Øyvind Thingstad Myhrvold

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An analysis of remote driving technology and a possible pilot project in Norway

Master's thesis in Engineering & ICT
Supervisor: Nils Olsson
June 2023

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Abstract

With the approaching implementation of the next generation of railway communication systems in Europe (Bane NOR, 2022a; UIC, 2023), an evaluation of the potential technological features it could integrate is very timely. One such possible feature is facilitation for remote driving of the rolling stock. This thesis is split in two main topics. First, a literary study on the state of remote driving technology is conducted, with a focus on the railway sector. In this section, key technological subsystems needed for achieving railway remote driving are reviewed. This includes railway communication infrastructures, data communication requirements, and remote driving software. Throughout, an extra emphasize is put on the recent development, and the different alternatives currently available. The motivation for utilizing remote driving, both theoretical and from existing projects, is reviewed. Some of the most frequently mentioned issues associated with railway remote driving is also addressed.

All of these elements is used to discuss the current capabilities of remote driving, as well as the possible future trajectory of the technology. Infrastructural needs, potential value creation, and current obstacles is among the elements that are taken into account. The thesis concludes that remote driving is a highly feasible feature to integrate into the smart railway. It is argued, however, that it is highy dependant on other features, such as a high grade of automation, to realize it's full value. With the upcoming discontinuation of GSM-R (Bane NOR, 2022a), it is argued that remote driving should not be the primary motivation for a costly upgrade to a 5G rail network.

The second topic for this thesis revolves around a specific remote driving project. As part of EU's FutuRe-project on revitalizing regional train lines (EU-Rail, 2023a), NTNU was tasked with selecting a railway line where a highly automated prototype vehicle can be tested. It was decided that the first iteration of this vehicle should be operated by remote controls. The important characteristics of suitable railway line-candidates is therefore reviewed in this report, before a list is presented. Extensive information gathering is performed, which is used as a foundation for selecting a shortlist of the preferable options. A more in-depth analysis is then conducted on the shortlist of options, in part by the use of a trade-off study. The thesis concludes by suggesting that the southernmost part of Thamshavnbanen, between Løkken and Svorkmo, is the preferable location for testing the remotely driven prototype.

Sammendrag

Med den nært forestående implementeringen av neste generasjons jernbanekommunikasjonssystem i Europa (Bane NOR, 2022a; UIC, 2023), er det svært aktuelt å evaluere de potensielle teknologiske funksjonene som kan integreres. En slik mulig funksjon er tilrettelegging for fjernstyrt kjøring av tog. Denne oppgaven er delt inn i to hovedtemaer. Først gjennomføres en litteraturstudie om den nåværende situasjonen for fjernstyringsteknologi, med tog i fokus. I denne delen gjennomgås de viktigste teknologiske delsystemene som trengs for å oppnå fjernstyring av jernbanen. Dette inkluderer infrastruktur for kommunikasjon, behov for datakapasitet, metoder for videooverføring, og programvare for fjernstyring. Det legges ekstra vekt på utviklingen i de senere årene, samt de ulike alternativene som eksisterer i dag. Motivasjonen for å bruke fjernstyring, både teoretisk og fra eksisterende prosjekter, blir gjennomgått. I tillegg blir noen av de ofte nevnte problemene med fjernstyring av jernbane addressert.

Alle disse elementene brukes til å diskutere de nåværende mulighetene for fjernstyring, samt den mulige fremtidige utviklingen av teknologien. Infrastrukturelle behov, potensiell verdiskapning og aktuelle hindringer er blant elementene som tas i betraktning. Avhandlingen konkluderer med at fjernstyring er en funksjon som det er fullt mulig å integrere i den smarte jernbanen. Det argumenteres samtidig for at den er svært avhengig av andre funksjoner, for eksempel en høy grad av automatisering, for å oppnå sitt fulle potensiale for verdiskapning. Gitt den kommende avviklingen av GSM-R (Bane NOR, 2022a) argumenteres det for at fjernstyring ikke bør være den primære motivasjonen for en kostbar oppgradering til et 5G-basert jernbanenett.

Det andre temaet i denne oppgaven dreier seg om et spesifikt fjernstyringsprosjekt. Som en del av EUs FutuRe-prosjekt om revitalisering av regionale toglinjer (EU-Rail, 2023a) fikk NTNU i oppdrag å velge ut en jernbanestrekning der et høyt automatisert prototypekjøretøy kan testes ut. Det ble bestemt at den første versjonen av dette kjøretøyet skal bruke fjernstyring. Viktige egenskaper ved egnede jernbanelinjer gjennomgås derfor i denne rapporten, før en liste over alternativer presenteres. Det gjennomføres en omfattende informasjonsinnhenting, som brukes som grunnlag for å velge ut en liste over fire gode kandidater. Avhandlingen konkluderer med å foreslå den sørligste delen av Thamshavnbanen, mellom Løkken og Svorkmo, som det foretrukne stedet for testing av den fjernstyrte prototypen.

Preface

This article was written by Øyvind Thingstad Myhrvold as a master's thesis for the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology (NTNU). The motivation for the topic selection was a personal interest in railways and the development of sustainable transportation systems for the future. It has, however, been a conscious priority to remain critical towards the research material and sources as it was important to counteract confirmation bias of the technology's potential and value.

A large gratitude is owed to my supervisor Nils Olsson, who has been supportive and helpful throughout the process of writing this thesis.

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Abbreviations

NTNU	Norges teknisk-naturvitenskapelige universitet
ER	Europe’s Rail/EU-Rail
ERTMS	European Rail Traffic Management System
FRMCS	Future Railway Mobile Communication System
GoA	Grade of Automation

1 Introduction

The railway is the backbone to a sustainable transportation network (Djordjević, Mane and Krmac, 2021). European governments and the European Union have expressed an ambition to further increase the reliance on trains (Islam, Ricci and Nelldal, 2016; Singh *et al.*, 2021) and this will require new methods for improving and innovating the railway sector (Lagay and Adell, 2018; Djordjević, Fröidh and Krmac, 2023). Among these new innovations is the push for further automation, as this can reduce the needed staff, increase safety, and optimize the utilization efficiency of lines (Trentesaux *et al.*, 2018).

The European Union's railway organization has therefore issued several flagship projects (EU-Rail, 2023b). Among these is the FutuRe-project, with the goal of finding new solutions for revitalizing regional train lines (EU-Rail, 2023a). As part of this project, NTNU and partnering institutions were tasked with performing a demo of an automated train on a regional line. It was agreed upon that NTNU should contribute with a definition of the GoA level 3/4 demo work, as well as special aspects of the demo for Norwegian regional rail. The latter also includes identifying a railway line suitable for performing tests. In the early stages of testing, the plan is to build a remotely controllable prototype that can successfully transmit video to a control center, which in turn is able to safely operate the train's basic actuators.

The motivation for the test project is divided between the different benefits it could bring. Firstly, it is seen as a milestone in the work towards achieving fully autonomous trains in mainline operation (Singh *et al.*, 2021). Secondly, having the capability for remote train control could be an important complement to autonomous train systems, as many believe there could always be situations with a need for remote intervention (Masson *et al.*, 2019; Jansson, Olsson and Fröidh, 2022). There could also be other benefits such as location flexibility for the driver staff, increased capacity, timetable flexibility and reduced costs (Zulqarnain and Lee, 2021a).

This thesis will review the state of remote driving and the technological building blocks that make it possible. Afterwards, a review of suitable testing locations for the pilot project will be described. Based on these two main topics, the following research questions were created:

Research question 1: Before proceeding with a pilot project on remote driving it is important to do an analysis of the technology's development and status. This also includes looking at some of the distinct technological components that are needed, and how they can be vital to the value of integrating remote train operation in the future.

> **RQ1:** What is the current state of remote train control technology?

Research question 2 & 3: Evaluating the state of the remote driving, and the results of previous projects gives great insight into the contemporary value of the technology. It is, however, very important to also assess if and how the solution could be beneficial to the railway systems of the future. This means looking at the potential further evolution of the technology and how it could fit or compare with the development in other areas.

> **RQ2:** What does the recent technological development forecast for the future trajectory of railway remote driving?
>
> **RQ3:** How can remote driving be a valuable asset in the future of railways?

Research question 4: Selecting a location for a test project differs from a regular project in many ways. The criteria that decide what railway lines to prefer can vary significantly, and so it is important to define what the goals for the test project are and how the testing locations conditions can fulfill them.

> **RQ4:** What are the defining traits of a good testing location for remotely controlled train operation in Norway?

Research question 5: After defining the characteristics of a suitable line for testing the prototype, this information can be used to select a prioritized list of preferable options. This selection process should be done based on an extensive information gathering process to ensure that the suggested railway line options can provide valuable test results.

> **RQ5:** What are the alternatives of railway lines for performing the test project and which of them are preferable?

2 Methodology

Before proceeding with the literary study on remote driving and the case study for the pilot project, it is important to disclose how the research has been conducted. This chapter on methodology describes the process, information gathering strategy, and other considerations made.

2.1 Process

This section covers how the decisions in this project's topics, scope, and development has been handled.

2.1.1 Topic selection

In the fall semester of 2022, I wrote a specialization project on the current state of automation in railway. The academic advisor for this project, Nils Olsson, believed it was a logical next step to move into a more practical project in the same field for the succeeding master project. Olsson had agreed to fulfill some tasks in an EU project on autonomous train implementation and among these was to execute a pilot project with Grade of Automation level 3/4. The preparation needed for such a project includes locating a suitable test track, researching the current state of the technology, identifying the requirements, and building the test machinery. The academic advisor already had a team in Linköping, Sweden that were working on creating a small test vehicle and so we agreed that this master thesis should focus on remote driving technology and the testing location in Norway.

2.1.2 Selection of pilot project location

As part of EU-Rail's FutuRe"-project (EU-Rail, 2023a), NTNU was tasked with finding a railway line for a pilot project with a high grade of automation locomotive. The search for suitable locations began with the academic advisor, Nils Olsson, suggesting some general outlines of what traits we were looking for. This was the foundation for the general search for railway lines that met the basic requirements, utilizing the book Banedata 2013 (Bjerke *et al.*, 2013) and other material described further in 2.2.2.2. After identifying a collection of 15 potential candidates and listing some of their features, as seen in Table 3, Nils Olsson and the author discussed the best candidates. This resulted in a narrowed list of four main options which were given a more in-depth evaluation. Included in this final stage of the process was contacting the owners of the tracks and inquiring their possible interest in participating in the project. The evaluation of candidates was performed based on principals and methods from project management and systems engineering, such as a risk assessment and trade off study. The end result was a suggestion list of the lines with the most beneficial attributes for performing the test.

2.2 Research

With limited prior knowledge on several of the topics in this thesis, it was vital to have a methodological and thorough research process. This section describes how the information gathering needed for the project was conducted.

2.2.1 Inclusion criteria

Regarding the timeframe of articles to include, there was not a clear point in time that could be used as a separation line. It did, however, seem logical to weigh recent articles more heavily as they were likely to contain less outdated information. At the same time, it can be useful to evaluate earlier development in the technology to get a better perspective of the timeline. This can also enhance the understanding of the possible progress that remote driving technology will have in the coming years. Favoring newer articles does not only apply to technological development. Information on the current state of railway lines can quickly become outdated, for instance by a cease in active operation, which further can cause tracks to deteriorate or even be dismantled.

It was important to have scientific material that could support non-trivial statements made in this article. This was done by evaluating the credibility of the author, publisher, and database, the latter also based on whether the grant of access was provided by NTNU. In some cases, it was necessary to utilize other sources, either to supplement, or find specific information. How the information gathered from these sources were utilized is further described in the succeeding section.

2.2.2 Search strategy

As previously emphasized, this thesis both covers a literary study on the state of remote driving, and a more practical research on possible testing locations in Norway. Therefore, it was reasonable to adopt two different search strategies for the two purposes.

2.2.2.1 Literary study on remote driving

NTNUs guidance on report writing lists some suggested search engines. This report has utilized Google Scholar, NTNU Open and Oria, relying mostly on the former due to the user friendliness and wide array of articles. There are however a drawback to Google Scholar as search results could be shown based on earlier use of the program. NTNU-Digit (2020) refers to this as a "biased filter bubble", and could be problematic alongside a possible confirmation bias from the author (Klayman, 1995). As part of this project relies on finding both positive and negative aspects of automation implementation projects, it was extra important to be cognizant with this. The Institute of Electrical and Electronics Engineers (IEEE), Springer, Elsevier, Taylor & Francis, and several train focused institutions were among the most highly utilized databases. For some topics, such as data communication, the source material largely consisted of quantitative research studies. As it is important to be critical of the reported result data (Heale and Twycross, 2015), the numbers were regularly compared to other sources. In the case of differing reports, an estimation was often made based on either a median or average of the sources, exemplified in Table 1 on characteristics of the network generations. For quantitative research studies it was also important to evaluate the conditions for the test (van Raan, 2013).

2.2.2.2 Search for test locations

The previously mentioned scientific search engines displayed a very limited amount of relevant information on Norwegian railway lines. As a substitution, it seemed logical to adopt a more qualitative approach (Maxwell, 2008) and have the information collection rely on three different main pillars. The first was a book on Norwegian railway lines, named Banedata 2013 (Bjerke *et al.*, 2013), which contains comprehensive information on almost every railway line that has ever been built in Norway. This was a helpful tool for getting an overview on the available options. The second pillar was open google searches on the railway lines in the book, which provided mostly newspaper articles, home pages, or other tourist sites. This was a useful supplement to the information in the book, often giving more insight into the current condition of the line, what stretches were being maintained for use, as well as some track traits that were not stated in the book. This search also provided contact information to the owners and operators of the different lines. Communication with these stakeholders then became the third important pillar for information gathering. They could either confirm the information found via the other sources or provide more recent updates on the situation. In addition to the information they could provide, it was also important to survey the interest for participating in the project.

Combining these three gave a good confidence that the evaluation and decision-making in this thesis would be performed based on sufficiently accurate information. When the sources gave conflicting data, for instance on the number of level crossings on a line, the matter was researched more thoroughly, evaluating maps and the reliability of the sources. The book Banedata 2013 (Bjerke *et al.*, 2013) and communication with the operator of the lines were generally trusted over tourist information and other websites.

A supplemental source of information was the Norwegian "Kartverket" (Kartverket, 2023), which is a governmental institution that provides maps, photographs, and detailed geographical information about the country's territory. Together with Google Maps, this was used to get a more complete understanding of the position and geographical traits of the different lines. The Norwegian mobile operator Telenor (2023b) and Telia (2023) also provides maps of network coverage, which was used to get a rough understanding of the data throughput capability of video streaming. For the sake of reader understandability, the network coverage information referred to throughout is mainly based on Telenor. After the creation of a shortlist of the best candidates, other methods were utilized for more detailed research, including YouTube footage of the lines, Google Street View, and physical visits. This was continuously compared against the maps and aerial photographs, with potential sites of interest being mapped.

