Department of Mechanical and Industrial Engineering

TMM4540 - Industrial ICT Engineering Design and Materials, Specialization Project

Latency for Remote Control in ATO a Scope Review

Author:
Einar Thingstad Myhrvold

Student number:
543951

Supervisor:
Nils O.E. Olsson

Date: 16.12.2025

Preface

Information about me and relevant history, about the project and a thank you to Nils and other contributors.

This article was written for the subject TMM4540 - Industrial ICT Engineering Design And Materials, Specialization Project.

I have had no previous experience about ATO. But subject & knowledge from ...Insert subjects... has been used.

Abstract

A short summary of what the paper contains and why I have written about it.

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1 Introduction

The chapter of Introduction will contain text about purpose, research questions and a small bulk about history and the level of digitalisation we have reached right now.

1.1 Purpose

The purpose of this paper is to establish a structured foundation for understanding, measuring, and evaluating latency in remote train operation (RTO) systems. As the railway sector transitions toward higher Grades of Automation (GoA), particularly GoA 3 and GoA 4, remote control becomes an essential operational component. Previous research highlights that RTO is a required for safely deploying and validating autonomous capabilities, as it enables controlled testing and secure intervention when automated functions cannot perform as intended [1]. In this context, RTO functions as a mandatory fallback layer within the ATO architecture, ensuring continuity of safe operation during degraded modes or for unexpected track conditions [2].

A important requirement for such fallback control is the availability of reliable low-latency video transmission. Studies on remote train supervision emphasise that successful human intervention depends heavily on the stability and responsiveness of video streams when the physical control room is replaced by a remote workstation [3]. Industry demonstrations show that remote operation can supports practical tasks such as shunting, depot movements, and vehicle preparation and thereby improving efficiency while maintaining safety [4]. At the same time, the downgraded mode scenarios described in deliveries from Europe's Rail [5] show how responsibility will transition between automated systems and human operators. And it is therefore important to identify the operational limits imposed by latency, uncertainty, and reduced information quality.

An equally important aspect is understanding how latency affects human perception and reaction time. Human-factors research provides insight into how video quality, bitrate, and delay influence a remote operator's ability to detect signals, interpret scene dynamics, and perform corrective actions under time constraints. These findings contribute to defining minimum perceptual requirements for safe fallback operation and support the formulation of latency thresholds for high automation environments [6].

1.1.1 Research Questions

To achieve the purpose of this paper, the research questions listed below was created to help. z

1. RQ1: How is latency evaluated for railway and other industries?
2. RQ2: What parameters influence latency in remote train operation systems?
3. RQ3: How can we test different video streaming protocols and their impact on real-time performance of remote train operation systems?

1.2 Digitalisation in Railway

Railway digitalization has progressed from early computer-assisted signalling and centralized traffic control systems to modern Automatic Train Protection (ATP), ERTMS/ETCS deployments, and integrated traffic management platforms. Recent developments include communication-based train control (CBTC) in metros, ETCS rollout on mainlines, and the integration of predictive maintenance and data analytics tools. Projects such as national ETCS rollouts, the UK East Coast Digital Programme, and research initiatives like ATO-Cargo exemplify a shift from isolated automation pilots to system wide modernization that combines ATO, interoperability standards (TSIs), and remote supervision concepts [7, 8].

The current digitalisation also shapes how future railway operations are organised. Projects across Europe show that automation and improved connectivity all depend on reliable digital systems that support both automated driving and human supervision. Remote control is becoming a standard element in this transition because it allows operators to intervene safely when automated functions cannot handle a situation. It also supports new operational concepts such as remote supervision of rural lines and more efficient traffic management [1]. At the same time, the move toward FRMCS and 5G aims to replace GSM-R and provide the higher bandwidth and lower delay needed for real-time video and control during remote operation [3].

Digitalisation also increases the system's dependency on stable communication and sensor data. Research shows that issues such as reduced bandwidth, sensor faults, or missing information can directly affect whether remote operation is possible, making clear procedures for degraded modes essential [5]. Human factor studies further underline that the quality of digital perception. Especially video streams must be high enough to replace traditional visibility when operators supervise the train remotely [6].

2 Method

2.1 Research Methodology

The following sections detail the methodological approach and structured review process used to address the research questions of this study. This methodology is designed to ensure a robust foundation for the evaluation of latency for remote train operations.

As of a scoping study described by Arksey [9] the process followed the steps of deciding research questions before moving over to idenifying relevant studies. The research questions has been slightly modify to adapt to the information available and what was discover during the reseach fase. All the papers and studies was also selected before charting data, comparing, summarizing and reporting on the results. As altso mentioned in [9], one point of a scope study is to identify research gaps in the existing literature. Which was very useful and ended up being most of the focus for this paper.

This study uses a Mixed Methods approach. Which includes combining two types of information: qualitative (ideas, experiences, and opinions) and quantitative (numbers and statistics). This method is chosen because using both together gives us a complete picture, where relying on only one type of data would not be enough [10].

The study utelizes convergent parallel design for this. Which entails collecting and analyzing the numbers and the opinions at the same time. Then comparering the results from both to see how they fit together and explain our final findings [11]. The results from technical performance testing (quantitative) are thus validated and enriched by the practical feedback received from user trials (qualitative), leading to more actionable conclusions.

2.2 Literature Review Strategy

The literature review was conducted to establish a comprehensive theoretical and evidential basis for the research. The process was guided by the principle of Evidence-Based Standards to ensure methodological rigor and focus [12].

2.2.1 Search Strategy and Databases

A multi-platform search approach was utilized to retrieve a wide array of high-quality sources. The primary databases included:

- Scopus: For retrieving peer-reviewed, high-impact scientific articles.
- Google Scholar: For broader academic and institutional literature.
- *Andre kilder/databaser*

While maintaining a strong reliance on peer-reviewed scientific material, relevant non-academic reports and industry publications were also considered to provide a comprehensive perspective, with all information traced to reliable sources. Espacially theoretical part of the background research has benefitted from non-academic sources.

2.2.2 Inclusion Criteria

To ensure the study is based on the most relevant and current information, specific criteria were applied to filter the search results. Given the rapid pace of technological change, a focus was placed on recent publications. Where modern papers have refrenced to older papers, I have include some as to say and show where certain numbers are comming from and how they have influenced results.

Table 1: Inclusion Criteria for Literature Review

ID	Inclusion Criteria (IC)
IC1	Publication Date: Between 2020-2025
IC2	Language: Written in English
IC3	Document Type: Primarily "Article", "Conference Paper" or "Thesis"

I did not include a spesific keyword criteria because of the exploratory nature of the research questions. Instead, broad search terms were used initially, with relevance determined through title and abstract screening against the inclusion criteria.

2.2.3 Search Queries and Refinement

Initial broad queries were executed and subsequently refined to focus on specific research gaps, such as the intersection of video communication and system latency. For example, Table 2 illustrates a query targeting the core technological elements of the study.

Table 2: Summary of Refined Search Queries.

Search Query	Initial Hits	Filtered Hits
"Remote" "Train operation" OR "Train control"	12 900	5 380
"Automatic" "Train operation" OR "Train control"	17 600	11 900
"Vehicle" "streaming" "protocols" "real-time" "performance"	36 800	17 400
"Ethics" "Remote" Control" "Vehicle"	298 000	34 200
"Cybersecurity" "Remote" "Control" "Vehicle"	42 600	21 600
"Latency awareness" "Remote" "Control"	460	294

For more detailed searches and for finding reports to compare with, the following queries in Table 3 stands for the majority of papers.

Table 3: Summary of Refined Search Queries.

Search Query	Initial Hits	Filtered Hits
"Remote" "Latency" "Operation" OR "Control"	841 000	83 000
"Remote" "Latency" "Operation" OR "Control" "Railway"	11 800	6 580
"Remote" "Latency" "Threshold" "Operation" OR "Control"	245 000	33 700
"Remote" "Latency" "Threshold" "Operation" OR "Control" "Railway"	4 350	2 530

The results of the query clearly show a minor part of the total remote control "community" specialize in railway operation. There is also possible to see a trend showing that it has become increasingly more popular in recent years as around half of the papers are from the last 5 years.

2.3 Supporting Tools

Several digital tools as mentioned below were used for this paper. The main purpose of the usage was to enhance clarity, assisting in latex, and in general increase quality. Spesifics include writing reference list in correct format. Structuring sentences and paragraphs. Checking for typos and grammatical errors.

