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The Effect of Haptic Guidance on Driver Steering Performance during Curve Negotiation with Limited Visual Feedback

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Abstract—**Visual feedback from the road ahead is required for steering a car. When visual feedback is limited or only partial road is visible, driver steering performance declines. To solve this problem, haptic feedback is expected to assist drivers by providing guidance torque on the steering wheel. This paper focuses on the effect of haptic guidance on driver steering performance during curve negotiation when visual feedback is limited. Twelve subjects participated in the experiment conducted in a high-fidelity driving simulator. Levels of haptic guidance were none, weak, and strong, and levels of visual feedback were whole, near, medium and far. The steering performance was assessed by drivers' turning maneuver when approaching and leaving curves, and time-to-lane crossing during curves. Results indicate that mean value of time-to-lane crossing decreased due to the implementation of strong haptic guidance when visual feedback was limited. The start point of turning maneuver was earlier resulting from the implementation of strong haptic guidance under the condition of visual feedback from near segment. In conclusion, the drivers tended to rely on haptic guidance to achieve better steering performance when visual feedback was limited.**

I. Introduction

Steering a car always requires real-time visual feedback from the road ahead [1]. However, this situation seems to be changing due to the development of autonomous driving technology. Full automation is not likely to happen in the near future, but more and more advanced driver assistant systems become available. One of them is haptic guidance system that assists drivers to achieve better lane-keeping performance by implementing guidance torque on a steering wheel [2]. Considering this, the effect of diverse visual feedback associated with haptic feedback on driver steering performance remains an open question.

Visual feedback is necessary for a driver to maintain a vehicle within the lane and to account for the upcoming roads [3]. Visual feedback from near region of the road contributes to lane maintaining task, and visual feedback from far region of the road contributes to estimation of upcoming road curvature. The driver model of steering behavior is based on both current and predictive visual feedback from road [4]. When visual feedback from road ahead is limited, driver steering performance would be influenced.

In addition to visual feedback, haptic feedback provided by active torque on the steering wheel is also used to guide drivers' turning maneuver [5], [6]. This kind of assistant system is designed to provide human-machine cooperation, instead of to accomplish autonomous driving, so drivers are always responsible for the steering task [7]. A predictive haptic guidance model based on a look-ahead algorithm was presented for better aiding the driver's steering task [8]. A range of values of haptic feedback torque was found to be sensible to the driver, and the haptic feedback had remarkable effect on driver steering performance [9].

When a haptic guidance system is implemented, driver steering performance is influenced by both visual feedback and haptic feedback. The nervous system of human seems to integrate visual and haptic information based on a statistically optimal fashion [10]. The haptic feedback on the steering wheel not only improves the lane-following performance but also contributes to reducing visual demand of a driving task [11]. The continuous haptic feedback is also beneficial to drivers under the condition of low visibility caused by fog [12], [13]. In addition to the condition of visual feedback from near region, it is also important to study visual feedback from other regions in order to understand the effect of haptic feedback on driving performance when visual feedback is limited.

Driver steering performance has been widely investigated based on curve negotiation performance. The driving data before, during, and after curves were collected to calculate the steering angle and lane position which were used to evaluate driver steering performance [14]. It is known that driving data during curves considerably reflects driver steering performance, but driving data before and after curves are also meaningful. The first steering movement of turning into a curve shows the driver's steering response to visual feedback of the beginning of the curve [15]. It is hypothesized that driver steering maneuver would become dependent on haptic feedback when visual feedback from road ahead becomes limited, and this tendency could be observed by analyzing the first steering movement of turning into or turning out a curve.

For the reason that inducing limited visual feedback is a safety-critical task, it is considered to use a driving simulator to carry out this kind of experiment. Moreover, by using a driving simulator, visual feedback can be precisely controlled to make sure that only certain parts of the road are displayed [3]. A high-fidelity driving simulator with wide forward field-of-view and a six-degree-of-freedom motion base can produce a highly realistic driving environment [16], and it is

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possible to emulate feelings of on-road driving in a high-fidelity driving simulator.

The motivation of this study is therefore to investigate the effect of haptic guidance on driver steering performance during curve negotiation when visual feedback is limited. This paper is organized as follows. Section II describes an experiment conducted in a high-fidelity driving simulation, including haptic guidance steering system, scenario, driving procedure, and measures of driver steering performance. Section III illustrates the statistical analysis results, followed by section IV that discusses the effect of haptic guidance on driver steering performance. Finally, conclusion is presented in section V.

II. Experimental Method

A. Participants

Twelve healthy males were recruited to participate in the experiment. Their age ranged from 22 to 31 (mean = 24.3, SD = 2.4). All had a valid Japanese driver's license for at least 1 year (mean = 4.3, SD = 2.6), and their average driving frequency was once per week.