2.2.3 Keywords

In scientific search engines I have utilized the following keywords, either stand alone or in combination with each other:

- Remote operation
- Remote driving
- GoA 4 remote driving
- Autonomous railway
- Communication
- Cybersecurity
- Jamming
- Legal framework
- Evolution of wireless networks
- 6G / 5G / 4G / 3G / 2G
- Teleoperation
- TELECARLA / CARLA
- Voysys
- GStreamer

- Network stability
- Mobile network frequencies
- Tunnel propagation
- Handover high-speed
- Beijing–Zhangjiakou high-speed railway
- GSM-R
- LTE-R
- Communications-based train control (CBTC)
- Future Railway Mobile Communication System (FRMCS)
- Wi-Fi railway
- SNCF
- European Union/EU Railway
- Types of Communication Protocols
- Video communication service performance
- Live streaming latency
- TCP
- UDP
- Video Communication Platforms
- ICMP ping
- Europe's Rail
- Shift2Rail
- TC-Rail

2.3 Previous experience

My study programme at NTNU is a five-year integrated Master of Science (MSc). At the time of delivery for this thesis, I have studied two years of Engineering & ICT at NTNU, followed by three years with specialization in Production Management. In this period, I also studied two semesters as an exchange student at the Polytechnic University of Turin. Here I took courses in production management, computer programming, and business economics. The programme at NTNU combines courses on different aspects in ICT with courses on project and production management. While most of the courses in my degree has some relevance, I have listed some in specific that I feel to different degrees were useful for this thesis, either through the syllabus or projects:

- Quality and Performance Oriented Management
- Shipbuilding and Customized Manufacturing
- Optimization Methods and Algorithms
- Introduction to Artificial Intelligence
- Applied AI and Machine Learning
- Production Strategy
- Project Flexibility
- Sustainable Systems Engineering

In addition to these courses, I wrote my specialization project on automation implementation in railway. While there is a difference between autonomous operation and remote operation, the project gave a good foundation of understanding for many aspects of the subject matter. In fact, one of the conclusions of the report were that remote operation could be a possible solution for autonomous railways to combat unexpected situations, similarly to what Jansson et al. (2022) argued for.

3 Railway remote driving

This section is a literary study on remote driving, with an extra emphasize on the railway sector. Aspects such as motivation, technological subsystems, existing projects, and areas of concern will be covered.

3.1 Terminology

Automation:

Automation was defined by Lee and See (2004) as technology that actively selects data, makes decisions, transforms information, or controls processes.

Grade of Automation:

Grades of Automation or GoA for short, is a commonly used model for separating the different extents to which a system is automated into distinct tiers. In the context of railway, it is normal to separate into five of these tiers, from GoA level 0 to GoA level 4 (Athavale, Baldovin and Paulitsch, 2020).

Autonomy/autonomous:

In the context of this article, an autonomous vehicle is meant as a vehicle that can operate without the direct need for human interference. While the term "automation" is broader and can be used throughout the spectrum, "autonomy" generally refers more to the higher GoAs, especially level 3 and 4.

Remote driving:

Remote driving is bringing a human operator into the control of a vehicle by network connection (Liu *et al.*, 2017).

Remote operation:

While sounding similar to remote driving, remote operation is a broader term for controlling something over a distance. For this article, there is a distinction between remote operation of the tracks and of the vehicle running on it.

Teleoperation:

Another term that is commonly used to refer to remote operation over a network. Similarly to "remote operation", it is used as a wide term. "Teleoperated driving" is a variation which more specifically refers to remote control of the actuators.

3.2 Brief history

The first use of remotely controlled train operation in Norway occurred in 1933, when track changes and signals were sent from a central station (Bjerke *et al.*, 2013). Throughout the 20th century, almost every main railway track in Norway became remotely operated. It is important to emphasize once again that this does not mean that the trains themselves are remotely operated, only the tracks. In earlier years, remote operation of railways largely meant control of track switching, signaling and similar features. These tasks are generally handled by traffic control centers. In recent years, there has been a large centralization project in Bane NOR, reducing the number of traffic control centers in Norway to just three, located in Oslo, Bergen and Trondheim (Bane NOR, 2022b).

Similarly to many other European countries, Norway is in the process of gradually digitalizing their signaling system, adopting the ERTMS (Bane NOR, 2015). In this period towards 2030, the GSM-R network that was deployed 20 years ago (Finne *et al.*, 2019) will be replaced (Bane NOR, 2022a). This will open the possibility for integrating new features into train control systems. While the technology for remotely communicating with track actuators have been around for a century, it is just in the last few years that the possibility of remote driving the vehicles has become a feasible option. This is because of the network-demanding feature of live streaming video from the train (Dayoub *et al.*, 2020).

3.3 Why remote driving?

It is important to evaluate what value remote driving can realize. This section covers some of the main motivations that have been or could be had for implementing remote driving into railway systems.

3.3.1 A step towards full autonomy

Remote driving is commonly referred to as a building block towards achieving full autonomy (Masson *et al.*, 2019; Tonk *et al.*, 2021). This is mainly because it could ease the transition of tasks from the driver to the automatic system. One of the reasons for this is the substantial amount of testing required before commercial implementation. As argued for by Bishop and Bloomfield (2000), any safety case requires a body of evidence which supports that the technology can be considered safe. Many companies testing autonomous driving, also for other methods of transportation, has been required to have a safety driver (Favarò, Eurich and Nader, 2018; DMV, 2020). Testing an automatically controlled train where the onboard computer handles certain tasks, can with remote driving be remotely intervened, removing the need for having personnel onboard. This reduces the risk of human lives associated with testing and makes it possible to let the computer gradually handle more tasks, while still being monitored remotely. In an example of an autonomous testing project, Khastgir *et al.* (2021) mentions that there is a remote operator as part of the automatic train control system, which makes it possible to test hazard case scenarios involving switching of GoAs, and other human-machine interaction.

3.3.2 A supplementary tool for autonomous driving system

While many see it as a steppingstone towards full automation, remote driving is also often referred to as a possible long-lasting supplement to railway systems with GoA level 3 or 4 (SNCF, 2018; Fodor *et al.*, 2021). Kemp (2018) suggested to add some additional b-levels to the GoA-categorization, where remote driving is an option. The reason for this faith in remote driving is the belief that there will continue to exist situations that require the intervention of human operators, as argued for by Jansson, Olsson and Fröidh (2022). In context of the automation of the Helsinki metro, Karvonen *et al.* (2011) did an analysis of the "hidden roles" of the driver and found that they contribute with more than just the basic task of driving. The major TASV project mentions remote driving as a useful backup to autonomous driving, as there could be a need for a human in the system (Rouzé, 2019; Gadmer *et al.*, 2022). Brandenburger and Naumann (2018b) did an analysis of the possible safety-relevant tasks that could be handled by a remote operator on GoA level 3. They found that GoA level 3, as opposed to GoA Level 1, had a significantly lower frequency of tasks that needed to be handled by the operator. This could be very beneficial to the cognitive function of the driver and thereby the overall safety (Brandenburger, Naumann and Jipp, 2021).

A study on air traffic control found that automation could make the staff transition from constantly monitoring and making decisions, to a more observing supervisor role (Wang, Y. *et al.*, 2021). It is reasonable to think that this could apply to the aforementioned vision of remote train drivers intervening in certain situations. Zulqarnain and Lee (2021a) argues that the future application of remote driving could be with an operator that is responsible for many vehicles at the same time. As they argue, the increased benefit would have to be considered against the risk of spreading the human operators too thin. While the management have economic incentives for reducing the staff (Abe, 2019), the ideal situation is where the ratio between the number of vehicles and operators is within the limits of the operator's capability for monitoring safely.

3.3.3 Operation in remote/rural areas

The foundational advantage of remote driving instead of on-board driving, is the flexibility in location of the driver. Zieger and Niessen (2021) points out how high degrees of railway automation could make trains a viable option in rural areas. The mining industry has been on the forefront of the development of higher automation in railway, as they are often operating in rural areas (Singh *et al.*, 2021; McNab and Garcia-Vasquez, 2011). Related to the Rio Tinto automation project in Western Australia, Carter (2008) emphasizes the importance of work location for being an attractive employer.

Another aspect of this is regional railway lines, the focus area of European Rail's FutuRe project (EU-Rail, 2023a). Although railway lines in rural areas have a low utilization rate compared to big inter-city mainlines, they can be essential to the local population (Sieber *et al.*, 2020). The low customer-utilization naturally leads to the company operating the line choosing to reduce the frequency of departures (Sharav, Givoni and Shiftan, 2019; Šipuš and Abramović, 2017). This, in turn, can increase the idle time of the staff onboard the train, as they wait at the end stations. Improved scheduling can be very beneficial for reducing the idle time of staff (Rählmann and Thonemann, 2020).

3.3.4 In train depots

Another possible area that remote-control could be valuable for is depot management (Lagay and Adell, 2018). Depot management refers to all the actions performed at the railway depots, where the rolling stock is often located between the time in active use (Darmanin, Lim and Gan, 2010). This is also where a lot of the preparation and maintenance can take place, and as a result there is a significant amount of associated logistics (Wang, J. *et al.*, 2021). In 2022, Siemens presented a remotely operated tram depot for the Potsdam tram, where many of the tasks now could be handled by a control center (2022). This can significantly reduce the need for on-site personnel, with the associated risks (Crosby, 1988; Vithanage, Harrison and DeSilva, 2019), as well as the staff needs in general. Remote monitoring could also help reduce the time spent in maintenance (Fraga-Lamas, Fernández-Caramés and Castedo, 2017).

3.4 Railway communication systems

Throughout the progress of railway technology, many different systems for railway communication have been utilized. This section will briefly look at some of the systems that are common in Norwegian and other railways today, and what is in the works for the future.

3.4.1 GSM-R

GSM-R stands for Global System for Mobile Communications – Railway. It is a specialized version of the GSM wireless communication system designed for the needs of the railway industry, and works as a part of the ERTMS signaling system (Lindström, 2012). GSM-R enables reliable voice and data communication between trains and dispatchers. The bandwidth is sufficient for exchanging what has traditionally been the needed information, such as position and speed. In the Norwegian network, GSM-R was fully implemented in 2007 as a response to a train crash in 2000 (Amundsen, 2013). There has been some criticism about this decision in later years as GSM-R, which is similar to 2G in data throughput capability, has been severely bypassed by the rapid technological development (Finne *et al.*, 2019).

GSM-R operates at a frequency of about 900 Mhz and is therefore limited to a low peak data rate of about 21 kb/s (ETSI-TS, 1999). For comparison, 4K video streaming in high movement requires a throughput of about 26,8 mb/s (An *et al.*, 2022). In return, the lower frequency makes it more resistant to reflections, meaning it can travel longer distances (Davis and Agarwal, 2003; Neruda, Vrana and Bestak, 2009). The great coverage of lower frequency signaling has made it a reliable tool for the railway (Abadir Guirgis, 2013), and is a large reason why it is so commonly utilized by militaries around the world (Poonkuzhali, Alex and Balakrishnan, 2016; Yusof *et al.*, 2021).

3.4.2 LTE-R

Long-Term Evolution or LTE is commonly referred to in railway as a possible solution for the next generation of signaling (Calle-Sánchez *et al.*, 2013; He *et al.*, 2016; Zhou *et al.*, 2015). Sniady and Soler (2013) points out that the main benefit of this upgrade would be that LTE can support many of the more advanced data services needed in a modern, dense, and high-speed rail network. Furthermore, LTE shares support with the GSM partnership, which could ease the transition (Sauter, 2010). A concern with LTE was that the packet-switching technology was not reliable enough for safety-critical solutions (Sniady and Soler, 2014). Tests in later years has found the technology sufficiently reliable compared to GSM-R (Chen, Zhan and Niu, 2022) and so China and a few other countries have started to implement the railway-designed LTE-R (He *et al.*, 2022). Although it is a large upgrade from GSM-R, the bandwidth of LTE-R will likely not be sufficient for supporting the high-end smart railway features such as high quality video transmissions and remote maintenance (Ai *et al.*, 2020). The teleoperation company Voysys (2023) disagrees, stating that their system is capable of remote driving on LTE-networks.

3.4.3 CBTC and WiFi

Communications-based train control (CBTC) uses radio communication, often with Wi-Fi, to transmit precise and timely train control information. With more than a hundred systems now installed worldwide, CBTC seems to be the preferred technology among mass-transit railroad operators today (Farooq and Soler, 2017). This is because urban metro systems have significantly more traffic and subsequently shorter headways, and so GSM-R did not have the sufficient capacity (Lardennois, 2003). Alvarez and Roman (2013) points out how the low costs of commercial WiFi solutions has made it ideal for covering the relatively small distances of metro systems with frequent access points (AP), also covering the many underground sections. On the opposite side, Farooq and Soler (2017) points to that the benefits of WiFi-coverage in urban transportation systems is a weakness on mainline, as the short range would require too many APs on the long distances.

There are typically three main components to a CBTC system; the ground control, the train's subsystem, and the data communication system (Li *et al.*, 2020). With a very simplified explanation, the trains are given movement authority (MA), meaning the speed it can move in a given zone (Kadri, Collart-Dutilleul and Bon, 2022), based on the position data that the trains are sending to the ground computer. The onboard computer then calculates the operation commands using the automatic train control system (Wang, Yu and Jiang, 2016).

3.4.4 FRMCS

The Future Railway Mobile Communication System (FRMCS) is the next generation wireless technology for railway, that aims to revolutionize the way trains communicate with each other and with the control center (UIC, 2023). The system will enable faster, more reliable, and more efficient communication between trains, trackside equipment, and control centers, while also being capable of supporting systems for alternating control (Adriansyah *et al.*, 2022). It therefore has the potential to be a valuable system for supporting autonomous or remote driving. FRMCS could possibly be powered by a 5G satellite communication system (Iacurto *et al.*, 2022) or by a more traditional tele network (UIC, 2020).

The time frame for an implementation of FRMCS is still uncertain. The project was first launched by UiC in 2012 (Rispoli, 2020), and in 2020 the first step came when the European Conference of Postal and Telecommunications Administrations - Electronic Communications Committee (CEPT-ECC) decided to adopt 1900-1919 MHz frequency for railway mobile radio (Hu *et al.*, 2022). Many have pointed to 2030, as GSM-R is nearing its abandonment (Vizzarri, Mazzenga and Giuliano, 2022; Allen *et al.*, 2022). Bane NOR, responsible for the Norwegian railway infrastructure, also believes the implementation will come in the time period from 2025 to 2030 (2022a).

3.5 Required data communication capacity

Remote driving is reliant on a network quality that is sufficient for delivering reliable, low-latency video to the remote operator (Feng *et al.*, 2019; Kim *et al.*, 2022). This section covers different aspects of both current capabilities, and requirements for network communication.

