Remote Driving Operation (REDO) project

Final report

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Foto: Achtin/Mostphotos.com

VTI rapport 1180A
Published 2023
vti.se/publications

VTI rapport 1180A

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Reg. No., VTI: 2019/0300-8
Publication: VTI rapport 1180A
Published by VTI 2023

Publicationsuppgifter – Publication Information

Titel/Title

Remote Driving Operation (REDO) projekt. Slutrapport./ Remote Driving Operation (REDO) project. Final report

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Utgivare/Publisher

Swedish National Road and Transport Research Institute (VTI)
www.vti.se/

Serie och nr/Publication No.

VTI rapport 1180A

Publicerad/Published

2023

VTI:s diarienr/Reg. No., VTI

2019/0300-8

ISSN

0347–6030

Projektnamn/Project

REmote Driving Operation – REDO

Uppdragsgivare/Commissioned by

Vinnova/Vinnova (Sweden's innovation agency)

Språk/Language

Engelska/English

Kort sammanfattning

Denna rapport presenterar studier och experiment inom REDO-projektet samt resultat ifrån dessa. Studierna är utförda mellan december 2019 och februari 2023 och rapporten täcker fem huvudämnen: 1) den effekt latens och siktvinkel har på körprestanda; 2) feedback och kontroll vid fjärrkörning; 3) uppkoppling samt mobilnätsstöd för fjärrstyrning; 4) videoöverföring för fjärrkörning; och 5) lagar och föreskrifter gällande fjärrstyrning. Innehållet i denna rapport avser att täcka tekniska detaljer och fynd inom samtliga av dessa ämnen, den är dock inte avsedd för att innehålla samtliga detaljer och resultat som redan har publicerats som vetenskapliga artiklar. Denna rapport bör ses som ett komplement till tidigare publicerade resultat.

Nyckelord

Fjärrstyrning, teleoperation, remote driving, autonoma fordon.

Abstract

This report presents experimental setups and findings from the REDO project, which had been conducted between December 2019 and February 2023. Five main topics are covered in this report: 1) Effects of latency and field-of-view on driving performance; 2) Remote driving feedback and control; 3) Connectivity and mobile network support for remote driving; 4) Video transmission for remote driving; and 5) Laws and regulations concerning remote driving. Contents of this report dives into technical details and findings within each topic. Nevertheless, this report does not intend to repeat all detail and results published in scientific publications, and thus this report should be seen as complementary material to the published results.

Keywords

Remote operation, teleoperation, remote driving, automated vehicles.

Preface

This report summarizes findings and results from Remote Driving Operation (REDO) project, which was conducted between December 2019 and February 2023. The project was funded by Vinnova, Sweden's Innovation Agency (Dnr. 2019-03068). The project was coordinated by VTI in collaboration with CEVT, Einride, Ericsson, Ictech, KTH, NEVS, and Voysys as project partners.

The REDO project focuses on technical and non-technical challenges in implementing *remote driving operation* of road vehicles, which is referred to as a case where a vehicle is controlled remotely by a *remote operator* (i.e., *remote driver*) from a distance via wireless communication network.

While most of the results are published in scientific publications, we believe some technical details that may be omitted from scientific publications are valuable to practitioners and researchers focusing on remote driving operation of road vehicles. Therefore, this report summarizes the technical detail and findings, which should be seen as complementary material to the published results.

We would like to thank everyone in the project team for their contributions to the project, with special thanks to Jeanette Andersson (VTI), Christian Jernberg (VTI), Pontus Larsson (Ictech), Mikael Nybacka (KTH), Tomas Nylander (Ericsson), and Magnus Persson (Voysys) for their contribution to this report. Finally, the project would like to also thank the external reference group: Erik Røsæg (University of Oslo), Frank Diermeyer (TUM), Johnny Svedlund (Trafikverket), Jonas Andersson (RISE), Kristina Andersson (RISE), Muhammad Imran, Stas Krupenia (Scania), and Stefan Neumeier (Technische Hochschule Ingolstadt) for their valuable feedback during the project.

Gothenburg, August 2023

Maytheewat Aramrattana
Project Leader

Granskare/Examiner

Ingrid Skogsmo, VTI.

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1. Introduction

In recent years, *remote operation* or *teleoperation* has been applied in automotive domain, for enhancing capabilities of connected (and automated) vehicles. Remote operation of such vehicles can be categorized into three different operation modes: *remote driving*, *remote assistance*, and r*emote supervision*. Please refer to (Skogsmo, et al., 2023) for detail definition of these modes.

This report focuses on remote driving operation, where *remote driving operation* of a vehicle refers to a case where a vehicle is controlled remotely by a *remote operator* (i.e., *remote driver*) from a distance via wireless communication network. This terminology and definition will be used in this report, although the reader should be aware that, at the time of writing this report, the terminology in this research field has not been completely agreed upon.

An example of prominent use cases of remote driving operation is when a remote driver supports vehicle operation by taking full control when the automated driving system encounters ambiguous traffic situations or fails. In some cases, the remote operator can act as a safety driver in highly automated vehicle operation and testing, and thus allow testing on public roads. Since vehicle automation systems are not yet perfect to achieve full driving automation (SAE Level 5), we believe that using remote driving capabilities together with automated driving systems can accelerate and support the deployment of highly automated vehicles (SAE Level 4) on public roads. Furthermore, the possibility of having a remote driver outside a vehicle is especially important for new vehicles that may not have space for a human driver, or do not have traditional driving interfaces (e.g., a steering wheel and pedals).

This report summarizes findings and results from Remote Driving Operation (REDO) project, which was conducted between December 2019 and February 2023. The project was funded by Vinnova, Sweden's Innovation Agency, and was coordinated by VTI in collaboration with CEVT, Einride, Ericsson, Ictech, KTH, NEVS, and Voysys.

The REDO project has been focusing on five different aspects of remote driving operation, each has its own respective work package in the project: 1) challenges for the remote operator; 2) requirements on driver feedback and vehicles during remote driving; 3) Systems-of-systems architecture and infrastructures to support remote driving and control tower operation; 4) demonstrator for potentials of remote driving; and 5) laws and regulations concerning remote driving.

Each work package begins the work with state-of-the-art review, which has been conducted separately in each work package. While most of the results are published in scientific publications as listed in the end-of-project report to Vinnova[1], we believe technical details that may be omitted in scientific publications are valuable to practitioners and researchers focusing on remote operation of road vehicle. Therefore, technical detail and findings are summarized in this report, which should be seen as complementary material to the published results.

This report is outlined as follows. Chapter 2 presents detail on experimental setup and results from studying effects of latency and field-of-view on driving performance of remote operator. Experimental setups and results on feedback to the remote operator are reported in Chapter 3. Chapter 4 and 5 focuses on mobile network and video transmission over mobile network, respectively. Relevant laws and regulations during the project time are summarized in Chapter 6. Finally, this report concludes in Chapter 7.

[1] https://www.vinnova.se/globalassets/mikrosajter/ffi/dokument/slutrapporter-ffi/system-av-system-rapporter/2019-03068eng.pdf?cb=20230628100110

2. Effects of latency and field-of-view on driving performance

To define the state of the art for research on remote operation of autonomous vehicles a literature search was undertaken. In doing so, we focused on literature related to effects on behaviour and performance of remote operator caused by different aspects of system design. There have been several studies conducted on effects of different aspects such as latency, video quality and presentation, on performing different tasks under different speeds. However, the tasks studied in the literature are mostly artificial, such as slalom courses or straight roads. Furthermore, the interaction effect between those aspects (i.e., effect caused by a combination) has not been included. Studies in a more naturalistic setting was even mentioned as relevant future work within the literature (Neumeier, et al., 2019). Also, as an extra variable we found that there had not been any studies conducted where the background of a potential remote operator had been taken into account.

This led to the following research questions:

RQ1: What interaction effects can be found between i. latency, ii. type of task, and iii. presentation view in a remotely operated vehicle?

RQ2: Is there a difference in behaviour between experienced drivers and experienced gamers during a study with a simulated a remotely operated vehicle?

In order to answer these questions, a scenario was developed for a simulator (see Figure 1) to be used in a driver performance study.

Figure 1. Simulator used for experiments in this section. (Photo: Maytheewat Aramrattana).

The scenario consisted of five hazardous events, see below, chosen for their likelihood to occur during normal driving, and two driving environments in which the events would occur. The driving environments were an urban road with a speed limit of 50 km/h and a rural road with a speed limit of 70 km/h. Other road users (e.g., traffic) are included to make the scenario more realistic.

The events were categorized into hazardous events and proxy events. The hazardous events were labeled as **H1** to **H5**, and consisted of:

H1: Car cutting in (see Figure 2) - A parked vehicle starts to indicate that it will take off and then cuts in, in front of the participant.

Figure 2. Hazardous event 1 (H1) in rural and urban environment. The white number in the middle indicates speed of the ego vehicle. (Screenshots from VTI's driving simulation software).

H2: Left turn by vehicle in opposing lane (see Figure 3) - A vehicle coming in the opposing lane indicates a left turn and cuts in right in front of the participant.

Figure 3. Hazardous event 2 (H2) in rural and urban environment. The white number in the middle indicates speed of the ego vehicle. (Screenshots from VTI's driving simulation software).

H3: Vehicle from right does not stop (see Figure 4) - A car comes from the right at a crossing and drives across the road in front of the participant.

Figure 4. Hazardous event 3 (H3) in rural and urban environment. The white number in the middle indicates speed of the ego vehicle. (Screenshots from VTI's driving simulation software).

H4: Child running into traffic (see Figure 5) – There is a bus that is already stopped at a bus stop indicating that it will stay there, and a child runs out from behind it.

