Influence of sound, vibration, and motion-cueing feedback on driving experience and behaviour in real-life teleoperation

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Abstract. Driving feedback is an important way of providing remote drivers with physical world information during teleoperation. In this study, a teleoperation experiment is conducted to explore how sound, vibration and motion-cueing feedback influence the drivers' driving experience and behaviour. To this end, four types of driving feedback modes are used as variables to investigate this, including no feedback, motion-cueing feedback, sound and vibration feedback, and a combination of sound, vibration, and motion-cueing feedback. A prototype of teleoperation platform is first built, which includes a teleoperated vehicle and a driving station capable of generating sound, vibration, and motion-cueing feedback. Then, the scenario with disturbances is built to investigate how the driving behaviour changes under various driving feedback modes. Both subjective and objective assessments are used in this study. For driving experience, the driving feeling, such as presence feeling, road surface feeling, etc, are explored. For driving behaviour, the throttle reversal rate is investigated. Furthermore, the relationship between throttle reversal rate and driving experience is studied. The results show that the combined feedback mode could provide drivers with the highest rated driving experience; the motion-cueing feedback could provide better road surface feeling while the sound and vibration feedback could provide better speed feeling. The throttle reversal rate with motion-cueing feedback is higher than without it, which may be caused by the increased road surface feeling provided by motion cues.

Keywords: Teleoperation, driving feedback, driving experience, driving behaviour, motion-cueing feedback, sound and vibration feedback, subjective assessment, objective assessment.

1 Introduction

Automated vehicles (AVs) are developing at a rapid pace in recent years, with some of them already begin running on public roads [1], such as DiDi [2] and Waymo [3]. However, there is still a long way to go before full level 5 AVs will be applied, and safety drivers are still needed. Teleoperation could act as a bridge between level 4 and 5 AVs. A remote driver could take over an AV in non-time critical situations where the AV cannot assess the situation fully, such as public city event and roadwork scenarios [4]. Additionally, it can also relieve safety drivers who have to stay in the AVs. Based on this, teleoperation could act as a catalyst for accelerating the commercialisation of AVs.

However, many challenges remain for the application of teleoperated driving systems. First, latency between teleoperating driving station (TDS) and teleoperated vehicles can cause problems, as it delays the transmitted signals in both directions [5]. Furthermore, situational awareness of remote drivers also deteriorates due to the loss of information about the physical world. This could potentially lead to new problems such as changed driving behaviour and decreased driving performance compared to real-life driving [6].

Some research groups [7] and companies [8] work in the above mentioned areas to overcome the possible challenges of teleoperation. To overcome latency, Ge *et al.* [9] used model-free predictive frameworks to predict delayed teleoperation signals. Prakash *et al.* [10] used a Smith predictor to correct image projection to provide remote drivers with forecast video. To improve situational awareness, driving feedback from the channels of video and steering force could be used. Hosseini *et al.* [11] studied head-mounted display (HMD) effects on driving performance compared to conventional video in teleoperation. They found that driving performance can be improved using the proposed Human-Machine Interface (HMI) display. Furthermore, Georg *et al.* [12] used the fused display information from both camera and lidar to enhance the situational awareness of remote drivers. In addition, Zhao *et. al* [13] explored the influence of steering force feedback on driving behaviour and experience in teleoperation. They also compared differences in driving behaviour between real-life driving and teleoperation when exposed to different steering feedback models. However, few of them explored how other feedback channels influence the teleoperation, such as audio and motion-cueing feedback.

Audio is an important channel that may provide remote drivers with a sense of speed, as its amplitude and frequency change with the vehicle speed. The vibration has the similar effect with audio in terms of speed reflection, such as engine vibrations. Motion-cueing feedback is a channel that can give a sense of the road surface and the motion states of vehicles, which can help them judge vehicle behaviour. Therefore, we present our investigation on how sound, vibration, and motion-cueing feedback affect driving experience and behaviour in teleoperation.

