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Driver-Automation Shared Control: Modeling Driver Behavior by Taking Account of Reliance on Haptic Guidance Steering

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Abstract—**This paper presents a driver model in shared control that focuses on driver interaction with haptic guidance steering for a lane-following task. A weight parameter in the driver model was developed to describe driver interaction and reliance on haptic guidance steering. A driving simulator experiment with 5 participants was conducted to identify the model parameters. One experimental condition was driving with the haptic guidance steering system, and another condition of manual driving was conducted as a comparison. The identification results showed the relationship between driver model parameters and characteristics of driver behavior, including the driver interaction with haptic guidance steering and the steering effort. Taking the degree of driver reliance on haptic guidance steering into account improved the fitness of modeling driver steering behavior. The proposed driver model in shared control driving was shown to be appropriate, as the model matched the driver's input torque with a fitness of 68% on average.**

Index Terms—**Driver model, haptic guidance steering, shared control, human-machine interaction, system identification**

I. INTRODUCTION

Automated driving has drawn much attention in recent years and remarkable outcomes have been achieved [1]. The continuous progress in the development of automated driving has led to the design of various advanced driver assistant systems (ADAS), such as adaptive cruise control, and lane keeping assistance system [2, 3]. The development of ADAS results in a great need of understanding about the driver-vehicle-road model. Many attempts have been made to model driver behavior in a mathematical way, including control theory [4, 5], fuzzy logic [6], stochastic methods [7], and hybrid methods.

Recently, driver-automation shared control, which combines the benefit of vehicular automation and human driver during a driving task, has been investigated to realize semi-autonomous driving [8]. Regarding shared control in a lane-following task, haptic guidance is an intelligent system that continuously shares the steering control with the driver, so that they can determine the inputs to the steering system together [9-11]. Haptic guidance steering has been reported as a promising way to reduce the workload of drivers while keeping them in the control loop of the driving task, and meanwhile to improve the lane-following performance [12, 13]. However, the beneficial effects of haptic guidance steering are accompanied by downside effects. When the haptic guidance does not match the individual driver's steering intention, a conflict occurs between the driver's input torque and haptic guidance torque [12]. This conflict could result in an intrusive feeling to the driver [14], which would limit the introduction of haptic guidance steering systems to the market. In the case of designing a haptic guidance steering system, when the prediction of driver behavior is taken into consideration by establishing a driver model, the conflict between the system and the human driver has been reduced [14], and the driving performance during lane following and lane changing has been improved [15, 16]. Moreover, it is assumed that the model accuracy will be further improved when the interaction between the driver and haptic guidance steering is considered. However, study on modeling the driver interaction with haptic guidance steering through haptic feedback has been scant.

Previous research has found that driver behavior can be significantly influenced by driver interaction and reliance on the intelligent transportation systems [17]. Thus, it is crucial to understand and model driver interaction and reliance on haptic guidance steering for better design of the assistance system. When driving with the haptic guidance steering system, the driver's steering behavior is influenced by both visual feedback from the road ahead and haptic feedback from the system [18]. It is necessary to understand how the driver integrates visual feedback and haptic feedback to achieve an optimal driving performance. It has been found that human perceptual judgements rely upon visual feedback and haptic feedback in a weighted fashion, in which the more reliable feedback is given a higher weight [19, 20]. Therefore, it is hypothesized that the driver's reliance on haptic guidance steering can be described by a weighted fashion in the driver model.

The aim of this study is to propose a driver model in driver-automation shared control that considers driver interaction and reliance on haptic guidance steering in a lane-following task. This paper is organized as follows. In Section II, a driver-vehicle-road model is comprehensively introduced. Section III describes a driving simulator

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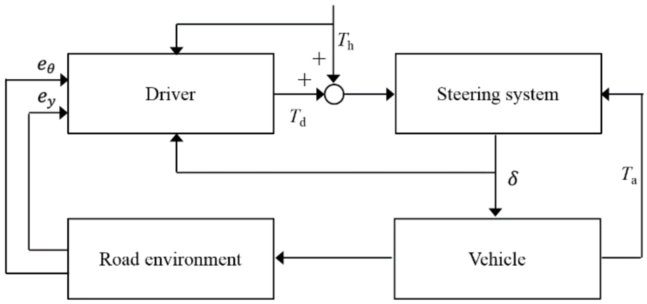

Fig. 1. General structure of driver-vehicle-road model

TABLE I
SYSTEM VARIABLES OF DRIVER-VEHICLE-ROAD MODEL

	Definition
e_y	Lateral error at the near point
e_θ	Yaw error at the far point
δ	Steering wheel angle
δ'	Determined steering wheel angle by driver
T_a	Aligning torque
T_h	Haptic guidance torque
T_d	Driver input torque

experiment, including participants, apparatus, driving course, and measurement of driver steering behavior. Section IV illustrates the parameter identification of the driver model and the identification results from 5 participants. Finally, the conclusion and future work are presented in Section V.