Figure 5. Hazardous event 4 (H4) in rural and urban environment. The white number in the middle indicates speed of the ego vehicle. (Screenshots from VTI's driving simulation software).

H5: Bicyclists (see Figure 6) - Two bicyclists are cycling in the participant's lane while there is oncoming traffic, forcing the driver to slow down before overtaking.

Figure 6. Hazardous event 5 (H5) in rural and urban environment. The white number in the middle indicates speed of the ego vehicle. (Screenshots from VTI's driving simulation software).

Each hazardous scenario has its corresponding proxy scenario, which consisted of identical events, but with larger safety margins, meaning that the test subject did not have to perform any actions. These situations were called proxy scenario (indicated with **P**), and the difference is illustrated in Figure 7.

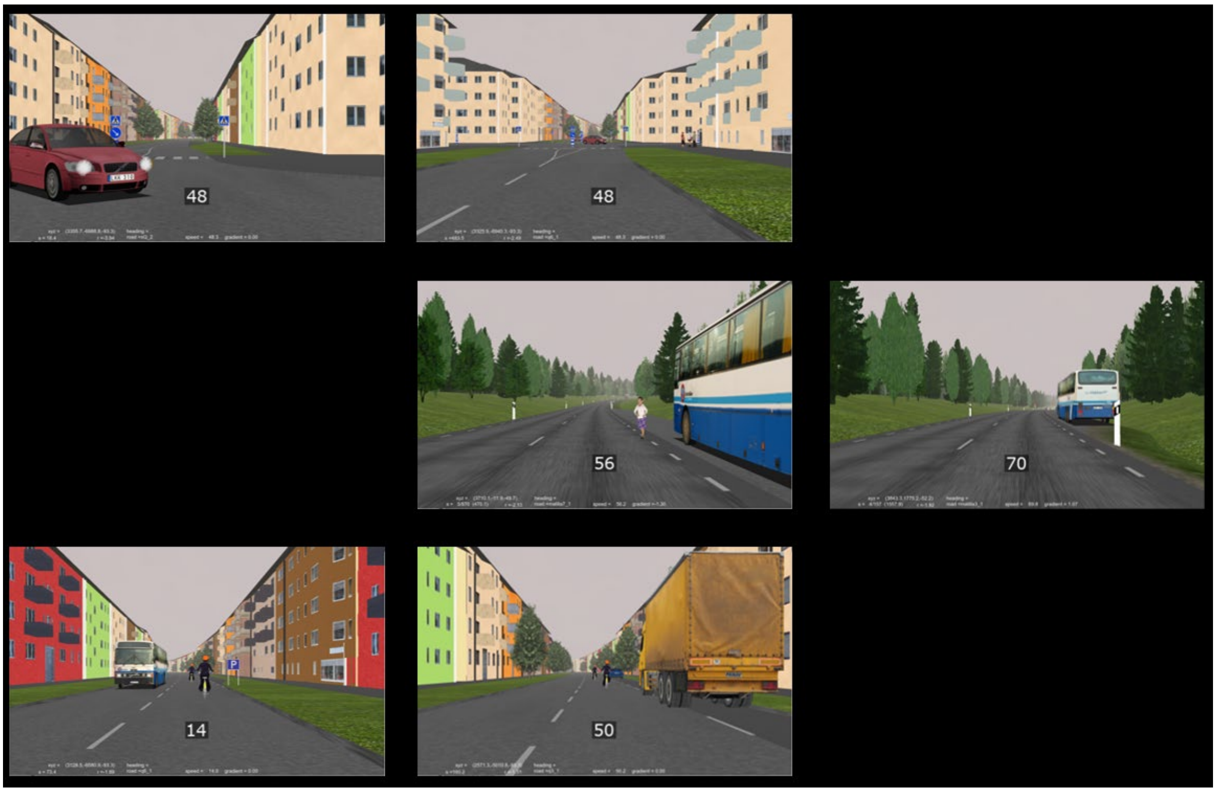

Figure 7. Hazardous events to the left (H2, H4 and H5), and corresponding proxy event to the right (P2, P4 and P5). The white number in the middle indicates speed of the ego vehicle. (Screenshots from VTI's driving simulation software).

Two studies were conducted using these scenarios. Both studies focused on the interaction between latency, task and environment/speed, as well as the difference between the two groups of participants (*experienced drivers and experienced gamers)*, while the second study also included the presentation view. Both studies were conducted in Gothenburg, Sweden, and both group of participants were recruited from population in nearby areas, where experienced drivers were recruited from taxi company (Taxi Göteborg). Experienced gamers were recruited by contacting gaming clubs at a local university. Remaining experiment slots were then filled up empty slots with participants from general public[2]. In the second study, all participants were recruited via ads in social media and on VTI's website.

In study one, the participants drove the scenario three times, each time with a different latency. This was a masked condition, i.e., the participants were not told that the latency would change, nor in which order they were subjected to the different latencies.

Also, there were some interaction effects of latency and task. Even though the participants could not guess what change had been made between the scenarios, nor guess in which specific order they drove with the different latencies after being told, for some tasks the reaction time increased more than the manipulation of the simulator. This incidates some kind of implicit adaptivity of the participants that affect their driving during the experiment.

After the statistical analysis of the objective data gathered by the simulator was performed, we notice that experienced gamers seemed to keep a larger safety margin during the hazardous events than experienced drivers. Further studies would be required to determine if this is a result of their gaming

[2] Including those who have registered their interests in simulator study in VTI's database.

experience or if this is caused by the group being on average almost 15 years younger, or something completely unrelated.

After a statistical analysis of the subjective data gathered through questionnaires, it was also clear that a higher latency affected the self assessed sense of performance negatively, as well as how much in control of the vehicle the participants felt. Study One resulted in Paper A, see below.

Study two focused on the interaction between latency, task, environment/speed and presentation view, as well as the difference between the two groups of participants. This study used the same scenario as the first study, but with two latencies and the participants drove with two different presentation views: one corresponding to that of a driver in the driver seat, and one raised above the vehicle (i.e., the same height as the camera installed in Einride's remotely operated pods during the project). The data for this study is currently being processed and will result in Paper B.

Further detail on scientific results can be found in materials listed below.

- Paper A: The effect of latency, speed and performed task on remote operation of partly autonomous vehicles, Christian Jernberg, Jan Andersson, Jesper Sandin och Tom Ziemke. Submitted to Transportation Research Part F: Traffic Psychology and Behaviour, 2023. *(under revew; this work was also presented at the Young Researchers Seminar (YRS) 2023[3])*
- Paper B: The effect of field of view, latency, speed and performed task on remote operation of partly autonomous vehicles, Christian Jernberg, Jan Andersson, Jesper Sandin och Tom Ziemke. *(in progress under 2023)*
- Presentation: "Prerequisites of remote operation of vehicles", presented at 14th International Conference on Applied Human Factors and Ergonomics (AHFE 2023) and the Affiliated Conferences, July 20-24, San Francisco, USA (2023).

[3] https://www.ectri.org/activities/young-researchers-seminar-2023/

3. Remote driving feedback and control

What we found initially during the state-of-the-art review is that there are many aspects in terms of human-machine-interaction that are still unclear and unstudied in remote driving operation. Firstly, there is no quantitative study about how the driving behaviour and experience change in remote driving operation compared to normal driving (i.e., driving a vehicle from inside the vehicle). Secondly, it is still unclear how different human-machine-interfaces for the remote operator influence the driving behaviour and experience. For instance, it is uncertain how much influence the feedback—such as steering force feedback, motion-cueing feedback, sound/vibration feedback—has on behaviour of remote operator in the remote driving operation context. This is one of the topics that the REDO project has been focussed on.

3.1. Steering and haptic feedback

In order to study the above-mentioned areas, we needed to develop suitable experimental equipment and experimental setups. Hence, a lot of the work initially was to further develop the *Remote Driving Station* including driving simulator (to make it become the remote driving operation station) and its connection to the test vehicle, which is the *Research Concept Vehicle (RCV-E)* at KTH[4]. To ensure similar experiences, the same steering interfaces were installed both in the vehicle and in the simulator (remote driving operation station).

Three research questions were posed during this part of the REDO project and they are listed below together with a summary of the respective findings.

RQ 1: How does the driving experience and behaviour in teleoperation differ from that of real-life driving?

In order to tackle this research question, an experiment was conducted to compare real-life driving with remote driving. The test participants were recruited to drive the RCV-E several laps on a test track. The experiment includes both real-life driving and remote driving for all participants. The comparison of the two driving conditions were made using a set of objective metrics and subjective assessments, which were developed specifically to study the behaviour of remote drivers and their experience. The objective metrics such as lane following deviation, time consumption, average speed, throttle engagement, etc. were used and found to capture both the longitudinal and lateral behaviour of the drivers in a good way. Please refer to (Zhao, et al., 2021) for more detail.

With the setup of the *Remote Driving Station* used in our experiments it was clear that it was relatively much harder for the remote drivers to perform as well in terms of precision and smoothness in the driving task compared to when driving in the real car on the test track. The recorded mental workload was also considerably higher in the remote driving compared to real car driving. The reported reasons from the test drivers were that they need a higher degree of realistic feeling, better sense of speed, better visibility, etc., in remote driving. This feedback has been used to design the subsequent coming experiments on motion, vibration, and sound feedback.

In addition, it was also found during the studies that the test subjects started to get familiar with the new environment and could perform rather consistently already after 4-5 laps of the test track.

RQ 2: How does the steering force feedback affect the driving experience in teleoperation?

