increasing fleet availability and improving punctuality, as supported by earlier work from Yin et al. [20] and Powell et al. [13]. Additionally, this study illustrates how ATO is projected to optimize resource utilization, leading to increased productivity and cost reductions, building upon insights from Fröidh [36], Powell et al. [13], and Ganesan et al. [37]. The anticipated safety benefits are also emphasized, with ATO reducing the human factor in accidents, aligning with the findings of Fernandez-Rodriguez et al. [32], Fraszczyk et al. [38], and Song et al. [39]. Beyond organizational and technical impacts, the adoption of ATO may also generate broader socioeconomic benefits. These include improved service accessibility, reduced operational costs that can translate into public savings, and enhanced mobility for users—particularly in urban areas where public transport is essential for social inclusion and economic participation. While user acceptance and concerns remain important considerations, this study suggests that ATO has the potential to contribute to a more efficient and sustainable urban mobility system.

Turning to the challenges, this research offers clear evidence of the legal obstacles that operators and suppliers encounter when deploying ATO in an urban public street environment, thereby building on the theoretical foundations established by Gebauer and Pree [41]. It reinforces the critical need for robust legal frameworks to regulate the use of such technologies, aligning with the works of Pattison et al. [42]. From a managerial and organizational perspective, this study provides valuable understanding of challenges related to job displacement and union negotiations, as highlighted in previous research by Karvonen et al. [17] and Brandenburger and Jipp [16]. It sheds light on underexplored issues, such as the necessity for strong leadership and strategic alignment, while emphasizing the pivotal role of effective change management. By addressing these elements, this paper directly responds to calls for further research on these topics, as noted by Morin, Olsson, and Lau [43].

Finally, this study provides a novel perspective on ATO's implementation pathway in urban public street situations. It exemplifies how RTC can serve as a foundation for ATO in this context. While there is no universal model for the relationship between RTC and ATO, the research identifies three possible approaches: (1) RTC acting as a steppingstone toward higher GoA levels; (2) RTC serving as a backup system when ATO is not fully operational; and (3) RTC being deployed in areas without ATO coverage, such as sidings or specific sections of depots.

Following RTC implementation, the transition can progress through assisted driving systems, allowing operators to address early challenges, refine operational procedures, and build confidence in automation before advancing to higher GoA levels. This staged

approach not only minimizes organizational and operational risks but also facilitates the integration of automation technologies into existing infrastructure. By outlining this structured pathway, this study contributes to the theoretical discourse on RTC and ATO, providing a strategic roadmap for their implementation in the railway sector.

5.3. Practical Contributions

Building upon its theoretical contributions, this study provides actionable insights and concrete recommendations for the practical implementation of RTC and ATO in an urban public street setting. It notably sheds light on the necessity of addressing organizational challenges early in the digitalization process. Public transport authorities and operators must prioritize developing comprehensive retraining programs for personnel to build the skills required for handling new technologies effectively. These programs should be tailored to different employee profiles (e.g., drivers, technicians, planners) and include both technical and soft skills components. Implementing robust change management strategies and fostering alignment across leadership levels are necessary to ensure a smooth transition. Practical steps include appointing change champions, conducting readiness assessments, and offering regular internal communications to explain the purpose and progress of the automation process. These measures reduce resistance to change, minimize disruptions, and help foster innovation. This study also underscores the importance of engaging with employees and employee representatives to address concerns about workforce displacement. Transparent and collaborative negotiations can ensure that automation efforts are implemented in a way that supports organizational goals and reinforces public trust in transport automation initiatives. This includes conducting early consultation rounds, offering transition pathways for affected roles, and ensuring social dialogue mechanisms are in place throughout the implementation process.

RTC offers a means to enhance depot management by enabling operators to allocate resources more efficiently and improve fleet availability. Integrating remote control systems can facilitate precise scheduling, streamline maintenance activities, and maximize the utilization of rolling stock. These enhancements lead to increased productivity and cost savings, directly supporting operational efficiency. By minimizing the need for drivers to operate in hazardous physical environments, RTC significantly improves workplace safety, setting a foundation for broader automation initiatives like ATO.

This study also identifies critical legal and technical barriers that must be addressed to fully unlock the anticipated benefits of RTC and ATO in an urban public street environment. Transport regulators and industry stakeholders are encouraged to actively participate in shaping regulatory frameworks that govern the deployment of these technologies. This includes addressing ethical concerns about data collection and usage while ensuring compliance with data protection laws. Recommended actions include establishing national level working groups to develop shared standards, updating legislation to account for automated functions, and conducting legal impact assessments for each deployment phase. In parallel, technical challenges such as system latency and cybersecurity risks demand attention. Operators should adopt industry-standard cybersecurity frameworks to conduct regular vulnerability testing, and implement real-time monitoring systems to ensure data integrity and system reliability. Cybersecurity protocols and advancements in connectivity are essential to maintaining the reliability and safety of automated systems, making these priorities for operators aiming to integrate RTC and ATO technologies.