- OpenAI's ChatGPT: Employed as a helpful resource for LaTeX formatting suggestions, generating structured content (tables and lists), translating between Norwegian and English, and reviewing text for synonyms and restructuring ideas to ensure arguments were effectively communicated.

- Google Gemini: Used for simialar fields as ChatGPT, but also for general proofreading, and refining sentence structure and tone to maintain a high standard of academic writing.
- Visual Studio Code: was used as the main LaTeX editor because of its powerful extensions for LaTeX support, syntax highlighting, and version control integration. *Other tools*

2.4 Validitity

As for finding papers, I have tried different setups and keywords to make sure they give the wanted output. An example is to use just "Train" instead of "Railway" will give alot more results as it will includes all reports talking about training personel or computers. Or if you restrict to "Train Control" the results drop signifaicantly, loosing important papers for this topic. It is difficult to determine if the aspects I have focused on is the best and correct way to compare and find a good solution. However, as I will also discuss in Chapter 5 "Results and Discussion", many of the other vehicle industires have decided to focus on the same aspects.

2.5 Reliability

This report takes a varying span of reports from different industries before trying to compare. By the amount of papers read, and the amount of papers used, I belive to have found a pretty general results in the theme of latency and threshold that any other will be able to duplicate, even with none of the same reports. As this is very broad examination of the topic the general result should be reproducible. For the subject of how we can test and evaluate tools and protocol, other people will be able to come to a different conclusion as it is more personal and decided from spesific prevoius examples.

3 Theory

3.1 ATO

Automatic Train Operation (ATO) describes systems that automate driving tasks normally performed by a human driver. ATO implementation range from assisting the driver with speed guidance, optimized speed profiles and other information to fully unattended operation where starting, cruising, stopping and door control are automatic. The primary goals are improved punctuality, energy efficiency and safe, repeatable performance [13] .*In freight-specific research such as the ATO-Cargo project, ATO is combined with existing train protection systems (for example ETCS Level 2) and a Remote Supervision and Control Centre (RSC) to allow remote human oversight and intervention during degraded operation or faults* [8].

3.2 GoA

The Grade of Automation (GoA) classifies how much of the train operation is automated. Standards such as IEC 62290 and industry reports [14] describe the commonly used levels from GoA 0 to GoA 4. The table below summarises the practical meaning of each level.

GoA	Meaning / operator role
GoA 0	On-sight, manual operation without automatic protection.
GoA 1	Atomatic Train Protection (ATP) Manual driving with assisted protection rutines. Human driver performs traction, braking and door tasks while safety limits are done automatic. That includes track speed, safe routing and safe separation.
GoA 2	Semi-automated (STO). ATO handles start/stop and trajectory control between stations; a driver remains onboard for door operation, obstacle response and degraded mode handling.
GoA 3	Driverless (DTO). No driver needed for normal operation. Staff may be on board for passenger assistance and emergencies. ATO handle operational tasks including avoiding collision with obstacles and persons.
GoA 4	Unattended Train Operation (UTO). Fully automated operation without staff onboard. Remote supervision and controls are required for special incidents.

Table 4: Grades of Automation (GoA), summary based on IEC and industry sources.

Remote Train Operations (RTO), as we will discuss in this paper, is a part of stage GoA 3 as a disruption management handling system and as a safety system for GoA 4 if it were to fail. [6]

GoA also changes and updates regularly because of new technology added that shifts the definition. The figure below is UITP's definition of how GoA is graded.

Grade of Automation	Type of train operation	Setting train in motion	Stopping train	Door closure	Operation in event of disruption
GoA1	ATP* with driver	Driver	Driver	Driver	Driver
GoA2	ATP and ATO* with driver	Automatic	Automatic	Driver	Driver
GoA3	Driverless	Automatic	Automatic	Train attendant	Train attendant
GoA4	UTO	Automatic	Automatic	Automatic	Automatic

**ATP - Automatic Train Protection; ATO - Automatic Train Operation*

Figure 1: UITP's simple definition of GoA

Source: [15]

The formal definitions and required functions per level are described in IEC 62290 and discussed in CBTC Solutions as well as UITP [14–16].

3.3 ERTMS

The European Rail Traffic Management System (ERTMS) is the standardized signalling and control framework developed to improve interoperability, safety, and capacity across European railways. Its introduction replaces diverse national signalling systems with a unified architecture consisting primarily of the European Train Control System (ETCS) and a digital radio communication layer (GSM-R, and in the future FRMCS). According to the European Union Agency for Railways, ERTMS is designed to harmonize train control and supervision across borders while enabling higher automation levels and modern traffic management solutions. [17]

The shift toward ERTMS is the result of decades of signalling evolution from mechanical and relay-based interlocking to computer-based systems. Early interlocking systems (mechanical, relay, and later electronic) require local signal interpretation and fixed block sections, limiting both network capacity and flexibility. [18]

ERTMS is built around ETCS, which operates in multiple "levels" depending on how information is transmitted.

1. **Level 1:** Uses Eurobalises for spot transmission and may coexist with lineside signals.
2. **Level 2:** Adds a continuous data connection via GSM-R to a Radio Block Centre (RBC), removing dependence on optical signals and enabling real-time supervision.
3. **Level 3:** Removes track-based train detection and relies on train integrity confirmation, reducing infrastructure needs.

Norway's national program adopts ERTMS Level 2 across the entire network, using axle counters as train detection and preparing for future migration to Level 3. The system architecture in the Bane NOR program material shows a fully digital backbone connecting interlockings, RBCs, the Traffic Management System (TMS), and onboard ETCS equipment. [19]

3.4 ETCS

The European Train Control System (ETCS) is a signalling and train protection element developed and included in the ERTMS initiative. ETCS provides movement authorities and intermittently or continuously supervises train speed and braking to ensure safe train separation. It replaces or complements national trackside signals by delivering standardized information to onboard equipment, enabling safer and more interoperable cross-border operation [17, 20].

3.4.1 Levels

ETCS is commonly described with levels that express how information is exchanged:

- **Level 0:** Applies to trains equipped for ETCS, but there is no ETCS trackside. Effectivly going back to regular control and legacy signalling.
- **Level STM:** Applies to trains equipped for ETCS, but runs on tracks with national system with ATP. Allowing ETCS to interface for the ATP
- **Level 1:** Spot transmission threw Eurobalises providing intermittent movement authorities and speed control while legacy signalling remain in place.

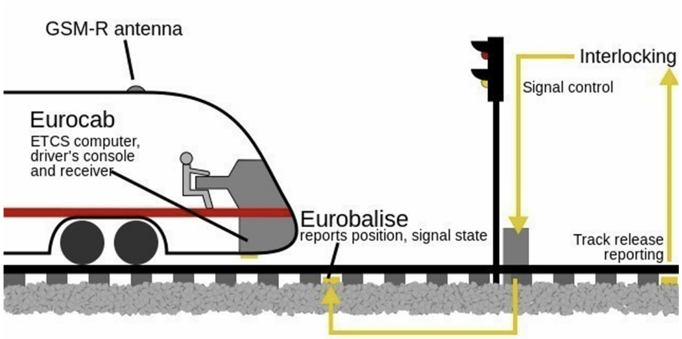

Figure 2: Train following regular signal with assisted speed and position with balises

Source: [20]

- **Level 2:** Continuous radio exchange to Radio Block Centre (RBC), typically via GSM-R or a successor. Movement authority is provided by the RBC. Eurobalises, if used, are primarily for precise positioning. Legacy signalling system are no longer needed and optional.

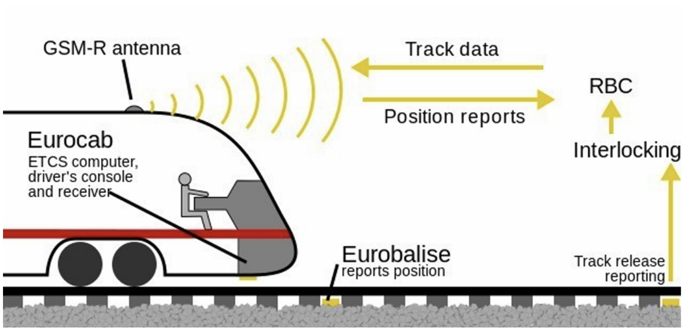

Figure 3: Train operating speed and signal with RBC threw GSM-R signal

Source: [20]

[20].