II. DRIVER-VEHICLE-ROAD MODEL

A. General Structure

Figure 1 shows the general structure of the driver-vehicle-road model, which consists of four subsystems, namely: driver, steering system, vehicle, and road environment. The variables in the driver-vehicle-road model are shown in Table I. T_h is haptic guidance torque provided by a steering assistance system, namely haptic guidance steering system, and the manual driving corresponds to $T_h = 0$. The details for the subsystem of the driver model are discussed below.

B. Two-point Driver Visual Model

Figure 2 shows the geometric relationship between the vehicle, the target trajectory, and a two-point driver visual model. The centerline of the lane is set as the target trajectory. This driver visual model relies on both near and far points of the road ahead: a near point to maintain a central lane position, and a far point to account for the upcoming road curvature [21]. The lateral error, e_y, is defined as the distance between the vehicle and target trajectory at the near point. The yaw error, e_θ, is defined as the angle between the movement direction of the vehicle and target trajectory at the far point. The look-ahead time for the near point is 0.3 seconds, and the look-ahead time for the far point is 0.7 seconds. A proportion-integral controller dealing with e_y at the near point, and a proportion controller dealing with e_θ at the far point, have been proposed [21]. The visual system within the whole driver model is shown in Fig. 3.

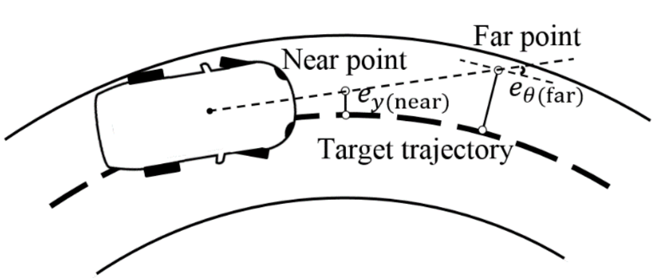

Fig. 2. Schematic of two-point driver visual model

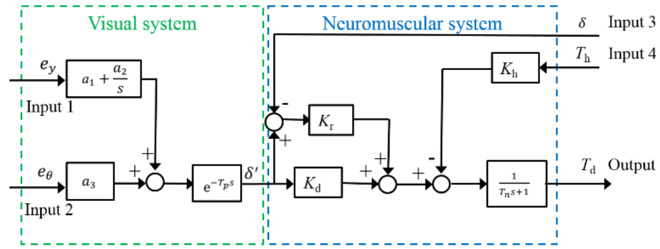

Fig. 3. Proposed driver model by taking account of interaction with haptic guidance steering

TABLE II
SYSTEM PARAMETERS OF DRIVER MODEL

	Definition
a_1	Constant gain for e_y
a_2	Constant gain for integral of e_y
a_3	Constant gain for e_θ
T_p	Processing time delay
K_d	Angle to torque gain
K_h	Coefficient of haptic
K_r	Neuromuscular reflex gain
T_n	Neuromuscular time constant

C. Driver Steering Model

Figure 3 shows the driver steering model including the visual system and neuromuscular system. The variables in the driver model are shown in Table I, and the parameters are shown in Table II. The time delay, T_p, accounts for the processing delay of the sensory signal by the human brain. The determined steering wheel angle, δ', is converted into the driver input torque T_d by means of the neuromuscular system. K_d represents that the neuromuscular system provides a steering torque proportional to the determined steering wheel angle. K_r represents the neuromuscular reflex that rejects any disturbance on the steering wheel that is caused by an external torque. K_r continuously acts to minimize the difference between the actual steering wheel angle δ and the determined steering wheel angle δ'. T_n approximately describes the time response of a driver's arms for a steering maneuver [5].

It should be noticed that the coefficient of haptic, K_h, is expected to describe driver interaction and reliance on haptic guidance steering. When K_h equals 1, it indicates that the driver does not rely on the haptic guidance steering. This is because the variation of T_h is included in the driver input torque T_d, as shown in Fig. 3, and it almost does not influence the sum torque of T_h and T_d into the steering system, as shown in Fig. 1. Consequently, the driver steering performance will be barely influenced by T_h. As a comparison, when K_h equals 0, it indicates that the driver relies on the haptic guidance steering. This is because the variation of T_h is not included in the driver input torque T_d, as shown in Fig. 3, and it remarkably influences the sum torque of T_h and T_d into the steering system, as shown in Fig. 1. Considering this, the range of K_h from 0 to 1 is assumed to represent the degree of the driver's reliance on haptic guidance steering.