This paper demonstrates how ATO is expected to contribute to advancing sustainability goals and enhancing the passenger experience. Standardizing driving patterns through automation can reduce energy consumption and operational costs, directly supporting environmental objectives. Simultaneously, ATO is projected to improve fleet punctuality

and availability, which enhances customer satisfaction and encourages ridership. These anticipated benefits highlight ATO's potential to address both operational efficiency and broader societal goals.

A key recommendation from this research is the adoption of a phased approach to automation in an urban public street context. Transport agencies should begin with RTC and ATO in closed areas before deploying assisted driving systems that are scalable to various grades of GoA2. This allows operators to address initial challenges while gradually building confidence in automation. A recommended action plan includes identifying suitable pilot sites, defining KPIs for operational success, involving end users early in testing, and planning for scalable infrastructure upgrades. This incremental approach enables iterative learning, allowing organizations to refine systems and processes before scaling up to full automation. Practical steps include piloting ATO in controlled environments, collecting performance data, and expanding its application based on validated outcomes. This risk-mitigation approach fosters stakeholder confidence and supports the long-term sustainability of automation initiatives.

Finally, this research underscores the importance of viewing RTC as a foundation for ATO in an urban public street setting. By integrating RTC systems into existing infrastructure, operators can lay the groundwork for advanced automation. The preparatory phase of leveraging RTC allows organizations to build experience with novel technologies before transitioning to more complex and automated systems. This gradual integration ensures that the benefits of RTC are fully realized, and the challenges addressed, thus creating a foundation for achieving higher levels of automation in the future.

6. Conclusions

This section will acknowledge the contributions of this research, while examining its limitations to provide a balanced perspective. This paper will conclude by outlining potential directions for future research, identifying areas where further investigation could build upon the findings presented.

6.1. Limitations

This paper showed that potential organizational, legal, and technical challenges can limit the expected benefits of using RTC and ATO in an urban public street context, especially in terms of productivity, safety, and sustainability. By offering these theoretical and practical contributions, this study bridges the gap between academic advancements and real-world applications. It provides operators, suppliers, and policymakers with a comprehensive overview for addressing challenges and harnessing the transformative potential of RTC and ATO in urban public street situations. By doing so, this research lays a foundation for ensuring that the adoption of these technologies is both effective and sustainable, thereby driving progress in the digitalization of the railway sector.

The authors acknowledge that this research has limitations. One constraint lies in the distinct characteristics of each city in terms of rail transport infrastructure, regulatory frameworks, and operational dynamics, which can influence the anticipated challenges and benefits identified in this case study [65]. This study's qualitative approach, while enabling a detailed exploration of stakeholder perspectives, inherently limits the generalizability of the conclusions, as qualitative data is often context-dependent and shaped by subjective interpretations [66]. To address these limitations, the authors recognize the need for robust quantitative metrics and are actively working toward incorporating quantitative evaluations for Figures 1 and 2. These efforts aim to enhance this study's rigor by providing numerical evidence to support the identified challenges and benefits. Further limitation arises from potential response bias among participants [67]. Given that interviewees

were directly involved in the implementation of RTC and ATO, their perspectives may be overly optimistic, emphasizing expected benefits while downplaying potential challenges. Another limitation is this study's primary focus on the perspectives of suppliers and operators, thereby overlooking the viewpoints of infrastructure managers, policymakers, and other key stakeholders who may offer alternative insights or highlight additional expected challenges and anticipated benefits [68].

6.2. Future Research

The limitations of a single case study can be mitigated through future research aimed at broadening its scope and enhancing its generalizability [69]. Given the potential response bias observed in interviews, future studies should incorporate more objective, quantifiable metrics to validate or refute the expected challenges and anticipated benefits of RTC and ATO in an urban public street environment. Expanding the research beyond supplier and operator perspectives to include additional stakeholders would provide a more balanced and comprehensive understanding of the challenges and opportunities associated with these technologies.

Since each city has unique rail transport characteristics, comparative case studies across different urban environments could help identify common patterns and contextual factors influencing implementation outcomes. Investigating advancements in cybersecurity measures, system latency solutions, and AI-driven tools could also offer valuable insights into overcoming technical barriers. By pursuing these research directions, scholars and practitioners can refine the understanding of automated transport in urban public street contexts and contribute to more informed policy and management strategies.

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