3.4.2 Modes

ETCS defines different operational modes such as Full Supervision, On-Sight, Staff Responsible, Shunting, and Automatic Driving. Modes determine how the onboard equipment supervises movement authority and interacts with ATO where present. Automatic Driving mode is used when conditions for ATO are satisfied and ETCS provides the required movement and track data while Full Supervision is when ETCS is supplied with all possible train and track data needed [20].

3.5 Cellular communications

A very import part of latency for operating a train remotly will be cellular communication. It is extremly vital to have a stable and good source of communication between the remote operator and the train.

3.5.1 5G URLLC

5G is built up by OFDM, Orthogonal Frequency Division Multiplexing wich divides "Spectrum" into small subcarriers. 5G is designed to support three different service categories, one of which is Ultra-Reliable and Low-Latency Communications (URLLC). URLLC is a communication service characterized by the need to successfully deliver packets with strict requirements in terms of availability, latency, and reliability. This capability is essential for providing connectivity to new services and applications from vertical domains, such as autonomous driving and factory automation. [21, 22]

URLLC could be crucial for supporting emerging applications like wireless control and automation in industrial factory environments. For the specific use case of Remote Control, the required key performance indicators are an end-to-end latency of 5 ms and a reliability of 99.999%. Remote control applications often involve closed-loop control applications, like the use of collaborative robots in a factory, which require URLLC services. [21, 22]

3.5.2 GSM-R

The Global System for Mobile Communications - Railway (GSM-R) serves as the unified radio communication platform for ERTMS, designed to take over from incompatible legacy analog systems with a standardized digital solution. Its operation is crucial for the railway system as it functions as the essential data carrier for ETCS, facilitating the continuous and real-time supervision of the train movement. [23, 24]

GSM-R is built upon the commercial GSM standard, the system operates within a dedicated harmonized frequency band, with 876-880 MHz uplink and 921-925 MHz downlink, and utilizes a linear network of base stations to ensure continuous connectivity for trains traveling at speeds up to 500 km/h. GSM-R employs Time Division Multiple Access (TDMA) to organize radio resources and primarily relies on circuit-switched connections to guarantee dedicated bandwidth for critical transmissions. [23, 24]

3.5.3 FRMCS

FRMCS or Future Railway Mobile Communication System is product of International Union of Railways (UIC) to find a successor for GSM-R as it was getting older. FRMCS is built upon 3GPP standards with 5G URLLC and other more modern techonology. FRMCS is set to replace GSM-R as the unified radio communication for ERTMS and will be a huge part of the future of railway technology.[25, 26]

3GPP Rel-16 define video quality for railway operations. And is already used for setup of remote control by CAF. Mejias mention that the minimum requirments mentioned int the report is of

H.264 codec, 320x240 resolutuion at 10 fps, but a recommended 1920x1080 at 30 FPS [3]. This will evolve as we get closer to acquiring FRMCS in the system used today.

3.5.4 Wi-Fi

Wi-Fi is a wireless communication technology following the standars of IEEE 802.11 that enables data transmission across networks. It operates across specific frequency bands such as 2.4 GHz and 5 GHz and the technology has evolved to support high speed data transfer and robust connectivity through advanced methods like beamforming, which strengthens wireless connections by targeting specific devices rather than broadcasting signals. [27, 28]

In the domain of vehicular control, Wi-Fi functions by establishing Local Area Networks (LAN) that allow for the secure transmission of real-time control commands and audiovisual feeds, demonstrating in some specific single-access point configurations a lower median latency compared to LTE and 5G cellular networks. Although primarily associated with general data networking, the principles of Wi-Fi signal extension are relevant to railway logistics with the concept of relay chains. Wireless networks can employ repeating nodes to extend the operational range of remote monitoring and control systems to trains far away from the operator. [27, 28]

3.6 ERTMS/ATO

Because of the international rollout of ERTMS, ATO will have to follow along. ERA has designed a solution to have an integrated ERTMS/ATO solution as you can see in the figure below. It showcase how ETCS can be independent, but for ATO to be operational it is crucial for ETCS to garantee safety.

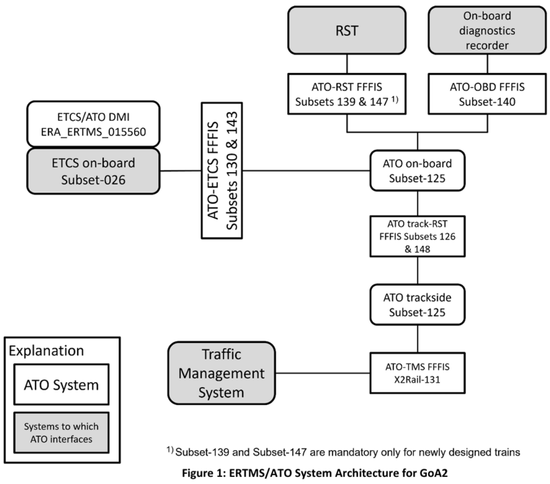

Figure 4: Architecture of ERA's ERTMS/ATO solution

Source: [17]

Showcasing different ATO working togheter with different responsibility and how they communicate with eachoter [17].

3.7 Latency

Latency is the time delay between when a command or data packet is sent and when it is received or acted upon. In railway automation, latency is critical for control loops, including brake initiation following an emergency command, and for ensuring the onboard ATO and remote systems remain synchronized.

The impact of latency, such as excessive one-way delay or variable delay can degrade braking calculations, delay alarm propagation, and reduce the margin available for safe intervention. For real-time safety commands systems are designed with strict latency and reliability budgets and use prioritized and redundant communication channels.

3.7.1 Latency Measurements

There is many ways to measure and structure latency. Some of the most commonly referred to are:

- **Round-Trip Time (RTT):** Refers to the total time it takes for a data packet to travel from the source to the destination and back again to the source. It is commonly used to assess the overall latency of a network connection.
- **One-Way Delay (OWD):** Refers to the time it takes for a data packet to travel from the source to the destination in one direction. This measurement is particularly important for applications requiring real-time responsiveness, such as train control systems.
- **Glass to Glass (G2G):** Refers to the total latency from the moment a signal is generated until the corresponding action is observed. This measurement includes image capture, encoding, transmission, decoding and displaying.
- **End to End (E2E):** E2E can vary depending on papers, but most refers to the total latency from the initial source of a command or data packet to its final destination, including all intermediate processing and transmission steps. This measurement includes G2G as well as operator response time, sending control signals, transmission time and system processing delays.

Following the different structure of latency measurements, there is different protocols and methods to get these measurements. Many have been posted and created through Request for Comments (RFC) which is a series of publications from Internet Engineering Task Force (IETF) and other institutions working on standardization of the web. Many of these RFC's has been backed further by institutions as International Telecommunication Union (ITU) and Institute of Electrical and Electronics Engineers (IEEE). [29, 30].

Table these protocols to match structure above Internet Control Message Protocol (ICMP): With ICMP we can use two effective methods, Ping and Traceback. Both return the Round-Trip Time(RTT) latency but in different ways. Ping sends data packets to a specified destination, and report the time it takes before a the same data packets is received. Traceback also sends data packets waiting for return, but tracks routes and notifies if certain routes use to long time. [31].

Two-Way Active Measurement Protocol (TWAMP) and One-Way Active Measurement Protocol (OWAMP): Protocols designed for measuring one-way and two-way latency, often used in network performance testing. *Needs more depth* [29].

Need more protocols we can use

Test tools. Measurements are typically expressed in milliseconds and include metrics for delay variation and loss.

3.8 Regulations

Check master til Emilia om hva hun found av rules

Railway automation must satisfy national and EU regulatory frameworks. In the EU, the *Technical Specifications for Interoperability* (TSIs) notably the Control-Command and Signalling (CCS) TSI define safety and interoperability requirements for ETCS, ATO interfaces and signalling subsystems. The European Union Agency for Railways (ERA) provides technical guidance, variables coordination and ERTMS documentation [7, 17].

National authorities, for example the Norwegian Railway Directorate and the Norwegian Railway Authority, implement national legislation, issue national safety rules, and specify how EU TSIs map to national processes where operators must demonstrate compliance with both national rules and applicable TSIs for approval and operation [32, 33]. For freight ATO trials (such as ATO-Cargo), project teams must prepare evidence on safety, human factors (remote supervision ergonomics), communication performance and conformity with the CCS TSI and national rules before trials are permitted [7, 8].

