Remote Driving Operation - REDO

Public report

Project within System-of-systems for urban mobility - spring 2019

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Content

1 Summary

Remote driving operation, enabled by recent developments in wireless connectivity, can support realization of connected and automated vehicles on public roads. This topic is sometimes referred to as “teleoperation” in technical documents. *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.

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 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, a 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).

Overarching goal of the project is to build knowledge and strengthen Swedish industry competitiveness in the field of remote driving. Before its deployment on public roads, remote driving systems needs to be integrated into the current systems-of-systems (SoS) within the context of intelligent transport systems (ITS). Safety, efficiency, and reliability need to be guaranteed during such integration process. Therefore, the main challenge addressed in this project is on how to guarantee safety, efficiency, and reliability during deployment of remote driving systems onto public roads.

There are several challenges—both technical and non-technical— associated to deployment of the remote driving systems on public roads. This project has been focusing on five different aspects, each has its own respective work package in the project: 1) challenges for the driver of teleoperated vehicles in a system of systems; 2) requirements on driver feedback and vehicles during teleoperation; 3) Systems-of-systems architecture and infrastructures to support teleoperated driving and control tower operation; 4) demonstrate potentials of teleoperated driving and present a reference architecture for teleoperated driving; and 5) laws and regulations concerning teleoperated driving.

The project has built up methods and toolchains to tackle challenges within different technical aspects listed above. Research participants were recruited from the public as well as specific target group to perform remote driving task under different conditions in order to assess effects of such conditions on driving performance. These conditions include varying delay, driving perspectives (e.g., front-view vs top-view), and different

feedback modes such as auditory and/or haptic and motion feedback together with visual feedback (i.e., a video feed(s) from the vehicle).

Within the scope of this project, the results suggest that:

1. Latency and driving perspectives have effects on driving performance, where we observe behavioral changes despite some drivers adapting to the added latency.
2. Steering feedback can improve driving experience and also need to be tuned differently for remote driving, while sound and vibration feedback are important for providing speed awareness.
3. Sound feedback can be beneficial for remote driver as it conveys several aspects of the current (remote) driving environment, e.g., status of the vehicle, speed, other moving objects, etc.
4. Current mobile network, especially with 5G technology, is feasible to support remote driving operation. Given that correct settings are implemented.
5. Video transmission techniques can help tackling latency in data transmission and provide reliable and sufficient feedback to the driver.
6. With respect to laws and regulations, remote driving has been sparsely treated, although driving as a remote operation activity have been introduced in some examples of regulatory initiatives in forms of informal documents and regulatory proposals.

Several aspects and challenges remain as future work, and they shall be addressed until remote driving can be deployed on public roads. Research in this field will continue in the continuation of this project, REDO2 project[1], where the scope is expanded beyond remote driving (i.e., to also consider remote assistance and remote supervision), and applications of this technology on a vehicle fleet will be considered (as opposed to a single vehicle in this project).

2 Sammanfattning på svenska

Fjärrstyrning av vägfordon, något som möjliggjorts genom den senare tidens utvecklingen av nätverk för telekommunikation, är en viktig pusselbit för att stödja utvecklingen och införandet av uppkopplade och självkörande fordon på allmänna vägar. I denna rapport används begreppet *fjärrstyrning av fordon*, som ibland även kallas för ”*teleoperation*” i teknisk litteratur. Begreppet syftar huvudsakligen på de tillfällen då ett fordon styrs av en *fjärroperatör*, på avstånd, över ett trådlöst kommunikationsnätverk.

En viktig tillämpning där fjärrstyrning kan vara avgörande är när en fjärroperatör stöttar automatiserad körning. Detta kan innebära att föraren helt tar över kontrollen från det autonoma systemet i situationer där systemet fallerar, antigen på grund av att situationen

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

är svårtolkad för fordonet eller på grund av tekniska fel på automationen. En fjärroperatör kan också agera som säkerhetsförare vid utveckling av autonom funktionalitet. Idag är krav på säkerhetsförare för att genomföra tester av högre automationsnivåer på allmän väg i Sverige. Mycket utveckling kvarstår för att helt kunna automatisera fordon i de flesta körförhållanden. Kombinationen av fjärrstyrning och ett automatiserat kör-system kan vara ett sätt att accelerera säkert idrifttagande av automatiserad körning på SAE nivå 4 på allmän väg. Möjligheten att ha en fjärroperatör som finns utanför fordonet blir särskilt viktigt för nya typer av fordon som främst är utvecklade för förarlös drift och kanske saknar en traditionell förarplats och/eller vanliga förar-reglage.