III. Experimental Study

A. Participants

To validate the proposed driver model and identify the model parameters, a driving simulator experiment with 5 participants was conducted. The participants all had a valid Japanese driver's license for at least 1 year, and had normal or corrected-to-normal vision when performing the driving tasks. Each participant received monetary compensation for the involvement in the experiment. The experiment was approved by the Office for Life Science Research Ethics and Safety, the University of Tokyo.

B. Apparatus

The experiment was conducted in a fixed-based driving simulator with a 140° field-of-view of the driving scene visualized by three projectors. The driving environment was a two-lane expressway road with 3.6 m width lanes and an emergency lane on the left, as shown in Fig. 4. Lane markings were solid lines and dashed lines. To emulate the feeling of on-road driving, two stereos were used to provide the engine sound, and other vehicles appeared at various intervals. The participants were requested to grab the steering wheel in a "ten-and-two" position during the driving task and to keep the vehicle in the centerline of the left lane as accurately as possible. Raw data of driving performance was recorded in the host computer at a sampling rate of 120 Hz.

Fig. 4. Driving environment in the experiment

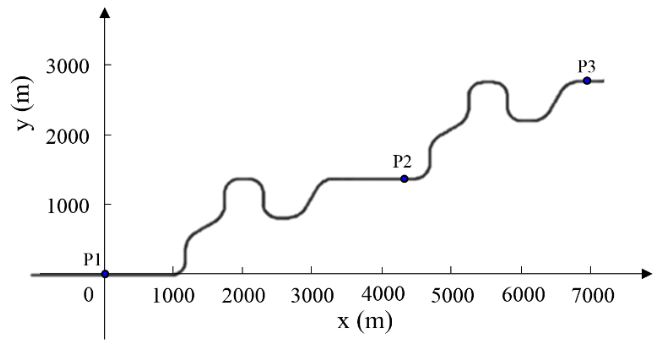

Fig. 5. Driving course in the experiment

C. Haptic Guidance Steering System

A haptic guidance steering system continuously generated active torques on the steering wheel to assist the participants with the lane-following task. In the driving simulator, an electronic steering system was connected to the host computer through a controller area network bus. The electronic steering system consisted of a steering wheel, a servomotor and an electronic control unit (ECU). The haptic guidance torque was real-time calculated in the host computer, and then inputted to the ECU to actuate the servomotor, by which the haptic guidance torque was implemented on the steering wheel.

Both the driver torque and haptic guidance torque directly determined the input to the steering system. The algorithm for calculating the magnitude and direction of the haptic guidance torque is also based on a two-point visual model, as shown in Fig. 2. The target trajectory was designed as the centerline of the lane in the scenario and was stored in the host computer. The haptic guidance torque, T_{h}, is expressed as

$$T_{\mathrm{h}} = K\big(b_1 e_{y(\mathrm{near})} + b_2 e_{\theta(\mathrm{far})} + b_3 \dot{e}_{\theta(\mathrm{far})}\big) \tag{1}$$

where b_1, b_2, b_3, and K are constant gains [18]. Driver input torque was measured by a torque sensor with a resolution of 0.005 N·m, and steering wheel angle was measured with a resolution of 0.1 degrees.

There were two experimental conditions: One condition was driving with the haptic guidance steering system, and another condition of manual driving was conducted as a comparison.

D. Driving Course

As shown in Fig. 5, the driving course consisted of straight roads and curves. The length of each curve was 314 m, and the radius was either 200 or 300 m. The driving task started at P1, and ended at P3. The driving speed was fixed at 60 km/h by software setting in the scenario, so that the participant was only requested to operate the steering wheel. For the reason that the participants needed time to adapt their driving behavior to the haptic guidance steering system, the data from the first half of the driving course were omitted, and the data recorded between P2 and P3 were used for driver model identification.