Two different designs of steering force feedback models were developed for *Remote Driving Station*, one physical-based model and one modular model. The physical-based model is a pure mathematical model where the feedback comes from a tyre model and inertia and friction forces in the steering

[4] https://www.itrl.kth.se/research/completed-projects/research-concept-vehicle-model-e-1.917925

column. The modular model is similar to the physical model, but one main part of the feedback torque comes from the direct input of the current used to control the steering actuators in the vehicle. This means that is driving over a curb the steering actuator will need to adjust the wheel angle and that will be passed on then to the driver as a disturbance.

An experiment was conducted in the *Remote Driving Station*, where test participants experience both steering force feedback models. This test was conducted with a real vehicle (both remotely and driving in the real car). Preliminary tests were conducted in a simulation environment prior to the experiment.

Comparing these two models, it was found during the studies that the physical model gives better steering feel and confidence during remote driving. The modular model, on the other hand, can give more real-world feeling. But the modular model was sensitive to the latency, and thus it was also found that total roundtrip latency has to be considered. The latency in this case includes the telecommunication latency, mechanical actuator latency, and data processing latency. Therefore, in order to use real vehicle signals, one would need to work with filters and prediction techniques to counteract the latency issue.

It was also noted during the studies that drivers during remote driving do not need as large feedback force and rates as drivers in a real car. Our initial studies indicate that the steering feedback need to be designed and tuned differently compared to real life, and lower based on our initial studies.

RQ 3: How does the motion-cueing, sound and vibration feedback affect driving behaviour and experience in teleoperation?

To study this question the *Remote Driving Station* was further developed to include vibration actuators. A motion cuing algorithm was developed to give motion feedback to the remote driver, making use of the small motion space available in the small hexapod platform. Real life disturbance signals were recorded by driving with a real conventional car over speedbumps, damaged asphalt, cobblestone and manholes. This was later used in the simulator station and merged with the CarMaker simulator software to create both a low speed and a high-speed driving scenario.

From this experience we could see that the vibration and sound feedback gave a good sense of speed. When having access to motion feedback the subjective ratings on usefulness of the motion feedback were better in low-speed disturbance scenario. But in high-speed dynamic scenario the motion did not add much extra value. In fact, it was highlighted that the inherent latency of the motion platform could induce a latency in the driver's response making them having different precision as if they were driving without motion feedback. Our hypothesis here is that a speed-dependent motion, vibration and sound model should be created to give the driver the information the driver need at the right time.

List of relevant publications during the REDO project:

Zhao, L., et al. (2021). **Study of different steering feedback models influence during remote driving**. Proceedings of the 27th IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks. Presented at the 27th IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks, The Emperor Alexander I St. Petersburg State Transport University in Saint-Petersburg, Russia, August 16-20, 2021. DOI: https://doi.org/10.1007/978-3-031-07305-2_78

Zhao, L., et al. **The Influence of Motion-Cueing, Sound and Vibration Feedback on Driving Behaviour and Experience - A Virtual Teleoperation Experiment**.
(Submitted for publication in IEEE Transactions on Intelligent Transportation Systems [Under review])

Zhao, L., Nybacka, M., Rothhämel, M., Drugge, L. **Driving Experience and Behaviour Change during Teleoperation Compared with Real-Life Driving**.
(In preparation for publishing in IEEE Transactions on Intelligent Vehicles)

Papaioannou, G., et al. **Unraveling the correlation of motion comfort with driver feel in remote and normal driving**.
(In preparation for publishing)

Zhao, L., Nybacka, M., Rothhämel, M. **A Survey of Teleoperation: Driving Feedback**
(Presented at IEEE Intelligent Vehicles Symposium 2023)

Zhao, L., Nybacka, M., Rothhämel, M., Drugge, L. **Influence of sound and motion-cueing feedback on driving experience and behaviour in real-life teleoperation**,
(Submitted for publication in IAVSD 2023, 28th Symposium on Dynamics of Vehicles on Roads and Tracks)

Zhao Lin.: **Teleoperation - The influence of driving feedback on driving behaviour and experience**, Licentiate Thesis, KTH Royal Institute of Technology, Sweden.
(Presented on 24th of May 2023)

3.2. Auditory feedback

Remote operator interfaces for commercially available road vehicle teleoperation systems are predominantly visual in nature. This is not surprising as driving is a highly visual task, but the fact that we use all our senses when experiencing and navigating in the world should encourage the exploration of including other sensory modalities in a remote operation station. The current work has focused primarily on how the use of sound may improve the situation for a remote operator of a road vehicle.

Several different reasons for using sound in a remote operator station have been identified within REDO and are discussed below.

Information and warning. Today's cars, trucks, and other road vehicles employ a number of different sound interfaces that guide or warn the driver on several different levels of urgency. Examples of sounds that can be presented through a driver-vehicle interface (DVI) are turn signal, seatbelt reminder, parking assistance, and collision warning. Some of these sounds are required to be presented by the DVI to fulfil safety ratings such as Euro NCAP or IIHS and/or legal requirements. While the legal framework for remote operation stations is yet to be fully defined, it is reasonable to assume that the sounds required in normally driven vehicles will also become mandatory in remote driving operation. Other sounds, such as the turn indicator or parking assistance sounds, may be included to enhance the understanding of the vehicle's state and/or improve the operator's performance.

Sense of speed and ego-motion. While driving is a highly visual task, the sense of how fast the vehicle is going has been shown to be very much influenced by sound. Without propulsion sounds (consisting of the noise from the powertrain and the road noise), people tend to underestimate the speed with which the car is traveling. In a remote operation station, where visual cues are limited as they are usually monoscopically mediated through a camera-display system and physical motion cues could be non-existing, propulsion sound may become extra important for the operator to be able to regulate the speed properly. Ensuring accurate perception of a remotely controlled road vehicle's speed is essential for safe operation and avoiding unwanted conditions such as discomfort for passengers, strain on the vehicle, and energy inefficiency. Vision is a critical factor in speed perception, but studies have also shown the influence of in-car noise on perceived speed. For example, studies have demonstrated that noise reduction can lead to slower speed judgments and that passengers with diminished hearing tend to estimate speeds to be lower than they are. In another study, participants were found to drive faster in the absence of sound feedback, and their ability to maintain correct speed was much worse at higher speeds. These findings suggest that remote operation stations lacking propulsion sound feedback could lead to operators driving too fast, particularly when no speedometer is visible. It is crucial to consider the integration of different sensory cues, including sound, when designing a remote operation system for road vehicles.

Apart from understanding what speed the remote car is currently traveling at, it may be advantageous for the operator to get a sense of actually moving to further increase and provide an intuitive sensation of the awareness of the remote vehicle state. Visual stimuli are capable of creating such sensations but as previous research has shown, auditory stimuli alone can also create ego-motion sensations as well as contribute to an increased sensation in an auditory-visual display. Ego-motion can be induced by exposing individuals to spatially moving auditory sources, but also the use of propulsion sound can increase the sensation of actually moving.

3.2.1. Situational awareness

Situational awareness. Situational awareness (SA) is a broad term that may be defined in various ways, but it is generally believed to be important for operators of vehicles and systems. In the context of remote driving operation, it is believed that SA is one of the key aspects to consider in operator interface design. In this report we will use the model by Endsley (1995) which states that SA consists of awareness on three levels, each stage being a necessary (but not sufficient) precursor to the next, higher, level: 1) Perception of elements in the environment (e.g. perception of other objects around the car, current speed, etc.); 2) Comprehension of the current situation (understanding of the different elements' significance to the driving mission, e.g. if an object is on a collision path with the vehicle); and 3) Prediction of future status (being able to predict the future status of the elements, e.g. knowing where the car or other objects will be within a relevant timeframe). We have hypothesized within REDO that an auditory display may enhance SA in several different ways. Better speed perception through ego sound presentation is one such SA aspect that we already touched upon and that likely will enhance all three levels of SA. Another possibility is that being able to hear the remote environment will allow operators to both identify, localize and predict the trajectory of surrounding road users which most likely also will enhance SA on all levels. Appropriate reproduction of the soundscape, both in terms of its spectral, temporal, and spatial qualities, is likely crucial to gain this SA enhancement.

Sense of presence. The sensation of presence—the sensation of "being there"—is an often-discussed aspect of the experience of virtual environments. Presence and telepresence, i.e., the sense of being in a remote environment, is important to study in relation to remote road vehicle operation since it can have an effect on task performance. It is also natural to assume that making an operator feeling more present in the vehicle in a remote environment would make the operator act more natural as if controlling the vehicle directly, which would likely mean a safer operation. The importance of auditory displays in achieving a sense of presence has been emphasized by several researchers. Several aspects of sound have been shown to influence presence. For example, background sounds are particularly important for the sensation of "being part of the environment," and adequate representation of one's own voice is also essential. While spatialized sound is in general important for creating presence, the sensation can be further enhanced by means of individualized Head Related Transfer Functions (HRFTs) and head tracking. In other words, enhancing a certain sound source depending on the heading of the operator could further enhance the sense of presence.

3.2.2. LAVA auditory display prototype software

Within REDO, an auditory display prototype software, called LAVA (Layered Augmented Vehicle Audio), for remote driving and monitoring was developed in Max8[5], a software for creating and processing audio, to enable exploration of the different types of sound-related benefits discussed above. The software uses the Spat Max[6] package to render spatialized sound over headphones (so-called binaural presentation) and has an Open Sound Control (OSC) interface that allows for receiving

[5] https://cycling74.com/products/max

[6] https://forum.ircam.fr/projects/detail/spat/

positions, speeds and types of surrounding road users, as well as ego vehicle speed. The software can also receive head orientation angles as input via OSC to enable head tracked binaural rendering in Spat. Each road user, i.e., a source, is rendered using the Spat.Binaural~ object. Distance attenuation factor as well as high frequency distance roll-off and Doppler effect can be adjusted. The LAVA software has the capability of synthesizing both realistic ego-sound (propulsion sound) and the sound of surrounding road users such as cars, bicyclists and pedestrians using a combination of additive synthesis and recorded sound files. The main interface of LAVA is shown in Figure 8 below:

Figure 8. Main interface of LAVA. (A screenshot from LAVA software).