Ett övergripande mål för detta projekt är att bygga upp kunskap för att stärka svensk industri inom området fjärrstyrning av vägfordon. Fjärrstyrning måste integreras i befintliga system-av-system tillsammans med intelligenta transportsystem, samt i befintliga kommunikationsnätverk, innan en driftsättning kan ske i större skala på allmänna vägar. I en sådan process behöver säkerhet, men även robusthet och effektivitet, kunna garanteras. Dessa aspekter är några av huvudutmaningarna som projektet adresserar.
Det finns flera utmaningar – både tekniska och icke tekniska – med att introducera denna teknologi på marknaden. Detta projekt har fokuserat på fem olika aspekter, där varje aspekt har ett eget arbetspaket: 1) förarens utmaningar att köra fjärrstyrda fordon i ett system-av-system; 2) krav på återkoppling till förare och fordon vid fjärrstyrning; 3) system-av-system-arkitektur och infrastruktur för att stödja fjärrstyrning och övervakning med ”kontrolltorn”; 4) demonstrera potentialen av fjärrstyrning och föreslå en referensarkitektur för fjärrstyrning; 5) lagar och regler kring fjärrstyrning av fordon.

Projektet har utvecklat metoder och en verktygskedja för att adressera ovannämnda tekniska utmaningar. Försökspersoner har rekryterats från så väl allmänheten som från specifika målgrupper för att delta i förarstudierstudier. De har där fått genomföra uppgifter i olika förhållanden och med olika mål för att utvärdera påverkan på fjärrstyrningen, främst med avseende på framdrivningen av fordonen och förarens prestation. De olika studierna inkluderade variationer i fördröjning av dataöverföring, olika förarperspektiv (vanlig-vy och topp-vy), samt olika typer av återkopplingar till föraren, såsom ljud-, haptisk- eller rörelseåterkoppling tillsammans med visuell återkoppling.

Inom detta projekt visar resultaten på följande:

1. Fördröjning och förarperspektiv har påverkan på förarprestation. Vi har observerat beteendeförändringar och en viss nivå av anpassning även i de fall där förarna inte vet om att systemet har infört en fördröjning av den visuella datan.
2. Styrkraftsåterkoppling kan förbättra körkänslan och behöver också ställas in annorlunda än i verkliga fordon, medan ljud- och vibrationsåterkoppling är viktiga för att ge känsla av hastighet.
3. Ljudåterkoppling kan vara bra för fjärrförare eftersom det kan ge återkoppling kring flera aspekter i nuvarande fjärrstyrningsmiljö, t.ex. status hos fordonet, hastighet, andra rörliga objekt, mm.

4. Nuvarande telekommunikationsnätverk, speciellt med 5G teknologi, är lämpligt för att stödja fjärrstyrning. Givet dock att rätt inställningar är implementerade.
5. Videoöverföringstekniker kan hjälpa att hantera fördröjningar av dataöverföringen och möjliggöra pålitlig och tillräcklig återkoppling till förare.
6. Gällande lagar och reglering så har fjärrstyrningfått väldigt lite fokus., Det finns dock fall där fjärrstyrning som aktivitet har implementerats i vissa regelverksinitiativ i form av informella dokument och förslag till regelverk.

Många aspekter och utmaning återstår att lösa. Fortsatt forskning på området kommer att ske i ett uppföljande projekt, REDO2, där ansatsen är breddad till mer än fjärrstyrning (även fjärrövervakning och fjärrassistans) och tillämpningen av denna teknik på fordonsflottor kommer att beaktas. Det vill säga att en operatör övervakar flera fordon, till skillnad från REDO projektet som fokuserat på grundläggande förutsättningar för att en fjärroperatör skall kunna fjärrstyra ett fordon.

3 Background

This project is based on a pre-study, with the short name “Remote pre-study”, carried out during the fall 2018.