Three main contributions are included in this paper. Firstly, the effects of sound, vibration and motion-cueing on driving experience and behaviour are studied, which paves the way on how to provide suitable driving feedback for remote drivers. Secondly, the TDS prototype is developed with multiple feedback channels. This provides an indication on how to develop a TDS with regard to human factors and driving feedback in both academic and industry areas. Finally, this study also explores how different driving feelings correlate with each other. This gives insight into how to improve some perceived feelings in teleoperation, such as confidence and trust, by providing a particular driving sensation.

The structure of this paper is organised as follows. The experiment setup is shown in Section II. Section III describes the experiment protocol. The results and discussion are presented in Section IV. Finally, the conclusions are described in Section V.

2 Experiment setup

2.1 Experiment platform

The teleoperation test platform is presented in Fig. 1, in which the research concept vehicle model-E (RCV-E) is used as the teleoperated vehicle. The straight line distance between vehicle and TDS is close to 30.7 km. The '*glass to glass*' latency of this setup is nearly 120 ms. To realise the motion-cueing feedback, a six Degree-of-Freedom (DoF) hexapod platform is used in TDS. The washout filter based on [14] is used to provide remote drivers with motion-cueing feedback, where the original vehicle motion signal is from the inertial measurement unit (IMU) that is installed on the chassis of RCV-E. Due to the limited motion space of the driving simulator, only three angular rates are fed back to remote drivers in this experiment, namely, yaw rate, pitch rate, and roll rate. In addition, a Saramonic stereo microphone is installed in the vehicle to capture the stereo sound for sound feedback. To enhance remote drivers' feeling of speed, four Dayton audio vibration actuators are installed under the seat. The vibration frequency and amplitude change with speed. In addition, it can also reflect high frequency vibrations on the surface of the road, such as vibrations on a gravel road. The physical steering force feedback model in [13] is used to provide the steering feel. Further detailed designs in terms of communication protocol and hardware usage can be found in [13].

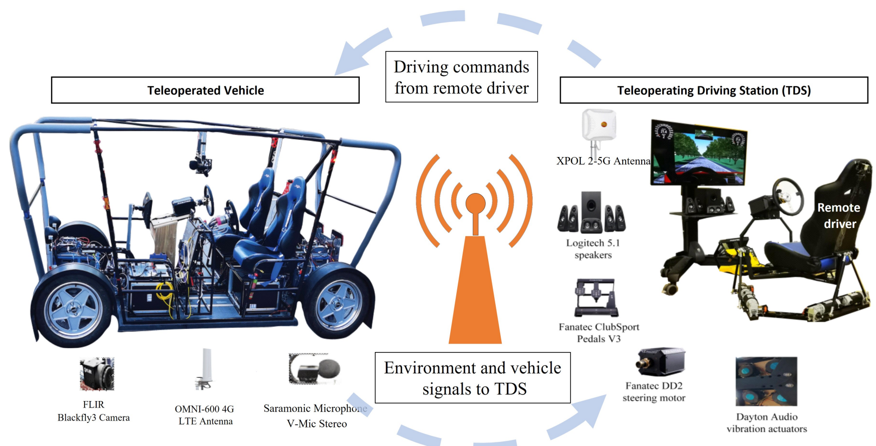


Fig. 1: Teleoperation platform, teleoperated vehicle (left) and TDS (right).

2.2 Scenario design

Two scenarios were used in this experiment (see Fig. 2). The first scenario (Fig. 2 left) was a combination of slalom manoeuvre and half circular road. The scenario was used to help participants practice and get familiar with the driving station. For slalom, the distance between the cones was set to 20 m and the diameter of the circular road was 100 m. The formal experiment track (Fig. 2 right) was a combination of different disturbances including metal bar, simulated manhole, speed bump, and gravel road. On the gravel road manoeuvre, the left tyres run on the gravel and the right tyres run on the conventional road, so that the vehicle will not be stuck in the gravel. Through this scenario, remote drivers could feel enough feedback from motion platform. Therefore, its influence on driving experience was deemed possible through this experiment setup.