3.5.1 Comparison of the network generations

There has been a rapid surge in the capabilities of mobile networks. Table 1 is meant to illustrate this, with the exponential growth in the ability for transferring data. It is important to note that there are many variances inside each generation of technology, and so it is possible to find examples of vastly different bitrates within the same technology. From the 2G-technology which GSM-R is equal to, and till the 5G-technology that is being widely deployed for commercial mobile networks today (Blind and Niebel, 2022), the potential for data throughput has multiplied by about 300 000. As Finne *et al.* (2019) points out, the difference between the standard in railway and the standard in commercial use for mobile phones has become glaring.

Table 1: Rough estimation of the capabilities of different generations of networks, based on ((Gnatzig *et al.*, 2013; Churi *et al.*, 2012; Patel, Shah and Kansara, 2018; Zeqiri, Idrizi and Halimi, 2019; Narayanan *et al.*, 2021; Al Mtawa, Haque and Bitar, 2019).

Technology	2G	2,5G	3G	3,5G	4G	4G+	5G
Max downlink speed	100 Kb/s	1 Mb/s	3 Mb/s	40 Mb/s	100-150 Mb/s	1 Gb/s	20 Gb/s
Average downlink speed	40 Kb/s	500 Kb/s	1 Mb/s	4 Mb/s	10 Mb/s	30 Mb/s	260 Mb/s
Max uplink speed	40 Kb/s	250 Kb/s	500 Kb/s	11 Mb/s	50 Mb/s	1 Gb/s	10 Gb/s
Average uplink speed	10 Kb/s	50 Kb/s	100 Kb/s	500 Kb/s	3 Mb/s	8 Mb/s	34,97 Mb/s
Frequency range	900-1800 MHz	900-2100 MHz	1800-2500 MHz	1800-3000 MHz	1000 MHz-3500 MHz	1000 MHz-8000 MHz	450 MHz – 24-53 GHz
Meant for	Audio	SMS/MMS/ Internet access	SD video streaming	SD video streaming	HD video streaming	1080p video streaming	4K video streaming

With the speedy development of the technology, the question becomes what the correct time to settle for a new system to implement. Tikhonov, Schneps-Schneppe and Schneps-Schneppe (2021) points out that there is a decision to be made between upgrading to the fourth, or immediately jumping to the fifth generation. The network solutions LTE and LTE-Advanced, which some countries has started to adopt as the successor to GSM-R, is often referred to as a variation of 4G and 4G+ respectively (Sârbu *et al.*, 2019). This solution for railway is usually referred to as LTE-R. Meanwhile, the fifth generation of railway networks is named 5G-R. Due to the increased capacity and resulting increased capabilities (Zhao *et al.*, 2021), many believe that 5G could finally be the technology that is worth upgrading from GSM-R for (Chen *et al.*, 2018). The next generation, 6G, is still in the early developmental phase (Abdel Hakeem, Hussein and Kim, 2022) and will still be some years away from commercial implementation.

3.5.2 Video streaming demand

In a measurement of video streaming in the resolutions 720p, 1080p and 2160p (4K), Di Domenico *et al.* (2021) found the average bitrate used to be 8, 29 and 44 Mb/s respectively. There was, however, a high relative variation, especially for 720p and 1080p. This seems to be close to the consensus (An *et al.*, 2022; Sidaty *et al.*, 2019), although there are obvious variations, created for instance by different framerates. In order to mitigate the fluctuations in network throughput, there are solutions, such as MPEG DASH, that can dynamically switch the resolution of the video to aid in creating smooth playback (Vlaović *et al.*, 2021). Another important method that is widely utilized for improving performance for video transmission is encoding (Li *et al.*, 2022). This refers to techniques that compresses video before uploading to reduce the needed data capacity (Sullivan and Ohm, 2010). Dror *et al.* (2021) suggests that a content adaptive solution will be preferable for vehicles in motion, due to the variance in network quality.

While it is important that the control center is able to receive the video stream in sufficient quality, the more difficult part is being able to upload the live stream from the train moving in varying network areas. Furthermore, as Table 1 illustrates, the average upload speed is significantly lower than the download speed. Even for the high-speed 5G networks, there could be issues with latency for high definition and especially 4K video uploading (Ren *et al.*, 2021). According to a test run by Fadda *et al.* (2021), normal video chat applications require about 5 Mb/s both ways, while 4K video uploading requires a continuous data speed of about 30 Mb/s. The latter is near what (Telenor, 2023a) is claiming to average in tests among their 5G-users, which seems believable given higher result values elsewhere (Daengsi, Ungkap and Wuttidittachotti, 2021). An important method that is widely utilized for improving performance of video transmission is encoding (Li *et al.*, 2022). This refers to techniques that compresses video before uploading to reduce the needed data capacity (Sullivan and Ohm, 2010). Dror *et al.* (2021) suggests that a content adaptive solution will be preferable for vehicles in motion, due to the variance in network quality.

3.5.3 Network protocols

While there exists many different network protocols, there are mainly two foundational ones that could be utilized for video communication: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). They are both situated at the transportation layer (Al-Dhief *et al.*, 2018), but differs significantly from each other in philosophy. TCP ensures that all data packages have been received and structured correctly, while UDP ignores this. In simplified terms, this means that stability is sacrificed in favor of speed (Yu and Lee, 2022b). The TCP has also been known to struggle with bandwidth on long distance network paths (Tashtarian *et al.*, 2022). The WebRTC, which is a commonly used collection of APIs that can be used for browsers and mobile applications (Holmberg, Hakansson and Eriksson, 2015), is based on UDP (Jansen *et al.*, 2018). (Farooq and Soler, 2017) states that UDP is preferrable to TCP also for the radio communication system used in CBTC.

Hypertext Transfer Protocol (HTTP) has been nicknamed the internet’s multimedia courier, as it is responsible for a large portion of the communication between servers and web applications (Gourley *et al.*, 2002; Lederer, Müller and Timmerer, 2012). It is a very useful tool for delivering stored multimedia content to the requesting user (Mok, Chan and Chang, 2011). HTTP adaptive streaming (HAS) is currently the most used option by streaming services such as Netflix and YouTube (Seufert *et al.*, 2014; Barman and

Martini, 2019). Meanwhile, DASH or Dynamic Adaptive Streaming over HTTP, is a standard that addresses some issues with end-to-end streaming as it splits video into smaller video segments which is then transmitted with different methods, and then displayed to the client with the best possible quality that is available for that segment (Alzahrani *et al.*, 2018). DASH is also excellent for avoiding handover when a stream travels to a different PLMN, meaning a new country (El Marai and Taleb, 2020).

The real-time protocol (RTP) provides end-to-end network transport functions that are suitable for transmitting real-time data (Schulzrinne *et al.*, 2003). (Loonstra, 2014) points to RTP as the preferable option for video streaming, given that firewalls do not require the use of HTTP. Gnatzig *et al.* (2013) also found RTP the best for keeping delays to a minimum. In a comparative study of real-time communication platforms, Nistico *et al.* (2020) found that the RTP was the most commonly used. The same study found that most of these services opt to use peer-to-peer communication layer when only two parts is participating, in addition to a lot of other protocols for different purposes. The real-time streaming protocol (RTSP) is situated over RTP and acts as controller for the RTP-transmission, selecting the channel and method, as well as keeping control of the multiple recipients (Jianbing and Shuhui, 2019). It is very useful for minimizing latency, but can have shortcomings when entering a new PLMN if the handover issue is not mitigated (El Marai and Taleb, 2020).

Transport Layer Security is the most-widely used secure communications protocol on the internet (Al Fardan and Paterson, 2013; Serrano *et al.*, 2021). The variant DTLS or Datagram Transport Layer Security was designed for data exchanges over UDP instead of TCP (Carrascosa and Bellalta, 2022). This solution is common in the WebRTC, and for remote playing of video games it is often used for sending the input of the controller to the hardware (Di Domenico *et al.*, 2021). DTLS extensions could also aid in providing secure RTP (McGrew and Rescorla, 2010).

3.5.4 Two-way communication

Remote driving requires two-way communication between the vehicle and the control center (Kang *et al.*, 2018). The driver sitting at the control center needs video input sent from a camera aboard the train, as well as other information such as measured speed. In the other direction, commands made by the driver needs to be sent to the train and performed by the actuator. Figure 1 is a simplified model of how the signals could travel in the remotely operated test project. The network tower represents the closest tower that picks up the video signal from the onboard video camera, before it transmits it through to the platform of choice, which the remote operator then receives from. Upload and download processes are colored green and red respectively, as there are differences in the speeds of these actions. Inside the prototype, there is a computing unit that is capable of processing the signals received from the remote operator and translate it into the correct actuator response (Gnatzig *et al.*, 2013).

In a test where a commercial car was fitted with a standard 4G dongle connected to the UK mobile network, and remotely operated, they found that the delay from operator action to actuator action was at about 32 ms (Saez-Perez *et al.*, 2023). In the other direction they found that video streaming of 1280 x 720 and 640 x 480 pixels had a delay of 648 and 563 ms respectively. While this is not a clear precedence for how delays will be, it demonstrates that the major concern regarding latency will be in the direction from the train towards the remote driver. According to Davis, Smyth and McDowell (2010), the driver performance for cars was significantly affected when the delay exceeded 700 ms. It was also found that having fixed delays gave better results than variable due to the predictability of steering. Due to the one-dimensional nature of railways (Bruzelius, Jensen and Sjöstedt, 1994), this is likely to be less true for railways.

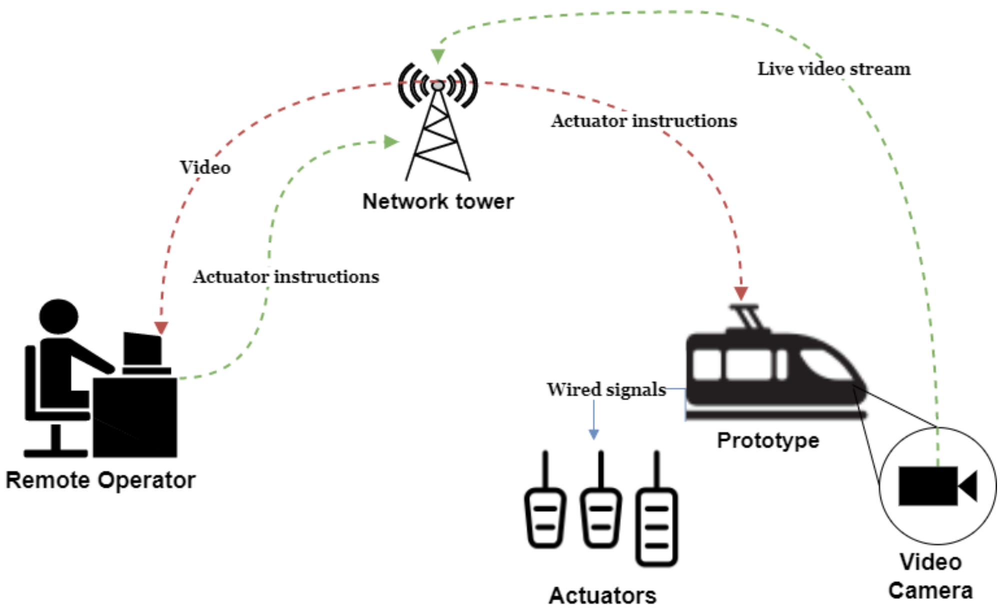

Figure 1: Simplified illustration of the communication in the test project

3.5.5 Current capabilities

In the specification for the project, it is stated that the public tele network will likely have to be utilized (EU-Rail, 2023c). This is because the existing GSM-R network is not built for delivering the required amount of data for video uploading (Sniady and Soler, 2012). The next generation of railway communication system will likely be a massive upgrade in this regard. Iacurto *et al.* (2022) found in a simulation that video streaming is likely to be the most network-demanding feature for the FRMCS, but that it should be feasible. Some early standalone examples of smart railways have already been implemented, such as the Beijing–Zhangjiakou high-speed railway (Ai *et al.*, 2020). In general, 5G as a technology is rapidly maturing, and being implemented for commercial use in many countries around the world (Pandav *et al.*, 2022). A 5G solution that can satisfy the railway specific needs (5G-R) is therefore a possibility (Schumacher, Merz and Burg, 2022; Duan *et al.*, 2021). While 5G is often referred to as a requirement for remote driving, it is important to emphasize that it also can be achieved at lower speeds. The Swedish company Voysys creates solutions for teleoperation that allows video transmission over 4G/LTE (Amador, Aramrattana and Vinel, 2022). Given that 5G coverage requires more network stations to be built (Geradin and Karanikioti, 2020), 4G/LTE is a cheaper alternative.

3.5.6 Difference for moving vehicles

Another aspect when discussing network capacity in moving vehicles is the handover (HO), meaning the process of switching what network tower the device is connected to. In a study on 5G performance for streaming video aboard high-speed trains, there was a significant drop-off in throughput after every handover (An *et al.*, 2022). Meanwhile, for the testing done at 80-120 km/h, which is more similar to the running speed of most Norwegian lines (Rodal, 2002), the dip in throughput and video resolution were significantly less severe. This lower speed also reduces the concerns regarding the impact of the Doppler effect (Adriansyah *et al.*, 2022; Farooq and Soler, 2017). While 5G for railway, 5G-R, is still in the early stages (Sun *et al.*, 2023), the fourth generation LTE-R is already being implemented in some countries and are reported to have great reliability for high-speed rail (Chen, Niu and Wang, 2021).

3.6 Communication services

As previously disclosed, remote driving relies on two-way communication. If a full implementation were being planned, it would be sensible to develop, adopt or purchase a customized and exclusive system which could provide these services. For a test project, however, it seems more reasonable to utilize existing services. Therefore, it is useful to do a review of the different options that are available commercially, and how they would fit to the needs of this pilot project.

3.6.1 Live video streaming options

Since the early days of the internet 30 years ago, many different methods for online video streaming have been developed (Li *et al.*, 2013). Today, there are many actors in the market of providing live video streaming, both one- and two-way. As there is no need for mutual video communication, the evaluation will only be based on the quality of one-way live streaming. Ray *et al.* (2019) makes a good point in that not all live streams have the same purpose. There is a great difference between live streams that are reliant on interaction with the viewer and not. In the case of remote driving, there is a definite need for viewer interaction with low delay. This often comes at the expense of stability in the framerate, as there is reduced time to buffer (Li *et al.*, 2014). An example is teleconferencing tools such as Zoom, which can deliver very low latencies (Boland *et al.*, 2022). They are generally based on the UDP-layer (Sander *et al.*, 2021). It is important to note that this technology has been in rapid development in the past years, especially expedited by the covid-19 pandemic, and today there are many new solutions for achieving low-latency live (Li *et al.*, 2023).

YouTube is a well-known website, with a vast catalogue of user uploaded videos. They do also offer a live streaming option, which could be utilized for the test project. YouTube Live offers an ultra-low latency option at 2000 ms, but this is only available for video quality lower than 1440p (Arunruanggsirilert *et al.*, 2022). Twitch, who shares a lot of similarities with YouTube Live, is mainly used for live streaming of video games and other events. As of 2018, the measured latency from the content creator performs an action until the viewer receives it was about 12 seconds, equal to 12 000 ms (Glickman *et al.*, 2018). It is important to stress that as YouTube and Twitch is based on distributing good quality video content, there is a sacrifice made in latency. As Uitto and Heikkinen (2021) and many others point out, it is very possible with modern technology to achieve significantly lower latency with sufficient quality and stability. A more specialized multimedia framework, such as GStreamer, has significantly more flexibility and power for this specific use case (Govindarajan, Bernatin and Somani, 2015). Studies by Kang *et al.* (2018) and El Marai and Taleb (2020) also utilized the GStreamer framework for their testing of real time streaming.