From ERA's [17] rules about during ATO operation, it shall be possible to:

1. Supervise train location by monitoring trains automatically using train identification and status (including delay information) to recognise deviations from normal operation as soon as possible;
2. Input the journey profile from the planning system;
3. Start the journey profile;
4. Dynamically modify the journey profile in real time to take account of changes in operating conditions including: disruption management; re-routing; re-timing.
5. Adapt the trail's journey profile to meet any update of the operational timetable;
6. Regulate trains to avoid bunching of trains and to reduce delays to trains in the case of disturbances;
7. Dispatch ATO trains to harmonise the starting of ATO trains, corresponding to results of train regulation and ensuring connecting services;
8. Operate both ATO and non-ATO trains simultaneously;

A way to guarantee these rules are followed and maintained is to implement a safety for when ATO is not working like intended, demanding a downgrade either to manual and physical steering or a option of remote control.

3.8.1 WP41 - Validation Criteria Tramways

WP41 is a collection of test cases and validation criteria for remote driving of tramways. It is delivered by Sporveien Trikken AS with the assistance of CAF, UITP and FP2R2Dato in the Europe's Rail program and contains detailed plan and procedures for testing remote control of tramways. Which includes functionality of electric circuits implemented, TCMS, CERES actions, and safety supervision. Its a standardisation for defining Key Performance indicators and how they should be measured including: Solution QoE (1-5), Image Quality (1-5), Image latency (ms), Availability (Failure rate). Since remote control will come in the light and collaboration with Europe's Rail program. A similar design validation criteria should be expected and produced for railway infrastructure as well, which makes the WP41 a good resource on possible future regulations for RTO. [34]

3.8.2 3GPP TS 22.289

3GPP TS 22.289 is a technical specification report. Done by 3GPP in the works with UIC and European Telecommunications Standards Institute (ETSI), which among other list performance requirements for main lines[25, 35]. These requirements are set to ensure safe and good communications for the future of railway, but as mentioned in the report it is of now only target values.

GoA3 and GoA4 is mentioned with the necessary high level of communications needed for operation. Here they also mention video-based remote control as a part of GoA3/GoA4 and put them in the same category for "Very Critical Video Communication".

Relevant information from table in 3GPP TS 22.289 about requirements for FRMCS can be seen in Table 5

Table 5: Some regulations from 3GPP TS 22.289 Rel-17

Scenario	**End2End Latency**	**Reliability**	**Speed limit**	**Data rate**	**Traffic density**
Very Critical Video Communication	$\leq$ 100 ms	99,9%	500 km/h	10 Mbps up to 20 Mbps	Up to 1 Gbps/km
	$\leq$ 10 ms	99,9%	40 km/h	10 Mbps up to 30 Mbps	Up to 1 Gbps/km

In the table we can see end to end latency being mentioned, and they have defined it as the same as G2G [35] End-to-end latency: the time that takes to transfer a given piece of information unidirectional from a source to a destination, measured at the communication interface, from the moment it is transmitted by the source to the moment it is successfully received at the destination.

The work of 3GPP, TS 22.289, is not yet considered in ERA's TSI CCS and therefore not completely applied. Yet it is still to be expected to be the regulations of future work and something to keep in mind under future development. [7]

4 Related Work

Experiences from other similar fields, remote controlled cars, drones, cranes and other remote controlled railway vehicles. These experiences and papers tests viable aspects for the project of ATO, mainly focusing on the remote controlled

4.1 Railway Control

As showed in Table 3 there is only a handful of papers connected to Railway control compared to the rest. Therefore have I selected a few of the papers discussing latency, ATO and remote control of exactly trains.

4.1.1 ATO-Cargo Project

The ATO-Cargo project, led by the German Aerospace Center (DLR) in cooperation with DB Cargo AG, Digitale Schiene Deutschland (DSD), and ProRail B.V., focuses on developing and testing highly automated technologies for freight trains. The goal is to enhance rail freight efficiency by optimizing speed profiles, improving route utilization, and increasing competitiveness with road transport [8].

A key component of the project is the integration of an Automatic Train Operation (ATO) unit on locomotives in combination with the European Train Control System (ETCS) Level 2. This setup allows for real-time automation while maintaining human oversight. In case of system malfunctions or degraded operation, human operators at a Remote Supervision and Control Centre (RSC) can take over tasks such as remote monitoring, diagnosis, and manual control.

The project also emphasizes human factors engineering, ensuring that the RSC is ergonomically designed for operator efficiency and safety. For this project, researchers have employ virtual reality tools to simulate realistic control room environments and train personnel for future remote supervision tasks. Tests are being conducted on Betuweroute, a freight only railway, linking Rotterdam and the Ruhr region to validate the technical and operational readiness of this automation concept. The ultimate goal is to establish a European reference model for automated freight train operation [8].

4.1.2 Jürgensen 2025

The report by Jürgensen focuses on developing a functional remote control system for autonomous rail vehicles, using the REAKTOR project as the primary use case. Its main purpose is to enable safe human intervention during intermediate automation stages and to act as a fallback solution during fully autonomous GoA 4 operations. The report frames remote control as a crucial safety mechanism, both during prototype development and as an operational safeguard in future autonomous traffic scenarios [1].

The work develops a complete client-server architecture for remote driving, consisting of a Web Client for user interaction, a server coordinating data exchange, and a vehicle-side component interfacing with the autonomous controller. The system enables control over speed, and braking while providing a livestream from onboard cameras. The thesis additionally evaluates the type of cellular network needed for stable operations and includes a case study of network quality along the Malente - Lütjenburg track [1].

Overall, the paper concludes that a remote control system is essential for autonomous rail, but its reliable operation depends heavily on network latency and coverage. Full-scale deployment requires improved cellular infrastructure, ideally 5G, to ensure continuous low-latency transmission [1].

4.1.3 Kozarevic 2025

The report by Kozarevic aims to develop a remote control fallback system for autonomous rail vehicles, with a strong focus on identifying what functionality a remote operator must have in order to safely intervene when autonomy becomes unavailable. The main purpose of the work is to ensure that a human operator can reliably take over control in a downgraded mode. The thesis explores this by narrowing down required features and by analysing user needs, system safety conditions, and operational constraints for future automated railway environments.[2]

The work proceeds by starting from a broad set of functions that a driver normally performs and reducing them to the subset that is strictly necessary for remote operation. The thesis focuses on determining which controls, displays, and sensory feedback elements a remote fallback system must include and evaluates the role of human factors, describing how situational awareness degrades when control is exercised remotely. The thesis ends talking about how remote fallback operation is feasible but requires a carefully reduced function set tailored to remote conditions. [2]

4.1.4 Mejías 2024

The paper by Mejías et al. [3] examines how video streaming can support remote railway driving, focusing on keeping latency low enough for safe operation. The authors compare RTSP and WebRTC in a test setup that imitates an onboard camera system sending video over a 5G network to a remote operator. A key part of the work is a method for measuring true end-to-end latency by embedding timestamps directly into each frame. They also develop a simple adaptive bitrate mechanism that reacts to jitter and packet loss to keep the video usable under degrading network conditions. Tests in two laboratory setups show how latency grows as bandwidth drops and how bitrate adaptation delays freezing and pixelation under poor network conditions.

4.1.5 FP2R2Dato, EuropesRail 2024 D41.2

This deliverable D41.2 from Europe's Rail and FP2R2Dato project presents the testing results and assessments from the first remote driving demo for tramways. Its main purpose is to document how the system behaved during the initial demonstration phase, where auxiliary, static, and dynamic tests were performed on a modified SL18 tram in Oslo. The work focuses on verifying whether the new remote driving and command functions were correctly integrated, safe and aligned with the defined use cases. All tests were done with a structured procedure with reports, and acceptance criteria where each test case was evaluated as compliant or not. The document also includes KPI assessments such as image quality, latency, operator experience, availability, and productivity impact. Overall, the results show that the demonstrator reached the target and that the remote driving solution works reliably across the tested scenarios [4].

4.1.6 FP2R2Dato, EuropesRail 2023 D5.4 - Chapter 12

Chapter 12 in the deliverable D5.4 describes how remote driving should operate when faults occur in the remote control chain. The purpose is to define use cases for degraded remote control conditions, such as poor visibility, weak communication links, sensor failures, or loss of track information. These use cases outline how a remote driver should react and what operational limits apply when the supporting systems no longer provide full information. The chapter does not aim to solve the failures but to describe expected driver actions and system behaviour in each degraded mode [5].