IV. Identification

A. Parameter Identification

A parameter identification of the proposed driver model was conducted, using e_y, e_θ, δ, and T_h as inputs, and T_d as an output. The driver model is represented as a structured state-space realization, as follows:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t)\\ y(t) &= Cx(t) + Du(t) + e(t)\\ x(0) &= x_0\end{aligned} \tag{2}$$

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix} 0 & 0 & 0\\ a_2\dfrac{2}{T_p} & -\dfrac{2}{T_p} & 0\\ -a_2\dfrac{K_d+K_{nms}}{T_n} & \dfrac{2(K_d+K_{nms})}{T_n} & -\dfrac{1}{T_n}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix}$$

$$+\begin{bmatrix} 1 & 0 & 0 & 0\\ a_1\dfrac{2}{T_p} & a_3\dfrac{2}{T_p} & 0 & 0\\ -a_1\dfrac{K_d+K_{nms}}{T_n} & -a_3\dfrac{K_d+K_{nms}}{T_n} & -\dfrac{K_{nms}}{T_n} & \dfrac{-K_h}{T_n}\end{bmatrix}\begin{bmatrix}e_y\\ e_\theta\\ \delta\\ T_h\end{bmatrix}$$

$$\begin{bmatrix}T_d\\ \delta'\end{bmatrix} = \begin{bmatrix}0 & 0 & 1\\ -a_2 & 2 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0 & 0 & 0 & 0\\ -a_1 & -a_3 & 0 & 0\end{bmatrix}\begin{bmatrix}e_y\\ e_\theta\\ \delta\\ T_h\end{bmatrix} \tag{3}$$

In the above state-space representation, a first-order Pade expansion to approximate the time delay T_p with a rational transfer function is performed, as follows:

$$e^{-T_p s} = \frac{1-0.5T_p s}{1+0.5T_p s} \tag{4}$$

The discretized state-space realization is given by:

$$\begin{aligned}x(k+1) &= Ax(k) + Bu(k)\\ y(k) &= Cx(k) + Du(k) + e(k)\\ x(0) &= x_0\end{aligned} \tag{5}$$

The parameters of the driver model were identified by using the Prediction Error Method (PEM) implemented in the Grey Box Identification Toolbox of Matlab. Minimum percentage difference between the current value of the loss function and its expected improvement after the iteration was set as 0.01%, which means that the iteration stopped when the expected improvement was less than 0.01%. The estimate of the expected loss function improvement at the next iteration was based on the Gauss-Newton vector computed for the current parameter value.

TABLE III
Driver Model Parameters

	Default value	**Variation interval**
a_1	0.05	[0-0.5]
a_2	0.001	[0-0.01]
a_3	3.7	[3-5]
T_p	0.1	[0.01-0.3]
K_d	3	[1-5]
K_h	0.5	[0-1]
K_r	1	
T_n	0.1	

A further analysis indicates the low identifiability of the model when only considering the output of driver torque. It may result in an identified model with a higher fitness but the vehicle does not follow the target trajectory accurately in a simulation study. For this reason, the target steering wheel angle is also considered as an additional output of the driver model.

Table III shows the default value and variation interval of the identified driver model parameters, which were obtained through a trial-and-error process, and by referring to [15].

B. Identification Results

The identification results of neuromuscular system in the driver model are summarized in Table IV. The results indicate that the proposed driver model matches driver input torque with a fitness of 68% on average in the condition of haptic, and 76% on average in the condition of manual. This is a satisfying performance after considering the individual difference in driver steering behavior. In addition, the value of K_h is 0.7 on average, which indicates that the drivers relied on the haptic guidance steering to a relatively low degree. This is expectable because the visual feedback from the road ahead was sufficient and the driving workload was not high in this experiment. As a result, the driver steering behavior was mainly determined by visual feedback for the lane-following purpose.

TABLE IV
Identification Results of Neuromuscular System in Driver Model

Subject	**Condition**	K_d	K_h	**Fitness of T_D**
No. 1	Manual	3.861		76.2%
	Haptic	3.624	0.749	66.5%
No. 2	Manual	3.587		70.2%
	Haptic	3.589	0.820	62.0%
No. 3	Manual	3.855		74.5%
	Haptic	3.825	0.727	69.2%
No. 4	Manual	4.044		82.6%
	Haptic	3.497	0.638	71.6%
No. 5	Manual	4.080		79.9%
	Haptic	3.712	0.629	73.7%

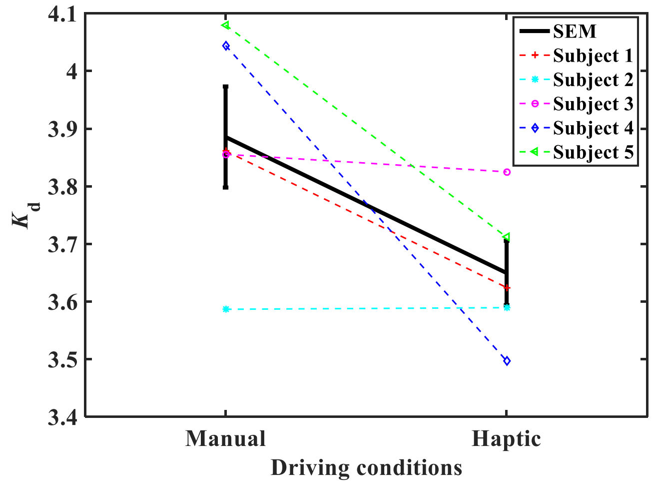

Fig. 6. Comparison in K_d between the driving conditions of manual and haptic. Data error bars represent mean +/- SEM (standard error of mean)