A market segment which could have directly transferrable experience is cloud-based video games. Solutions like Playstation Now, Google Stadia and GeForce Now, with more on the way, utilize a model where the gamer "streams" the visuals from a remote hardware and then interacts with the controls accordingly (Graff *et al.*, 2021). This requires lightning quick latency, as it should feel like the commands made by the human are instantly performed. Di Domenico *et al.* (2021) did an analysis of the data flow of the three aforementioned services and found that all of them use varying forms of UDP connections for their video and audio streaming.

3.6.2 Actuator communication options

While the options for live video streaming are based on sending the largest amount of data as efficiently and smoothly as possible, the actuator commands require very little data to be sent (Vishay, 2013). Therefore, many of the traditional solutions for actuators are based on reliability and uses lower, but more stable frequencies. In the case of remote train control, this means that the transmission method is very flexible.

Several test projects with remote driving have built their own user interface for their remote-controlled operation (Yu and Lee, 2022a; Lin *et al.*, 2022). Many of these are based on a Robot Operating System (ROS) architecture. According to Schimpe *et al.* (2022), TELECARLA, is the only available, open-source software for teleoperated driving, while other systems such as SILAB has a license fee (Ihemedu-Steinke *et al.*, 2015; WIVH, 2023). The system tested very well, performing almost identically for local and remote driving (Hofbauer *et al.*, 2020a). It is also scalable, meaning that it is possible to change the amount of sensor information transmitted to fit needs and network capability, as well as be integrated with other simulators that provide a Robot Operating System bridge. For the actuator communication, the GUI uses Simple DirectMedia Layer (SDL2) for registering commands made by the remote operator and the Remote Procedure Call (RPC) protocol for sending the control commands.

Like with video streaming, there are commercial actors in the market as well. Many of these, like Voysys (2023) and Imperium Drive (2023), deliver a software solution that handles both directions of communication. These are specially designed for remote driving, utilizing methods for dynamically adapting to network conditions, with the focus on maintaining a low latency (Amador, Aramrattana and Vinel, 2022).

3.7 Existing projects

Remote driving as a concept is not completely new. Worldwide, there are many examples of different types of projects involving remotely controlled operation, or comparable technologies. This section will cover some examples of previous remote-control projects, both tests and in-use.

3.7.1 A step towards full autonomy

A common use of remote driving has been as part of larger projects with the end goal of achieving full autonomy. The French National Railway (SNCF) successfully finished a test of a remotely controlled locomotive in July 2019 (Singh *et al.*, 2021). The first round of testing consisted of checking the capability for performing the tasks of traction and braking via video, testing the actuators' response to control center action, and configuring a temporary 4G network (Masson *et al.*, 2019). The end goal of the full project is having the train capable of operating automatically.

An autonomous railway project that already is in active use is the Rio Tinto mining line in western Australia. The first run was monitored remotely from the control center in Perth, over 1500 kilometers away (Gattuso, Cassone and Mai, 2022). The train is not the only thing that has been automated, as other parts of the mine hauling process is now handled either remotely or autonomously (Voronov, Voronov and Makhambayev, 2020). While the train now operates automatically, Wardrop (2019) notes that also the autonomous train have use for some form of CCTV-monitoring. Capability requirements for remote monitoring and remote operation is similar, and so remote driving is natural as a steppingstone, or as a measure for handling emergency situations (Tonk *et al.*, 2021).

3.7.2 Remote driving in other sectors

Work is also being done in other sectors of transportation, which could contribute with valuable insight, and technological progress, also for remotely operated trains. Teleoperated driving of cars is among the areas where a lot of research is being performed (Ackerman, 2015; Etherington, 2017). Li *et al.* (2014) performed a test with a WiFi-network, similar to what many local transit CBTC-systems uses. Chucholowski, Tang and Lienkamp (2014) and Jang *et al.* (2009) are examples of 5G-network throughput tests for cars and the results share many of the same concerns as trains. In later years, many teleoperators such as Ericsson, Verizon and Telefonica have made a push towards making remotely driven cars a reality (Zaidi *et al.*, 2018). In 2017, Ericsson and Verizon performed a test where they managed to stream 4K, 360-degree video captured from a car in motion to a driver's VR headset (Ericsson, 2017). In early 2023, the German startup company Vay, together with Ericsson and Deutsche Telekom, performed a demo with a remotely driven car on public roads in Berlin (Ericsson, 2023). At a tech conference in the end of February 2023, they even remotely operated a car in Germany from the showroom floor in Barcelona, showing the capabilities also at longer ranges (Reuters, 2023).

While tests like this is useful for displaying the potential of the technology, it is important to stress that they are performed under good conditions with a lot of preparation. There are still some obstacles before the technology could be fully functional in an open environment with a lot of simultaneous users. Neumeier *et al.* (2019) suggests a system where the vehicles are constantly reporting their network quality and followingly becomes prohibited from driving in zones without satisfactory connection. This control process could use the ICMP or other solutions for checking ping (Bogdanoski and Risteski, 2011), which would require a minimal use of network capacity. Saeed *et al.* (2019) questioned the feasibility of having remotely driven vehicles on a full road network, as even areas with high density of 5G support struggled with stability. A main factor for this was the unpredictability and variation in traffic, which causes interference and heavy strain on the area network. They do however emphasize that remote driving support is a lot more feasible in planned and structured environments, such as trucks or buses. Fewer simultaneous users in an area will have a positive effect on down- and uplink speeds (Tenorio *et al.*, 2010).

3.8 Concerns of remote driving

The number of railway accidents has been steadily decreasing in Europe over the last 20 years (Rungskunroch, Jack and Kaewunruen, 2021). While railway is among the safest methods of transportation (ETSC, 2003), the consequences of an accident can be catastrophic due to the number of passengers (Gely, Trentesaux and Le Mortellec, 2020). This has resulted in railways having very high safety standards (Yan, Wu and Wang, 2018). This section will cover some of the challenges that remote driving is facing, as well as some of the mitigation measures that can be made.

3.8.1 Reliability

Reliability is among the major concerns for any new technology. For remote driving specifically, a hindrance for reliability could be in the form of lacking network stability, leading to high latency or even loss in communication (Zulqarnain and Lee, 2021b). The most obvious countermeasure to the issue of reliability is to actively build a cohesive system for network coverage, as for instance with the 200 5G antennas built for the Beijing-Zhangjiakou high-speed railway line (An *et al.*, 2022). However, although network connectivity can be proclaimed to be highly reliable, there is always a concern related to Murphy's law (Bloch, 2003) that everything that can go wrong, will go wrong. This is especially true when considering the massive areas that needs to be almost perfectly covered by adequate network signals. Mitigating the remaining percentages where this issue is present will likely rely on creating solutions that is flexible and manages to predict and prepare for disturbances (Sato, Kashihara and Ogishi, 2022; El Marai and Taleb, 2020).

3.8.2 Reduction in driver awareness

A major concern with remote driving is that it could increase the driver's fatigue, while reducing the situational awareness. Based on tests in simulators for the TC-Rail project, Gadmer, Pacaux-Lemoine and Richard (2021) reported that the drivers, among other things, noted how they lacked proprioception, meaning a perception of the train's location and movement. For driver fatigue and responsiveness, another test performed showed that operating with higher GoA could combat the negative impact of operating remotely (Brandenburger, Naumann and Jipp, 2021). A solution to mitigate the issue would be to conduct thorough test of the driver's awareness in the remote system (Hofbauer *et al.*, 2020b), perhaps with improved iterations based on the results. Mutzenich *et al.* (2021) concurs with this, stating that the best possible situational awareness is achieved when the measures for providing the driver information and feedback is balanced against the additional workload.

3.8.3 Shared task responsibilities

Another concern, pointed out by Inagaki and Itoh (2013), is the risk that an actor in the system can become over trusting of the other actor's capabilities. This could imply that the remote driver trust of the automatic mechanisms makes him/her over reliant on the system. Balfe *et al.* (2012) found potential issues with train drivers' performance in systems where there was a conjunction between tasks handled by the human operator and the automatic system. Brandenburger (2022) concurs with this, finding the results extra worrying at GoA level 2. This is in many ways the intermediacy of automation, in which many tasks are handled automatically, but there is still a need for constant monitoring from the human operator. It is important to emphasize that is not an issue exclusive to remote driving, as it is very much applicable to all automation processes in railway. Due to how interconnected the process of increasing automation and introducing remote driving is, it is still a relevant concern to consider. This is exemplified by how the test locomotive for the FUTURE project is planned to have the capabilities for implementing different sensors (EU-Rail, 2023c). To mitigate the issue, it is important to have a transparent system where the remote drivers receive full understanding of the capabilities of the system and their own responsibilities (Pacaux-Lemoine, Gadmer and Richard, 2020).

3.8.4 Cybersecurity

Cybersecurity is a collective term for the methods that can be used to hinder network-related intrusion of control (Craigen, Diakun-Thibault and Purse, 2014). As remote driving is reliant on wireless communication, it is in need of systems for protecting it against outside actors that, for different reasons, seek to interfere with the communication between train and control center (Gadmer *et al.*, 2022). A study on passenger acceptance of teleoperated railways (Cogan, Tandetzki and Milius, 2022) found that the participants largely agreed that cybersecurity was a significant threat. According to Fraga-Lamas, Fernández-Caramés and Castedo (2017), this fear is justified, as cybersecurity will be a continuous threat to the smart railway. In the TC-Rail project there is in fact a team committed to working on cybersecurity (Aktouche *et al.*, 2021).

In general, the major concern is that outside actors could hack into the vehicle, effectively taking control of things like the train's actuators and communication (Eiza and Ni, 2017). This is not an entirely new issue (Gabriel *et al.*, 2018), but it will be magnified by the increased reliance on network communication (Cosic, Schlehuber and Morog, 2019). El-Rewini *et al.* (2020) argues that there are three layers: sensing, communication, and control, that could be attacked in a modern vehicle. Sensing refers to the vehicles' sensors and dynamics, communication refers to the V2X-signaling, and control refers the vehicles' steering systems. This could for instance be done through sending fake messages and instructions to the train, and finding ways for the vehicle to ignore outside sources could be critical (Bharati *et al.*, 2020).

Jamming, meaning deliberately interfering with signals, is another threat that railways will become more vulnerable to with increased wireless communication. The TC-Rail remote driving project seems to focus heavily on how to mitigate the issue (Masson *et al.*, 2019). Zhu *et al.* (2020) proposed a defensive system that could combat the issue for a CBTC system. Railways are not alone in being threatened by jamming, as it has been an increasing issue also for the military in later years (Vadlamani *et al.*, 2016). With a modern military seeking to adopt 5G capabilities, new techniques such as frequency hopping and beamforming could be utilized to mitigate jamming (Skokowski *et al.*, 2022).

4 Possible testing routes in Norway

As part of EU-Rail's flagship projects on revitalizing regional railway lines with new technologies, NTNU and partnering actors has been tasked with testing a prototype of a GoA level 3 or 4 train. The first part of testing is planned to be performed with a remote operated vehicle on railway lines in both Sweden and Norway. This section will cover all aspects of the search for a suitable testing location in Norway.

4.1 Description of the remote driving project

Prior to describing the search for a fitting test location, it seems valuable to provide some insight into the project. This section will cover some aspects of the project's background, specification, and potential execution.

4.1.1 The FutuRe project

Europe's Rail Joint Undertaking, or EU-Rail, is the European Union's partnership for rail research and innovation (EU-Rail, 2023b). One of their flagship projects is named FutuRe and is focused on revitalizing regional railway lines through cutting costs while ensuring reliability and high service quality (EU-Rail, 2023a). In order to achieve these cost-efficient regional lines, new technological opportunities will have to be capitalized on. Among these is the transition towards a high grade of automation that has been made possibly by the rapid technological developments in network communication and machine-learning technology (Trentesaux *et al.*, 2018; Lagay and Adell, 2018). Weichselbaum *et al.* (2013) points out how automation is ideal for regional lines with lower traffic rates. The Norwegian Railway Directorate believes that regional lines could be among the first to be automated (Jernbanedirektoratet, 2015).

4.1.2 FutuRe: work package 8

As part of the FutuRe project's push towards achieving a high grade of automation, Linköping University, NTNU, VTI, and other partners were tasked with performing work package 3 and 8. The latter has a deliverable description of "ATO GoA3/4 including perception and remote driving on G1 regional lines" (EU-Rail, 2023c). The plan is therefore to create and test a vehicle with GoA level 3 or 4 that can be driven on lines in Sweden and Norway. As a segment in the process, the first prototype is planned to be a remotely driven vehicle.

4.1.3 The test vehichle

At Linköping, the vehicle is being built in stages by new teams of students each semester. The first team was tasked with creating the framework and mechanical parts of the vehicle, such as the braking and acceleration functions. This team were given some preliminary specifications that they should fulfill. The most relevant of these are listed in Table 2. At the time of writing this report, the first team is nearing completion for the wheel axle, including braking system and electric propulsion. The next student team will focus on implementing the technical components onto the vehicle frame.

The vehicle will be operated from a control center in Linköping, Sweden. The preliminary specifications were made for the team building the foundational mechanical components, and so the specifications for the communication and other technological solutions have not yet been concretized.

Table 2: Preliminary specifications of the test vehicle

Specification	Requirement	Additional information
Weight	Max 1 ton	Transportable on a smaller truck
Track width	891mm-1435 mm	Possibility for adjusting within this range
Speed	~30 km/h	Using electrical propulsion (batteries)
Room	2 people	
Controls	Drag and brake	Also including an emergency brake
Sensors	Camera	Should be weather protected

4.1.4 Test execution

Although it is planned to gradually introduce sensors and improvements to the prototype, there is a wait until the team in Linköping has made the vehicle ready for the basic features of remote driving. The time window for executing the test will then have to fit with both the normal use of the line and the availability of the prototype. Combined with the possibility that the vehicle will require governmental approval (SJT, 2012), it seems difficult to set a definitive time period for the pilot project's execution.

Compliance with the Norwegian legislations for testing of self-driving vehicles (Lovdata, 2021) is of high importance. This will, among other things, involve a thorough risk assessment and mitigation. Throughout the testing, many measures will have to be performed, as the aforementioned legislations demands thorough use of all means for risk reducing. Making sure that the test vehicle does not tear on, or in other ways affect the track's condition will also be an important evaluation before the full test runs commences.