The deliverable also describes allowed latency by comparing it to a previous drone test, where it does calculations of speed and creates a allowed speed limit depending on latency experienced [5].

4.1.7 Brandernburger 2023

Brandenburger et al. [6] present exploratory studies on how video quality affects a remote driver's ability to perceive information and react in time. The purpose of the work is to understand how bitrate, frame rate, and stimulus type influence perception accuracy and reaction speed when supervising trains through video feeds. The authors ran two small-scale studies where participants identified either light signals or distance markers in short video clips of varying quality. Results showed a clear trend: higher bitrate generally improved accuracy and reduced response time, while frame rate showed no meaningful effect. Distance markers were consistently identified faster and more reliably than light signals. Overall, the work provides early evidence that bitrate is the more critical parameter for supporting remote train operation.

4.2 Car Control

Remotely operation of cars has been thoroughly researched as it is one of the most common vehicles in the market. Still, remote operating them bring a lot of challenges and demands which makes it a ever continuing research objective.

4.2.1 Ouden 2022

The paper [36] investigates how remote driving performs over commercial 4G and 5G networks. Its purpose is to evaluate whether current mobile networks can support safe remote control of vehicles at low speeds. The authors design a complete remote driving architecture with vehicles, remote stations, fleet management, and a 5G mobile setup. They test the system both in Hardware in the Loop simulations and in real field trials using straight line braking and slalom manoeuvres. The study measures position accuracy, reaction time effects, and communication latency, comparing 4G and 5G performance. Results show that 5G halves network latency compared to 4G and that overall network performance is sufficient for remote driving below 40 km/h, although total reaction delay is still dominated by video processing and human reaction time rather than the network itself.

4.2.2 Jernberg 2024

Jernberg [37] investigates how latency, driving speed, and task type affect remote operation performance in a controlled simulator environment. The study exposes participants to rural and urban driving scenarios containing several hazards while systematically varying latency between baseline, +100 ms, and +200 ms. The aim is to understand how these factors influence reaction times, safety margins, perceived control, and driving behaviour.

The study measures several quantitative performance indicators such as reaction time from hazard onset to brake input, speed variation across the hazard segment, minimal distance to the hazard object, and post-encroachment time. These measurements are logged automatically in the simulator with fixed measurement windows before and after each hazard event. Hazards and environments are fully balanced so that each participant encounters all combinations of latency, speed, and task. The study also collects subjective ratings between each condition to capture perceived control, workload, and comfort. Comparisons between conditions are performed using mixed-design ANOVAs, allowing the authors to analyse how each factor independently and jointly influences the measurement values.

4.2.3 Kaknjo 2018

Kaknjo et al. [38] present a study on how to measure real-time video latency between a robot and a remote control station. The main purpose is to build a method that reliably captures one-way video delay with higher accuracy than existing tools, especially for applications that require low latency video feedback. The authors design a measurement setup using dedicated NTP servers, synchronized nodes, and software that generates precise visual events. Latency is measured by comparing timestamps from the event generator with the detection time in the received video frames. They test several configurations including web camera scenarios, PPS LED triggering, and network streaming over LAN and the Internet, while separating capture and display delay from pure network transport delay.

Their method enables accurate measurement of both one-way and total video latency in different streaming conditions, providing insights into how camera settings, encoding, and network type influence delay. They show that latency can vary significantly depending on protocol, encoding, and connection type, and that reliable measurement requires tight time synchronization.

4.2.4 Neumeier 2019

Teleoperation: The Holy Grail to Solve Problems of Automated Driving? Sure, but Latency Matters of Neumeier et al. [39], which is a highly cited and used report, investigate how latency affects human performance in teleoperated driving. The purpose of the study is to evaluate how different fixed and varying latency levels influence controllability, workload, and driving behaviour when a human remotely operates a simulated vehicle. The authors implement a static driving simulator with three large displays and inject controlled input and output delays to simulate realistic network conditions. Participants drive several predefined scenarios including following a lane, slalom, parking, and a long track with changing latency while the system continuously logs steering, speed and lane deviation.

Data collection focuses on quantifying behaviour through objective metrics such as Mean Lateral Position, Standard Deviation of Lateral Position, maximum steering angle, speed, and acceleration patterns. Latency conditions are compared using statistical methods to understand how increasing delay changes performance. The study also includes subjective workload measurements and questionnaires. In general, the work shows that higher latency increases workload and negatively impacts control, while smaller delays are easier to compensate for.

4.2.5 Kang 2018

Kang et al. [40] explore how remote control can act as a fallback when a self-driving system encounters situations it cannot interpret. The paper outlines typical failure cases, such as unclear road signs, malfunctioning traffic lights, or confusing construction layouts, and argues that a remote human operator can manage these situations when autonomy fails. Supporting the claim that remote operation is necessary for full automation. To investigate feasibility, the authors build a real-time video streaming test and measure how current LTE and WiFi networks affect frame latency. In the report they vary resolution and bitrate across multiple settings while streaming compressed video from a mobile device to a remote server and back. Measurements include two-way frame delay, frame-loss rate, and how latency scales with frame size. The study provides reference values for achievable streaming performance under real conditions and highlights technical challenges that future remote driving systems must account for.

Going to hold on Sato and Nakamura too see if needed

4.2.6 Sato 2021

Base of 150 ms buffer time of 150, 200, 400. (ignoringing base)

Showing latency imporved performance on every latency The improvement increased as well for higher latency 150 200 400 14-¿3, 8-¿6, 7-¿6

4.2.7 Nakamura 2021

Same as the rest, sim with added latency

4.3 Drone Control

Drones are only remotely operated as it is a unmanned aerial vehicle (UAV) / unmanned aircraft system (UAS). Making research on latency or remote operating extremly relatable to RTO. Even though drones are controlled very differently and operated in a completely different environment, there is much to learn from the research done for remote operation.

4.3.1 González 2023

González et al. [41] study how live video for first person view (FPV) drone control behaves over LTE and WiFi networks. The purpose is to assemble a full test and measure how telemetry, control, and video traffic perform under different connection setups. They build a quad-rotor platform, connect it to LTE through an interface module, and test three schemes: LTE server-based, LTE direct, and WiFi direct. The authors record packet-level data, video quality, and latency to understand how each aspect influences FPV usability. They then define a QoE model combining VMAF video scores with frame-delay measurements, and use controlled packet loss and delay to evaluate how image quality and latency affect operator experience. This provides a structured method for assessing FPV performance in cellular networks.

4.3.2 Larsen 2022

Larsen et al. [42] examine whether a 5G network can support safe drone control when very low latency is required. The report looks at how delay is created as data travels from a drone, through the radio link, into the 5G transport network, and finally to a ground control station. To understand this, the authors break the network into segments and study how distance, number of switches, message size, and link speed each add delay. They then use these factors to calculate how far a drone can realistically fly from the control station while still meeting strict real-time requirements. The work also compares autonomous flight and manual remote control to show how their communication needs are different. In general, the report provides a framework for deciding how strong and fast the network must be, depending on how far drones are expected to operate and how much data they send.

4.3.3 Böhmer 2020

The report done by Böhmer et al. [43] investigate how open communication stacks can be used for remote drone control while still achieving low and predictable latency. The authors build a full test system around the Crazyflie nano-drone by extending it with a Raspberry Pi to enable WiFi communication and by developing a bridge that forwards control messages between the drone and a ground station. They implement two different bridges, one in Python and one in Rust before they analyse how each contributes to overall delay in the control loop. Using detailed timestamp logging and cross-layer analysis, the paper breaks down latency into processing steps on the Raspberry Pi, UART transfer times, and the wireless path. This allows them to compare their open protocol stack with the drone's original proprietary radio link and determine whether the open solution is viable for control tasks.

4.4 Crane Control

Cranes are very different to railway, yet it has it similarities. As cranes are often also operated with joysticks and have certain set of possibilities in motion, it can be compared to trains in the aspect of how humans are effected mentally by remote operation.

4.4.1 Brunnström 2020

Brunnström et al. [44] study how latency affects the user experience when operating a forestry crane in a VR simulator. The goal is to understand how delays in the visual display and in the joystick controls influence task performance and comfort. The authors design three structured user studies where participants load logs in a VR environment using real crane joysticks and a head-mounted display. They systematically add different amounts of delay to the video update and to the joystick signals, and collect both performance metrics such as number of logs handled and subjective ratings of picture quality, responsiveness, comfort, immersion, and overall experience. Simulator Sickness Questionnaire (SSQ) scores are also gathered before and after each session to evaluate discomfort. The work provides a controlled methodology for evaluating latency sensitivity in immersive remote-operation tasks.

