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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 does other industries set threshold for latency?
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?

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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, 24].

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 Theory

2.1 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 [19] .*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* [1].

2.2 GoA

The Grade of Automation (GoA) classifies how much of the train operation is automated. Standards such as IEC 62290 and industry reports [11] 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 1: 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.

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: [22]

The formal definitions and required functions per level are described in IEC 62290 and discussed in CBTC Solutions as well as UITP [2, 11, 22].

2.3 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*

2.4 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 [8, 23].

2.4.1 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.

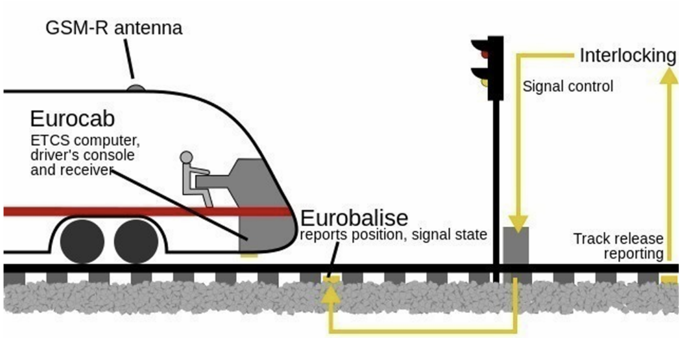

Figure 2: Train following regular signal with assisted speed and position with balises

Source: [8]

- **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.

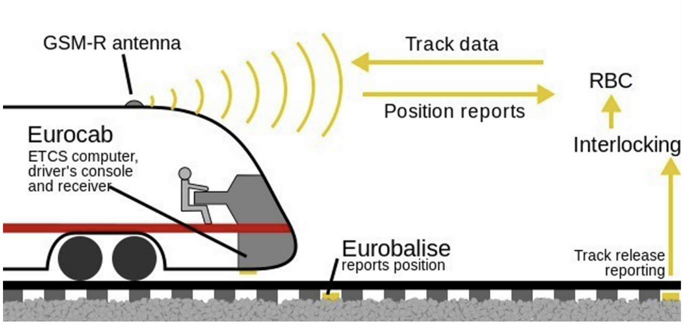

Figure 3: Train operating speed and signal with RBC threw GSM-R signal

Source: [8]

[8].

2.4.2 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 [8].

2.5 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.

2.5.1 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. [4, 17]

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. [4, 17]

2.5.2 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. [10, 25]

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. [10, 25]

2.5.3 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. [5, 16]

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. [5, 16]

2.5.4 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.

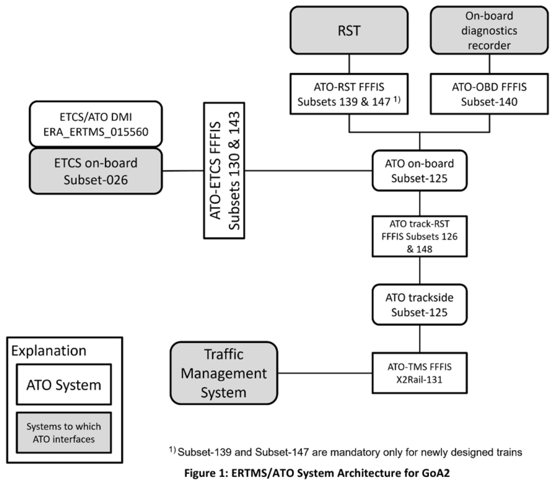

Figure 4: Architecture of ERA's ERTMS/ATO solution

Source: [23]

Showcasing different ATO working togheter with different responsibility and how they communicate with eachoter [23].

2.6 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.

2.6.1 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):** 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). [3, 26].

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 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. [7].

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* [3].

Need more protocols we can use

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

2.7 Differnt aspects of latency

What is the difference Fixed, static v dynamic.

2.8 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 [23, 24].

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 [12, 21]. 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, 24].

From [23] 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 train'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 Related Work

3.1 Other Experiences

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

3.1.1 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 [23]

3.1.2 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 [1].

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 [1].

(Jürgensen 2025) [14] Is a project in . . . 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" (OHS, 2022) Which references (Lane, 2002) and (Neumier, 2019)

Jernberg(2024) [13] - 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) - was not given a latency 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.

(Neumier 2019) [20] - 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

Sjekk T-teknikk

3.1.3 Car Control

//Distraction lantecy?

3.1.4 Drone Control

//Sjekk Emilia sin

3.1.5 Crane Control?

3.1.6 Offshore Control

3.2 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 adapt to stable v unstable latencies.

"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. Jernberg(2024) [13]

(Neumier 2019) [20] Could not confirm that fixed latency resultet in any better result than varied latency.

3.3 Ethics

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

3.4 Cyber Security

How we can protect the system from attacks. What regulations are in place.

3.5 Calculation of latency

The math behind calculations of latency. How to measure most precisely and what errors we find in the calculations.

Very difficult from related works: Real time video latency: [15] 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*

4 Method

4.1 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 [6].

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 [9]. 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.

4.2 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 [18].

4.2.1 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.

4.2.2 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.

Table 2: 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.

4.2.3 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 3 illustrates a query targeting the core technological elements of the study.

Table 3: 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

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.

4.3 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*

4.4 Parameters for latency testing

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

4.5 Parameters for latency evaluation

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

4.6 Calculations of parameters

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.

[13] This article conlcude that the remote operators adapt to the circumstances. Adding safety margins adjusted for their personal limit.

5.2 Comparment of latency for different vehicles

Important to mention the hazards and proxy hazards that driving met on: [13] 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.

How in control of the vehicle were you during the drive (1-5) Baseline 3.7, 100ms 3.5, 200ms 2.9

5.3 Threshold for acceptable latency

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.

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