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Department of Mechanical and Industrial Engineering

TMM4540 - Industrial ICT Engineering Design and Materials, Specialization Project

# "Latency of Remote Control in ATO"

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# 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

Introduction to the paper and theories that are going to be used.

## 1.1 Purpose

*What is the purpose of this paper. Why are we doing it.* Find a way to effectively measure, validate and evaluate latency for remote train operation systems. Establish acceptable latency thresholds that ensure safety and performance. Identify key factors influencing latency and propose optimization strategies.

### 1.1.1 Research Questions

*What are we hoping to answear and/or achieve during this paper* To achieve the purpose of this paper, the research questions listed below was created to help.

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 Digitalization in Railway

Railway digitalization evolved from early computer-assisted signalling and centralized traffic control, through modern Automatic Train Protection (ATP) systems, to full ERTMS/ETCS deployments and traffic management platforms. Recent steps have focused on 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 [1, 2].

## 1.3 System Overview

A section to go threw the system as it stands.

### 1.3.1 Components

A overview of the components in use. Also mentioning alternatives to the ones we have in use.

# 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.

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 [3].

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 [4]. 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 [5].

### 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.

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.

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" |

### 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 (IC Applied) |
|---|---|---|
| "Remote train operation" | XX | XX |
| "Remote train operation latency threshold" | XX | XX |
| "Remote control latency threshold" | XX | XX |
| "Automatic train operation" | XX | XX |
| "Video streaming protocols AND real-time performance" | XX | XX |
| "Ethics remote control" | XX | XX |
| ""Latency awareness" AND "Remote control"" | XX | XX |

The analysis *confirmed* a limited number of high-relevance articles specifically addressing the impact of video streaming protocols on real-time performance, thereby confirming a critical area for this research to address.

## 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

## 2.5 Reliability

# 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 [6] .*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* [2].

## 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 [7] 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 3: 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 distruption management handling system and as a safety system for GoA 4 if it were to fail. [8]

GoA also changes and updates regulary because of new techonology 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 defintion of GoA

Source: [9]

The formal definitions and required functions per level are described in IEC 62290 and discussed in CBTC Solutions as well as UITP [7, 9, 10].

## 3.3 ERTMS

European Rail Traffic Management System (ERTMS) is a new system popular in Europa, but also countries as XX XX XX, (Source). ERTMS is built by ETCS, XX and XX togheter (Source) As of now both Norway and Sweden? har implementing ERTMS which will be crucial for all ATO projects. *Få inn bane nor her*

## 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 [11, 12].

#### 3.4.0.1 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.

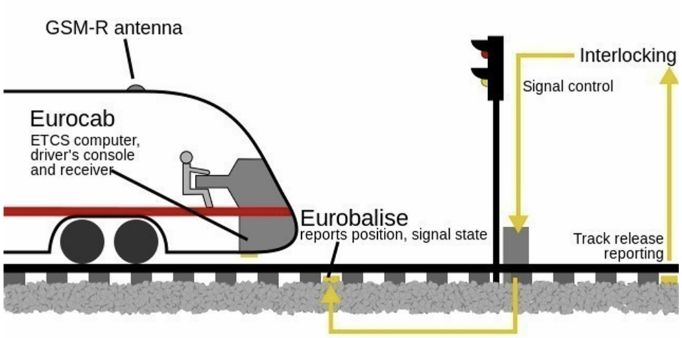


Figure 2: Train following regular signal with assisted speed and position with balises

Source: [12]

- **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.

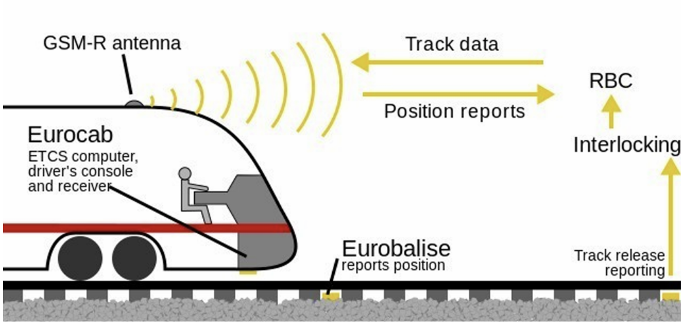


Figure 3: Train operating speed and signal with RBC threw GSM-R signal

Source: [12]

[12].