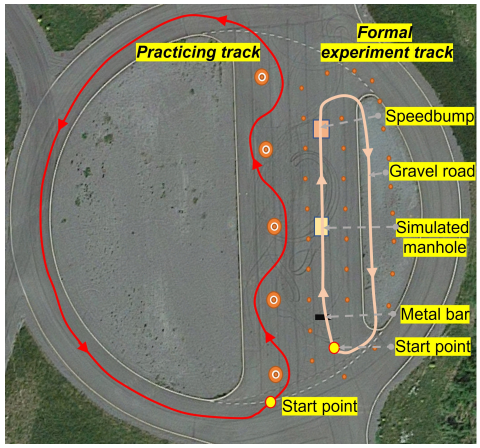


Fig. 2: Scenario design, the practice track on the left and the formal experiment track on the right.

3 Experiment protocol

Four types of variables were used in the experiment: No Feedback (NF), Motion-cueing Feedback (MF), Sound and vibration Feedback (SF), and a Combination of motion-cueing, sound and vibration Feedback (CF). The within-subject design method was used for exploring how each independent variable influences the driving behaviour and experience. There were 8 participants in this experiment and all had a passenger car driving licence. The average age of them was 25 (SD=3.02). They had no experience with teleoperation. At the start of the experiment, the responsible person of the experiment first described the instructions, scenarios, and requirements to the participants. Then, they were required to practise near 3 mins on the practicing track where only steering feedback was provided. In the formal test, drivers were required to drive two laps for each feedback mode on the formal experiment track. To reduce the influence of the sequence, each participant drove with different feedback sequences. It took about 2 mins to finish the driving under each feedback, and they had near 1 min rest between each feedback mode. The questionnaire was immediately asked after finishing each driving feedback mode so that the first-hand answer could be collected. They were also asked to rank the four types of driving feedback modes after completing the test.

4 Results and discussion

To investigate how driving feedback affects driving experiences and behaviour of remote drivers, subjective and objective assessments are used separately to assess them. First, a summary of the main driving experience results obtained from part of the questionnaire is presented. Then, the interplay between different driving experiences is studied. Finally, the objective metric result of driving behaviour is shown, and the correlation with driving experience is also analysed.

The paired t-test is used to compare the differences between each feedback mode. In addition, boxplots are used to show the distribution of the data points (see Fig. 4). In the boxplots, the red squared points are the mean values of the dataset; the top and bottom edges of the box are the 75^{th} and 25^{th} percentiles; the central red bar in the box indicates the median value; the marker "+" in red colour represents the outliers; the significance of the t-test is represented by "$*$", where "$*$" denotes $p \leq 0.05$, "$**$" denotes $p \leq 0.01$, and "$***$" denotes $p \leq 0.001$, i.e. lower p value means higher significance. .

4.1 Driving experience investigation

This section presents and discusses the results of the subjective assessment in terms of driving experience based on the questions shown in Appendix. Due to the limited space, only part of the main results are presented in this paper.

Final rank from participants: Fig. 3 presents the final rank of the four driving feedback modes after they finished the whole experiment process. It shows that CF is the most preferred, which is followed by SF and MF, while NF is the least one as expected. This means that the combination of these feedback channels could give participants the best driving experience, whereas no feedback would give them the worst driving experience. Compared with MF, SF is preferred when comparing these two modes individually. This may be because the sound and vibration feedback could provide them with better detailed driving feelings, such as presence and speed feeling (see Figs. 4 (b) and (d)).

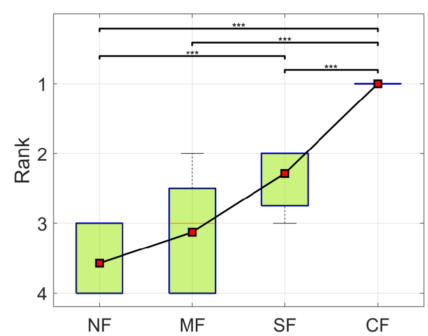


Fig. 3: Final rank of the four feedback modes (NF, MF, SF, and CF).