The experiment was approved by the Office for Life Science Research Ethics and Safety, the University of Tokyo (No. 14-113). Each participant received monetary compensation for his involvement in the experiment.

B. Apparatus

As shown in Fig. 1, the experiment was conducted in a moving-based driving simulator with brake and accelerator pedals, an actuated steering wheel, and an instrument dashboard. The driving simulator is considered to be high-fidelity, for it also includes a 140-degree field-of-view and a moving platform with six degrees of freedom.

To emulate the feeling of on-road driving, high frequency vibrations were produced by the moving platform, engine sounds were provided by two stereos, and a self-aligning torque was generated by the actuated steering wheel. Raw data of driving performance were recorded in the host computer of the driving simulator at a sample rate of 120 Hz.

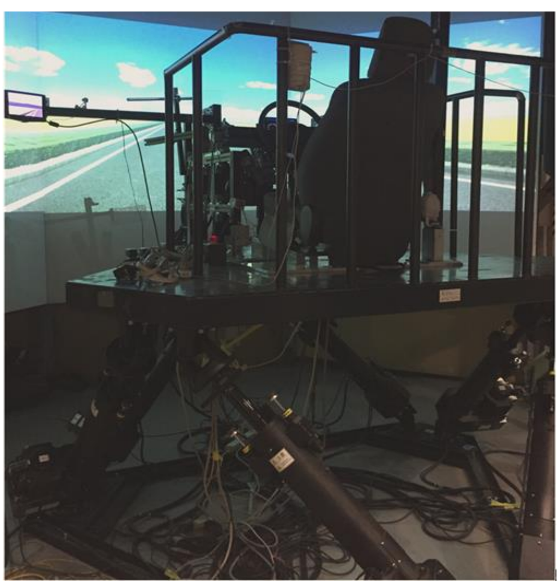

Fig. 1. Driving simulator used in the experiment.

C. Haptic Guidance Steering System

A haptic guidance steering system is a type of interactive driving assistance that continuously generates active torque on a steering wheel to inform a driver about errors between the vehicle and target trajectory, and assists the driver to perform an appropriate maneuver. Accordingly, the steering wheel is cooperatively actuated by the human's arm torque and haptic guidance torque. It is important to notice that the system is designed to assist the driver instead of to control the vehicle automatically. Consequently, the driver can choose to overrule the system at any time by exerting more torque on the steering wheel. In this experiment, the haptic guidance torque was limited to 5 Nm [17].

Vehicle trajectory is mainly affected by steering wheel angle. Considering haptic guidance torque, steering wheel angle, φ, can be expressed as

$$\frac{d^2\varphi}{dt^2} = I^{-1}(T_{\text{human}} + T_{\text{haptic}} - T_{\text{aligning}}), \tag{1}$$

where I is inertia of steering wheel system; T_{human}, T_{haptic}, and T_{aligning} are human's arm torque, haptic guidance torque, and aligning torque, respectively.

In the driving simulator, an electronic steering system was connected to the host computer through a CAN communication. The electronic steering system mainly consisted of a steering wheel, a servo motor and an electronic control unit (ECU). The haptic guidance torque was real-time calculated in the host computer, and then inputted to ECU to actuate the servomotor; whereby, the haptic guidance torque was implemented on the steering wheel.

The magnitude and direction of haptic guidance torque were determined by comparing vehicle trajectory and target trajectory. The target trajectory was designed as the centerline of the lane in the driving scenario. The coordinate of the target trajectory was stored in the host computer of the driving simulator. Parameters of the vehicle trajectory and target trajectory are presented in Fig. 2. The current lateral error, $e_{y(\text{cur})}$, is defined as the distance between the current position of vehicle and target trajectory, and predictive yaw error, $e_{\theta(\text{pre})}$, is defined as the angle between the direction of vehicle and target trajectory at a look-ahead point. The look-ahead time is 1 second.

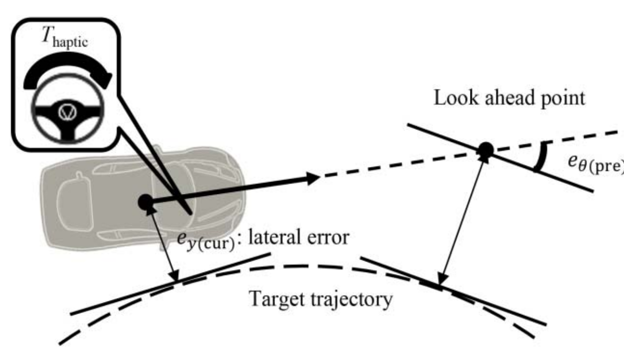

Fig. 2. Diagram of haptic model following target trajectory.