Control Authority Transfer Method for Automated-to-Manual Driving Via a Shared Authority Mode

Takahiro Saito, Takahiro Wada, *Member, IEEE*, and Kohei Sonoda

***Abstract*—Although automation-initiated and driver-initiated control transfers from automated to manual driving may yield unstable steering activity even when the drivers are focused on the road environment ahead, there are few studies on the development of control transfer methods at an operational level after a request to intervene. Therefore, we propose a shared authority mode connecting the automated and manual driving modes and a method for transferring control authority using haptic shared control to achieve smooth transfer. The results of driving simulation experiments demonstrate that the instability in the steering angular velocity originally present during control transfer is significantly improved by introducing our proposed method.**

***Index Terms*—Automated driving, authority transfer, human factors, human machine systems, shared authority.**

I. Introduction

In LEVELS 2 and 3 of automated driving (SAE [1]), drivers are required to assume control of the driving tasks, and there are cases in which it is necessary to transfer authority from automated to manual driving. Therefore, many human factor research studies have been conducted for automated driving [2]. For example, humans' trust in automated driving systems (ADSs) was investigated as a basis for establishing safe and secure ADSs [3], [4]. An ADS is thought to cause the situation awareness (SA) of drivers to depreciate because they tend to be out of the control loop during its use. Thus, a considerable amount of effort has been expended to improve a driver SA when using an ADS so that humans can properly resume control of the driving operation as necessary [4]–[7].

There are also many research studies on methods for transferring control authority between humans and ADSs, as it affects driver control performance during and after the transition. Authority transfer can be classified according to 1) the direction of authority transfer or who takes control following the transition, and 2) who initiates the transition [8]. ADS-initiated authority transfer to human drivers has been a topic of great interest, as sudden authority transfers to the driver for reasons such as a functional limitation could lead to a delayed response of the driver. To overcome this problem, several researchers have studied methods to issue a request to intervene (RTI) and the subsequent reaction of the driver to the RTI. As an example, Blanco *et al.* [2] demonstrated that an RTI adding haptic information to visual cues improved driver response during Level 2 driving automation. To gain insight into the amount of time required to regain control, Mok *et al.* [9] investigated the driver behavior subsequent to an RTI being issued immediately before an unexpected hazardous situation to discuss the necessary time for regaining control. In addition, research has shown that the employment of driver seat vibration that is coincident with an RTI improves driver response [10], [11]. Conversely, Payre *et al.* [12] demonstrated that, although increased trust in the automation led to a delay in the driver response to the RTI, this delay could be suppressed by having the drivers practice resuming control. Moreover, Merat *et al.* [13] compared the driver behavior by implementing a fixed interval of 6 min between RTI issuance to that by an RTI that was issued when the driver was not focused on the road ahead. It was found that vehicular motion was more stable when the driver could anticipate the RTI. Alternatively, Nilsson *et al.* [14] proposed a method to determine whether a given traffic condition is appropriate as a basis for issuing an RTI by evaluating the ability of the driver to assume and maintain control. Furthermore, Kaustubh *et al.* [15] derived a mathematical model for a driver–ADS system using a hybrid control framework to investigate when to switch the control authority between the human driver and the ADS.

In terms of driver-initiated control transfer, control is transferred to the human immediately after they turn the steering wheel or depress the brake pedal in most of the research studies mentioned above. However, research has demonstrated that the steering activity tends to be unstable following system-initiated transfer; this was found to hold true even in cases in which the driver is paying attention to the road environment ahead [16]. Wada *et al*. showed that, whichever transfer was initiated by the driver or the ADS, an instantaneous transition may lead to

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T. Saito is with the Graduate School of Information Science and Engineering, Ritsumeikan University, Kusatsu 525-8577, Japan (e-mail: is0215vv@ed.ritsumei.ac.jp).