Realistic and presence feeling: Fig. 4(a) presents the results of realistic feeling, where CF also gets the highest grade and NF gets the lowest grade. This is likely because there are multiple channels in CF that could provide driving feedback, which can provide them with realistic feeling from various aspects, such as speed and road surface feeling. In contrast, participants will lose the feedback in NF and therefore result in the least realistic feeling. The result also shows that there is no significant difference between MF and SF. This means that MF and SF give drivers a similar realistic feeling when used individually. The results of the presence feeling (see Fig. 4(b)) have a similar trend to those of the realistic feeling, which could be explained by the strong correlation between realistic and presence feeling (see Fig. 5(c)). It shows that the increase of realistic feeling could enhance drivers' presence feeling as well.

Paying attention: Fig. 4(c) presents the drivers' feeling of attention during teleoperation. It shows that SF could give them the best feeling of attention. However, NF and MF have the similar low attention level. Considering both of the two modes lose sound effects, it can be deduced that the sound seems to have a larger effect on drivers' feeling of attention.

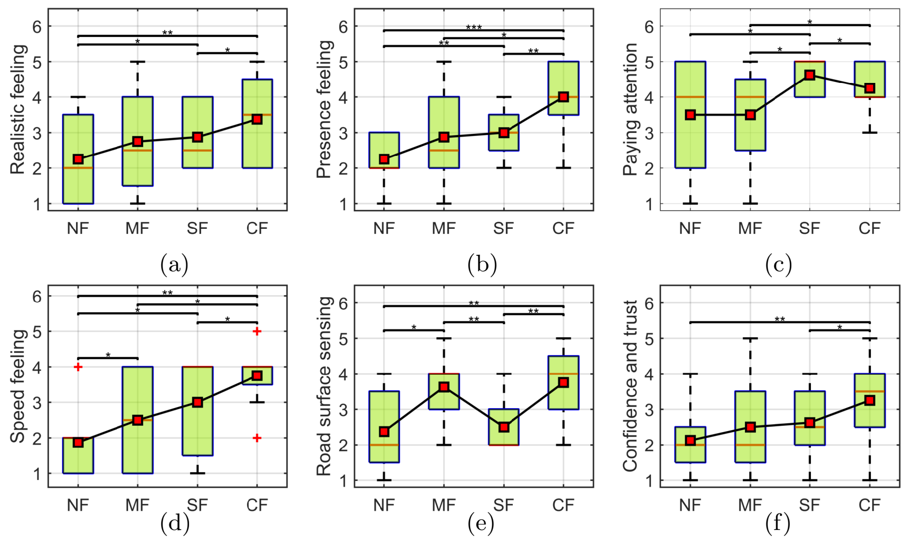


Fig. 4: Subjective assessment results. (a): Results regarding Question 2 (Realistic feeling); (b): Results regarding Question 4 (Presence feeling); (c): Results regarding Question 3 (Paying attention); (d): Results regarding Question 5 (Sense of speed); (e): Results regarding Question 7 (Road surface feeling); (f): Results regarding Question 11 (Confidence/trust in driving).

Speed and road surface feeling: The questions of speed and road surface feeling are used to investigate how remote drivers understand the vehicle behaviour, such as speed and motion of the vehicle. The results of speed feeling (see Fig. 4 (d)) show that CF could provide the best sense of speed, followed by SF and MF in third and NF is the last one from the perspective of mean value of the dataset. This indicates that both motion-cueing, and sound and vibration feedback could provide a sense of speed. Motion-cueing feedback could provide a sense of speed by using the tilt angle that will change when there is a change of longitudinal acceleration. Sound effect could provide the sense of speed by reflecting the changed amplitude and frequency of the sound of vehicle. The combination of two channels (CF) could thus be better in providing the speed sensing.

For road surface sensing, MF and CF give participants a significantly better feeling compared to NF and SF ($p < 0.05$). This is likely because both MF and CF include feedback from motion cues, which can provide remote drivers with the feeling of vehicle motion when going through disturbances, such as a speed bump. These motions could reflect more clear changes of road surface and therefore participants are prone to give them a higher grade.