The software also allows for receiving microphone feeds from the remote vehicle and downmixing these to binaural sound. Two microphone types are currently supported: Ambisonics (1st order) and Spaced Array, where the Spaced Array mode can be configured to match different types of array configurations. This feature was tested within REDO in a proof-of-concept study together with Einride. A custom sound transmission plugin for the Voysys' Oden framework was developed that enables multichannel sound transmission from the remote vehicle to the operator station. Eight microphones were mounted around one of the Einride's Pod according to Figure 9.

The microphone signals could then be transmitted to the operator station and routed to the LAVA software where the sound would be rendered spatially and downmixed to headphones and then presented to the operator. The complete setup was tested in a remote driving setup of Einride (including both remote operation station and the Pod) at AstaZero in a right-turn scenario including a cyclist traveling alongside the Pod. Although some technical problems and limitations were encountered that limited the sound transmission, the concept setup seemed promising in terms of giving a spatial awareness of the bicyclist. Additionally, it was found that allowing the operator to hear all the minor sounds that the Pod makes (e.g., when the brakes engage or that the backup alarm is sounding) is a quite useful feature of the spatial sound transmission and rendering.

Figure 9. Microphone positions on Einride's Pod in concept study. (Photo: Einride AB).

3.2.3. Experiment

A controlled user study was conducted in a simulated environment to further test some of the aspects of sound for remote operation. In the following description, the term "**propulsion sound**" is used to denote the sound of the user's own car (road noise and electric engine sound) and "**augmented sound**" denotes sound of surrounding road users: pedestrians, cyclists, and other cars. The main aim of the study was to test the following hypotheses:

Hypothesis 1: Propulsion sound and augmented sound both contribute to the sensation of ego motion and the perception of speed (but propulsion sound to a higher degree)

Hypothesis 2: Augmented sounds and propulsion sound contribute positively to situational awareness and presence (but augmented sound to a higher degree).

The study involved a within-group 2x2 full factorial design with two independent variables: spatial augmented sounds (on/off) and propulsion sound/vibrations (on/off). The experiment was conducted with 28 participants, 21 of whom were male and 7 were female, with a mean age of 32.5 years (SD = 7.24). The materials used in the study included a driving simulator based on the CARLA OpenSource software, three curved 27-inch screens, Logictech G29 steering wheel and pedals, Beyerdynamic DT-880 headphones, and a Supperware head tracker. The CARLA software's Town01 model provided a base map for the four user scenarios: Car 1, Car 2, Pedestrian, and Cyclist. A night-time setting was used, and the auditory stimuli included propulsion (ego) sound (PS) and augmented sound (AS) consisting of three different source types: other cars, pedestrians, and cyclists. Participants' task was to keep 50 km/h on straights (no speedometer was visible except in pre-trial training sessions) and in general drive as if it was a real car they were controlling. The user study setup is shown in Figure 10.

Figure 10. User study setup. (Photo: Pontus Larsson).

Dependent variables included both subjective and actual ego-speed (mean and standard deviation), number of collisions, self-rated ego motion, situational awareness, presence and driving performance. In addition, participants' general experience of the experiment and their perception of the sound was acquired through semi-structured interviews after the test.

Data obtained from ratings and objective measures were analysed using 2x2 repeated measures ANOVA. The results in general supported both hypotheses ($p = 0.002$ or less). First of all, it was shown that participants were more accurate in keeping the speed of 50 km/h with sound than without (both in terms of mean speed and standard deviation of speed). While the propulsion sound contributed to the feeling of being able to keep the correct speed, the augmented sound did not have any effect on this item. As hypothesized however, both the propulsion sound and the augmented sound contributed to the sensation of ego motion. Moreover, participants felt more present and situationally aware in the environment with sound compared to when no sound was active, and both the propulsion sound and the augmented sound contributed to this effect. The results above agreed also with participants' subjective opinions (acquired through post-experiment interviews) regarding the different conditions.

In sum, the work carried out within the REDO project showed that sound can be beneficial for the remote operator in many ways, as it can convey several aspects of the remote environment that may be crucial for the safe and efficient operation of the vehicle. The experiment carried out showed that both subjective and objective measures can be improved by propulsion sound and augmented sound (surrounding road users): Presence, awareness, ego-motion, and speed keeping. Future research should test whether these effects can be found also in more realistic settings. It would furthermore be interesting to look more into potential long safety benefits over longer times of use and how operators prefer using these types of auditory displays in daily operations. Another sound-related aspect that has not been explored experimentally to great extent in the current project is the use/role of warning and information sounds in remote operation.

Further details regarding the experiment can be found in the upcoming paper:

Larsson, P., Bergfelt Ramos de Souza, J., Begnert, J. **An auditory display for road vehicle teleoperation that increases awareness and telepresence.**
(Presented at ICAD (International conference on auditory display) 2023)

4. Connectivity and mobile network support for remote driving

Information flows between a remotely-operated vehicle and a remote operation station were analysed to understand what a mobile network needs to handle, i.e., their characteristics and requirements.

Different mobile network deployments and network enablers were analysed to assess their applicability and constraints to support remote operation. Additional descriptions of deployment scenarios and network enablers, e.g., for Time Critical Communication (TTC)) can be found in this webpage[7]. Note that several of the TCC features are intended for general industrial scenarios and thus may not be applicable in certain automotive scenarios. Nevertheless, relevant deployment scenarios, enablers, and features of mobile network with respect to remote driving operation are discussed in this section.

4.1. Deployment scenarios

The main deployment scenarios for remote control scenarios are summarized here:

- Local Dedicated Networks (i.e., private network)
    - This would be to support remote control in a local area, likely confined area, having a controlled radio deployment and 'known' users, this could for example be in a mine, airport, port, transport hub.
    - In this type of deployment, legal requirements, permits and safety is less of an issue since the area can be fenced off and unauthorized persons can be kept out, authorized persons that potentially need to be in the area can be 'connected' e.g., using a connected vest and thus be monitored and protected. A digital twin type of applications can stop vehicles at eminent danger. In this deployment the mobile network can be tailored to suit the environment. A number of enablers and features as outlined in Chapter 4.2 below can be applied to support 'remote control', e.g., ensuring good uplink performance for video, and controlling which users have access to the network and how much network resources/capacity are allocated to each user. Application related to 'remote control' can be local on 'site' allowing that E2E QoS[8] of remote control is managed and controlled.
    - Note: A dedicated network could be built to cover a large geographical area for certain scenarios and special needs, i.e., a so called 'Wide-area dedicated network'. However, an enhanced general public network as described below could, in most cases, be sufficient to serve the needs.
- General public networks
    - This would be to support remote control in a general wide area, with enhanced radio deployment and unknown mix of users. This could for example be along a bus or a transport route.
    - In this type of deployment, legal requirements, permits, and safety is more challenging since the area is public and may include unconnected vehicles and humans, which can behave irrationally. However, for the connectivity, the mobile network can be enhanced with enablers and features as outlined in Chapter 4.2 to support 'remote control', for example the radio network can be enhanced along the route to ensure good coverage, ensuring good uplink performance for video to the remote control

[7] https://www.ericsson.com/en/internet-of-things/iot-connectivity/cellular-iot/time-critical-communication

[8] End-to-end Quality of Service.

application. Priority for the remote control can be achieved by allocating a certain percentage of the radio resources (capacity) in the radio network along the transport route for the 'remote control' application ('slice') or by allocating a certain Quality of Service (QoS) class to the 'remote control' application. The 'remote control' application could be hosted within the mobile network operator domain to allow 'managed latency', i.e., that the E2E QoS of the session is managed and controlled by the mobile operator, thus avoiding that internet is part of the E2E session and potentially causing fluctuations in performance.

4.2. Network enablers and features

A number of features and enablers available in a 5G mobile network was analysed for their applicability to support remote driving. Some are also available in 4G networks, but 5G provides additional capabilities and a higher number of connected and active users.

The following are examples of available enablers and features:

- *Frequency bands,* 5G provides a substantial number of frequency bands in mid bands (below 6 MHz) and high bands (above 6 MHz). These bands are very wide, e.g., 100 MHz or more, which provides a huge capacity. In other words, a certain band(s) can be dedicated to specific applications such as remote driving operation. Low bands are also available and are being re-farmed from 4G (LTE) use. Functions are also available to share the resources on the band between 4G and 5G instantly to serve the users in a best way.
- Carrier aggregation and dual connectivity, multiple bands can be used by a mobile device simultaneously to provide high capacity.
- *Time Critical Communication (TCC)*[9]*,* is a collective term for a number of features that can be applied to enhance the performance and latency, e.g., provide 'Bounded latency' to reduce jitter. Some examples are:
  - 'Slicing', a.k.a. network slicing. A mobile network can be configured so that the users get a 'private network' (a slice) with a certain amount of resources. This can be done in multiple ways, e.g., the radio network can be partitioned so that the users when present get their configured percentage of resources if needed. If users are not present or if all resources are not needed, other users can use the resources. If only the radio network applies slicing, this is referred to as 'Radio Resource Partitioning'.
  - Uplink (UL) configured grant, i.e., to reduce latency, a user equipment has pre-granted permission to send data uplink without needing to request permission from the network.
  - Low Latency Low Loss Scalable (L4S), the network can indicate to applications that queues are building up and thus give the application a heads-up that latency may increase and that applications should take action, e.g., reduce video quality.
- *Quality of Service (QoS),* the network can give priority to certain users or flows. This can be configured or being controlled dynamically by calling an HTTP API of the mobile network and request QoS when temporarily needed, e.g. due to high load in a radio cell affecting video quality

[9] https://www.ericsson.com/4a9e9f/assets/local/internet-of-things/docs/19102021-time-critical-communication-brochure.pdf

- *Real-time Kinematic (RTK) for accurate position,* the mobile network can provide correction information so that clients can achieve centimetre position accuracy by correcting the position obtained by GPS receivers.
- *Local connectivity*, the user plane gateways of a mobile network can be distributed and thus provide that applications can be located close to the relevant area.
- *Hosting of applications,* applications can be hosted within a mobile network operator domain. This allows that the transport connectivity can be managed and controlled, thus avoiding potential fluctuations of internet performance.

