講演番号 220

Experimental Investigation of Acceptable Latency from the Perspective of Driving Operability in Vehicle Driving Simulators

Takeshi Yoshida [1)] Takayuki Aoki [1)] Daisuke Itagaki [1)] Tsubasa Oguro [1)] Hirotaka Sakamoto [1)]

1) TOYOTA MOTOR CORPORATION

1, Toyota-cho, Toyota, Aichi, 471-8572, Japan (E-mail: Takeshi_yoshida_ad@mail.co.jp)

KEY WORDS: **human engineering, sensitivity/vision/visibility, driving simulator(C2)**

Introduction: With the advancement of Software Defined Vehicles (SDVs), vehicle cockpits are increasingly transforming into driving simulators for applications such as remote assistance and immersive driving experiences. In these systems, driving is a closed-loop process involving perception, judgment, and operation. Communication and processing delays within this feedback loop, particularly Visual/Audio (Display) and Haptic (Force Feedback: FFB) delays, can significantly degrade operability. Previous research in the literature has extensively investigated visual latency and its effects on driving operability and perceived realism. Prior research has also addressed the role of Force Feedback (FFB) latency in lane-keeping performance, as well as its influence on driver confidence and immersion. However, despite these efforts, the individual effects of Display latency and FFB latency on driving operability, and the interaction between steering torque intensity (FFB torque) and operability, remain insufficiently understood and have not yet been quantitatively clarified.

Methodology: This study developed an experimental platform integrating a prototype vehicle equipped with a steer-by-wire system, a computing device with vehicle simulation software, and a display device (Fig.1). The system was designed to independently control Display latency and FFB latency using signal and video converters. We established nine experimental conditions combining various latency levels and two FFB torque intensities: "Big" (equivalent to real-vehicle forces) and "Small" (reduced by approximately 20%). To ensure high sensitivity, the experiment involved expert drivers, such as professional esports players, driving a high-performance GT-class racing car on a short-course circuit. Eight participants provided sensory evaluations (Q1–Q5) which were analyzed using a multivariate Bayesian hierarchical ordinal logistic regression model to estimate the "Sensory Evaluation Achievement Areas" where operability remains acceptable.

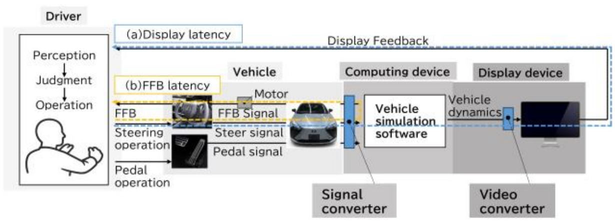

Fig.1 Evaluation system and definition of Display latency and FFB latency

Results and Discussion: The analysis of the "Sensory Evaluation Achievement Areas" in Figure 2 confirms that both Display and FFB latency negatively impact operability, with drivers exhibiting a markedly higher sensitivity to FFB latency. The boundaries in Figure 2, representing the conservative 95% confidence interval lower limits, show that acceptable FFB latency thresholds are consistently tighter than those for Display latency across all sensory indices. Crucially, the figure illustrates that the acceptable area expands significantly when FFB torque intensity is reduced from "Big" to "Small". This result and participants comments indicate that lower torque mitigates the perceived phase lag and the resulting "weaving" or "divergent" steering behaviors, which are more difficult to compensate for than Display latency — the latter of which drivers can more easily predict as a manageable vehicle response characteristic.

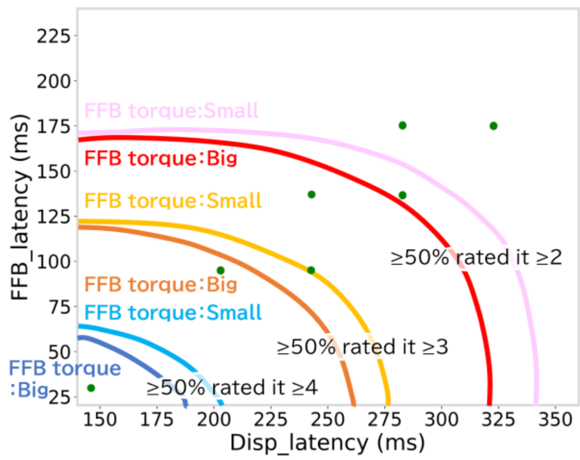

Fig.2 Comparison of "Sensory Evaluation Achievement Areas"

Conclusion: This research proposed a method to visualize "Sensory Evaluation Achievement Areas" as design requirements for simulators. The findings highlight that FFB latency is a more critical factor than Display latency for operability. It suggests that haptic design — specifically adjusting FFB torque — is an effective mitigation strategy for latency-induced degradation in driving simulators.