T. Wada is with the College of Information Science and Engineering, Ritsumeikan University, Kusatsu 525-8577, Japan (e-mail: twada@fc.ritsumeikan.ac.jp).

K. Sonoda is with the Research Organization of Science and Technology, Ritsumeikan University, Kusatsu 525-8577, Japan (e-mail: koheisonoda@gmail.com).

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unstable steering operation when rapid steering maneuvering is necessary [17]. These suggest that the driver's readiness to drive a car at the operational level can be insufficient even when the driver *judges* that he/she is ready to *start* to take over control. Therefore, research into control transfer methods subsequent to an RTI should be performed at an *operational level* to ensure stable and safe authority transfers, which is not dealt with in detail in the previous research mentioned above.

Sharing authority in human–machine collaboration is thought to be promising for smooth authority transfers [18], [19]. As for collaboration or cooperation in human and automation at the operational level, attention has been focused on the concepts of cooperative control [20], [21] and shared control [22]–[25]. In shared control, a human operator and an automated system achieve a single operational task via a single operation input such as an automobile steering wheel [23], [25]. In contrast, cooperative control is understood as collaborative work between a human and a machine over a wider range than shared control, with a human and an automated system working together to achieve tasks involving more than one maneuver [21], [26]. Griffiths proposed a basic form of haptic shared control (HSC) that exerts a virtual spring torque on the steering wheel whose equilibrium point is designed as the angle calculated from a preview driver model and showed an improvement in the lane tracking performance [22]. The authors of [27] and [28] proposed another HSC controller, in which a torque that reduces the lane tracking error was added to the steering stiffness term, and the effects of each term on the performance were investigated. Mars *et al.* [29] proposed a shared control method using an optimal controller [30], compared the performance of the lane tracking control of a vehicle at various strengths, and showed that the performance is comprehensively high at a relatively low control strength. On the other hand, the H-mode was proposed as an implementation of cooperative control [20], and it was demonstrated that "loose rein," in which automation performs almost all control but presents its behavior to the driver via the steering torque and communicates decision-making results such as changing a lane to the system, allowed the drivers to respond properly, even in the case of a system failure. In such shared and cooperative controls, it is thought to be possible to smoothly connect automatic control and manual control by changing the control strength, the level of control authority [22], or the level of haptic authority [28] in principle. However, a concrete method for safe control authority transfer between ADSs in Level 2 or 3 in SAE [1] and human drivers has not yet been proposed, despite the efforts to date.

Therefore, we propose to establish a shared authority mode that connects automated and manual driving modes and apply it to a method to transfer control authority via HSC to achieve smooth transfer. The effectiveness of the proposed method is investigated by driving simulator experiments. The preliminary research for this study is presented as a conference proceedings [31], which reports the fundamental idea and partial results. Accordingly, the current paper is a refined, archival version of the preliminary research that also presents the experimental results for vehicular motion and driver workload in addition to providing a detailed discussion of the results.

TABLE I
COOPERATIVE STATES

		w_c		
		$\leq -\gamma_1^2$	else	$\geq \gamma_1^2$
w_{ads}	$\geq \gamma_2^2$	(III) System-led cooperative or uncooperative		(I) Driver-led cooperative
	else	(V) Dead zone		
	$\leq -\gamma_2^2$	(IV) Passive: No active operation exists		(II) Driver-led uncooperative: driver resisting AS

II. COOPERATIVE STATUS IN HAPTIC SHARED CONTROL

We utilize HSC in a shared authority mode to achieve smooth control transfer, as is explained in the next section. The purpose of this section is to introduce the cooperative status in HSC, which is implemented in the proposed method.