5. Video transmission for remote driving

During the project, Voysys AB conducted network connectivity tests with respect to video transmission in the surroundings of Norrköping (Sweden) using public 4G networks, and found the quality of network operators Telia and Tele2 to be best for video transmission (Telia is substantially better in uplink bandwidth).

The tests indicate that using Voysys' streaming technology in conjunction with multiple links from these operators provides a stable and low-latency video link from a moving vehicle in the inner city of Norrköping (see Figure 11). During the tests, ping times stayed below 25 ms. Glass-to-glass latency using the Voysys system stayed well below 100 ms, without any severe latency peaks. For these tests a severe latency peak was defined at 300 ms.

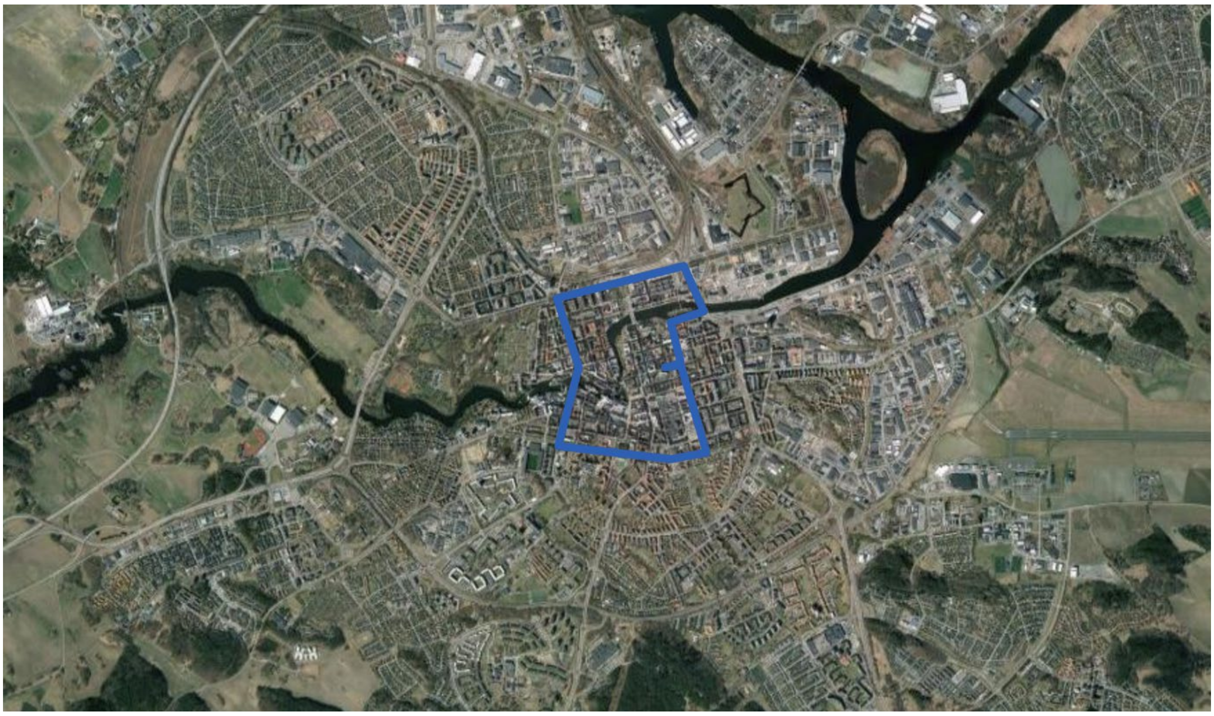

Figure 11. Area in the inner city of Norrköping, where Voysys' multiple links approach for video streaming is tested. (Photo: Voysys AB).

In order to find more challenging test environments, Voysys also conducted tests on the outskirts of Norrköping and found "Djurövägen" to be an exceptional challenge in terms of network coverage (see Figure 12).

Tests were carried out using a vehicle with a physical driver in it. One network camera was used as a live video source and was connected to three different streaming systems in the vehicle:

1) Single-link reference system with Telia public 4G
2) Single-link reference system with Tele2 public 4G
3) Multiple-link system with Voysys technology (different setups and link combinations tested from time to time)

The three video streams were received at the Voysys office in Norrköping (using a wired Internet connection) by one single computer running the Voysys application "Oden Player" which merged the three receiving videos into one synced video containing all three video streams for comparison and analysis. Each setup was tested at least three times in each direction on Djurövägen, at different times of the day.

Trying many different network setups, using two Telia links and two Tele2 links at the same time proved to be the setup providing the most stable latency, totally avoiding severe latency peaks even in areas where the reference systems with single-link setups had very severe latency peaks and picture freezes. In the tests at Djurövägen, ping times stayed well below 25 ms and glass-to-glass latency using the Voysys system stayed well below 100 ms when using the multiple links setup (two Telia links and two Tele2 links).

Videos from Djurövägen are available, and one example showing the results when reference links had the worst possible results can be watched at https://www.youtube.com/watch?v=DbiRTuLThTI .

Figure 12. Djurövägen on the outskirt of Norrköping, where Voysys' multiple links approach for video streaming is tested. (Photo: Voysys AB).

6. Laws and regulations concerning remote driving

This chapter of the report will address legal aspects relating to remote driving operations, with a specific focus on laws and regulation development, the driver definition as well as requirements of the remote driver and remote driving system respectively.

The chapter is structured as follows. Firstly, the aims, research methodology and research questions are presented in Section 6.1. Secondly, relevant regulation and regulatory development are investigated and mapped on an international, EU- and national level (6.2) Then, the definition of driver is analysed and discussed in relation to the mapped regulatory frameworks (6.3) followed by a review of legal requirements of the remote driver (6.4). Remote driving system requirements are thereafter explored in a separate Section 6.5. Finally, conclusions, recommendations and future work are presented in Section 6.6.

It should be noted that the report content of this chapter 6 is based on but also complements the results set out in the research article “Regulating Road Vehicle Teleoperation: Back to the Near Future” (Linné & Andersson, 2021) published as a deliverable of REDO’s WP6. It should also be noted that this work has been conducted between 2020 and 2022. Lastly, parts of the content are related to contents in (Skogsmo, et al., 2023), which focuses on remote operation of multiple vehicles.

6.1. Aims, methodology and research questions

A general and overarching aim of the research performed in WP6 was to increase the knowledge about legal and regulatory aspects of remote driving to support the overall project goal to build knowledge and create opportunities in the emerging field of remote operation of road vehicles. This involved to establish some fundamental legal matters in relation to remote driving by examining its regulatory development in different jurisdictions. In addition, a specific aim was to identify potential regulatory obstacles to the development and introduction of remote driving on public roads.

The research was carried out by use of a combination of methods. Based on a legal method a continuous review of relevant regulation, regulatory development and regulatory initiatives was performed. In addition, methods used involved participation in several workshops[10] and stakeholder dialogue and interviews were performed.

The research questions of WP6 investigated an analysed were as follows.

1. What are relevant laws and regulations that concern remote driving operation?
2. How should the definition of who is a remote driver be formulated legally?
3. What requirements should be linked to the remote driver and the remote driving system respectively?

The outcome of the analysis of these research questions are presented and discussed below.

6.2. Relevant laws and regulations that concern remote driving operation

The legal analysis related to the questions regarding the definition of a remote driver, remote driver requirements and remote driving system requirements are based on the regulatory sources and material presented and discussed in this section. The regulatory review included considering the discussion of remote driving at the international regulatory level by UNECE. In addition, the EU implementing regulation on type-approval of automated driving systems (ADS) of fully automated vehicles was considered in the review. Also, the regulatory development and initiatives of some specific European

[10] Remote timber, IEEE IV, Drive Sweden

jurisdictions in were considered and reviewed: Sweden, the UK, Germany and France. The choice of jurisdictions was motivated by a European perspective as well as the level of regulatory activity.

6.2.1. UNECE (WP.1)

At the international level, it is of interest in this context to put forth by way of introduction that there is an ongoing work within the UNECE Global Forum for Road Traffic Safety (WP.1) to draft a new legal instrument on the use of automated vehicles in road traffic to complement the International Conventions on Road Traffic of 1949 and 1968. For this purpose, WP.1 has established a Group of Experts on the use of automated vehicles in traffic (LIAV GE). The new instrument will include, in addition to the typical sections on definitions and final clauses, a set of legal provisions for the safe deployment of automated vehicles in international traffic with a specific aim to ensure road safety, in particular the safety of vulnerable road users. Upon the completion, the LIAV GE will submit the complete draft new legal instrument to its supervising body, the WP.1 for consideration and decision (UNECE, 2021).