Diarienummer	2018-02018
Titel	System av system för fjärrstyrning av automatiserade vägfordon
Call	System-av-system för mobilitet i städer (SoSSUM) - FFI - 2018-03-20
Beslutande myndighet	Vinnova

With recent developments in vehicle automation and connectivity, remote driving operation of road vehicles is one of the emerging research fields, which can support realization of connected and automated vehicles on public roads. This topic can also be referred to as “teleoperation”; the terms are often used interchangeably within the field.

In the context of this project, remote driving refers to the operation of one or several vehicles by a human operator from a remote location, in a broad sense which is mentioned in *[1]*. The specific case when one human operator remotely controls one vehicle including all aspects of the dynamic control task, will be referred to as remote driving (a.k.a. teleoperated driving). The scope of the project is to specifically consider one driver driving one vehicle, although cases of one driver driving several vehicles, or several drivers driving one or several vehicles exists. The entire remote driving operation ranges from only doing strategical planning to performing the complete dynamic driving task of controlling the vehicle. Therefore, activities within the project will focus mainly on remote driving of a vehicle by one driver since it is the base to generate valuable knowledge and data.

An example of prominent use cases of remote driving operation is when a remote operator 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 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 4) on public roads.

Therefore, the project aims to support deployment of remote driving services to market and make new applications of automation possible through the remote driving services. The main problem that the project addresses is how we can support deployment of remote driving services for (automated) vehicles that does not require a driver or may not have a driver in the vehicle. Remote driving of vehicles can serve as a solution for new services and businesses in several ways:

1. Remote driving can be a solution in applications where automation is not possible or too expensive.
2. Remote driving can serve as an interim solution, and thus provide shorter time to market for services that eventually will be automated.
3. Remote driving can serve as a fallback solution when automation fails, or the situation is too complicated for the automated function, making automation more robust and easier to bring to market.
4. Remote driving can be needed to safely maneuver the vehicle to a safe location or finalizing its task in case of a fault.
5. Remote driving might be needed due to legal restriction or technical restraints.
6. Using human operators as the “remote” drivers makes it possible to enhance efficiency of automated vehicles as humans can make more pragmatic decisions in ambiguous traffic scenarios.
7. Remote driving is the only means to provide a safety driver in the testing phase of autonomous vehicles that are not equipped with an operator compartment i.e. are designed to be driverless.

Thus, remote driving can serve several purposes to improve how transportation needs within cities can be fulfilled for both people and goods. The main challenge is being able to guarantee safety, to analyze and develop efficient and reliable complex system of systems that is required to bring these services to market and integrate it with the extremely complex and heterogenous road transport system of our public road network. To cope with these issues, a current approach is to establish advanced test platforms and demonstrators of the remote driving concepts.

4 Purpose, research questions and method

4.1 Purpose

This project has the goal to build knowledge and create opportunities in the emerging field of remote driving operation (a.k.a. teleoperation/road vehicle teleoperation). The project should support the competitiveness of Swedish industry and start-ups, with potential effects of smart urban mobility solutions based on remote control of (autonomous) vehicles in a Systems-of-Systems (SoS) setting and creating a knowledge base for SoS engineering in the urban transportation domain.

4.2 Research questions

This project adopts a broad view of remote operation of a vehicle. However, there is main emphasis on the application of remote driving, which is believed to be a main driver of system-of-system requirements. The main research questions listed below are addressed within this project. Subtopics for each research question covered in the project are also listed as bullet points.

RQ1: What are the benefits and roles of a remote driver in future transportation systems within SoS context?

- How can system level effects be evaluated?

RQ2: How can SoS be organized to include remote driving (in the context of intelligent transport systems)?

- How would a SoS architecture be organized for remote driving?
- Can a SoS architecture be designed that fulfils safety requirements and simultaneously be flexible to support new services and features?
- What are the requirements on wireless communication architecture?

RQ3: How can safe remote operation of vehicles be ensured?

- What are interaction effects between latency and type of task? For instance, what is the maximum latency that should not be exceeded when performing an overtaking of a stand-still object at different speeds?
- What is the preferred driver visual perspective for safe operation?
- What feedback models are needed for driver to manoeuvre the vehicle safely and precisely?
- What are the requirements on the vehicles (to make it feasible to be teleoperated)?