5 Results and discussion

Results in 2 parts. 1. part analysis 2. part future steps

5.1 Human factors results

Human performance is a decisive part of remote train operation, because every control action is performed by a human operator who must interpret a video feed, react to system feedback, and compensate for delays. The results in this subsection focus on how operators respond to different levels and types of latency, and how stable versus unstable delay affects their ability to perform remote driving tasks. By comparing findings from railway, car, drone and crane studies, a sense of which latency ranges operators can adapt to, which conditions cause performance loss, and how these observations influence acceptable thresholds for remote train control. These insights form the basis for evaluating how much latency the system can tolerate before performance is affected.

In Table 6 I have sorted some of the previously introduced papers and compared them. Method and added effect show how the research has decided to set up the tests, while task define what the participants had to do. The results were many and varying for each research, but I have extracted a specific number the paper decided represents performance downgrade.

Table 6: Human evaluation of Signal Attributes and Latency

Vehicle	Paper	Published	Method	Added Effect	Task	Slight performance downgrade	Major performance downgrade	Test subjects
Railway	Brandernburger [6]	2023	Sim, Different bitrate and FPS	1, 6, 24 Mbps and 5, 15, 25 FPS	React to light signals / distance marker	6 Mbps	1 Mbps	31 subjects, Novice train drivers, Age 42 SD 19
Car	Ouden 2022 [36]	2022	Sim, Artificial latency	$0, 10 \pm 3$ ms, 20 ± 5 ms and packet loss	Drive slalom and parking	Packet loss at 1%	Packet loss 2%	-
	Jernberg 2024 [37]	2024	Sim, Artificial latency	+100, +200 on base 89 ms	Adapt to Hazards	280 ms for lane bypassing	-	30 subjects, Experience drivers or gamers. Age 35 SD 11
	Neumeier 2019 [39]	2019	Sim, Artificial latency	+100, +300, +500 on base 97 ms	Drive slalom and parking	300 ms	500 ms	28 subjects, Experienced drivers. Age 27 SD 7
Drone	N. González 2023 [41]	2023	IRL, Artificial latency	+25, +50, +100, +200, +300, +500 on base 53 ms and packet loss	Fly drone	0.2% packet loss or 250 ms	0.3% packet loss or 300 ms	-
Crane	Brunnström 2020 [44]	2020	IRL, Artificial latency	+10, +20, +50, +100, +200, +400, +800 on base 80 ms	Offload lumber from truck	480 ms	880 ms	18 subjects, Experienced log lifters and novice, Age 40 SD 9

Its important to include how humans act in different scenarios, as regardless of the systems, the remote operator will always be a constant high latency of at least 500 - 1000 ms [36]. And how they react to a possible system latency will also be crucial for the full remote operation. [6] - Evaluates latency by performance, (human) IRL

Test of human factors and realiable communcations via 5g "Limited literature on:" "Positive effect of bitrate on quaility", "Stalling has worse effect on QoExperience, if bitrate is higher" "Higher frame rate not linked to information assimiliation, but increased user enjoyment"

Tested with three different levels of bitrate 1, 6, 24 Mbps 5, 15, 25 FPS Stimulus Light signal, Distance marker

MeasurementsResponce accuracyResponce speed

Study 1: Higher bitrate -¿ faster answears, more correct Higher FPS -¿ same speed on answear, same amount of correct Study 2: Higher bitrate -¿ same speed on answears, more correct Higher FPS -¿ same speed on answear, same amount of correct

Bitrate is more important (source 5 in PP: https://dl.acm.org/doi/abs/10.1145/2072298.2072351) Stimulus type: Distance marker signs where answeared faster and more correct than light signals 5000 -¿ 3000 speed, and 0.51 -¿ 0.58 and 0.61 -¿ 0.69

This is promosing new with the implementation of ERTMS as the only input stimulus in signalling threw camera and video stream will be signs as the remote control operatior will get the ETCS directly in the control room. After certain bitrate less helpful

[36] - Evaluates Latency by performance, (people) IRL

- Evaluate Latency threshold on SIMulation

- 4G and 5G - 4 times 120 angle camera - H.264 - Split latency up into Control and video and does - min, mean, 95%ile, max latency in ms

- Speed of 10, 20, 30 and 40km/h 100 manual test runs for benchmark 180 runs of RC with 4G 300 runs of RC with 5G One Trip Latency." Every unit was time synchronized with a GPS-PPP source. Packets logged using tcpdump.

Includes a test that results in at 300ms, you get loss of performance, and at 1000ms the delay becomes unfeasible.

Did not find resonable difference in the latencies of straight acceleration test. [39] - Evaluate latency by performance, (people) Sim

- Round-Trip Time (RTT) - Average delay of 67 ms and added conditions of +100 +300 +500 - Was given the ca. latency

Talks about how participent leave the car lane significanlty more with higher latency, even tho with stable high latency. But: "In the Parking scenario, even no differences for whatever latency could be revealed" Scenarios, was driving with turns, and one parking. No hazards except latency. [44] - Evaluate latency on performance, (Humans) Sim

To study QoE. - VR. - 270 angle HMD video threw 4 cameras on crane. Mission is to offload a truck full of logs. Tested with diffrent delays for display and joystick. Baseline was 25 ms for display and 80 ms for joystick. - Display, 5, 10, 20, 30 -¿ 25, 30, 35, 45, 55 - Joystick, 10, 20, 50, 100, 200, 400, 800 -¿ 80, 90, 100, 130, 180, 280, 480, 880

Comfort of the subject was not affected by joystick delay, but the display delayed had an negative effect of Comfort quality. Why this could be discussed alot. Might have to do with VR and a more moving image. 480 ms gave a mild reduction in effect and quality of the work at hand but at 880 it was a major decrease in effect and operatbility.

[37] - Evaluates Latency by performance, (people) Sim

- Voysys - G2G - Average delay of 88.8 ms and added conditions of +100 -¿ 188 ms and +200 -¿

288 ms - 50km/h and 70km/h (Try to keep speedlimits) - driver was not given a latency

+100 and +200 was chosen because of Neumeier result. Reference Neumeier et al. (2019) stated that 300 ms might be manageable for trained operators but in some conditions during their simulator study there were tendencies that even smaller latencies affected the performance of the operator negatively.

That was: H1/P1: Car pulling over into your lane. H2/P2: Car crossing from opposing lane threw your lane. H3/P3: Car with "vikeplikt" does not stop in crossing. H4/P4: Child runs into traffic from behind a bus. H5/P5: Bicycal in lane that driver needs to pass in oppsing lane.

According to Jernberg [37], when performing a study with more naturalistic driving scenarios, speed and type of task is significant for results as well as latency. They also adapt to cerumstances, adjusting speed and safetymargins.

[41] - Evaluation tools for latency, - People tested

URLLC 4K quality res 1080 x 720, at 30 FPS H.264 encoded

LTE server, LTE direct, WiFi -¿ avg packet delay = 500 ms, 42 ms 4 ms Can activate low latency mode. Connection requirments of 100 ms for video streaming, set by 3GPP TS 22.829 for unmanned aerial vehicles Found added latency of around 180 start causing lower MOS / QoE, and steady deteriation making it 1, lowest grade at around 460 ms concludes with a e2e of 250 ms is vaiable for service usability.

[37] "However, it also seems to be the case that remote operators adapt to the circumstances they find themselves in; for example, they drive with a safety margin reducing risks to their personal chosen limit and do not override the barriers of their own choice."

"The reaction time in H1 (a car cutting in into the ego lane) increased more for each latency condition than the offset in time that the manipulation created. This suggests that even an unperceived increase in latency (based on subjective ratings) is affecting the participants in a way that makes them less observant of their surroundings. Combined with a self-reported decline in performance and control as the latency increases, a conclusion could be that the added mental workload is turning the primary driving task into a distraction in itself, by forcing the operator to devote an unusual amount of attention just to maintain speed and lane position."