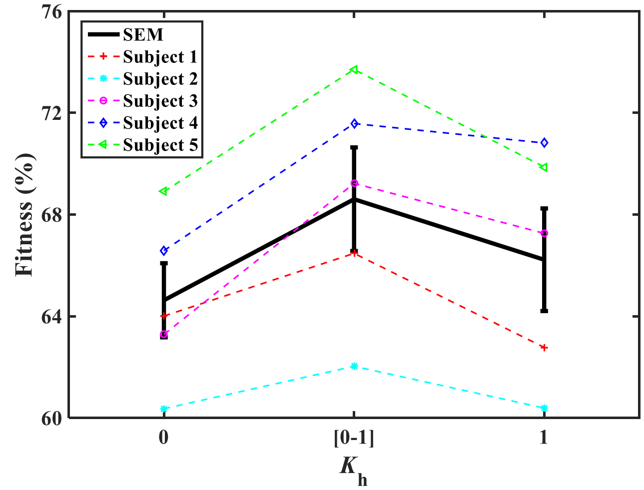

Fig. 7. Fitness of driver input torque with different K_h. Data error bars represent mean +/- SEM (standard error of mean)

As for the result of fitness, it should be noticed that the fitness is lower in the condition of haptic compared to manual. This is because the driver's reliance on haptic guidance steering was approximately described by the coefficient of haptic, K_h, whereas the actual driver behavior should be more complicated. Regarding the identification results of K_d and K_h in the neuromuscular system of driver model, promising findings were drawn among the 5 participants, which are discussed below.

By comparing the value of K_d between the conditions of manual and haptic, as shown in Fig. 6, we found that the mean value of K_d was lower in the condition of haptic than manual. This indicates that haptic guidance reduced driver steering effort, as K_d represents that the neuromuscular system provides a steering torque proportional to the determined steering wheel angle, as shown in Fig. 3. The analysis of individual subject's K_d revealed that this finding was evident for Subject 1, 4 and 5. Moreover, by comparing the value of K_h from each participant, there was a tendency that the relatively lower value of K_h (relatively higher degree of reliance on haptic guidance steering), led to more reduction of K_d from the condition of manual to haptic. This is in accordance with that the drivers' steering effort can be reduced when they actively followed the haptic guidance torque provided by the assistance system [9].

In order to test the influence of parameter K_h on the modeling fitness of driver input torque, we fixed the value of K_h to 0 and to 1 as comparisons when performing the model identification. Figure 7 shows the result of fitness, which indicates that the proposed driver by taking K_h (degree of driver reliance on haptic guidance steering) into consideration matches the driver input torque with a higher fitness. By comparison, when K_h equals 0 (full reliance on haptic guidance), and when K_h equals 1 (no reliance on haptic guidance), the fitness of driver input torque is lower. After looking into the result of each participant, we found that there was a consistency in the above tendency. It suggests that the accuracy of the driver model was improved by including the degree of driver reliance on haptic guidance steering. Considering the important role K_h played in the driver model, as a future work, simulation study would address the effect of different values of K_h on driver steering behavior in various shared control driving situations.

V. Conclusion

A driver model that focused on driver interaction with haptic guidance steering in shared control was proposed for a lane-following task. A weight parameter in the driver model was developed to describe the degree of driver reliance on haptic guidance steering.

The proposed driver model was shown to be appropriate for identification of driver steering behavior when driving with haptic guidance steering, based on the data collected in the experiment, as the model matched driver input torque with a fitness of 68% on average among 5 participants. Taking the degree of driver reliance on haptic guidance steering into account improved the fitness of modeling driver input torque. In addition, the identification results suggest the tendency that higher degree of driver reliance on haptic guidance steering led to more reduction of driver steering effort. Furthermore, the model would be suitable to be used for the designing of haptic guidance steering system.

In future work, more participants will be selected, and statistical analysis will be conducted. Additionally, future work will address the driver model with reliance on haptic guidance steering when different levels of haptic guidance torques are applied.

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