RQ4: What are relevant laws and regulations that concern remote driving?

- What requirements should be linked to the remote driver and the remote driving system?

- How should the definition of who is a driver be formulated legally?

4.3 Method

The project is organized into 5 main work packages (WPs), and 2 supporting work packages related to administration, communication, and dissemination. The main WPs cover five aspects of remote driving operation, i.e.:

1. Challenges for the driver of teleoperated vehicles in a system of systems (WP2)
2. Requirements on driver feedback and vehicles during teleoperation. (WP3)
3. Systems-of-systems architecture and infrastructures to support teleoperated driving and control tower operation. (WP4)
4. Demonstrate potentials of teleoperated driving and present a reference architecture for teleoperated driving. (WP5)
5. Laws and regulations concerning teleoperated driving. (WP6)

Almost all project partners have budget to be involved in all WPs. Two PhD students were employed for WP2 and WP3, one at KTH and one at VTI respectively. All project partners are called to a project meeting at least twice per year, where all WPs were discussed together with recent updates from the project.

Furthermore, the project had established a steering group, which monitors and take important decisions for the project, and an external reference group for knowledge exchange during the project.

5 Objective

As stated in the project proposal, overarching goal of the project is to build knowledge and strengthen Swedish industry competitiveness in the field of remote driving. This goal was broken down into sub-goals that the project should achieve, as listed below. Therefore, the objectives are listed below together with deviations (if any) during the project:

O1: “Remote operations - Demonstrate safe and high performing remote operation through integration of telecommunication, vehicles and traffic control tower.”

- Since the research area and technology have not been matured enough, i.e., there are several research and implementation challenges in different aspects of remote driving operation, the project could not demonstrate a high performing remote driving system. Due to the reasons above, emphasis has been put on tackling challenges in different components rather than system integration.

O2: “Capacity for research and innovation - To provide scientific results on operational requirement for the system of system performance (considering from perspectives of the operators, vehicles, and infrastructure) and provide proof of concept of several integral parts in the system. Thereby strengthening Swedish industry.”

- There was no change in this objective. The project has achieved this by providing scientific results and conduct research related to requirement and system performance. Proof-of-concepts of different parts of the system are presented as results from the project, please refer to Chapter 6 and the project’s upcoming final report [2] more detail.

O3: “Competence – Build and share competence within partners (both small and large enterprises) organizations and an extended community. Provide 2 research students reaching a licentiate level.”

- There was no change in this objective. The project has achieved this by involving 2 newly enrolled PhD students, who have been conducting their research in WP2 and WP3. At the time of writing this report, the students have not achieved their licentiate degree yet, due to delay in recruitment and relocation during Covid-19 pandemics. Several workshops with partners have been organized and a workshop connected to IEEE conference have been organised by VTI hence extending learnings from REDO with the wider communuity.

O4: “Competitive research environment - Establish test platforms and thereby support excellent research and competitive innovation environments, where different actors can meet and experience novel systems and services.”

- There was no change in this objective. During this project, research platforms have been adapted and established to accommodate experiments related to remote driving operation, e.g., RCV-E research platform at KTH, VTI’s driving simulator, software for experimenting with auditory feedback developed by Ictech, etc.

O5: “Cross cutting cooperation - Establish and build on existing demonstration sites and thereby support cooperation between actors within Sweden, in particular between the telecommunication and vehicle industry.”

- There was no change in this objective. There has been close cooperation between partners within the project where results are often generated from cooperation between at least two partners. However, the emphases may not have been specifically on close collaboration between telecommunication and vehicle industry. Also, establishing and utilizing existing demonstration site may not have been the main focus, since the research area and technology have not been matured enough for on-site demonstrations (at least at the beginning of the project).

O6: “Communicate results – Results from the project will be communicated through scientific publications, public demonstrations and participation in seminars and conferences, thus strengthen competitive research and innovation environments.”

- There was no change in this objective. Please refer to Chapter 7 for more details regarding this objective.