#### 3.4.0.2 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 [12].

## 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. [13, 14]

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. [13, 14]

### 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. [15, 16]

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. [15, 16]

### 3.5.3 FRMCS

*3GPP Rel-16* Defines video quality for railway operations. Min requirments of H.264 codec, 320x240 resolutuion at 10 fps. Recommended 1920x1080 at 30 FPS [17]

### 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. [18, 19]

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. [18, 19]

## 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.

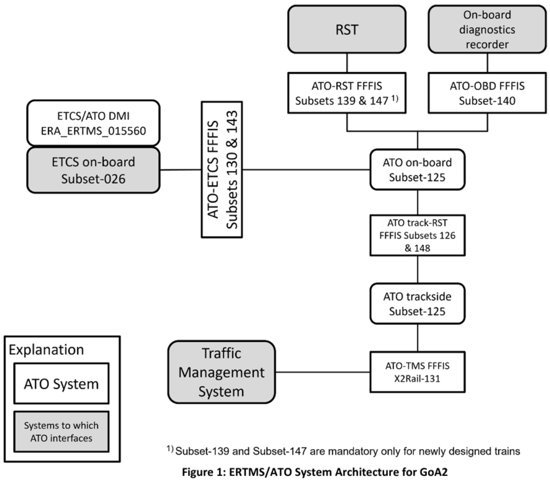


Figure 4: Architecture of ERA's ERTMS/ATO solution

Source: [11]

Showcasing different ATO working togheter with different responsibility and how they communicate with eachoter [11].

## 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 refered 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 methodes to get these measurments. 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 standarization 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). [20, 21].

*Table these protocols to match structure above* Internet Control Message Protocol (ICMP): With ICMP we can use two effective methodes, Ping and Traceback. Both return the Round-Trip Time(RTT) latency but in different ways. Ping sends data packets to a spesified destination, and report the time it takes before a the same data packets is recieved. Traceback also sends data packets waiting for return, but tracks routes and notifies if certain routes use to long time. [22].

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* [20].

*Need more protocols we can use*

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

## 3.8 Differnt aspects of latency

*What is the difference* Fixed, static v dynamic.

## 3.9 Regulations

*Sjekk master til Emilia om hva hun fant av regler*

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 [1, 11].

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; operators must demonstrate compliance with both national rules and applicable TSIs for approval and operation [23, 24]. 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 [1, 2].

From [11] 8.2 ATO 2: Supervision and regulation 8.2.1 ATO 2.1 - Supervise train operations During ATO operation, it shall be possible to: • 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; 8.2.2 ATO 2.2 - Manage the train service During ATO operation, it shall be possible to: • Input the journey profile from the planning system; • Start the journey profile; • Dynamically modify the journey profile in real time to take account of changes in operating conditions including: disruption management; re-routing; re-timing. • Adapt the trai's journey profile to meet any update of the operational timetable; • Regulate trains to avoid bunching of trains and to reduce delays to trains in the case of disturbances; • Dispatch ATO trains to harmonise the starting of ATO trains, corresponding to results of train regulation and ensuring connecting services; • Operate both ATO and non-ATO trains simultaneously.

I think this could be very useful: Commission Regulation (EU) 2016/919 of 27 May 2016 on the technical specification for interoperability relating to the "control-command and signalling" subsystems of the rail system in the European Union

### 3.9.1 WP41 - Validation Criteria Tramways

[25]

WP41 - Collection of test cases and validation criteria for remote driving of tramways demonstrator. Is delivered by Sporveien Trikken AS with the assistence of CAF, UITP and FP2R2Dato in the Europe's Rail program. Contains detailed plan and procedures for testing remote control of tramways. Including, functionality of electric circuits implemented, TCMS, CERES actions, and safety supervision. 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)

# 4 Related Work

Experiences from other simialar fields, self driving cars, drones, maybe other remote controlled trains in different countries

## 4.1 Train Control

As mentionted in ERA's ERTMS. Commission Regulation (EU) 2016/919 of 27 May 2016 on the technical specification for interoperability relating to the "control-command and signalling" subsystems of the rail system in the European Union [11]

### 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 [2].

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 [2].