Confidence and trust: The drivers' confidence and trust of their driving in teleoperation are presented in Fig. 4(f). From the perspective of the mean value, it shows that CF could give them the highest trust. In order to explore how drivers' confidence and trust are affected, the correlations between different driving feelings and confidence feeling are constructed (see Fig. 5). The detailed descriptions in terms of them are shown in the following subsection.

4.2 Interplay between driving experiences

To explore how the confidence and trust of remote drivers are influenced, linear regressions between the driving experiences are illustrated (see Figs. 5(a) and (b)). It shows that both the realistic and presence feelings have a significant ($p < 0.001$) influence on the confidence and trust. More specifically, the increased feeling of realism and presence will enhance remote drivers' confidence and trust in driving the teleoperated vehicles. Furthermore, the relation between presence feeling and realistic feeling is also explored (see Fig. 5(c)). It shows that there is still a significant correlation ($p < 0.001$) between them. This means that the drivers' realistic feeling and presence feeling are highly correlated, which also gives the indication that one of the questions may be redundant when setting up the questionnaire.

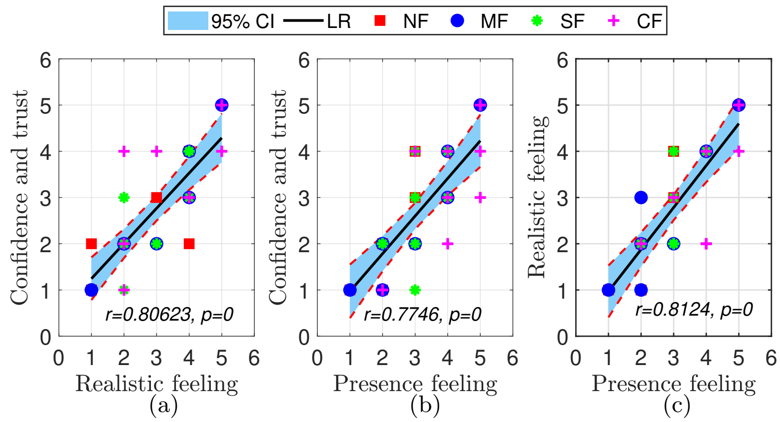
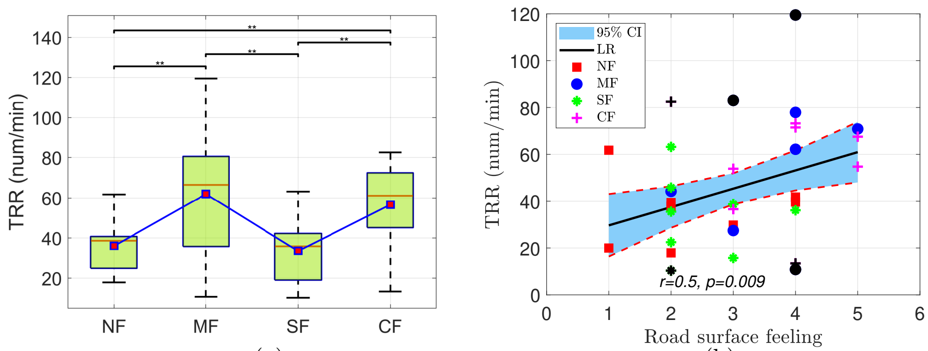


Fig. 5: Correlations between driving experiences. (a). Confidence and trust vs Realistic feeling; (b). Confidence and trust vs Presence feeling; (c). Realistic feeling vs Presence feeling.

4.3 Driving behaviour investigation

To explore how different driving feedback modes influence behaviour of remote drivers, the throttle reversal rate (TRR) is studied, which represents the throttle pedal tuning frequency during driving. The calculation method of TRR is similar to that of the steering reversal rate (SRR) [15]. The throttle gap size is set to 5 % in this paper, indicating that the TRR value will count once if the throttle pedal travel is bigger than 5 %. The raw data is also filtered using a 10 Hz low-pass filter to remove the possible noise data that may be caused by the outside environment.