6 Results and deliverables

Several project results and deliverables are in forms of publications, which are listed in Chapter 7.2 below. These publications contribute to all objectives listed in Chapter 5, mostly O2-O6. For more detail regarding results will be published in a separate final report [2]. The report includes results on the following topics: 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; and 4) laws and regulations concerning remote driving.

Besides contributing to the objectives of the projects, the results also contribute to the objectives of the FFI-program[2]. Therefore, other key results and explanation on how they contribute to the objectives are listed in Table 1 below:

Table 1 Key results and their relevant objectives.

Key results	Relevant objectives
Demonstration of NEVS vehicle being remotely driven using Voysys' software.	O1, O3, O4
RCV-E has been extended with remote driving capabilities using Voysys's software.	O2, O3, O4
Implementation of steering, haptic and motion feedback from RCV-E to driving simulator at KTH. The platform has been used for experiments in WP3.	O2, O3, O4
LAVA, an auditory display prototype software for teleoperated driving and monitoring was developed by Ictech. • The software has been used in collaboration with Einride, enabling auditory feedback from Einride's vehicle. [O3] • The software was also used in a simulator study on investigating benefits of auditory feedback in remote driving operation. [O2, O4]	O2, O3, O4
Ericsson analysed different sessions (flows) between a remote-controlled vehicle and a remote-control station to understand their characteristics and requirements, i.e., to understand what a mobile network needs to handle.	O1, O4
CEVT has conducted user experience study for robotaxi use cases, where it was found that the users think that teleoperation could be a solution when AD cannot manage the situation or malfunction, or when riders need assistance.	"develop and validate potential effects of smart urban mobility solutions based on SoS." (FFI-objective)
Organization of Road Vehicle Teleoperation Workshop at IEEE IV 2021 and 2022.	O6
Improved existing driving simulator at VTI in order to conduct experiments on remote driving under different conditions.	O3, O4
Field test on driving performance of drivers remotely driving Voysys' small-scale vehicles on a racing track in Norrköping. The test varies framerate (fram-per-	O2, O4

[2] https://www.vinnova.se/globalassets/utlysningar/2018-00136/omgangar/ffi-sossum-program-description.pdf845879.pdf (Accessed on 2023-03-17)

second) of the video shown to the driver and latency of the video transmission. Driving performance was then evaluated under these conditions.	
Experiment using the RCV-E vehicle to test with drivers driving both the vehicle normally and remotely with the same steering wheel and pedals to better understand differences between normal and remote driving and its steering feedback impact.	O2, O4

Please refer to an upcoming final report [2] for detail regarding some of the results listed above.

Expected results as stated in the project proposal were:

- **Methods** to evaluate a remote driving application in a system-of-systems context
- Development of a **tool-chain** that allows cross-validation between simulator–lab vehicle–demonstrator site**.**
- **Operational constraints** and indicators to measure performance on a system level.
- Build up of **competences** within Sweden and project partners
- 2 **licentiate degree students**: one at VTI and one at KTH-ITRL
- **Demonstrator and test facilities** on three different levels:
    - **Virtual test –** Demonstration of remote driver's interface in VTI's advanced driving simulators.
    - **Lab vehicle test –** Kista demonstrator running 5G remote driving with RCV-E will be developed to integrate with the Ericsson Innovation Cloud and to enable more advanced feedback models to the remote driver and more advanced control strategies for the RCV-E vehicle.
    - **Full-scale vehicle demonstration** on demo sites, e.g., Kista, Linköping, Halmstad, Jönköping (with Einride, Easymile, Navya and KTH RCV-E vehicles, etc.)

With respect to the expected results, the project has achieved most of the expected results without huge deviations. Methods and toolchains have been developed to investigate operational constraints by measuring the performance of remote driving operation under different conditions. Despite the travel restriction due to Covid-19 pandemic, project partners have been collaborating closely in small groups within the project, which build up competences among the project partners. Competence within Sweden has been built up through series of workshops and the final event, which were open to public. Two doctoral students have started their research within this project, although they have not obtained their licentiate degrees during the project time because of delays in recruitment process due to the Covid-19 pandemic. The project did not conduct full-scale vehicle demonstration on demo sites as expected. Nevertheless, the project has managed to build up demonstrators and test facilities in forms of two virtual test facilities (VTI's driving simulator and the simulator setup at Ictech) and a lab vehicle (KTH's RCV-E) with its remote driving station. The project was able to conduct tests with research participants toward the end of the project (after restrictions related to Covid-19 has been lifted).