### 4.1.2 Jürgensen 2025

[26] - 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) [27] Which references (Lane, 2002) and (Neumier, 2019)

### 4.1.3 Kozarevic 2025

- 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 Neumier, 170 ms and 300 ms have minimal impact on remote operators.

### 4.1.4 Mejías 2024

[17] - Evaluate latency depending on parameters / tools

Compare: - RTSP - WebRTC Web Real time communcation as their Real-time Transport Protocol (RTP) protocol.

- E2E - H.264

Methodology for latency measurment. Network Time Protocol (NTP) is necesarry to synchronize sender and receiver. Server obtains the TS1 when image is captured. Adds it to the RTP packets generated after the encoding. Player retrives 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 bitstream. 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 communcation via WebRTC, peer2peer, must connect to signaling server resposible for negotiation. RTSP server/client. Manage connection and send/recive 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.

### 4.1.5 FP2R2Dato, EuropesRail 2023 D5.4

[28] - Uses Drone latency to evaluate threshold

Based on drone latency. Enhensive calculations of latency to match to train.

### 4.1.6 FP2R2Dato, EuropesRail 2024 D41.2

D41.2 - Testing reports & assessment Results of the remote driving of tramways demonstrator. [29] - 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.

### 4.1.7 Brandernburger 2023

[8] - 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

Measurements Responce accuracy Responce 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

## 4.2 Car Control

### 4.2.1 Sato 2021

### 4.2.2 Nakamura 2021

### 4.2.3 Ouden 2022

[27] - 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.

### 4.2.4 Jernberg 2024

[30] - 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 [30], 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.

### 4.2.5 Kaknjo 2018

[31] - 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.

### 4.2.6 Neumier 2019

[32] - 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.

#### 4.2.7 Kang 2018

[33] - 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

### 4.3 Drone Control

#### 4.3.1 N. González 2023

[34] - 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.

#### 4.3.2 Larsen 2022

[35] - 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.

#### 4.3.3 Böhmer 2020

[36] - 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)

## 4.4 Crane Control

### 4.4.1 Brunnström 2020

[37] - 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.

## 4.5 Offshore Control

## 4.6 Human factors

All the ways human error can effect the results from the tests. All the ways human control needs to be adjusted for in acceptance levels. How humans act depending on knowing the latency they have and not knowing.

## 4.7 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. [30]

(Neumier 2019) Could not confirm that fixed latency resultet in any better result than varied latency. Could not confirm "Kang et al" [33] who stated that fixed latency leads to better driving performance than varying. [32]

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). [37]

## 4.8 Ethics

Who is responsible. Fully automated, or remote driver. What obligation do we have in a project like this.

https://www.tandfonline.com/doi/full/10.1080/01441647.2020.1862355

## 4.9 Cyber Security

How we can protect the system from attacks. What regulations are in place. "[CYB] CLC/TS 50701:2023, Railway applications - Cybersecurity" used in [28]

## 4.10 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: [31] 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 Results og discussion

A page with all the information i found and aanalyzise of it.

*Results in 2 parts. 1. part analyzise 2. part future steps*

## 5.1 Human factors results

Discuss how a high stable latency could be more acceptable than a low unstable latency due to info found in Theory, Human Factors.

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 atleast 500 - 1000 ms [27]. And how they react to a possible system latency will also be crucial for the full remote operation.