WP.1 has also been active in regulatory discussions regarding remote driving. During 2019, a proposed Draft Resolution on Remote Driving was published, (UNECE, 2021a) addressing automated driving and situations when a driver operates a vehicle from the outside of the vehicle. The draft resolution was submitted by the United Kingdom to facilitate progress in the area of remote driving and included inter alia a definition of and recommendations for remote driver and remote driving systems. In addition, the resolution included a conclusion that a "combination of the remote driver and vehicle that is able to safely exercise dynamic control as well as, or better than, a driver inside a vehicle, would be compatible with the road safety principles of the 1949 Convention and the 1968 Convention". The draft resolution also recommended contracting parties to amend their domestic legislation, regulation, and guidance to support the safe use of remote driving systems.

The draft resolution was in 2021 replaced by an Informal paper on remote driving providing a continued discussion for situations when a driver operates a vehicle from the outside of the vehicle (UNECE, 2021). The document was revised and updated in 2022 through further elaboration of

1. requirements for remote drivers and remote driving systems, and
2. requirements for service providers, developers and manufacturers in remote contexts? respectively.

It is stressed that the document only considers instances where the remote driver is in control of a single vehicle at any time. However, in an annex 1 scenarios of remote support, assistance and controlling are set out for further legal consideration acknowledging other possible scenarios for remotely facilitating driving, where a remote operator may provide support, monitoring or assistance to more than one vehicle at a time (UNECE, 2022).

Regarding the way forward, it follows from the agenda of the next Global Forum for Road Traffic Safety session in March 2023 that WP.1 is invited to discuss a second revision of the Informal document as well as to take part in a dedicated panel on the same topic. Also, it follows that the LIAV GE is invited to provide information on the on-going discussions, outcomes, and on the Group's general progress to-date (UNECE, 2022a).

6.2.2. EU

At EU-level, the European Commission on 5 August 2022 adopted a Commission Implementing Regulation 2022/1426 providing for uniform procedures and technical specifications for the type approval of the ADS of fully automated vehicles in the European Union. The regulation entered into force on 15 September 2022 and introduces new EU rules introducing specific requirements for automated and fully automated vehicles and the systems they employ, to ensure that they are safe to use. According to article 1 it applies to the following use cases:

- Fully automated vehicles, including dual mode vehicles, designed and constructed for the carriage of passengers or carriage of goods on a predefined area.
- ‘Hub-to-hub’: fully automated vehicles, including dual mode vehicles, designed and constructed for the carriage of passengers or carriage of goods on a predefined route with fixed start and end points of a journey/trip.
- ‘Automated valet parking’: dual mode vehicles with a fully automated driving mode for parking applications within predefined parking facilities.

The regulation does not apply to or regulate remote driving, but includes a definition of a “remote intervention operator” which is of interest in the context of remote operation as such and the question of the driver definition, see section 6.3. below (European Commission, 2022).

6.2.3. Sweden, United Kingdom, Germany, and France

In the following sections a variety of relevant regulatory developments and initiatives in different national jurisdictions throughout Europe are reviewed and presented.

Sweden

In Sweden a draft proposal of an Automated Traffic Act was presented in 2018. However, already in 2016 legislation for test operations was proposed which then entered into force in 2017 (SOU, 2016) (SOU, 2018) (SOU, 2018b). 1 January 2021 a concept of driver was introduced in the legislation for test operations and later in 2021 a Ministry Memorandum (DS 2021:28), investigated liability issues for the deployment of automated driving and proposed the introduction of a new legal actor, a driver-on-standby (förare i beredskap) who has to be present during automated driving, unless otherwise prescribed (Ds, 2021). The main focus in the regulatory development has been on the human inside the vehicle even though the driver concept for test operations and the proposed concept of a driver-on-standby also are relevant in a remote context. The legislative proposals are now being prepared by Government Offices. Thus, so far neither remote operation or remote driving have been thoroughly discussed or elaborated on in Swedish law.

UK

In the UK, remote operation has been explicitly considered under a broader program of activities aiming at a regulatory framework for automated vehicle technologies. Based on an extensive regulatory review, the Department of Transport has published guidance in a Code of Practice for automated vehicle trialling and the Law Commission has published several consultation reports on automated and remote driving respectively as well as remote driving advice to Government.

According to the Code of Practice from 2015, updated in 2019 and 2022, trialling any level of automated vehicle technology is possible on any UK road if carried out in line with UK law. Thus, trialling organisations do not need to obtain permits when conducting trials in the UK but will need to ensure that they have a driver or operator, in or out of the vehicle, who is ready, able, and willing to resume control of the vehicle. In addition, they must have roadworthy vehicle and appropriate insurance in place. The Code explicitly deals with the situation of remote-controlled trials (Department for Transport (UK), 2022).

The Law Commission has recommended, based on consultations, that remote operation should be legally directed to a specific regulatory path in a comprehensive legal framework for automated vehicles. The proposal introduces three new legal actors an Authorised Self-Driving Entity (ASDE), a user-in-charge, and a No-user-in-charge Operator (NUIC). The ASDE is the manufacturer or developer that puts the ADS forward for authorization and takes responsibility for its actions. The user-in-charge (UIC) is the human in the driving seat, whereas the NUIC operator is a licensed organization that oversees vehicles without a UIC. Thus, the NUIC operator is a legal actor taking responsibility for operating vehicles remotely which are authorized for use without a UIC. Overseeing the vehicle does not mean that the NUIC needs to monitor the driving environment, but NUIC operator staff will be expected to respond to alerts from the vehicle if it encounters a problem it cannot deal with, breaks down or is involved in a collision. It is anticipated that, in the great majority of cases, a NUIC operator will employ staff in a remote operations centre. However, it follows from the consultation report that a vehicle relying completely on remote driving is out of scope of the proposed framework. All operators of such vehicles are required to be qualified, operate remote supervision, maintain and insure the vehicle, install safety-critical updates and maintain cybersecurity and report accidents and near misses. Additional duties could apply to the operator if, for example they are running a passenger service or operating heavy goods vehicles. If there are people in the vehicle these are merely passengers with no obligation to intervene and no legal responsibility for the way the vehicle drives (Scottish Law Commission, Law Commission, 2022).

Remote driving has instead been addressed by the Law Commission in a specific Remote Driving Issues paper but also in Advice to Government (Law Commission, 2022b) (Law Commission, 2023). In the Issues paper both short-term and long-term options for legal reform are proposed to address problems with existing law as applied to remote driving and it includes definitions of a remote driver and a remote assistant respectively. Also, the Law Commission suggests an introduction of a licensing system, where remote operation should be overseen by an Entity for Remote Driving Operation (ERDO). According to the Law Commission, future regulatory attention should be directed to issues such as the adequacy of the communication network; cybersecurity; workstation layouts; staff training; staff health, fitness and vetting; staff attention and rest periods; and incident protocols (Law Commission, 2022b).

In the Advice to Government paper published in February 2023 the Law Commission, includes, due to the prevailing legal uncertainty, a recommendation to immediately prohibit remote driving for an interim period while a new regulatory system to govern remote driving is developed. During such prohibition period companies wishing to use remote driving in their operation could submit a safety case to the Vehicle Certification Agency to apply for a vehicle special order to perform remote driving. In addition, the Law Commission suggests that remote driving from overseas should be prohibited due to safety concerns and a lack of enforcement powers. The Law Commission recommends that the development of a new comprehensive regulatory regime involves licensing of entities, as previously suggested in the Driving Issues paper, subject to satisfying a safety standard (Law Commission, 2023).

Germany

Germany was the first country in the world to regulate the rights and obligations of drivers using automated driving functions, through the Act on automated driving, 2017, amending the Road Traffic Act (SAE level 3). The Act made it possible for automated systems to take over the task of driving under certain conditions. Under the Act, a person who activates a highly or fully automated driving function and uses such a function to control the vehicle, even though he does not control the vehicle manually, shall be deemed to be a driver. The driver may divert his attention from other traffic and control of the vehicle but must remain sufficiently alert at any time to be able to retake control of the vehicle and the driving task (Bundesministerium für Digitales und Verkehr, 2017).

On July 28, 2021, the Act on autonomous driving (SAE level 4) entered into force in Germany. The Act allows motor vehicles with autonomous driving capabilities, that is vehicles that can perform driving tasks independently without a person driving, in specified operating areas on public roads. It is a regulatory interim solution which will apply until superseded by European or international regulation. In other words, the act provides the legal framework until European and/or international laws supersede it. Vehicles with an autonomous driving function does not require a person to drive the vehicle during operation. However, a responsible person is still required. Thus, the Act introduces a new legal actor, a technical supervisor (technische aufsicht) who will be responsible for ensuring that the traffic law obligations are complied with. The technical supervisor will in most cases be located remotely. S/he is not required to monitor the driving operation on a permanent basis but is responsible for oversight and emergency manoeuvres (Bundesministerium für Digitales und Verkehr, 2021).

France

France has adapted its road and traffic regulations to allow for operation of fully-automated vehicles on public roads. A regulatory framework on automated vehicles, decree No. 2021-873 of 29 June 2021 adapting the provisions of the Highway Code and the Transport Code, sets conditions to allow automated vehicles and automated road transport systems to be deployed on predefined routes or zones from September 2022. Automation levels up to fully automated systems are covered, provided that these are under supervision of a person in charge of remote intervention and deployed on predefined routes or paths. Remote intervention, according to the system's conditions of use, is allowed only if the system is validated by the service organizer, after safety demonstration and opinion of an approved qualified body. The decree sets definitions and general safety provisions for these systems, as well as authorization requirements for the driver or the person in charge of remote intervention (Ministère chargé des Transports, 2022).