4.2 Relevant types of lines

For a track to be suitable for this type of test project, there are some traits that are vital. The most obvious is that the track is intact and in an acceptable condition. As the test locomotive has a fraction of the weight of regular trains, there should not be too much of a concern with the track's ground foundation. Instead, the relatively small size can increase the impact of obstructions, or other degradation to the track and its surrounding area. It therefore seems reasonable to prefer railway lines that, to some extent, are being utilized and maintained.

At the same time, it is important that the line is not too heavily trafficked. It is considerably easier to perform a test on a track when not relying on very strict time frames. Furthermore, all test projects are prone to issues, and any possible stops or delays will have exponentially worse ramifications on heavily trafficked lines. It therefore seems logical to select an option which is adequately maintained, while still having as little traffic as possible. This thesis landed on three main categories of lines that could satisfy these fundamental requirements.

4.2.1 Converted draisine lines

Draisine tracks are an attraction for tourists that wish to experience a decommissioned railway line. In Norway, there are currently at least five active draisine tracks. As these tracks are not in use by ordinary traffic, but still in a condition satisfactory for draisines, they could be highly suitable for testing a remote-controlled locomotive. This also applies to the weight of draisines with humans on, that should be somewhat comparable to the weight of the test locomotive.

4.2.2 Museum lines

A museum line, in the context of this article, is defined as a line that is operated by a museum or foundation who runs exhibition rides. There are at least 7 of these currently active in Norway and as there are trains currently running them, it seems likely that they are in an adequate condition for the prototype. A general concern with these lines is that they are often owned by private foundations or museums, which could complicate the process of getting permission to utilize them.

4.2.3 Low-traffic lines

In addition to draisine and museum lines, there exists some other railway lines which could be suitable for the test project. Among these are the scarcely utilized lines, where it could be possible to fit testing into the time schedule. This includes both local lines with limited passenger traffic as well as lines used exclusively for freight trains. Tracks where operation has recently ceased could also be relevant to consider, as they have had minimal time to deteriorate and should be very capable for this task.

4.3 Overview of testing track options

The search for possible test locations, as described in 2.2.2.2, consisted of many methods of information gathering. This included the book Banedata 2013 (Bjerke *et al.*, 2013), tourist and information websites, maps, as well as mail correspondence with the owners when needed. The result was 15 options that generally could be categorized under the previously stated relevant types of railway lines. In Table 3, they are all listed, alongside some basic information and characteristics about them. The data may not be fully accurate, as different sources have contained somewhat inconsistent information. The table should, however, give a good indication about the fundamental characteristics of the 15 options listed.

Table 3: List of potential railway lines for pilot project with key features

Name	Length	Between	# of tunnels	Height difference	Max gradient (‰)	# of major level crossings	Gauge width	Owner	Operator	Present use	Existing network support	Period of normal use
Numedalsbanen	32 km	Veggli-Rødberg	14	140 m	25	0	1435mm (N)	Bane NOR	Grenland Rail	Goods/ Draisine	4G+ (Sporadic 4G and 2G)	Middle of May – end of Sep.
Flekkefjordbanen	17 km	Flekkefjord-Bakkekleivi	17 (max 1,2 km)	54 m	Unknown (high)	0	1435mm (N)	Bane Nor	Flekkefjordbanen AS	Draisine	4G+ near Flekkefjord (rest: 4G/2G)	Start of May – end of Sep. (extra possible)
Valdresbanen	12 /23,7 km	Dokka-Hov	1	90 m	17	2	1435mm (N)	Bane NOR	AS Valdresbanen	Draisine	4G (Sporadic 4G+/5G)	Middle of May – end of Sep.
Ålgårdbanen	3 km	Ålgård-Figgjo	0	10 m	Negligible	1	1435mm (N)	Bane NOR/ Norges Statsbaner	Ålgårdbanens venner	Draisine	5G (4G near Ålgård)	Unknown season (only Sundays)
Setesdalsbanen	8 km	Grovane-Røyknes	1	55 m	Negligible	0	1067mm	Vest-Agdermuseet/ Setesdalsbanens venner	Vest-Agdermuseet	Museum	4G (Blind areas with 2G)	Middle of June – start of sep.
Namsosbanen	6 km	Grytøya-Namsos (Outside city)	1	15 m	Negligible	0	1435mm (N)	Bane NOR	Namsos Camping	Draisine	4G+/4G	Primarily May-Sep.
Urskog-Hølandsbanen	3,6 km	Sørumsand-Fossum	1	15 m	Negligible	1	750 mm	UHB	Museene i Akershus/ Venneforeningen Tertitten	Museum	5G (Sporadic 4G+)	Middle of June – middle of sep.

Name	Length	Between	# of tunnels	Height difference	Max gradient (‰)	# of major level crossings	Gauge width	Owner	Operator	Present use	Existing network support	Period of normal use
Hell-Muruvik (Old Meråkerbanen)	2,8 km	Hell-Muruvik	1	30 m	Negligible	0	1435 mm (N)	Bane Nor (Hernes AS)	Cargo Net, Bane Nor	Goods	5G (Sporadic 4G+) (ex. tunnel)	Unknown, sporadic
Rjukanbanen	16 km	Rjukan-Mæl	1	100 m	18	6	1435 mm (N)	Norsk Industriarbeidermuseum	Norsk Industriarbeidermuseum	Museum	4G/4G+	Middle of June – middle of August
Krøderbanen	25,7 km	Vikersund-Krøderen	1	65 m	10	12	1435 mm (N)	Stiftelsen Krøderbanen	Norsk Jernbaneklubb	Museum	4G+ (Vikersund 5G)	End of June – end of August
Gamle Vossebanen	18 km	Garnes-Midtun	6	45 m	Negligible	9	1435 mm (N)	Bane NOR	Museet gamle Vossebanen	Museum	5G (Sporadic 4G)	Middle of June – middle of Sep.
Thamshavnbanen	22(6) km	Bårdshaug(Svorkmo)-Løkken Verk	1	160 m	36	7	1000 mm	Orkla Industrimuseum	Orkla Industrimuseum	Museum	5G (Sporadic 4G)	Middle of May – middle of Sep.
Lommedalsbanen	1 km	Gundershugget-Smutterud	0	10 m	Negligible	0	600 mm	Stiftelsen Lommedalsbanen	Museene i Akershus	Museum	5G/4G, possible blindspots	May – Sep. (primarily June)
Stavne-Leangenbanen	5,1 km	Stavne-Leangen	2 (max: 2,7km)	15 m	9	0	1435 mm (N)	Bane NOR	SJ Norway	Passenger/Goods	Full 5G (ex. tunnels)	All year
Sydvarangerbanen	8,45 km	Kirkenes-Bjørnevatn	2	50 m	15	0	1435 mm (N)	Sydvaranger AS	None (previous Northern Iron)	Goods	4G/4G+ (Sporadic 2G)	None

4.4 Showstoppers

Before doing an in-depth evaluation of the options, it is important to identify some key factors that can exclude a line from consideration (Bahill and Madni, 2017). These factors are often referred to in project management as "showstoppers" or "killer criteria" and are a collective term for all elements that can stop or severely delay the project. It is important to emphasize that this does not include all negative elements to a line candidate, only the ones who will be a major hindrance to this project.

4.4.1 Track gauge

Although Norway was an early pioneer in the building of narrow railway tracks, the vast majority of the modern-era network uses the standard width of 1435 mm, similarly to most of Europe (Puffert, 2002). In the preliminary specifications for the prototype as seen in Table 2, it is stated that the prototype should be able to handle the track widths 891 mm and 1435 mm. In communication with the team manufacturing the machine, they expressed that it should be relatively easy to make additional notches for widths within this range, given that it was requested prior to the assembly. This does, however, exclude some lines from consideration with a track gauge significantly smaller than 891 mm, as rebuilding the machine is an expensive and unfavorable alternative.

4.4.2 Unwillingness to collaborate/share their line

Several of the railway lines listed as options is owned by private foundations or museums. They have the full right to decline a request to test the remote operated locomotive on their tracks. The governmentally owned Bane NOR could also decide that one of their lines should not be used for this purpose. There are several possible reasons for why the owner of a railway line could reach this decision, including:

- It could be conflicting with their business interests, hindering the normal use of the line.
- It could be an unwanted distraction or something they would have to schedule around.
- There could be skepticism towards new technology in railways, especially regarding automation.
- There could be concerns about the test vehicle harming or tearing on the track and its surrounding area.
- There could be internal rules or policies on what purposes the line is allowed to be used for.

4.4.3 Rules and compliances

In addition to receiving approval from the owner of the line, there could be governmental institutions that will require further permits and clearance for the line to be used. Among these is the Norwegian Railway Authority, Statens Jernbanetilssyn. They have comprehensive regulations on the use of railway lines. In the regulations on museum lines, (SJT, 2016) chapter 6 states very clearly that all vehicles should be approved by them before being allowed on the line. This requires an application with contact info, system description, vehicle building standards and a risk assessment report. Many of the other paragraphs in the regulation is general instructions that the current museum operator likely already has addressed. In the regulation on permissions (SJT, 2012) it is stated that the Ministry of Transport can make exceptions for small railway projects where the goal is not primarily transport of passengers or goods. This is based on the railway law's second paragraph (Lovdata, 2016). Although this description seems applicable to the traits of this pilot project, it is still worth to note that this still would require an approval decision from the Ministry.

Another governmental institution that could have interest in the use of old railway lines is Riksantikvaren, the Norwegian directorate for preservation of cultural heritage. A significant amount of the lines listed in Table 3 are included in their protection program (Riksantikvaren, 2022) and some are even on the UNESCO world heritage list (UNESCO, 2015). They might be concerned about any harm or tear that the test project could inflict on the tracks.

A possible solution to reduce complexity in the application process could be to either team up with the current owner/operator of the line or at least ask for information about how they got their concession for using the line and what measures they have already addressed. While they obviously are unable to provide relevant experience for the prototype vehicle itself, they possess the best knowledge about the current state of the infrastructure.

4.5 Important traits

In addition to the absolute showstoppers that can rule options out of contention, there are some factors that are important to consider in this evaluation.

4.5.1 Track accessibility

Many of the proposed lines would require travel through busy lines in order to be reached, or are not even connected to mainline railway at all. It therefore seems reasonable to prefer transportation by truck. The specifications for the locomotive listed that the vehicle should be transportable by a smaller-sized truck. This will however require accessibility to the track, so that the vehicle can be lifted on. As most of the track will likely be surrounded by nature not fit for the truck, the best option is likely at one of the train stations. There are, however, many stations that are either elevated, too narrow, or in other ways obstructing access to the rails. Finding ways to overcome this issue, such as renting a larger crane or constructing a path for the truck, would likely be expensive. It therefore seems detrimental to look into the accessibility of the track before deciding on a location. There could also be a need for accessibility elsewhere on the line in case of issues and stops during testing.

4.5.2 Network coverage

The demo relies on the locomotive's ability to transmit an acceptable video stream to the control center. There could be value in reviewing the performance of different network coverages. At the same time, it seems reasonable to expect that too weak network quality could harm the project's feasibility and overall success. As previously stated, a 2G level of network throughput will not be sufficient for streaming video to the control center. This would result in "blind spots" where the locomotive travels without being monitored, which could have some obvious associated risks. Mountains are among the geographical environments with the poorest network coverage performance (Fang *et al.*, 2021), due to the obvious obstructions in signaling (Khaled and Talbi, 2019). As Norway is a country characterized by mountains, valleys, and fjords (Hjelle *et al.*, 2015), the ability to cover the vast areas of railway lines with sufficient network coverage will be detrimental to the feasibility of remote driving.

In addition to the general concern of insufficient network coverage of the line, there is an increased risk of this inside the railway tunnels. While it is possible to create sufficient coverage inside long tunnels (Briso-Rodríguez, Cruz and Alonso, 2007), it requires precise planning and implementation (Chaitanya, Sravan and Ramanjaneyulu, 2020), especially for the higher frequencies needed for transferring video (Hu *et al.*, 2022).

4.5.3 Track characteristics

In addition to the aforementioned tunnels, there are some other elements on the track that could be important to consider. Junctions and especially level crossings, either for cars or pedestrians, is a clear factor of risk. According to UIC (2018), 24% of railway accidents happens at level crossings. Here it is also important to consider the legal framework that Norway has established for testing of autonomous and remotely operated vehicles. Here it is stated that the party performing the testing should take every necessary measure in order to prevent harm on life, environment, or property (Lovdata, 2021). This would likely mean that level crossings would have to be guarded or in other ways secured, as a risk mitigating measure. In general, densely populated areas, especially without trackside fences, poses an increased risk as trespassing has historically been a major cause of accidents (Rungskunroch, Jack and Kaewunruen, 2021).

Other characteristics are more related to the landscape that the line is built in. Steep inclines or declines is an example of this. In the event of lost network communication with the locomotive, there could be risks of great acceleration, which in turn could have severe ramifications. The plan is to build an emergency break for the train and if this could be activated upon a prolonged loss of signal, it would to some degree mitigate the issue. This extra brake system is also suggested by Gnatzig *et al.* (2013) as a solution when other system malfunctions occur.

4.5.4 Distance from Trondheim

The project members from NTNU are all located in Trondheim. While the city is located in central-northern Norway, there are still considerable driving distances to several of the railway lines listed as options. The estimated distance to the options listed in Table 3 is in a range between 30 minutes and 14 hours of active driving. As the full process of performing the demo could last an extended period of time, it would be useful to find a location within a reasonable distance from Trondheim. An option to mitigate this issue would be to locate the needed personnel in another city while working on the demo. This would, however, entail some extra cost, require more planning, and reduce the time flexibility of the execution. An exception to this would be railway lines located close to Oslo or Bergen. As Jernbanedirektoratet and Bane NOR already is located here, it is very much a possibility.

4.6 The shortlist of options

Based on discussions with councilor Nils Olsson and an overall assessment of the information found on the different lines listed in Table 3, we selected a few candidates to evaluate. These lines did not have any immediately recognizable showstoppers and seemed to score positively for most of the other important traits. There were many other options that could have been included, but for the sake of doing a more in-depth analysis, this seemed natural.

4.6.1 Thamshavnbanen

As seen in Figure 2, Thamshavnbanen is located very close to Trondheim and the entire line can be reached by car within an hour. The owner of the line is the Orkla Museum of Industry, and for 2023 they operate the line for tourism three days a week between the end of June and middle of August, and only on Sundays until the end of September (Orkla, 2023). It is important to note here that the train is only driven on the 5,5 kilometers between Løkken and Svorkmo. In 2017, there was a derailing on the line during one of these runs, which according to a governmental inquiry was caused by the aging ground beams giving in to the weight (Husby, 2018). The owners of the line ensured the public that they were properly handling the inspection of the line’s condition.

The line runs through a valley landscape and has a solid 5G network coverage throughout, according to Telenor (2023b). According to the book Banedata 2013 (Bjerke *et al.*, 2013), the track has a 1000 mm gauge (Orkla, 2023), which is narrower than the Norwegian standard, but within the margin of the test locomotive. A notch for width regulation was therefore made by the team in Linköping at request from NTNU.