Table 4: Human evaluation of Signal Attributes and Latency

| Vehicle | Paper | Published | Method | Task | Slight perfromance downgrade | Major perfromance downgrade | Test subjects |
|---|---|---|---|---|---|---|---|
| **Railway** | Brandernburger [8] | 2023 | Sim w/ Real image, Differentiation in bitrate and FPS to find responsetime | React to light signals / distance marker | 6 Mbps | 1 Mbps | 31 subjects, Novize train drivers, Age 42 SD 19 |
| | Paper E | 2022 | X | X | X | | |
| **Car** | Ouden 2022 [27] | 2022 | Sim, Artifical latency of 0, 10+-3 ms, 20+-5 ms and packet loss | Drive slalom and parking | Packet loss at 1% | Packet loss 2% | - |
| | Jernberg 2024 [30] | 2024 | Sim, Artificial latency of +100, +200 on base 89 ms | Adapt to Hazards | 280 ms for lane bypassing | - | 30 subjects, Experience drivers or gamers. Age 35 SD 11 |
| | Neumier 2019 [32] | 2019 | Sim, Artifical latency of +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 [34] | 2023 | IRL, Artificial latency of +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 | - |
| | Paper B | X | XX | XX | XX | | |
| **Crane** | Brunnström 2020 [37] | 2020 | IRL, Artificial latency of +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 |
| | Paper B | X | XX | XX | XX | | |
| **Offshore** | Paper H | 2025 | X | X | X | | |

[8] 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 at 5, 15, 25 FPS Stimulus: Light signal, Distance marker Measurements: Responce accuracy, Responce 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 ms speed, and 0.51 -¿ 0.58 and 0.61 -¿ 0.69 correct. 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

[30] "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."

## 5.2 Comparing latency for different vehicles

After reading threw an reasearch paper on the topic of how latency treshold are set. It became apparent to me that very few have done enhanced research on this very topic for railway remote control. Papers such as XX, who mentions anything about the maximum latency before loosing performance reference sources of other vehicles and their tests of remote control.

Table 5: Different Latency Measured and Thresholds used

| **Vehicle** | **Paper** | **Release year** | **Method** | **Latency found** | **Threshold used** | **Threshold Source** |
|---|---|---|---|---|---|---|
| **Railway** | Jürgensen 2025 [26] | 2025 | X | X | Ouden [27] | |
| | Kozarevic | 2025 | Method | Latency found | 300 - 500 ms | Neumeier [32] |
| | FP2R2Dato D5.4 [28] | 2023 | - | - | 500 ms | Drone |
| | FP2R2DATO[29] | 2024 | G2G, synchronized phone clocks | 340 - 380 ms | - | Own test |
| **Car** | Ouden 2022 [27] | 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 [32] |
| | Paper B | year | L1 | L2 | Method | Source |
| **Drone** | Paper A | X | X | XX | X | |
| **Crane** | Paper A | 2020 | X | XX | X | |
| **Offshore** | Paper H | 2025 | X | X | X | |
| | Paper I | 2025 | X | X | 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 mentionen in Section 4 "Related Work" [30] 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" [32] Scenarios, was driving with turns, and one parking. No hazards except latency.

[29] 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)

## 5.3 Threshold for acceptable latency

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 [28]

## 5.4 Tools and protocols for remote control

Table 6: Tools evaluation of Latency

| Vehicle | Paper | Published | Method | Tools | Major findings |
|---|---|---|---|---|---|
| **Railway** | Mejías 2024 [17] | 2024 | Method | | |
| | Paper C | 2023 | X | X | X |
| **Car** | Kaknjo 2018 [31] | 2018 | X | X | X |
| | Kang 2018 [33] | 2018 | X | X | X |
| | Paper C | 2023 | X | X | X |
| **Drone** | N. González 2023 [34] | 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 [35] | 2022 | X | X | X |
| | Böhmer 2020 [36] | 2020 | X | X | X |
| **Crane** | Paper A | X | X | X | X |
| | Paper B | X | X | X | X |
| **Offshore** | Paper C | 2023 | X | X | X |
| | Paper C | 2023 | X | X | X |

//Kanskje ikke ha ny tittel? Bare ha result og diskusjon om hverandre

# 6 Discussion

Discussion of the result from the measurements, what they could mean and possible use cases for the inforation gathered

## 6.1 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.

## 6.2 Future work

- MJPEG vs H.264

## 6.3 Parameters for latency testing

What parameters are we measuring. Latency, Jitter, Packet loss.

## 6.4 Parameters for latency evaluation

speed, distance, braking distance, reaction time, margin for error.

- Lateral Deviation - Max Steering angle - Out of Lane Ratio - Avg Speed - Acceleration

## 6.5 Calculations of parameters

# 7 Conclusion

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