7 Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	• Several published and upcoming publications as listed in Section 7.2. • Final report that is publicly accessible • Additional project connected to REDO, One2many project[3], CORD
Be passed on to other advanced technological development projects	X	The results from this project will be used as basis for the continuation of this project, which will be conducted between 2023-2025 (REDO2).
Be passed on to product development projects	X	Industrial partners would be able to utilize their results in internal or other related product development project.
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions	X	The project follows and discuss with relevant stakeholders regarding law and regulations related to remote driving, which will also continue in the continuation of this project.

In terms of communication with external partners, this project proposes a yearly workshop series on "Road Vehicle Teleoperation" in conjunction with IEEE Intelligent Vehicle Symposium (IV) conference; the workshop has been organized since 2021[4]. The workshop has served as a platform to exchange and increase knowledge within the field with international participants. This project has also been associated with SAFER network (Vehicle and Traffic Safety Centre at Chalmers)[5]. Moreover, a workshop was organized with the Remote Timber[6] project to discuss challenges around remote controlling of vehicles and exchange findings between the projects (February 2021).

Furthermore, project participants have been invited to give presentations about the project and within the field of remote driving operation at different venues, such as EUCAD2021, Human Factors in Road Vehicle Automation Subcommittee at TRB, COIN (Cognition and Interaction Lab department) seminar series at Linköping University, etc. Results and conclusions from the project, with focus on WP2, will also be presented at the AHFE 2023.

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[3] https://www.vinnova.se/p/one2many/
[4] Road Vehicle Teleoperation workshop 2021: https://www.vti.se/en/research/vehicle-technology-and-driving-simulation/project-redo/workshop-road-vehicle-teleoperation-2021
Road Vehicle Teleoperation workshop 2022: https://www.vti.se/en/research/vehicle-technology-and-driving-simulation/project-redo/workshop-road-vehicle-teleoperation-2022
[5] https://www.saferresearch.com/projects/redo
[6] https://www.vinnova.se/en/p/remotetimber---robust-and-secure-system-for-remote-controlled-timber-loader/

Lastly, the project also disseminates its results through organization of the final event on 10 February 2023, where about 65 people have registered. The event was held in Gothenburg with possibility to participate online.

7.2 Publications

As of March 2023, the project has 12 total publications: 5 accepted, 3 submitted, and 4 in preparation. The publications are listed below.

- O. Amador, M. Aramrattana and A. Vinel, "A Survey on Remote Operation of Road Vehicles," in IEEE Access, vol. 10, pp. 130135-130154, 2022, doi: 10.1109/ACCESS.2022.3229168.
- C. Jernberg, J. Andersson, J. Sandin, T. Ziemke, "The effect of latency, speed and performed task on remote operation of partly autonomous vehicles", *(submitted for publication in Transportation Research Part F: Traffic Psychology and Behaviour, 2023)*
- C. Jernberg, J. Andersson, J. Sandin, T. Ziemke, "The effect of field of view, latency, speed and performed task on remote operation of partly autonomous vehicles," 2023. *(In preparation)*
- P. Larsson, J. Bergfelt Ramos de Souza, J. Begnert, "An auditory display for remote road vehicle operation that increases awareness and presence," *(Accepted to ICAD 2023)*
- P. A. Linné and J. Andersson, "Regulating Road Vehicle Teleoperation: Back to the Near Future," 2021 IEEE Intelligent Vehicles Symposium Workshops (IV Workshops), Nagoya, Japan, 2021, pp. 135-140, doi: 10.1109/IVWorkshops54471.2021.9669226.
- L. Zhao et al., "Study of different steering feedback models influence during remote driving," in Proceedings of the 27th IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks, 2021.
- L. Zhao, M. Nybacka, L. Drugge, M. Rothhämel, A. Habibovic, H. Hvitfeldt, "The Influence of Motion-Cueing, Sound and Vibration Feedback on Driving Behaviour and Experience - A Virtual Teleoperation Experiment," 2023. *(Submitted for publication in IEEE Transactions on Intelligent Transportation Systems [Under review])*
- L. Zhao, M. Nybacka, M. Rothhämel, L. Drugge, "Driving Experience and Behaviour Change during Teleoperation Compared with Real-Life Driving," 2023. *(In preparation for publishing in IEEE Transactions on Intelligent Vehicles)*