6.3. The driver definition

The driver definition has been an essential element in international traffic conventions. The Vienna Convention on Road Traffic of 1968, developed by the United Nations Economic Commission for Europe (UNECE) forms the base of many national traffic laws (United Nations, 1968). The convention was built around the notion of driver and previously required the presence of a **human** driver who could take control of the vehicle at any time. However, an adopted amendment, article 34 bis, facilitate the use of ADS. The article states that the driver requirement is deemed to be satisfied provided it is using an automated driving system that complies with domestic and international technical regulations, and domestic legislation governing operation. It does not follow from the definition or other rules of the convention that the driver must be in or in direct sight of the vehicle. Thus, it does not seem to exclude remote operation as such.

Through the UNECE proposed draft resolution on remote driving it was set out that a "*Remote driver*" refers to a driver who is located outside of the vehicle (UNECE, 2021a). In addition, the informal papers on remote driving clarified that these documents only consider the situation where full dynamic control of the vehicle is performed by a remote driver, defined as the ***"****Real-time performance of all the Dynamic Driving Task (DDT) and/or DDT fallback (including, real-time braking, steering, acceleration, and transmission shifting)"* (UNECE, 2022).

In the EU context there is no regulatory definition of the remote driver. However, of interest to remote operation as such is the definition of a "remote intervention operator" set out in article 2 (25) of the Commission Implementing Regulation stating that, where applicable to the ADS safety concept, it means "person(s) located outside the fully automated vehicle who may remotely achieve the tasks of the on-board operator provided it is safe to do so". It is also expressly stated that "the remote intervention operator shall not drive the fully automated vehicle and the ADS shall continue to perform the DDT[11]" (European Commission, 2022). This definition makes clear that it is not applicable to a remote driver.

In Swedish law there's been an absence of a driver definition. The draft proposal of an Automated Traffic Act did not include such definition. However, on January 1, 2021, a concept of driver was introduced in article 7 of the ordinance concerning testing of autonomous vehicles (Sveriges riksdag,

[11] Dynamic Driving Task (DDT) as defined in SAE J3016 document.

2017). It states that in case of autonomous driving a driver must be present inside or outside the vehicle and that the person who activates the autonomous system will be considered the driver of the vehicle until the autonomous system is inactivated. Thus, it applies to remotely located drivers.

Also, in the previously mentioned Swedish Ministry Memorandum a new legal actor, a driver-on-standby (förare i beredskap) was introduced and proposed in 2021. A driver-on-standby is, according to the memorandum, the person who activates the automated driving or who takes over that task for a vehicle where such operation is activated. Such person could be present inside or outside the vehicle (Ds, 2021). It remains to be seen whether this concept will be used in Swedish law in the regulatory development of remote operation in general and remote driving in particular.

In the UK, the Law Commission has made a clear distinction between remote driving and remote assistance as such proposing different regulatory paths of licensing schemes for these remote operation activities respectively. The Law Commission has also proposed a definition of a remote driver and of a remote assistant respectively. Thus, a remote driver has been defined to be a driver who is outside the vehicle and who uses some form of wireless connectivity to control the vehicle, whereas a *remote assistant* sets out not to be a driver if not exercising direct longitudinal or lateral control, but only advise an automated driving system to undertake a manoeuvre (Law Commission, 2022b).

In Germany, there is no definition of a remote driver. However, a new legal actor, a technical supervisor, was introduced through the Act on Autonomous driving (Bundesministerium für Digitales und Verkehr, 2021). This technical supervisor is set out to be a natural person who deactivates automated driving and enables driving manoeuvres if necessary. The technical supervisor is responsible for ensuring that the obligations under road traffic law are complied with at all times, even if permanent monitoring of the driving operation is not required. Responsibilities are in particular:

- activation of alternative driving manoeuvres,
- assessment of transmitted data of vehicle and taking the necessary measures for traffic safety including immediate deactivation of the autonomous driving function in case of technical problems, and
- contacting passengers and taking necessary measures for road safety when vehicle is placed in minimum risk state - meaning greatest possible road safety.

It follows from these listed and described responsibilities that the technical supervisor is not a remote driver performing the DDT.

The role of a remote operator performing remote intervention is also introduced in French law. It follows from the definition of remote intervention that it only applies within an automated road transport system, that is a set of highly or fully automated vehicles, and technical devices allowing remote intervention or safety, deployed on predefined routes or zones, and complemented by operating and maintenance rules, for the purpose of providing a passenger road transport service (Ministère chargé des Transports, 2022). Remote intervention sets out to include actions such as to:

- activate and deactivate the system,
- give instruction to the system to perform, modify, or interrupt a manoeuvre,
- acknowledge manoeuvres proposed by the automated driving system, and to
- choose, modify the planning of a route or stop points.

It follows from the regulatory and literature review that there is a variety of different activities that can be related to remote operations[12]. A few have been mentioned above, such as remote assistance, remote intervention and remote driving, but there are others such as inter alia remote control, remote support, remote monitoring and remote management. However, there is an absence of generally agreed definitions and terminology is applied inconsistently by regulators, academics and industry. From a legal perspective this could be viewed as a barrier to the safe introduction and deployment of remote operation, including remote driving. Remote operation could rather be viewed as an umbrella term for remote driving or teleoperation (Kalaiyarasan, et al., 2021) (Lawson, 2021). Also, based on the regulatory review it could be concluded that a proposed legal definition of remote driver could be formulated to mean the individual conducting part of or all the DDT from outside the vehicle by use of some form of wireless connectivity.

6.4. Requirements of the remote driver

From reviewing the regulatory initiatives of remote driving it follows that the discussions and proposals of requirements directed towards the remote driver concern a variety of issues ranging from the physical and mental capabilities to requirements to safeguard the transport of passengers. However, the themes of the remote driver requirements are similar in the different regulatory initiatives and proposals and motivated by safe deployment reasons. Proposed requirements include inter alia that the driver:

- has the physical and mental capabilities,
- holds the appropriate license to use and operate the vehicle, and
- has the competence to undertake remote driving,

The remote driver relevant competence needs to be mapped and could, as suggested in literature, include system understanding, communication and technical knowledge, driving experience, knowledge of existing regulations, basic engineering knowledge, etc. (Ministère chargé des Transports, 2022) (Saha, 2021). The listed capabilities should safeguard that the remote driver could exercise dynamic control when required as well as be able to remotely activate and de-activate the ADS and the remote driving function (UNECE, 2022).

In addition, regulators have argued that future regulations for remote drivers need to consider health checks, targeted training and exercises, but also the need to regulate requirements related to rest periods and shorter shifts (UNECE, 2022) (Scottish Law Commission, Law Commission, 2022) (Law Commission, 2022b) (Ministère chargé des Transports, 2022) (UNECE, 2020).

It should, finally, be noted that the regulatory review displays that the remote driver requirements discussed and elaborated on differ in some respects from the requirements for remote assistance (Scottish Law Commission, Law Commission, 2022) (Law Commission, 2022b). For example, this applies to training and licensing requirements.[13]

6.5. Requirements of the remote driving system

From the regulatory review follows that the requirements of the remote driving system mainly has been specifically addressed in the UNECE informal papers on remote driving (UNECE, 2021) (UNECE, 2022). Also, it follows that the requirement list has, for each new revision, been extended to include additional requirements. These could be divided into four categories: (1) minimum

[12] This topic is further discussed and elaborated on in the REDO additional project, One2many, which reports on Remote operation of multiple vehicles (Skogsmo, et al., 2023).

[13] See also section 4.5 in REDO additional project One2many report on Remote operation of multiple vehicles.

requirements to safeguard road safety, (2) situations when the remote driving system should reach a suitably safe minimum risk condition, (3) requirements applying when carrying passengers within the vehicle, and (4) requirements to deal with medical emergencies and crashes.

The minimum requirements in category (1) address to a great extent the human factors (UNECE, 2020) and safety challenges of remote driving.[14] These requirements include inter alia that the remote driving system should at the minimum:

a) Allow the remote driver to have an appropriate field of view of sufficient resolution and clarity, and to receive appropriate auditory information; and supplement this information with additional cues which may be haptic, auditory or visual to alert the driver of high risk situations.

b) Present information to the remote driver which provides appropriate situational awareness and accurate feedback on how the vehicle is responding to their commands.

c) Have strategies to reduce the effects of the remote driver suffering motion sickness, information overload and change blindness.

d) Enable the remote driver to adjust the workstation, to ensure it is comfortable and adapted to their needs.

e) Have strategies to minimize the risk of signal loss and/or degradation, such as redundancy in sensing and connectivity, including the demands placed on bandwidth.

f) Consistency in data transmission to address variability in latency or time lag.

g) Be IT-secure by design, using state of the art technologies and standards, including consideration of operational resilience and response in the event of cyberattacks, to ensure that they can survive particular types of attack at fleet level, and prevent potential malicious use.

The situations referred to in category (2) when the remote system should have the ability to reach a suitable safe minimum risk condition include inter alia:

a) When the remote driver does not, or cannot, provide appropriate and timely input or the vehicle is unable to react in an appropriate and timely manner.

b) When the latency of the connection between the remote driver and vehicle has exceeded safety tolerances.

c) When the connection between the remote driver and the vehicle fails or is degraded, or the safety of the system is compromised.

The minimum risk condition that the remote driving system is required to reach will, according to the requirements set out, depend on whether an ADS is capable of safely taking over the dynamic driving task to continue the journey.

Examples of requirements in category (3) on the system when carrying passengers involve inter alia to:

a) provide passengers with solutions for them to request emergency stops as well as regular stop requests.

b) provide the ability to properly communicate any unexpected events, to avoid passenger confusion.