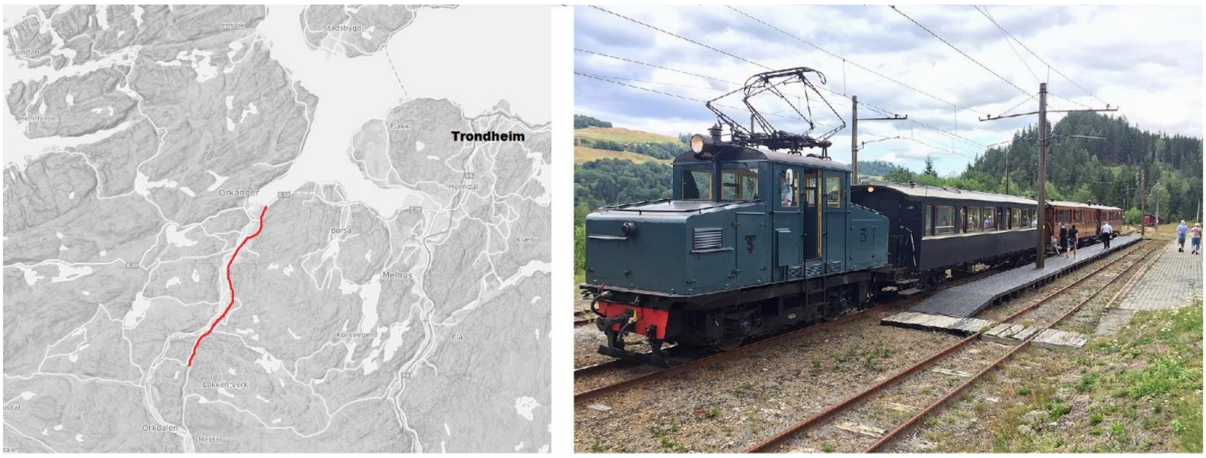

Figure 2: The Thamshavnbanen line. Map of route based on Kartverket (2023). Photo of Svorkmo station by Ree (2018).

4.6.2 Hell-Muruvik (Old Meråkerbanen)

The Hell-Muruvik option is, to a large degree, an unused sidetrack for the route between Hell and Trondheim. While the new main line, completed in 2011, runs through Gevingåsen tunnel (Welde, Bull-Berg and Olsson, 2017), as seen in Figure 3, the sidetrack is routed mostly alongside the water. It is important to note that the sidetrack also has a small tunnel, with the very similar name of Gjevingåsen, but this is only a few meters long. In the same year as the new tunnel opened, there was a landslide at the old line (Kilnes, 2012), which probably exemplifies why it was scrapped as the main line connecting Trondheim to northern Norway.

In Bane NOR’s capacity strategy (2023) they outline how sidetracks can be utilized for loading, unloading, and other logistical tasks. As per of 2016, there was some transport of gas on the line (Jernbaneverket, 2016), but there is limited information on the activity as of 2023. A physical visit to the track revealed that there were some stationary goods trains on the line.

According to Telenor (2023b), there is a solid 5G-coverage through most of the line, with some sporadic occurrences of 4G/4G+. The short tunnel of about 55 meters (Bjerke *et al.*, 2013) is a potential blind spot for the communication, but this is diminishing in comparison to many other tunnels which could have prolonged loss in network connectivity.

Figure 3: The Hell-Muruvik line. Map of route based on Kartverket (2023). Photo of the track switch at the start of the line by Andreassen (2011).

4.6.3 Krøderbanen

Krøderbanen is among the oldest railway lines in Norway and has since its closure in 1985 been operated as a museum line (Bjerke *et al.*, 2013). The line goes between Vikersund and Krøderen, which is approximately a 60- and 90-minute drive from Oslo respectively. From Trondheim, however, it is about an 8-hour drive. The vicinity to Oslo was one of the key beneficial factors for the option, particularly if the involved parties later decided that they want to do the test close to the capital. It is the foundation Stiftelsen Krøderbanen that owns the line and together with the Norwegian Railway Club (NJK) they operate a museum steam locomotive for tourists. For the summer of 2023, the tourist train is planned to run the line every Sunday from the end of June to the end of August (NJK, 2023).

The landscape of the 26 km long line is a shallow valley with negligible incline rates throughout. The network coverage along the railway line is somewhat varied. The area around Vikersund should have excellent 5G signals, but the rest of the line will likely vary between 4G and 4G+ (Telenor, 2023b). Similarly to Hell-Muruvik, there is only one tunnel, with a length of around 60 meters, which should not create a prolonged loss in communication. There are however several level crossings on the line, 12 major ones in total (Bjerke *et al.*, 2013), though the traffic on these crossovers is highly variable compared to many of the other lines in Table 3.

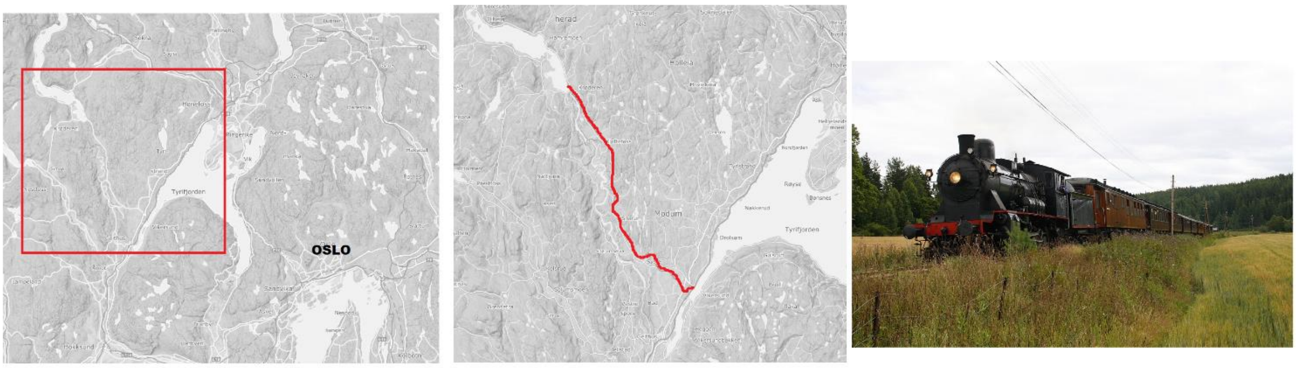

Figure 4: The Krøderbanen line. Map of route based on Kartverket. Photo of the museum train running the line, by Franck-Nielsen (2014)

4.6.4 Namsosbanen

Namsosbanen was the 52 km railway line connecting Grong and Namsos. The commercial traffic stopped in 1978 and in 2005 the bridge right after Skogmo station was removed, effectively splitting the line in two parts (Bjerke *et al.*, 2013). Today, although the track is still owned by Bane NOR, there is no railway activity on either side of the line. Instead, it is possible to rent draisines for a 6-kilometer stretch on the western side between Namsos and Grytøya. As covered in the section on draisine tracks, it seems reasonable to assume that this section should be sufficiently well-maintained for the purpose of the pilot project. According to the website of Namsos Camping (Namsos-Camping, 2023), who rents out the draisines, they are mainly open from early May until the end of August. In recent years there has been a local push for reopening the line, as it would connect Namsos to the major line Nordlandsbanen again (Nilsen, 2021).

As seen in Figure 5, Namsos is located in the Trøndelag-region, with the drive from Trondheim taking approximately three hours. The track moves through the Namdalen valley, alongside Namsen river. This means that the track terrain is very flat. The network coverage is solid 4G/4G+ throughout most of the 6 kilometers, but with a potential blind spot of only 2G coverage near the eastern end at Grytøya.

Figure 5: The Namsosbanen line, with zoom on the current draisine stretch. Map of route based on Kartverket. Photo of the track alongside Namsen river, by Frøyen (2009).

5 Discussion

5.1 Remote driving

This section will discuss the capabilities and limitations of remote driving technology as of 2023. Using Norway as an example, the thesis will also look at the infrastructural capacity and future requirements for implementing remote driving on a larger scale than individual test projects. Then, the possible future trajectory of the technology is discussed, including what value remote driving could bring in the coming years.

5.1.1 Current state of the technology

There are many technological components needed for realizing the vision of safe remote driving. Most of these are in the improving stage, while some can be said to have already reached mature status. From a technological readiness standpoint (Mankins, 1995), we seem to be fast approaching the higher levels where the technology can evolve from individual test projects (Masson *et al.*, 2019) to wide implementation. This would of course be highly dependent on large investments in infrastructure (Chen *et al.*, 2018; Geradin and Karanikioti, 2020; Hu *et al.*, 2022).

5.1.1.1 Capabilities

Network coverage is among the technologies that has seen the most rapid development, with throughput speed capabilities almost exponentially increasing for each iteration. The fifth generation, 5G, is currently being rolled out in Europe (Blind and Niebel, 2022) and is believed to be able to handle many of the new features in the railway system of the future. Among these features is high-quality video uploading, as 5G could enable even 4K resolution streams (Fadda *et al.*, 2021). However, as Iacurto *et al.* (2022) points out, there is a large difference between a single train uploading video and the strained capacity from a whole network of trains that are simultaneously uploading video streams. On the other hand, Saeed *et al.* (2019) points to how trams and buses can have a planned approach to network utilization. It seems reasonable to argue that this is very much applicable to railway lines as well, especially regional lines with lower traffic.

Remote controlling of actuators has been an area of research for many types of vehicles. A key focus area has been creating responsive systems that reacts to the operator's movement without delay. This requires low latency in both communication directions, as they add up together with the operators own reaction time. Teleoperated driving projects like Hofbauer *et al.* (2020a), the teleoperated car startup company Vay (Ericsson, 2023), and teleoperation company Voysys (2023) encourages that the possibilities of creating sufficiently low delays are there. While latency data from Vay's tests has not yet been disclosed, the distance between operator and vehicle in the demo is especially impressive (Reuters, 2023). Given the one-dimensional nature of railways (Bruzelius, Jensen and Sjöstedt, 1994), an argument can also be made that the required standard for latency could be slightly lower than for cars.

5.1.1.2 Limitations

Cybersecurity is a general issue for all network-based technologies and will definitely be an obstacle for any type of smart trains (Fraga-Lamas, Fernández-Caramés and Castedo, 2017; Ai *et al.*, 2020). It is therefore important to acknowledge the issue and actively seek to identify as many security threats as possible (Aktouche *et al.*, 2021). While all the threats and possible entry points may seem discouraging, there are some technologies for cybersecurity defense that could contribute greatly to the vision of safe and smart railway systems. Among these promising methods is for instance deep learning security systems, which actively detects, adapts, and improves when attacked (Kumar *et al.*, 2021). It is also important to note that this is not a new issue that will accompany the shift towards the FRMCS, as today's solutions are also vulnerable to hacker attacks (Gabriel *et al.*, 2018). The need for developing defense systems that can withstand outside interference is already present, however it has been magnified by the increased ramifications that cyber-attacks could have for remote- or autonomous vehicles (Eiza and Ni, 2017; Cosic, Schlehuber and Morog, 2019). The priorities set by the TC-rail project exemplifies that cybersecurity is still a major obstacle for full, commercial implementation of remote driving trains (Tonk *et al.*, 2021; Gadmer *et al.*, 2022).

Driver immersion is another issue that remote driving has not completely solved yet. Gadmer, Pacaux-Lemoine and Richard (2021) pointed out how driver's felt they lacked proprioception. While there are several ways to mitigate this issue, they generally have some drawbacks attached to them. Virtual reality headsets are a great way to give the drivers immersion and the ability to look around, but can have side effects such as sickness (Ricaud, Lietar and Joly, 2015), which can be further induced by lower framerates or latency (Saredakis *et al.*, 2020). Furthermore, uploading high quality 360° video will require a data bandwidth significantly higher than what even 5G can handle, and would require heavy compressing (Han, Liu and Qian, 2020). Other solutions, such as multiple cameras streaming to multiple screens, will also strain the bandwidth capacity to some extent, although there are frameworks, such as TELECARLA, that are able to incorporate it without too heavily sacrificing performance (Hofbauer *et al.*, 2020a).

5.1.2 Situation in Norway

In addition to the overall state of remote driving, there could be value in evaluating the conditions and situation in a specific country. This can give further insight and a clearer picture of the technological readiness level of a typical infrastructure system. As this thesis has evaluated railway line options in Norway, it seemed a fitting location to take a closer look at.

5.1.2.1 Preparedness

The Norwegian BaneNOR has gone through a centralization process in the last couple of years, convening their traffic control centers into three locations (Bane NOR, 2022b). It is important to keep in mind that a potential shift to remote driving will not directly impact the need for dispatching and traffic control, with further use of the ERTMS signaling system being planned in Norway (Bane NOR, 2022a). If the shift to remote driving is not complemented by an increase in automation, it is mainly the location of the driver that changes. It does however seem unlikely that an expensive investment in a 5G network for railway will be made without pursuing other benefits that smart railways can bring (Ai et al., 2022). As part of the European rail network, Bane NOR is digitalizing their signaling system, scheduling completion by 2032 (Bane NOR, 2015). In the national signaling plan (Bane NOR, 2022a), it is stated that this shift will happen in parallel with the implementation of the GSM-R-replacing FRMCS in the window from 2025-2030. Given that the FRMCS could be powered by a 5G-R network (He *et al.*, 2022; Allen *et al.*, 2022), the next ten years could be a vital period for pursuing remote driving opportunities.

The Norwegian railway is diverse, with some areas, especially around the capital Oslo running with small headways, while other parts of the network having very sparse traffic (Harris, Mjøsund and Haugland, 2013; Økland and Olsson, 2021). Aligning with Jernbanedirektoratet's vision towards 2050 (Jernbanedirektoratet, 2015), this could mean some excellent opportunities for testing high-GoA trains on local or regional lines. If successful, this could also help revitalize lines which would otherwise be financially unsustainable, in alignment with Europe Rail's vision (EU-Rail, 2023a).

5.1.2.2 Needed infrastructure

While there are three mobile operators that have built 5G networks in Norway meant for commercial use (Lee *et al.*, 2023), the railway is still using the second-generation GSM-R solution. As Geradin and Karanikioti (2020) points out, the reduced range of 5G requires more base stations to be built in order to cover an area sufficiently. Given that a rail network is both expansive and runs through rural areas between major hubs, it will likely be expensive to implement a 5G network for railways (5G-R), especially in a mountainous country like Norway (Hjelle *et al.*, 2015). This is similar to the reasoning for why WiFi-solutions currently has been almost exclusive used for urban transit systems (Farooq and Soler, 2017).

A shift towards remote driving would require building facilities for the train drivers. Many studies have been conducted on the experiences of the driver in remote operation scenarios. Brandenburger and Naumann (2018a) emphasizes the importance of creating and improving the driver environment through system iterations. It seems useful to rely on previous research before a potential full-scale implementation of remote driving in Norway. This can reduce the risk of widely deploying a flawed system, which could be a safety hazard or force a costly replacement. As for the location of the remote-control centers, there are many aspects to consider, ranging from political motivations, regional presence, staff availability and more. Aligning with the new traffic control centers (Bane NOR, 2022b) could be a good option.