5.1.1 Adaptation to stable latency.

Jernberg(2024) "Fixed latency seems to be better than varied latency" (Davis et al., 2010, Gnatzig et al., 2013)

Gorsich et al. (2018) found that a higher latency results in more inaccurate behavior, with a drastic decrease starting at a latency of 600 ms, and Gnatzig et al. (2013) found that a constant latency of 500 ms was unproblematic for drivers when the vehicle was steadily kept at 30 km/h on their track. [37]

(Neumier 2019) Could not confirm that fixed latency resultet in any better result than varied latency. Could not confirm "Kang et al" [40] who stated that fixed latency leads to better driving performance than varying. [39]

In the event of offloading a truck with a crane, the participents where exposed to constant levels of latency, and showing that delaly of joystick all the way up to 480 ms was basicly irrelevant for QoE and the results of task done pr time. However a delay of 880 significantly reduced the performance overall by atleast halfing the rating on the scores (1-5). [44]

5.2 Measured Latency for Different Vehicles

Different researchers have approached remote operation with their own measurement methods, system architectures and performance criteria, but the challenges of latency remain comparable. This subsection examines how latency has been measured across trains, cars, drones and cranes, what numerical values these studies reported, and which thresholds they used to classify acceptable and unacceptable delay. By reviewing both the technical measurement approaches, such as synchronized timestamping, G2G and E2E evaluation, the results illustrate how various industries establish practical latency boundaries. This comparison provides a reference point for railway applications, showing how today's measurements are compared to thresholds and discussing how more research on a dedicated railway threshold is still needed.

Table 7 contains the papers inclduing own latency measurments of real test of remote control operation. Which method they use to measure, the threshold they decided to compare it to and where that threshold has its origin.

Table 7: Different Latency Measured and Thresholds used

Vehicle	Paper	Release year	Method	Latency found	Threshold used	Threshold Source
Railway	Jürgensen 2025 [1]	2025	X	X	Ouden [36]	
	Kozarevic	2025	Method	Latency found	300 - 500 ms	Neumeier [39]
	FP2R2Dato D5.4 [5]	2023	-	-	500 ms	Drone
	FP2R2DATO[4]	2024	G2G, synchronized phone clocks	340 - 380 ms	-	Own test
Car	Ouden [36]	2022	E2E, Video and Control, 5G. Time synchronized with a GPS-PPP source.	G2G: 95 ms + 5 - 26 ms (95%) max: 500 ms + 43 ms	300 - 1000 ms	Neumeier [39]
	Paper B	year	L1	L2	Method	Source
Drone	González [41]	2023	X	X	X	X
	Larsen [42]	2022	X	X	X X	
Crane	Paper A	2020	X	XX	X	

In the case of XX who reference Jernberg 2024 adn their findings of. Jernberg goes into details of the hazards and proxy hazards that the driver were facing. As mentioned in Section 4 "Related Work" [37] How in control of the vehicle were you during the drive (1-5) Baseline 3.7, 100ms 3.5, 200ms 2.9

The most referenced remote control latency effect paper, Neumeier's paper XX, talks about how participent leave the car lane significanlty more with higher latency, even tho with stable high latency. But: "In the Parking scenario, even no differences for whatever latency could be revealed" [39] Scenarios, was driving with turns, and one parking. No hazards except latency.

[4] D41.2 - Testing reports & assessment Results of the remote driving of tramways demonstrator. Image latency - G2G, (capturing processing, compression, transmission, reception, decompressing, displaying) - Oslo to Berlin - Two atomic clocks on phones. - Measured to be 340 - 380 ms (Always under 400 ms)

[1] - Finds actually latency in project - Uses Car threshold to evaluate

Is a project in "Remote Control for Rail Vehicles" where they test a remote control train for a short track from "X" to "X" in Germany. Here they do "this" and found "that".

Says that at 300ms, you get loss of performance, and at 1000ms the delay becomes unfeasible. And references: "Design and Evaluation of Remote Driving Architecture on 4G and 5G Mobile Networks" (Ouden, 2022) [36] Which references (Lane, 2002) and (Neumeier, 2019) D41.2 - Testing reports & assessment Results of the remote driving of tramways demonstrator. [4] - Finds actually latency

Image latency - G2G, (capturing processing, compression, transmission, reception, decompressing, displaying) - Oslo to Berlin - Two atomic clocks on phones. - Measured to be 340 - 380 ms (Always under 400 ms)

Auxiliary circuit tests, - Driver safety - Remote wake up - R driving loop - R control commands - R ... Static functional tests, - Start Tram, CERES, - CERES do step 1.2.3...

Dynamis functional tests, - CERES Local brakte test - CERES Remote Brakte test - C Drive 5km/h - C Drive 100% dont break max speed - C loose communication. - C DSD brake sequence - C Local driver break priority over remote.

Reaction Time, reduction in time needed to perform spesific tram operations, fleet management and preparation, start-up and shut-down procedures, maintenance tasks, shunting. Time reduction in these processes are efficiency improvments. [2] - Finds actually latency in project - Uses Car / Drone threshold to evaluate Talks about the dangers of latency in high speed vehicles. Comparing it to drone operations. Reference drone and says 100 ms Reference Chen?, and Neumeier, 170 ms and 300 ms have minimal impact on remote operators.

5.2.1 Calculation of latency

The measurements and therefore the calculations of latency is not easily done. Since its a fluctuating measurement that varies alot depending on the components in the system used, the way to calculate various on what the personens want to find.

Very difficult from related works: Real time video latency: [38] Here, the time of the visual event in front of the camera is denoted as T1 and the time when the event was detected on the receiving end as T2. The start of frame processing is denoted as T3. *TVL =(T1 - T1)-(T2 -T3)=T3 -T1*

5.2.2 Threshold for acceptable latency

After reading threw research paper on the topic of how latency threshold are set. It became apparent that very few have done enhanced research on this very topic for railway remote control. Papers such as Jürgensen [1] and Kozarevic [2], who mentions the maximum latency measured before loosing performance reference sources of other vehicles and their tests of remote control.

Maybe include calculations of speed of train, compare to the previous and discuss a posible latency treshhold. End in that research on spesificly train drivers on railway should be tested. Use this report [5]

5.3 Tools and protocols for remote control

Remote operation depends not only on network performance but also on the tools and protocols used to capture, encode, transmit and display video. This subsection outlines the main technical options applied across the reviewed studies as well as encoding formats and measurement frameworks.This is done for the purpose of showing how different protocols influence latency, stability and video quality, and to compare their practical strengths and limitations for real-time control. By highlighting the variety of available tools and the results they produced in different vehicle domains, the subsection provides a foundation for identifying which approaches are most suitable for remote train operation.

Table 8: Tools evaluation of Latency

Vehicle	Paper	Published	Method	Tools	Major findings
Railway	Mejías 2024 [3]	2024	Method		
	Paper C	2023	X	X	X
Car	Kaknjo 2018 [38]	2018	X	X	X
	Kang 2018 [40]	2018	X	X	X
	Paper C	2023	X	X	X
Drone	N. González 2023 [41]	2023	Video in front of camera	LTE server, LTEdirect WifiDirect	500 ms for LTEs and 42 ms for LTEd, 4 ms for Wifid
	Larsen 2022 [42]	2022	X	X	X
	Böhmer 2020 [43]	2020	X	X	X
Crane	Paper A	X	X	X	X
	Paper B	X	X	X	X

[3] - Evaluate latency depending on parameters / tools Compare: - RTSP - WebRTC Web Real time communication as their Real-time Transport Protocol (RTP) protocol. - E2E - H.264

Methodology for latency measurement. Network Time Protocol (NTP) is necessary to synchronize sender and receiver. Server obtains the TS1 when image is captured. Adds it to the RTP packets generated after the encoding. Player retrieves the timestamp (TS1) from the RTP packets and compares it with the current time TS2 when the image is beeing displayed. To do this, you must retrive it from the package before the decoder and comapre it with the image comming out of the decoder.

1 Capture: the camera captures an image together with the timestamp. The timestamp is added to the metadata of the image. 2 Encoding: the image is encoded into a H.264 bit stream. The metadata is maintained unaltered along the encoding process. 3 Encapsulation: the H.264 video stream is encapsulated into RTP payload. The capture timestamp is extracted from the metadata and added to the RTP header. For this, it is required both the RTP standard header and its RFC 8286 extension. 4 Sender: RTP packets are sent on the communication channel. In the case of RTSP, the player opens a connection with the sender. For WebRTC, a negotiation between the sender and receiver is performed through the signaling server to determine the communication route.