The TRR data on gravel road is used for analysis, since remote drivers can feel a near 20-second continuous vibration in this manoeuvre. The results (see Fig. 6(a)) show that drivers are prone to give a significant ($p < 0.01$) higher TRR with MF and CF, indicating that remote drivers will tune the throttle in a high frequency with motion-cueing feedback, since both MF and CF include the feedback from motion cues. In order to explore how the motion-cueing influences the drivers' tuning frequency of the throttle, the correlation between the subjective feeling and TRR is analysed. The linear regression result in Fig. 6(b) shows that the feeling of the road surface could be a factor that influences the TRR ($r = 0.5, p = 0.009$). With motion-cueing feedback, the road surface feeling will increase (see Fig. 4(e)); therefore, the TRR will be influenced indirectly. This is because remote drivers may have the intention to tune the vehicle speed when they feel the vehicle is running on an uneven road surface, and thus the TRR will increase.



(a) (b)

Fig. 6: (a). Throttle reversal rate on gravel road; (b). TRR vs Road surface feeling. (*Note: The outliers are marked in black colour in the linear regression graph*)

5 Conclusions

In this paper, a real-life teleoperation experiment is conducted to explore how the sound, vibration, and motion-cueing feedback influence the driving experience and behaviour of remote drivers. In this study, it is found that the combination of motion-cueing, and sound and vibration feedback could bring the best driving experience to remote drivers; while no feedback mode is the worst case. sound and vibration feedback could bring better speed feeling to drivers and motion-cueing feedback could bring better road surface feeling to them. Furthermore, the confidence and trust in driving teleoperated vehicles is highly impacted by the feeling of realism and presence. For the driving behaviour, the drivers' throttle reversal rate will be significantly increased with motion-cueing feedback, which may be caused by the enhanced road surface feeling provided by the motion-cueing feedback.

Limitations of this study: As an explorative study, this experiment focusses on how different driving feedback influences drivers. However, the existing latency in the network and driving simulator actuators were not considered. To reduce its influence, the highest vehicle speed was limited to 18 km/h. Latency will be considered in future work for the following experiment. Furthermore, the number of participants in this experiment was limited. In future's study, more participants of various ages, gender, and driving experience could be recruited.

6 Acknowledgements

The authors would like to gratefully acknowledge the financial support from the Transport Research Environment with Novel Perspectives (TRENoP) and the Integrated Transport Research Lab (ITRL) at the KTH Royal Institute of Technology, and from the Strategic Vehicle Research and Innovation (FFI) funding programme (2022-01647).

Informed consent: Informed consent was obtained from all the participants included in the study.

Ethical approval: All procedures performed in the studies involving human participants were in accordance with the ethical standards of the national research committee (Swedish Ethical Review Authority Ref no.: 2020-05020) and the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