Another aspect is the facilitation for driver training. As Brandenburger and Naumann (2018b), Zulqarnain and Lee (2021a) and many others point to, the implementation of remote driving would mean a substantial shift in the drivers' work routines and tasks. The drivers could move from hands-on to observers. They could be asked to monitor several trains simultaneously, move to another part of the country, work different schedules and many other things. It seems likely that significant resources would have to be allocated for retraining and relocating the personnel.

5.1.3 Future trajectory

As we are still some years away from a potential full-scale implementation of remote driving, it is important to question how the different technologies involved is likely to evolve in the coming years.

5.1.3.1 Network capabilities

As seen in Table 1, the improvement in wireless network's capability for data throughput has been astonishing over the last 30 years. As Finne *et al.* (2019) pointed out, while GSM-R seemed to fit the important needs of railways at the time, it has been drastically bypassed by the commercial mobile networks. While 5G is still being implemented for mobile networks across Europe, different solutions for the 6th generation of networks are already being developed (Tang *et al.*, 2022; Abdel Hakeem, Hussein and Kim, 2022). As for every generation of networks, early work has already started on the new scenarios and capabilities this could bring to the railway (Guan *et al.*, 2021; Lv, Qiao and You, 2020).

The question then becomes when the right time is to invest in an upgraded network for railway communications, as well as what technology to invest in. As the Norwegian national signaling plan states a clear plan to replace GSM-R by 2030 (2022a), the timing for the transition to a new system might not be very interchangeable, although there could of course be some changes. As for the decision on technology, it is going to be heavily reliant on the development and design choices of the FRMCS by UIC and other industry powers (Lagay and Adell, 2018). Some form of 5G-R seems to be the option many are pointing towards (He *et al.*, 2022; Iacurto *et al.*, 2022).

With the rapid evolution, independent of the choice of technology, it does seem logical to create a system that is scalable, integrable, and compatible with other generations, similar to LTE-R (Sauter, 2010). Scalable referring to that the system can have different use case levels for different needs by the operator, integrable meaning that it will be easier to implement and compatible meaning that it will be able to function with other solutions. Inspiration could also be taken from the commercial mobile networks, with a multifrequency network coverage (Agiwal *et al.*, 2021). This way, network coverage could have a minimum for all lines, as well as increased capacity in areas of need.

5.1.3.2 Video communication

As previously discussed, video uploading is going to be among the most network-demanding features of the smart railways. Although the movement of trains could have some negative impacts on network stability (An *et al.*, 2022), there is also some clear advantages that the railway possesses over other means of transportation (Saeed *et al.*, 2019). Video uploading over a dedicated rail network could be designed to ensure predictability, with the minimum headways ensuring that there is a very limited number of trains uploading video to the same network tower, or satellite backup (Iacurto *et al.*, 2022; Masson *et al.*, 2019).

As Li *et al.* (2013) showcases, there has been many different solutions developed for live video streaming, using a wide variety of network protocols and architectural structures. On a foundational level it seems highly favorable that the remote driving systems of the future adopt an UDP-based streaming solution, due to its focus on low latency and high speed (Yu and Lee, 2022b). On a more specific level there are many protocols and solutions, such as DASH, RTP/RTSP, that seems to be able to deliver low latency streaming with various benefits between them (El Marai and Taleb, 2020).

Another aspect that is going to important for the success of video streaming in remote trains is the encoding and decoding techniques. With the substantial bandwidths needed for uploading high quality video, it seems very likely that new and improved methods for video encoding is going to be a key enabler (Li *et al.*, 2022). As Dror *et al.* (2021) suggests, it seems very plausible that a content adaptive solution will be the most fitting for vehicles in motion with changing network quality, at least until railway networks of sufficient quality throughout has been constructed.

The combination of increased network capabilities, continuously improving solutions for video encoding and streaming, as well as the possibility of a dedicated 5G-R infrastructure makes it reasonable to be optimistic about systemwide video monitoring of trains.

5.1.3.3 Stability and security

The incessant evolution of hacker capabilities and methods (Stent, 2018) makes the future prospects of cybersecurity for remote driving hard to predict. It is hard to deny that all forms of network connected vehicles are vulnerable to outside interference (Eiza and Ni, 2017). As there are many different methods and entry points that outside actors could use to manipulate or disturb signals, there is not one universal, but rather many different ways that the railway sector could combat the issue (El-Rewini *et al.*, 2020). There has for instance been a remarkable progress in intrusion detection systems, fueled by deep learning (Kumar *et al.*, 2021). This could for instance be used to early-identify that a threat is present and quickly deploy the best available measure, whether this means activating an automatic break, switching communication channels, or temporarily moving to a train-centric automated driving until a station is reached.

Another important area of threat that must be mitigated in the future is jamming, a major concern of the TC-Rail cybersecurity group (Masson *et al.*, 2019). Skokowski *et al.* (2022) highlighted some techniques that the military could use for mitigation. Among these, coordinated frequency switching seems like a good solution, as both hackers and jammers would have trouble interfering for a prolonged period of time. Directed signaling, so-called beamforming, seems less feasible to implement in a shorter timeframe, as the high speed would require very precise directional systems. In general, it could be useful to look towards the military in the future, as anti-jamming strategies has been a prioritized concern for many years (Vadlamani *et al.*, 2016).

5.1.4 Value in remote driving

As the time for implementation of a new railway signaling system in Europe is fast approaching (Bane NOR, 2022a; UIC, 2023), the next few years will be vital in deciding what technological solutions is facilitated for. This section will discuss the value that remote driving can potentially add to the next generation of railways.

5.1.4.1 How can value be realized?

The basic principle of remote driving is the created flexibility in the location of the driver. The question then becomes, how can this be utilized to make the railway better on any key performance parameters. This is the direct way of identifying benefits; to consider the immediate advantages that can be seized. It is also possible to evaluate it from a more systemwide perspective, meaning how it could complement other features made possible by the FRMCS (UIC, 2020).

Looking first at the direct effects of remote driving, Zulqarnain and Lee (2021a) pointed to the possibility of remote drivers moving into a monitoring role for multiple trains with a higher GoA. It could be argued that a driver could manage multiple trains during a shift also without the added automation. This could for instance occur at an end station, where a remote driver could be switched to another train who is about to depart from a station, thereby reducing wait times. This would of course demand a detailed timetable plan, scheduling switches and mandatory driver rest, while accounting for delays and other elements. A perfect system would be hard to achieve, but the flexibility of having many drivers at the same remote-control facility could even ease the use of having a reserve of substitute drivers on standby. Drivers switching between trains could especially be a benefit to Europe's Rails' vision of revitalizing regional lines (EU-Rail, 2023a) as the drivers' schedule could be designed to fit the low passenger demand for departures in rural areas while reducing dead time.

With the possibilities of smart railways, large amounts of data can be collected and analyzed in real time. This has been exemplified by the features of the previously mentioned Beijing-Zhangjiakou intelligent high-speed railway (Wang, 2021; Liu *et al.*, 2017). It seems logical that some of this up-to-date understanding of passenger behavior could fit well with the increased flexibility of remote driving. With the driver staff centralized at a few remote-control facilities, sudden changes in demand could easier be reacted to, as the availability of on-site personnel is less of an obstacle. A more dynamic railway that adapts according to passengers' use patterns will certainly be beneficial in the future competitive market of transportation.

5.1.4.2 Not a self-contained solution

Although there are some clear benefits to remote driving, it seems reasonable to argue that it needs other accompanying solutions in order to strongly improve the performance of the railway sector. This statement is consistent with the commonly projected use case of remote driving as a supplement to highly automated railway systems (Jansson, Olsson and Fröidh, 2022; SNCF, 2018). While the ability to remote-control trains can create flexibility in where and how the driver's work, there are also some clear potential drawbacks in terms of driver awareness, cybersecurity, and overall reliability that reduces the standalone value. Combining it with highly autonomous train control for instance, creates the opportunity for the remote driver to monitor several trains at the same time (Zulqarnain and Lee, 2021a), only intervening in special circumstances (Fodor *et al.*, 2021).

5.2 Location selection for pilot project

This section contains a more in-depth evaluation of the four railway lines listed on the shortlist of options in section 4.6. Some risks associated with the test are discussed, including possible mitigating measures. Then a trade-off study of the options is conducted. Finally, an evaluation of the results is performed, and a prioritized list of suggestions is presented.

5.2.1 Risks

Before deciding on a location for the line it is important to review the risks related to the project, as they could impact how the lines are evaluated. The first step in this process is to identify potential risks, before categorizing them. Risk is defined as "Probability x Consequence" (Anthony Cox Jr, 2008). It is therefore common to do a risk categorization that displays this, for instance by utilizing a risk matrix (Garvey and Lansdowne, 1998). Figure 6 displays the matrix, with probability and consequence as the two parameters. The coloring is a rough grading of the risks that should be highly prioritized, with red, yellow, and green indicating high, medium, and low importance respectively.

"Human obstructions" refer to all human-related objects on the track, both in vehicles and on foot. The probability of this rises in urban areas, especially level crossings or stretches without fences. It seemed logical to separate this from other track obstructions, as human involvement on the track is somewhat less likely, but more fatal. Studies have found that three-quarters of railway accidents in the EU occur due to trespassing (Rungskunroch, Jack and Kaewunruen, 2021).

Several of the risks are related to the remote driver to different extents losing understanding of the train's movement. This could be due to temporary performance issues such as a drop in video quality, or more systematic issues such as the driver losing situational awareness, which could be due to an unsatisfactory operator environment (Brandenburger and Naumann, 2018a). It is important to note that the risks displayed in Figure 6 are placed according to where they likely would be with only a minimal effort put into risk mitigation. This is done with intention, both to level the status of the risks and to emphasize the importance of measures to move them down the axes.

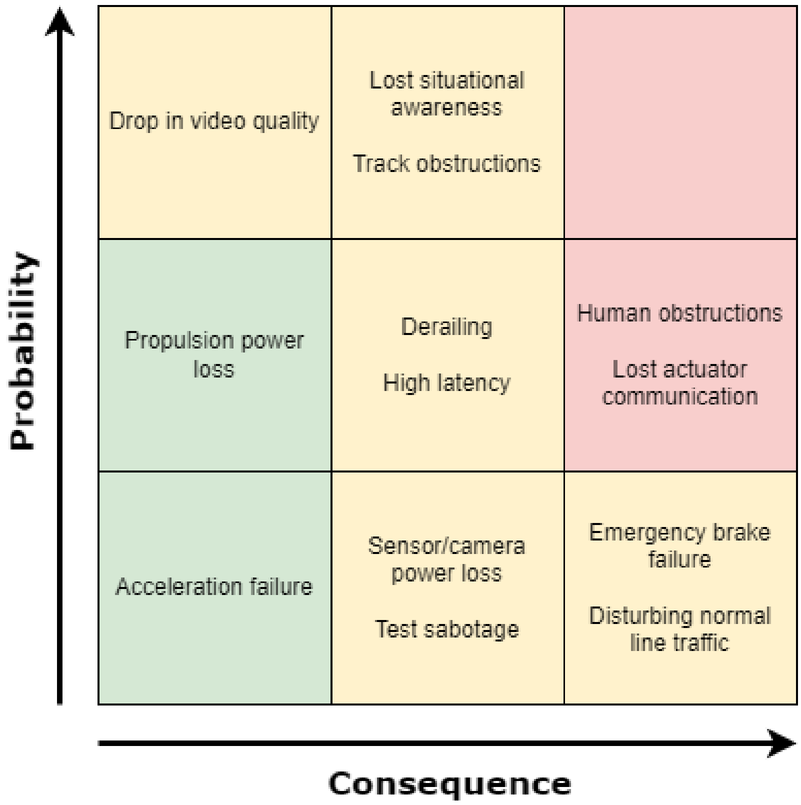

Figure 6: Risk matrix for pilot project execution

5.2.1.1 Risk mitigation

The risks listed in Figure 6 can be categorized into two main segments: technical and operational. The technical risks are a collection of all factors related to the performance of the prototype and remote driving system. It is therefore the team developing the vehicle that has the best ability to mitigate them. This can be done by using reliable components and creating smart solutions. How the emergency brake is activated is a good example. Having the vehicle automatically break after a given period of time without signals could decrease the consequence of losing actuator communications. In addition to the creation of the prototype, there is also an opportunity for risk reduction by performing proper testing. This could help decrease the probability of certain risks, thereby moving them "down" in the Figure 6 matrix.

As it is detrimental to take every precaution (Lovdata, 2021), the test execution will require a prepared security team. In the pre-test phase it seems important to identify key features such as level crossings, urban areas without fences, and other areas associated with increased danger. The team would then have to review these sites and find safety measures appropriate for the threat. This could include measures such as temporary warning signs, roadblocks, or even on-site personnel to direct the traffic during tests, all of which would require a logistical plan. In addition, it seems logical to send out neighbor alerts for the population in vicinity of the line, this way both creating awareness of the test and hopefully goodwill from the public. All of these measures combined should help the test in complying with Norwegian law and reducing the probability of dangerous situations occurring during tests.

5.2.2 Trade-off study

The candidates in the shortlist of options all have some clear benefits and drawbacks, and it is therefore important to find a good method for identifying the best candidate. When there is a decision of selecting a preferred option between alternatives that can be parallelly compared, then the problem is amenable to a trade-off study (Bahill and Madni, 2017). While it is difficult to accurately quantify the value of the different traits, the study can aid in obtaining an overview of the alternatives' value.

5.2.2.1 Evaluation criteria

The evaluation criteria are largely based on the factors covered in section 4.4 and 4.5. The weight was decided based on the independent importance of the criterion and an overall balance between the criteria topics.

Network coverage is a necessity for remote driving, and the pilot project's success is dependent on the prototype being able to send sufficient quality of video. This was therefore an obvious factor to include in the trade-off study. Three specific criterions were selected within the theme of network coverage. "Best covered area" refers to the ceiling of network on the line, meaning what the network quality is at the best section of the line. This was chosen as the section could serve as a backup option in case the full line proves too unstable for remote driving. "Average network coverage" is a rough estimation of the overall network coverage of the line. This is an important criterion as it represents what speed that can be expected for the video upload. "Blind spots/2G" is a negative factor, and a high score therefore implies that the line has few blind spots or areas with only 2G, or worse, coverage. The importance of this criterion is that every indication suggests that 2G will not be sufficient for video uploading (Zeqiri, Idrizi and Halimi, 2019; Finne *et al.*, 2019). This means that the remote driver will be unable to see the movement of the prototype throughout the section. Overall, the network coverage section was weighed as the third most important criteria, this was partly because the criterions were closely related and partly because there could be value in testing the impact of different network qualities.

As previously noted, the practicalities around the test execution would become easier if the location of the line was within a reasonable driving distance from Trondheim. The distance from Oslo/Bergen is listed a secondary criterion with lower weight, as there are some benefits to being in the vicinity of a city where Jernbanedirektoratet and Bane NOR is located. Although there are some locations that are highly preferable, this factor should not come at the expense of selecting a clearly superior option for the test's success. The overall travel distance score is therefore weighted lower than the other criteria categories.