- G. Papaioannou, L. Zhao, M. Nybacka, J. Jerrelind, R. Happee, L. Drugge, "Unraveling the correlation of motion comfort with driver feel in remote and normal driving," 2023
  (In preparation for publishing)
- L. Zhao, M. Nybacka, M. Rothhämel, "A Survey of Teleoperation: Driving Feedback," 2023.
  (Accepted for workshop at IEEE Intelligent Vehicles Symposium 2023)
- L. Zhao, M. Nybacka, M. Rothhämel, L. Drugge, "Influence of sound and motion-cueing feedback on driving experience and behaviour in real-life teleoperation," 2023.
  (Submitted for publication in IAVSD 2023, 28th Symposium on Dynamics of Vehicles on Roads and Tracks)
- Lin Zhao, "Teleoperation - The influence of driving feedback on driving behaviour and experience", 2023, Licentiate Thesis, KTH Royal Institute of Technology, Sweden.
  (Licentiate thesis will be presented on 24th of May 2023)

8 Conclusions and future research

Remote driving refers to the operation of one or several vehicles by a human operator (i.e., remote driver) from a remote location, in which the human operator is responsible for all dynamic driving tasks (DDTs) of the vehicle. Several benefits are expected from remote driving technology, especially in supporting deployment of connected and automated vehicles (CAVs) on public road. For instance, remote driving could support CAVs by enabling a remote driver to take over full control of the vehicles when the automated driving system encounters ambiguous traffic situations or fails. In some cases, the remote driver can act as a safety driver in testing phases, and thus allow testing on public roads. Despite many potential benefits, several challenges need to be addressed before remote driving can be implemented on public roads.

In order to address the challenges, remote driving operation (REDO) project has been conducted to build knowledge within the research field of remote driving. Overall challenges are related to guaranteeing safety, efficiency, and reliability of remote driving to bring these services to market and integrate it with the extremely complex and heterogenous road transport system. The REDO project addresses the challenges in five different topics: topics: 1) challenges for the driver of teleoperated vehicles in a system of systems; 2) requirements on driver feedback and vehicles during teleoperation; 3) systems-of-systems architecture and infrastructures to support teleoperated driving and control tower operation; 4) Demonstrate potentials of teleoperated driving and present a reference architecture for teleoperated driving; and 5) Laws and regulations concerning teleoperated driving.

Results have demonstrated examples of potential setups for remote driving operation through different platforms owned by project partners, e.g., Einride and NEVS. Several research platforms for conducting experiments within the research field has been established, e.g., at Ictech, KTH, and VTI. They were also used to conduct experiments during the project. With regard main topics of the project, the results suggest that:

1. latency and driving perspectives have effects on driving performance, where we observe behavioral changes despite some drivers adapting to the added latency.
2. Steering feedback can improve driving experience and also need to be tuned differently for remote driving, while sound and vibration feedback are important for providing speed awareness.
3. Sound feedback can be beneficial for remote driver as it conveys several aspects of the current (remote) driving environment, e.g., status of the vehicle, speed, other moving objects, etc.
4. Current mobile network, especially with 5G technology, is feasible to support remote driving operation. Given that correct settings are implemented.
5. Video transmission techniques can help tackling latency in data transmission and provide reliable and sufficient feedback to the driver.
6. With respect to laws and regulations, remote driving has been sparsely treated, although driving as a remote operation activity have been introduced in some examples of regulatory initiatives in forms of informal documents and regulatory proposals.

Apart from results of the main topics, the project has also conducted communication and dissemination activities to spread knowledge within the research field and establish cooperations with external parties both at the national and international levels. These activities are, for example, organization of “Road Vehicle Teleoperation” in conjunction with IEEE IV conference, association with SAFER network, organization of a public final event, etc.

As one of future work, the research in the field of remote operation of vehicles will continue in the continuation project, REDO2[7], 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).

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

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