The player receives the RTP packets through RTSP or WebRTC and calculates the latency: 1 Receiver: it receives the RTP packets through the channel established with the media server. 2 Decapsulation: the original H.264 content is extracted from the RTP payload. In addition, the timestamp contained in the RTP header is extracted and added as metadata of the H.264 content. 3 Decoding: the H.264 content is decoded to retrieve the uncompressed image. The metadata is maintained unaltered along the decoding process. 4 Displaying: the image is displayed. Moreover, the timestamp is extracted from the metadata and subtracted from the current time to obtain the End-to-End latency. This is shown to the remote driver, who will consider it during the operations.

BITRATE Change bitrate regarding quality of output (jitter or packet loss). Bitrate vary between 5Mbps, 3.5Mbps, 2Mbps. A change of 2% packet loss and 500Hz / 1000Hz jitter.

implementation. GStreamer framework. (Open source) Pylon source from Basler element that capture of camera images and timestamps. H.264 NVidia en/de coder. Provided by NVIDIA graphics cards. It is the key to enable bitrate adaption. RTP H.264 pay/depay. For packaging encoded video signal into RTP packets, and RTP includes timestamp in header.

WebRTCbin. Allows communication via WebRTC, peer2peer, must connect to signaling server responsible for negotiation. RTSP server/client. Manage connection and send/receive data.

Camera, Media server on Jetson Xavier (Either WebRTC or RTSP), Network equipment (switch or laptop simulating a router, allowing to evaluate against bandwith degradation). Computer as player and reciver.

Results E2E, time after capture to the time before display S2S, time in front of camera to time displayed on player image

Measurments for each camera and alternating available bandwidth. When enough bandwidth results in 150 ms S2S and ¡75 ms E2E Bandwidth of ¡=10 results in 570 ms - 1000 ms or pixelation freezing in both S2S and E2E

RTSP Difference in S2S and E2E is approx 70 ms - 100 ms which is image capturing and displaying.

WebRTC is faster E2E but not S2S

RTSP with rate control Allows the bandwidth to go past 7 Mbps that was issue before, although with high latency. Adjust itself back up again. Also we can see a shift in latency between latency when increased bitsize of video.

[38] - Evaluate latency by perfomance, (different tools) IRL,

- G2G - Time stamps - H.264 - MJPEG - RTSP (Real Time Streaming protocol) - TCP/UDP

Found MJPEG to be 300 ms lower latency than H.264. However it found H.264 to demand less bandwitdh 50-380Kbps as it compresses more enhensive than MJPEG 4.6-5Mbps. Found detoriation in performance in latencies above 300 ms and increase in errors during control for latencies larger than 500 ms.

5.3.1 Kang 2018

[40] - Evaluate latency by perfomance, (different tools) IRL,

- 3 different resulutions (320x240, 640x480, 1280x960) - 3 different bitrate (0.5Mbps, 1Mbps, 4Mbps) - LTE and WiFi - Video and camerea catching timestamps

5.3.2 Larsen 2022

[42] - Evaluation latency on perfomance, (tools) IRL

5G URLLC network H.264

Le2e = Lprop agation + Lproc essing + Lser ialisation Lprop = distance / v in medium Lser = S datasize / R transmission rate

Le2e = nLproc + (n+1)Lser + Lprop + LQ n = switches along the network n+1 = number of links LQ = queing latency.

0.5 Mbps video rate in uplink and a 60 Hz update rate in downlink. Further, we assume that the higher quality video for inspection require 8 Mbps. [43] - Evaluation latency on perfomance, (tools) IRL

Predictably Reliable Real-time Transport (PRRT) protocol [A. Schmidt, “Cross-layer latency-aware and -predictable data communication 2019] The Crazyflie is controlled by Bitcraze’s application layer protocol called Crazy Real-Time Protocol (CRTP)

Rasberry Pi including WiFi 2.4GHz due to Rasberry Pi constraints timestamps by controller to drone: tp1 -¿ packet1 -¿ drone tr1 ¡- response1 ¡- drone tp2 -¿ packet2 -¿ drone tr2 ¡- response2 ¡- drone

the Crazyradio communication path using the traditional radio link the PRRT communication path with the Python bridge, and the PRRT communication path with the Rust bridge.

IPT = tp2 - tp1 (Time between packets) RTT = tr1 - tp1 (Round-trip time)

[41] - Evaluation tools for latency, - People tested

URLLC 4K quality res 1080 x 720, at 30 FPS H.264 encoded

LTE server, LTE direct, WiFi -¿ avg packet delay = 500 ms, 42 ms 4 ms Can activate low latency mode. Connection requirments of 100 ms for video streaming, set by 3GPP TS 22.829 for unmanned aerial vehicles Found added latency of around 180 start causing lower MOS / QoE, and steady deteriation making it 1, lowest grade at around 460 ms concludes with a e2e of 250 ms is vaiable for service usability.

5.4 Theory v. Practical test

Compare from the PreDraft of what expected result and hopes were, and discussing them with the information of what happend in the test and measurments.

5.5 Future work

- MJPEG vs H.264

- Offshore or other remote controlled vehicles that can shead light or contribute to remote control railway.

Differnt aspects of latency *What is the difference* Fixed, static v dynamic.

6 Conclusion

This study explored how latency can be measured and evaluated for remote train operation systems, and how acceptable performance thresholds can be established. By reviewing research across railway, car, drone and crane control, and by analysing human responses alongside technical measurements, the study provides a clearer picture of what aspects of latency matter most and how they should be assessed.

Conclusion needs to be drawn up to RQ and try to give a little closure of what the paper discussed.

1. *RQ1: How is latency evaluated for railway and other industries?*
2. *RQ2: What parameters influence latency in remote train operation systems?*
3. *RQ3: How can we test different video streaming protocols and their impact on real-time performance of remote train operation systems?*

6.1 Evaluation of latency

The findings show that latency evaluation in train operation might need different methods than in other industries. Remote operation research on cars, drones and cranes often have different tests requiring movements, such as driving slalom or avoiding hazards, that train operation do not acquire. Making many of the latency's found in the research of other industries invalid or irrelevant. Only a few of the completed test for evaluation the latency can be comparable, these contain the setup similar to what a railway operator might be able to do in different scenarios, like acceleration, keeping speed limits, deceleration and stops. Still there is many ways RTO research can learn from these industries. By examining setups, experiment formats and attributes considered when evaluating latency there is possibilities to replicate or adjust for RTO research.

6.2 Important aspects of latency

The study also identifies the parameters that most strongly influence latency in remote train operation, addressing RQ2. Technical factors include encoding and decoding time, bitrate, packet loss, jitter, fps and network technology used. By being aware of the parameters affecting the total latency and how they interact together there is possibilities for finding individual limitations, identifying obstacles and ensuring progress by adjusting focus to problematic parameters and results.

6.3 Measuring latency

Just as other remote operation studies measure latency, train operation can also divide latency into one-way delay, round-trip time and glass-to-glass delay, and rely on synchronized timestamping to obtain accurate end-to-end measurements. By doing this, train operations can explore different setups, tools and protocols. The best way to accomplish a detailed and specific research on latency is to have a standardised setup where interchanging hardware and protocols to compare each aspect of the full remote operation transaction. To be able to decide for an approach it is necessary to have a complete understanding. Since remote train operation is a project for expansion, the research needs to be detailed enough to be able to predict how extra trains, extra distance, and extra disturbances will effect the system.

Overall, the study shows that remote train operation faces similar latency challenges to other teleoperated systems but benefits from the more predictable environment of railway infrastructure. While the literature provides useful initial thresholds, dedicated studies with trained railway personnel are still needed to define precise limits for safe operation. Future work should therefore focus on controlled human remote control experiments dedicated for train control as well as extended comparison of protocols, encoding tools, available hardware and all parameters affecting latency.

Unfinished thoughts:

Just as we have observed how different video streaming tools has been used, upgraded and replaced, we must anticipate that today's tools also will be upgraded. Not to mention the wast spectrum of different models, businesses and products on the market able to provide the video streaming service.

As businesses try to improve their products,

As discussed previously, there is a lot of different ways to set up a remote control operation. You can choose from many different protocols, specialised hardware, or opt for a developed solution from an outside business. And as time grows, more option are destined to also arrive as the market are not yet satisfied with today's level. If we are to achieve the requirements set up by 3GPP for remote control under GoA 3 GoA 4 [35], new protocols, hardware or a different way to do to remote operation is necessary. However, as of now, these requirment, should as mentioned in the paper be used as target values. When performing latency test

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