In the case of two agents, a human driver and an ADS, operating a steering wheel by which each agent utilizes independent steering maneuvering to control a single vehicle using their respective controllers, a methodology for evaluating the cooperative status between the two agents was developed based on the following two axes [25], [17]:

a) Initiative holder
b) Intent consistency

These two axes are evaluated according to the respective pseudowork exerted on the steering mechanism by the driver and ADS:

$$w_c := \frac{1}{\Delta T}\int_{t-\Delta T}^{t} \tau_c\left(s\right)\dot{y}\left(s\right)ds, \tag{1}$$

$$w_{ads} := \frac{1}{\Delta T}\int_{t-\Delta T}^{t} \tau_{ads}\left(s\right)\dot{y}\left(s\right)ds, \tag{2}$$

where τ_{c} and τ_{ads} denote the torques exerted by the driver on the steering wheel and the ADS on the steering shaft, respectively; and y denotes the lateral position of the vehicle. A time window ΔT of 1 s was used in this research.

a) Initiative holder: The initiative holder is the agent with predominant control of vehicular motion. The human driver has the initiative when the following is satisfied:

$$w_c(t) \geq \gamma_1^2, \tag{3}$$

where γ_1^2 is the offset for the judgment threshold.

b) Intent consistency: The intent consistency determines whether the human driver and ADS have the same operational intent. The intent of the two agents is consistent when the following is satisfied:

$$w_{ads}(t) \geq \gamma_2^2 \text{ and } w_c(t) \geq \gamma_1^2, \tag{4}$$

where γ_2^2 is the offset for the judgment threshold. The intents of the two agents are judged to be inconsistent when the inequality signs are in opposition. The cooperative states of the two agents are defined in Table I according to the initiative holder and intent consistency using $w_c(t)$ and $w_{ads}(t)$.

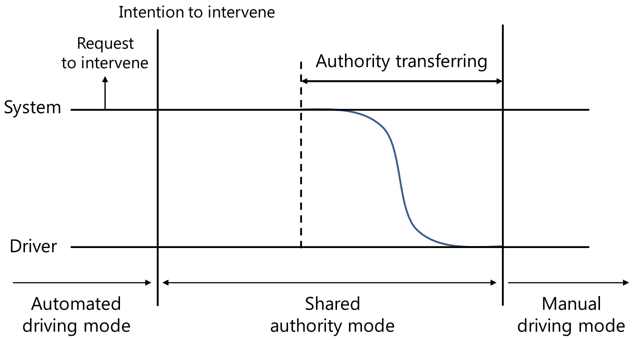


Fig. 1. Conceptual diagram of the authority transfer method via the shared authority mode.

State I: Driver-led cooperative state

The driver holds the initiative for vehicular operations in cooperation with the ADS. This state occurs when both agents exert torque in the same direction, causing the vehicle to move in the intended direction.

State II: Driver-led uncooperative state

The driver holds the initiative for vehicular operations, whereas the ADS attempts to steer against the driver's desires. In this state, the vehicle moves in the driver's intended direction, whereas the ADS exerts a warning torque in the opposite direction.

State III: System-led state

This state includes the following two substates, which are difficult to distinguish:

III-a System-led cooperative state
III-b System-led uncooperative state

State IV: Passive state

This state occurs in short time periods because of inertia or because a self-aligning torque is dominant.

State V: Dead zone

The blank area in Table I denotes a dead zone that is included to avoid misjudgments resulting from sensor noise.

III. ADS-TO-HUMAN AUTHORITY TRANSFER METHOD VIA AUTHORITY SHARED MODE

A. Overview

We propose an ADS-to-human driver authority transfer method that employs a shared authority mode connecting automated and human driving operations via a shared control technique.

To illustrate the proposed method, conceptual and flow diagrams are provided in Figs. 1 and 2, respectively. Assume that a vehicle is being driven via the automated system that is operating at its maximum designed strength. For an ADS-initiated authority transfer, the ADS issues an RTI to the human driver, to which the driver responds by expressing their intention to intervene or acknowledgment by performing an action such as pressing a button or steering. This results in the mode switching to a shared authority mode in which the HSC, which allows strength tuning, is used as a low-level controller. If the steering intention of the driver is detected as State II: Driver-led uncooperative state [25], [17], authority transferring control is initiated, thereby reducing the strength of HSC according to the exertion of a torque applied to the steering wheel. Subsequently, the manual driving mode is initiated when the strength of the HSC is lowered to a considerably small value. Note that Fig. 2 does not include an RTI judgment, which enables the application of the method to both ADS- and human-initiated transfers.