References

1. L. Chen et al., "Milestones in Autonomous Driving and Intelligent Vehicles: Survey of Surveys," *IEEE Trans. Intell. Veh.*, pp. 1–13, 2022.
2. IoT Automotive News. (2020, Jun.) Didi robotaxi service begins operation in shanghai. [Online]. Available: https://iot-automotive.news/didi-robotaxi-service-begins-operation-in-shanghai/
3. TechCrunch. (2022, March) Waymo opens driverless robotaxi service to sf employees. [Online]. Available: https://techcrunch.com/2022/03/30/waymo
4. O. Amador, M. Aramrattana, and A. Vinel, "A Survey on Remote Operation of Road Vehicles," *IEEE Access*, vol. 10, pp. 130 135–130 154, 2022.
5. J. M. Georg, J. Feiler, S. Hoffmann, and F. Diermeyer, "Sensor and Actuator Latency during Teleoperation of Automated Vehicles," in *2020 IEEE Intelligent Vehicles Symposium (IV)*, Las Vegas, NV, United States, Oct. 2020, pp. 760–766.
6. L. Zhao, "Teleoperation and the influence of driving feedback on drivers' behaviour and experience," Ph.D. dissertation, May 2023.
7. J. M. Georg and F. Diermeyer, "An Adaptable and Immersive Real Time Interface for Resolving System Limitations of Automated Vehicles with Teleoperation," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, Bari, Italy, Oct. 2019, pp. 2659–2664.
8. "Teleoperation software for remote control of vehicles, machines and robots," 2022, [Online]. Available: https://www.voysys.se.
9. X. Ge, M. J. Brudnak, P. Jayakumar, J. L. Stein, and T. Ersal, "A model-free predictor framework for tele-operated vehicles," in *2015 American Control Conference (ACC)*, Jul. 2015, pp. 4573–4578.
10. J. Prakash, M. Vignati, D. Vignarca, E. Sabbioni, and F. Cheli, "Predictive Display with Perspective Projection of Surroundings in Vehicle Teleoperation to Account Time-delays," Tech. Rep., Nov. 2022, arXiv:2211.11918. [Online]. Available: http://arxiv.org/abs/2211.11918
11. A. Hosseini and M. Lienkamp, "Enhancing telepresence during the teleoperation of road vehicles using HMD-based mixed reality," in *2016 IEEE Intelligent Vehicles Symposium (IV)*, Gothenburg, Sweden, Jun. 2016, pp. 1366–1373.
12. J. M. Georg, E. Putz, and F. Diermeyer, "Longtime Effects of Videoquality, Videocanvases and Displays on Situation Awareness during Teleoperation of Automated Vehicles," in *2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Toronto, Ontario, Canada, Oct. 2020, pp. 248–255.
13. L. Zhao, M. Nybacka, L. Drugge, J. Mårtensson, S. Vyas, C. Savant, W. Zhang, and R. Palmberg, "Study of different steering feedback models influence during remote driving," in *Advances in Dynamics of Vehicles on Roads and Tracks*. Cham: Springer International Publishing, 2021.
14. N. Murgovski, "Vehicle modelling and washout filter tuning for the chalmers vehicle simulator," Master's thesis, Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden, 2009.
15. G. Markkula and J. Engstroem, "A steering wheel reversal rate metric for assessing effects of visual and cognitive secondary task load," in *Proceedings of the 13th ITS World Congress*, London, England, Oct. 2006.

7 Appendix

Table 1: Subjective Assessment Questionnaire.

Overall assessment	1. Your overall assessment of your driving experience? 1———2———3———4———5 Very bad - Bad - Neutral - Good - Very good
Realistic feeling	2. Did it feel realistic? 1———2———3———4———5 Very unrealistic - Unrealistic - Neutral - Realistic - Very realistic
Feeling of presence	3. How much attention did you pay to your driving? 1———2———3———4———5 No attention - Little attention - Neutral - Much attention - Full attention
	4. How present did you feel in the environment you drove in? 1———2———3———4———5 Not there - Neutral - Fully there
Vehicle behaviour understanding	5. How well did you sense the vehicle speed? 1———2———3———4———5 Very bad - Bad - Neutral - Good - Very good
	6. How well did you predict the vehicle behaviour? 1———2———3———4———5 Very bad - Bad - Neutral - Good - Very good
	7. How well did you sense and recognise the road surface? 1———2———3———4———5 Very bad - Bad - Neutral - Good - Very good
Adverse emotion	8. How irritated, stressed and annoyed were you? 1———-2———3———4———5 Not at all - Low - Neutral - High - Very high
Motion sickness	9. How strongly did you feel any signs of motion sickness, such as nausea, dizziness, discomfort or disorientation? 1———-2———3———4———5 Not at all - Slightly - Moderately - Strongly - Very strongly
Usability	10. How helpful was the feedback for your driving? 1———-2———3———4———5 Not helpful - Little helpful - Neutral - Helpful - Very helpful
Confidence/ Trust of the driving	11. How much would you trust your driving in this remote driving? 1———-2———3———4———5 Very little trust - Little trust - Neutral - Some trust - Very much trust