Track characteristics is important for planning and executing safe testing runs. The number of level crossings is selected as a criterion because it could be a necessity to have a human security operator at every crossing for directing traffic. If this is not possible for every crossing, there should at least be put up stop barriers for the duration of a test run, which will require coordination and several people as well. Either way, it is clear that a higher number of level crossings would entail a higher needed amount of human test contributors. The level of traffic at the crossings is chosen as a criterion for three main reasons. Firstly, the higher traffic implies that stronger safety measures is needed, as there are more people that will be eager to get across. Secondly, there is a higher threshold for closing the larger road crossings, both in terms of permissions and public approval. Lastly, the higher traffic partially indicates that the area is more densely populated, meaning that there are increased risks of people by the tracks also outside the crossings. This category was given significant weight as it is a diverse set of factors which could impact the safety and execution of the test.

The last category was a collection of traits which could impact the ease of using the line for the pilot project. The first criterion, "accessibility", had earlier been identified as a "showstopper" and was therefore given high weight. Although all lines had earlier been recognized as somewhat accessible, this criterion was meant to separate the lines with paved, wide platform access right by the track and lines with dirt road access or other inconveniences. "Compliance with normal use" is referring to how easy it would be to schedule the test execution around the normal use of the track. This is a consideration on several levels, both on the length of season when it is in use and the and number of times pr week when there is activity. "Other preparation needed" refers to a rough estimate of how much preparation work would have to be conducted before the test can commence. This includes the previously discussed safety measures, as well as other preparations such as getting governmental and line owner approval. This category was weighed heavily as the criterions are factors with potential impact on the test preparation and execution process.

5.2.2.2 Assessing the scores

The research foundation for assessing the options' score in the different criteria was collected using several different methods. Firstly, the information sources for the options in Table 3 was reviewed more closely. Many maps and aerial photos were examined, including information-specific maps on network coverage, roads, and train tracks. Video footage from train's running the lines was then viewed, taking still frame pictures and notes of key features such as entry points for the truck carrying the prototype, major level crossings, and other important traits. The video footage was constantly compared to the aerial photos to understand location and look for preferable stretches of the line.

The trade-off matrix was filled out with 5 scores in the range of 0 to 1, with a lower score meaning a worse result in the criterion. This meant that all criterions were shifted to being positively aligned. "Distance from Trondheim" for instance, is rated so that a lower distance means a higher score.

5.2.2.3 Trade-off matrix

Table 4: Trade-off matrix for the shortlist of line options

Factor	Weight	Thamshavnbanen	Hell-Muruvik	Krøderbanen	Namsosbanen
Best covered areas	4	1	1	1	0,5
Avg. network coverage	7	0,75	0,75	0,75	0,5
Blind spots/2G	7	1	0,75	0,75	0,25
Network coverage score	18	16,25	14,5	14,5	7,25
Distance from Trondheim	8	1	1	0,25	0,75
Distance from Oslo/Bergen	2	0,25	0,25	1	0,25
Travel distance score	10	8,5	8,5	4	6,5
# of level crossings	6	0,5	1	0,25	0,75
High traffic crossings	8	0,5	1	0,75	1
Track altitude profile	3	0,75	1	0,75	1
Length	4	0,75	0,25	0,75	0,5
Track characteristics score	21	12,25	18	12,75	17,5
Accessibility	9	1	0,5	1	0,75
Compliance with normal use	6	0,5	0,5	0,75	0,75
Other preparation needed	6	0,25	0,5	0,5	0,75
Ease of use score	21	13,5	10,5	16,5	15,75
Total score	**70**	**50,5**	**51,5**	**47,75**	**47**

When examining the different options, it became clear that distinct parts of the same line could have highly contrasting characteristics. While most of the criteria is universal for the whole line, for some criteria, some of the options would have significantly different scores on certain stretches. It therefore seemed of value do a second evaluation based on the section of the lines with the most preferable conditions. It seemed logical to only consider significant portions of the lines for this, as a very short test track would lose some of the realism, as well as produce less varied test data.

For Thamshavnbanen, the southern part of the line from Løkken to Svorkmo had significantly fewer level crossings, less traffic at the crossings, and in general scarcely populated areas around the track. All of these factors aided in improving Thamshavnbanen's score for track characteristics significantly, as the level crossings was among the clear drawbacks of the option. On the counter, the tunnel becomes a more significant part of the track, resulting in a slightly lower score for potential network blind spots. For Namsosbanen, there is a significant improvement in network coverage when avoiding the easternmost kilometer of the line. As previously noted, this section is for the most part only covered by 2G, meaning that it would likely hinder video uploading from the prototype.

The other options are more consistent in their line characteristics and as a result had smaller changes in their overall score. The southern part of Krøderbanen has better average network coverage, but also more traffic on the level crossings. Hell-Muruvik is only 2,8 kilometers to begin with and, except for avoiding the tunnel, there is very little improvement in the overall score by selecting just a section of the line.

Table 5: Updated trade-off matrix for the preferable section of each line

Factor	Weight	Thamshavnbanen	Hell-Muruvik	Krøderbanen	Namsosbanen
Best covered areas	4	1	1	1	0,5
Avg. network coverage	7	0,75	0,75	1	0,75
Blind spots/2G	7	0,75	1	1	0,75
Network coverage score	18	14,5	16,25	18	12,5
Distance from Trondheim	8	1	1	0,25	0,75
Distance from Oslo/Bergen	2	0,25	0,25	1	0,25
Travel distance score	10	8,5	8,5	4	6,5
# of level crossings	6	0,75	1	0,25	0,75
High traffic crossings	8	0,75	1	0,5	1
Track altitude profile	3	0,5	1	0,75	1
Length	4	0,5	0,25	0,5	0,5
Track characteristics score	21	14	18	9,75	17,5
Accessibility	9	1	0,25	1	0,75
Compliance with normal use	6	0,5	0,5	0,75	0,75
Other preparation needed	6	0,75	0,5	0,5	0,75
Ease of use score	21	16,5	8,25	16,5	15,75
Total score	**70**	**53,5**	**51**	**48,25**	**52,25**

5.2.3 Evaluation

It is important to keep in mind that the trade-off matrix is only a tool meant to give an indication of the preferable options. It is hard to accurately quantify the weight of the different criteria, and the score for each respective line. It is, however, somewhat encouraging that the results, especially for the preferable stretches in Table 5, somewhat reflects the beliefs from the prior discussion with the academic advisor. On the other hand, this can also mean that the results could have been affected by a confirmation bias (Klayman, 1995).

As the options evaluated in the trade-off study were seen as preferable, it is unsurprising that they all received relatively high overall scores. Krøderbanen's score was negatively impacted by the high number of level crossings and the long distance from Trondheim. While some of the other options had a noteworthy upside to selecting just a stretch of the line, Krøderbanen was more consistent in its traits throughout and therefore did not improve significantly in Table 5.

The stretch between Hell and Muruvik has three clear benefits which has been reflected in the first three categories of criteria in Table 5. Firstly, the line is located just a 30-minute drive from Trondheim, which eliminates the need for relocation of the test execution team. Secondly, due to the vicinity to one of Norway's larger cities, a high percentage of the line is covered with solid 5G. Lastly, with the route situated between the sea and the steep hills, there are no major level crossings and also less danger of trespassing than many of the other lines. Simultaneously, this is also the line's biggest drawback. During a visit to the track, only two potential access points for lifting the prototype onto the track was identified, with none of them being as easy to use as the other lines' options. Furthermore, a vehicle malfunction on track leading to a stop would be significantly more regrettable, as the recovery between the sea and hills would likely be troublesome. A last concern found in the visit to the Hell-Muruvik stretch is that track is directly connected to the new mainline as seen in Figure 3. This has affected the ease-of-use score, as some form of measure would have to be conducted to ensure that the prototype does not travel further onto a line with heavy traffic.

If the evaluation was done primarily based on risks, then Namsosbanen would likely be the preferable option, as it is sparsely populated, has few crossings and no connection to mainline. Simirarily to Hell-Muruvik, the low threat of trespassing comes at the cost of reduced accessibility, although it must be said that this is less of an issue here. When only considering the roughly 4 km-stretch between Namsos Camping and Kvatninga, Namsosbanen should have solid 4G/4G+ throughout. This significantly improved its score for the network coverage criteria, but it is still ranked last among the four listed options. Namsosbanen could be an interesting option for testing the feasibility of remote driving in areas without 5G, but many of the other lines also have stretches with only 4G/4G+ that could serve this purpose.

The evaluation has shown that all four of the listed alternatives is highly viable locations for testing the remote-controlled prototype. Based on a combination of the score in the trade-off study and personal judgement, the southernmost part of Thamshavnbanen seems to be the best option. This is because the stretch seems to have many benefits and no major drawbacks, which is reflected by the solid score in every category in Table 5. With similar scores, the preference between Namsosbanen and Hell-Muruvik mostly relies on what factors the test execution team weighs more heavily. If the goal is strictly to have a successful test, then Hell-Muruvik seems slightly preferable due to the better network quality. Among the four options, Krøderbanen scored the lowest overall, which concurs with the personal assessment. It should be emphasized that this is still a very good solution, especially if the team executing the test wants vicinity to Oslo.

It is important to reiterate that this evaluation was made prior to requesting use of the lines, and so there could be a shift in priorities due to an unsuccessful application process. While these were singled out in the shortlist for the purpose of more in-depth research, there are also other alternatives listed in Table 3 that could be viable. Gamle Vossebanen and Valdresbanen, for instance, both seem highly viable for the pilot project.

5.2.4 Other suggestions for the pilot project

A substantial majority of the technological discussion in this thesis has been focused on the potential future implementation of remote driving. The test of a prototype from the FutuRe project will precede such an eventual implementation and will therefore not have access to the dedicated FRMCS wireless network and the other industry standards that might be implemented. This is also an advantage, as the development team is free to select the tools and methods of choice for performing the test.

There seems to be two main strategies that the team tasked with creating the prototype's remote-control functionalities can pursue. They could opt to do most of the work themselves, building the system based on available frameworks. The first suggestion for the development team would therefore be to look into open-source solutions for remote control that already has been developed. Specifically, a software that has been frequently mentioned in recent test projects is TELECARLA (Hofbauer *et al.*, 2020a; Schimpe *et al.*, 2022). This is an extension of CARLA, a driving simulation environment backed by Intel and Toyota (Dosovitskiy *et al.*, 2017). TELECARLA utilizes GStreamer, a powerful framework that allows the user to customize the video transmission process based on needs. This seems highly preferable for remote driving, as it is possible to customize for prioritizing low latency. This is the philosophy of UDP (Yu and Lee, 2022b) that remote driving should prefer, as it supports the needed responsiveness. Other popular solutions, namely YouTube and Twitch, operates with a significantly higher latency, because their business model is to deliver a constant flow of high-quality video to the viewer. It is important to note that while there are instructions available (Loonstra, 2014), the setup process for GStreamer will be significantly harder than for commercial solutions.

The other option is to purchase, or in other ways partner with, existing communication solutions from established companies. This could either be general solutions for video streaming, or ones specialized for remote driving, like the one built by Swedish teleoperation company Voysys (2023). The clear benefit here is that their solutions will have been made to overcome specific remote driving-related obstacles that this project also possesses. As the prototype test in Norway is planned to be remotely operated from Sweden, it could be important to consider handover issues when transmitting between Public Land Mobile Networks (El Marai and Taleb, 2020; Fernández *et al.*, 2023). As for handover between network towers and other issues regarding velocity, the prototype's planned running speed of ~30 km/h should be well below the threshold where this becomes a major issue (An *et al.*, 2022). These are, nevertheless, issues that commercial solutions likely will have mitigated.

In the end, the preference is heavily reliant on the current situation and goal for the development team. If there is sufficient technical capability, it should be feasible to create a customized solution for remote driving. If there is a reduced capability or manpower capacity for creating the system in-house, then a partnership could be an option. If there is also a minimal interest in testing the capabilities of remote driving, and this is mainly seen as a stepping-stone before adding other automation features to the prototype, then the easiest solution is to utilize a free commercial solution that is focused on low latency, generally UDP-based (Yu and Lee, 2022b). Examples of this is teleconferencing tools like Zoom (Sander *et al.*, 2021) Solutions focused on video quality, like YouTube Live and Twitch, seems unpreferable to use for this project and should be seen as a last option.

6 Conclusion

This thesis has sought to investigate the current state of remote driving technology. This has included reviewing the current capabilities and limitations, the existing projects, and the future prospects. It seems reasonable to conclude that key technologies, such as wireless network speed and video transmission solutions, has had a substantial increase in capability throughout the last decade. This is exemplified by other projects that has had great success with low-latency remote driving, continuing to prove the feasibility also for mainline railway. Currently, there are two main categories of obstacles: the infrastructural- and the technological shortcomings. The former consists of issues and concerns such as the immense costs that would be associated with upgrading the current rail network from GSM-R to a potential 5G-R, as well as other needs like the retraining, restructuring, and relocating of the large number of drivers employed in railway companies. The technological shortcomings on the other hand will require more research, and so it is harder to predict when and how these issues can be overcome. While the issues of reliability, and the driver's awareness can reach a point of sufficient quality and then improve from there, it is arguable that cybersecurity is going to be a continuous threat for smart railway systems and remote driving throughout its lifecycle.

This thesis has discussed the value of implementing remote driving. Due to the drawbacks and obstacles that has not been fully addressed, there is only minor value in implementing remote driving as a standalone solution. The benefit of remote driving is more likely to be realized when it is accompanying other capabilities such as high automation, intelligent information collection, and dynamic scheduling. This also implies that the potential investment into 5G, or other high-end network solutions, for the railway should not be motivated purely by the prospect of remote driving.

In addition to the obvious showstoppers, such as permission of use, and the track gauge, there are a few traits that determines what lines are preferable for the test project. Due to the safety standards that needs to be strived for, it seems highly preferable to perform the test on a section with few and low-traffic crossings, as well as avoiding urban areas without fences in general. Another factor that significantly eases the preparation and use of the line is the track accessibility, as it could be necessary to both insert and remove the prototype at several locations on the line. For the success of the test itself, it is vital that the large majority of the line is covered by a sufficient quality of 4G or better, as the significantly lower throughput of 2G will make the train incapable of transmitting signals. There could, however, be benefits to analyzing the effects from varying network quality, as well as temporary losses of signals caused by tunnels or other blind spots.

This thesis has evaluated many railway lines that could be used for testing the remote driving prototype in Norway. The concluded suggestion is to pursue Thamshavnbanen as the first option, specifically the southmost 5,8-kilometer section between Løkken and Svorkmo. This is due to the excellent reported network coverage in the area, the low number of level crossings, sufficient accessibility both at end stations and by the track. In addition, the vicinity to Trondheim makes it easier to perform the test for a team at NTNU. It is important to emphasize that all the lines in the shortlist found in section 4.6 should be considered highly viable for the test project.

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