[14] These challenges have been elaborated on more explicitly in the REDO additional project One2many report on Remote operation of multiple vehicles.

c) provide human-machine interface (HMI) solutions and protocols between passengers

d) remote drivers to support communication and interaction for both daily and emergency operation.

The requirements set out in category (4) concern medical emergencies and crashes involving the remotely driven vehicle. In such situations, the driving system must have mechanisms to deal with the incidents as these are considered to pose the most serious safety concern, are time critical, require accurate perception, comprehension, and an effective response. It is also added that these incidents will require stopping, securing the vehicle, attending the injured, coordinating passenger emergency exit and on-board communication with dispatch and emergency crew. Being a complex coordinated response it may require input from multiple remote drivers (UNECE, 2022).

6.6. Conclusions, recommendations, and future work

Having investigated the regulatory context and development of remote driving of partially automated vehicles as a way forward toward the long-term goal of more autonomous vehicles, it could be concluded that during the lifetime of the REDO project the regulatory development has been relatively intense with a particular focus on automated and autonomous driving. This implies that current regulatory frameworks and initiatives aim at a future with high-level automated vehicles. Remote driving, though, has been sparsely treated even though some examples of regulatory initiatives, set out in informal documents and regulatory proposals, specifically directed towards driving as a remote operation activity have been introduced and referred to in this report. In order to achieve the long-term goal of more autonomous vehicles, more regulatory attention needs to be directed specifically towards remote driving. Legal certainty is decisive in this context, and it is therefore recommended that more focus on and conscious inclusion of the concept of remote driving as well as remote operation are considered in current and/or future regulatory frameworks.

Another conclusion of the regulatory review as well as the literature review and workshop participation is the absence of generally agreed definitions, resulting in confusion and legal uncertainty. The absence of definitions and the fact that terminology is used inconsistently is a legal barrier of high relevance to the development of remote operations, including remote driving. Unresolved, this issue will counteract an efficient and successful introduction. It is therefore urgent and recommended from a legal and regulatory perspective to address the terminology challenge.

There are a variety of regulatory aspects and questions that need further attention. Future work and legal research could address issues such as the boundaries between and legal requirements for different remote operation activities, such as remote assistance, driving, and supervision. Also, the legal requirements or limitations regarding the number of vehicles to remotely operate and working conditions and hours for the remote operator as an employee are other urgent issues to resolve in order to support the development of remote operation. Finally, another urgent legal challenge which is of importance to address in future work is the switching between different driving modes such as from automated driving to remote driving.

7. Conclusions and future work

This report presents experimental setups and findings from the REDO project, which has been conducted between December 2019 and February 2023. Five main topics are covered in this report: 1) Effects of latency and field-of-view on driving performance; 2) Remote driving feedback and control; 3) Connectivity and mobile network support for remote driving; 4) Video transmission for remote driving; and 5) Laws and regulations concerning remote driving. The main topics are briefly summarized below.

7.1. Effects of latency and field-of-view on driving performance

With respect to the effect of latency and field-of-view, this report presents experimental setup that were used to conduct two simulator studies during the project, including five “hazardous” events that were used during the experiments. Two groups of participants—professional taxi drivers and experienced gamers—were recruited to participate in both studies, where effects of latency and field-of-view were studied, respectively.

From the first experiment, we observe that reaction time increased by about 1 second, when only 200 ms latency in overtaking event. From the second experiment, the filed-of-view (roof vs normal) did not have a clear effect on driving performance apart from participants keeping larger lateral distance in all tasks with the roof view. It highly depends on driving task and speed, i.e., the event and environment. Detail analysis of the results from the simulator studies are presented in the following publications and presentation:

- Jernberg, C., Andersson, J., Sandin, J., Ziemke, T., **The effect of latency, speed and performed task on remote operation of partly autonomous vehicles**, Submitted to Transportation Research Part F: Traffic Psychology and Behaviour, 2023.
- Jernberg, C., Andersson, J., Sandin, J., Ziemke, T., **The effect of field of view, latency, speed and performed task on remote operation of partly autonomous vehicles**. *(in preparation under 2023)*
- Jernberg, C., **Prerequisites of remote operation of vehicles**, presented at 14th International Conference on Applied Human Factors and Ergonomics (AHFE 2023) and the Affiliated Conferences, July 20-24, San Francisco, USA (2023). (*abstract and presentation)*

7.2. Remote driving feedback and control

Two main groups of feedback were explored in the REDO project: 1) steering and haptic feedback; and 2) auditory feedback.

With regard steering and haptic feedback, experiments were conducted using both real (experimental) vehicle and simulation environment. A *Remote Driving Station* was built and developed during the project to conduct two different studies exploring suitable steering and haptic feedback for remote operator compared to driving in real-life. Auditory feedback was also integrated into the Remote Driving Station for one of the studies.

Benefits of propulsion sounds (consisting of the noise from the powertrain and the road noise) and augmenting surrounding road user’s sound (namely “augmented sound” in this report) were explore both in simulated environments and on test track. For the test track test, a microphone array consisting of eight microphones was installed around a vehicle, where signals from the microphone array were processed by a software developed during the REDO project.

With respect to feedback to remote driver, it was found that:

1. Steering feedback needs to be designed and tuned differently for remote driver. It seems that remote drivers do not require the same magnitude of feedback force and rates as drivers in a real car.
2. Motion, vibration, and sound feedback gave a good sense of speed. However, this also depends on the driving speed and latency of the feedback, e.g., a delayed motion feedback in high-speed driving could worsen driver's precision and response.
3. Propulsion sound and augmented have shown to improve both objective and subjective measures in terms of presence, awareness, ego-motion, and speed keeping.

Further detail can be found in the following publications:

- Zhao, L., et al. (2021). **Study of different steering feedback models influence during remote driving**. Proceedings of the 27th IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks. Presented at the 27th IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks, The Emperor Alexander I St. Petersburg State Transport University in Saint-Petersburg, Russia, August 16-20, 2021.
DOI: https://doi.org/10.1007/978-3-031-07305-2_78
- Zhao, L., et al. **The Influence of Motion-Cueing, Sound and Vibration Feedback on Driving Behaviour and Experience - A Virtual Teleoperation Experiment**.
(Submitted for publication in IEEE Transactions on Intelligent Transportation Systems [Under review])
- Zhao, L., Nybacka, M., Rothhämel, M., Drugge, L. **Driving Experience and Behaviour Change during Teleoperation Compared with Real-Life Driving**.
(In preparation for publishing in IEEE Transactions on Intelligent Vehicles)
- Papaioannou, G., et al. **Unraveling the correlation of motion comfort with driver feel in remote and normal driving**.
(In preparation for publishing)
- Zhao, L., Nybacka, M., Rothhämel, M. **A Survey of Teleoperation: Driving Feedback**
(Presented at IEEE Intelligent Vehicles Symposium 2023)
- Zhao, L., Nybacka, M., Rothhämel, M., Drugge, L. **Influence of sound and motion-cueing feedback on driving experience and behaviour in real-life teleoperation**,
(Submitted for publication in IAVSD 2023, 28th Symposium on Dynamics of Vehicles on Roads and Tracks)
- Zhao Lin.: **Teleoperation - The influence of driving feedback on driving behaviour and experience**, Licentiate Thesis, KTH Royal Institute of Technology, Sweden.
(Presented on 24th of May 2023)
- Larsson, P., Bergfelt Ramos de Souza, J., Begnert, J. **An auditory display for road vehicle teleoperation that increases awareness and telepresence.** In Proceeding of the 28th International Conference on Auditory Display (ICAD 2023), June 26 – July 1, 2023, Norrköping, Sweden.

7.3. Connectivity and mobile network support for remote driving

An overview of using mobile network such as 5G for remote driving operation was presented. Different relevant deployment scenarios and network features were presented and their applications on remote driving operation were discussed. This would serve as a guideline, if mobile network would be considered for deployment of remote driving application.

7.4. Video transmission for remote driving

Experiments to assess quality of video transmission were conducted using public 4G mobile network. Trying many different network setups, it was found that using two mobile network providers with two links for each provider at the same time proved to be the setup providing the most stable latency, totally avoiding severe latency peaks even in areas where the reference systems with single-link setups had very severe latency peaks and picture freezes.

7.5. Laws and regulations concerning remote driving

Laws and regulations discussed within different European countries, forums, and organizations were studied for their impact and relevance to remote driving. It was concluded that remote driving had been sparsely treated, even though some examples of regulatory initiatives, set out in informal documents and regulatory proposals, specifically directed towards driving as a remote operation activity have been introduced and referred to in this report. In order to achieve the long-term goal, more regulatory attention needs to be directed specifically towards remote driving. Furthermore, it was found that there is still the absence of generally agreed definitions across the field, resulting in confusion and legal uncertainty.

7.6. Future work

Several other concepts exist as suggested in (Majstorović, et al., 2022), and there are still many remaining challenges in each of the topic covered in the REDO project. Therefore, as one of future work, the research in the field of remote operation of vehicles will continue in the continuation project, REDO2[15], which has already started (November 2022 – December 2025). The REDO2 project expands the scope from REDO considering different modes of remote operation, i.e., not limited to driving but also consider remote supervision and remote assistance as well. Also, the scope is expanded to consider one remote operator overlooking multiple vehicles (rather than one vehicle in this project).

Apart from the topics covered here, other relevant topics such as cybersecurity have not been considered within the REDO and REDO2 project. Hence, it is important to consider them in future work.

[15] https://www.vinnova.se/en/p/remote-automated-vehicle-operation-2---redo2/

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