

Effect of Steering Torque Feedback Timing on Driver Control in Teleoperation Driving

Ryotaro Hosoi ¹⁾ Keiji Jimi ¹⁾ Toshiki Kanbayashi ^{1) 2)} Ren Okuma ¹⁾

Hisato Fukuda ¹⁾ Toshihiko Kozai ^{1) 2)} Tsutomu Iwase ^{1) 2)}

*1) Gunma University, Graduate School of Science and Technology
29-1 Hon-cho, Ota, Gunma, 373-0057 Japan*

*2) SUBARU CORPORATION
1-1 Subaru-cho, Ota, Gunma, 373-8555, Japan*

KEY WORDS: Information, Communication, Remote control, Human interface, Driving simulator [E2]

Introduction: With the increasing importance of teleoperated driving technologies for uncrewed delivery and rural mobility, accurate vehicle control is essential for safely navigating complex road environments. However, since operators lack tactile and haptic information, they rely primarily on vision. This reduces steering accuracy, and the lack of Steering Torque Feedback (STF) can cause anxiety and increase workload. Although reproducing STF is vital, teleoperation inherently involves communication-induced video delays. When generating realistic steering feel, it remains insufficiently verified whether STF should be synchronized with the delayed video or presented earlier based on actual vehicle dynamics. Therefore, this study aims to clarify the effect of STF presentation timing on driving performance and subjective operational feel in teleoperated driving with video delays.

Methodology: To evaluate the effect of STF presence and presentation timing on driving operations in straight sections following curves, a driving simulator experiment using CARLA was conducted with a non-linear physical model to reproduce realistic steering feel. All participants experienced five conditions (Table 1), including a baseline with no video delay and four conditions under a 200 ms video delay combining different STF delays. Twenty-three participants completed the 5 km driving task containing various curves and turns in randomized orders.

Results and Discussion: To evaluate the smoothness of steering operations in the straight sections after each curve, Steering Entropy (SE) was calculated using the prediction error distribution of Condition 1 as a baseline.

The Friedman test and Bonferroni correction for multiple comparisons applied to the SE values (Fig. 1) revealed significant differences between conditions in the R25 and R12.5 sections. In both sections, Condition 2 (video delay only, no STF) exhibited significantly higher SE compared to Condition 1. Conversely, Condition 3 (200 ms video delay, 0 ms STF delay) showed no significant difference from Condition 1 across all sections. Subjective ease-of-driving evaluations followed the same trend. The increased SE in Condition 2 is attributed to the lack of STF causing unintended oversteering (overshooting) during straight-line recovery, which induced excessive corrective steering. In Conditions 4 and 5, where STF was delayed, drivers had to resist the STF that rose after they had finished turning the steering wheel, inducing weaving within the lane. Furthermore, in difficult scenarios such as the R12.5 curve maintained at 30 km/h, the negative effect of delayed STF was highly pronounced, showing significant differences between Condition 1 and Conditions 4 and 5.

Conclusion: This study verified the effect of STF presentation timing on driver control during teleoperation with video delays using both objective and subjective evaluations. The results demonstrate that even under 200 ms video delay, presenting STF earlier than the video (without delay) allows drivers to maintain stable operations equivalent to baseline conditions. In contrast, the absence or delay of STF induces excessive corrective steering and weaving, significantly degrading drivability in highly difficult situations like sharp curves. These findings will contribute to interface design guidelines for realizing safe teleoperated driving systems.

Table1 Experimental condition

Condition	Video Delay	Steering Torque Feedback(Delay)
Condition 1	0 ms	Present (0 ms)
Condition 2	200 ms	None
Condition 3	200 ms	Present (0 ms)
Condition 4	200 ms	Present (200 ms)
Condition 5	200 ms	Present (400 ms)

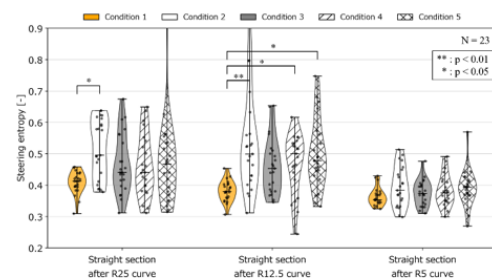


Fig.1 Evaluation of steering entropy after curves