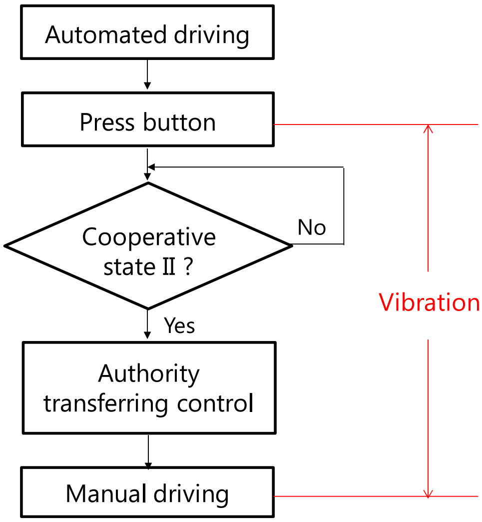


Fig. 2. Flow diagram of the proposed control method.

B. Intention to Intervene Via the Shared Authority Mode

The depression of a button located near the steering wheel is implemented as driver acknowledgment of the shared authority mode or demonstration of the intention to intervene. Additionally, for cases such as collision avoidance, in which a more rapid user response is required, we also propose the implementation of a direct transfer from the cooperative state to the driver-led uncooperative state [25] as the intention to intervene [17], which allows a quicker response for the user when required, such as for collision avoidance.

C. Method for the Lateral Control of Vehicles

The lateral motions of the vehicle are assumed to be controlled according to (5):

$$\tau_{ads} = K_p \left(\theta_d \left(t\right) - \theta \left(t\right)\right) - K_d \dot{\theta} \left(t\right), \tag{5}$$

where $\theta(t)$ and $\theta_d(t)$ denote the current steering wheel angle and desired angle, respectively, as determined by a second-order preview driver model to reduce the lateral error of the vehicle relative to its desired position. The controller in (5) operates as the automated driving controller when the gain, K_p, is significantly large. In addition, it operates as the HSC controller to allow the driver to interact with the steering control by grasping and exerting a torque on the steering wheel. In HSC, the tuning gain K_p enables authority transfer from the ADS to a human via a shared authority mode.

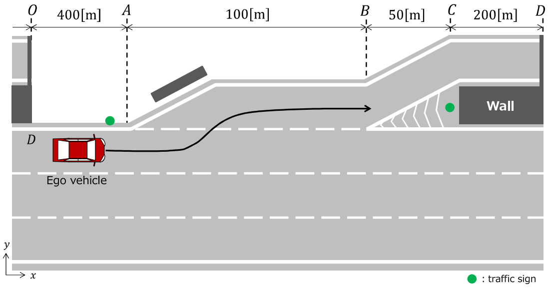


Fig. 3. Experimental scenario.

D. Authority Transfer Method Using HSC

In the authority transfer phase, K_p, as shown in (5), is tuned according to the torque input by the driver and is given by

$$\frac{d}{dt}K_p(t) := -G\mathrm{sgn}(K_p(t))\,|K_p(t)|^p f(W_c(t)), \tag{6}$$

$$f(x) := \begin{cases} x & x \geq 0 \\ 0 & x < 0. \end{cases} \tag{7}$$

With this update law, the gain is expected to converge to zero within a finite amount of time, as described in [32], thereby resulting in human authority mode initiation.

E. Displaying the Strength of Automatic Control Via Vibration

A vibrator using an eccentric rotating mass was attached to wristbands, and the driver wore the vibrating wristbands on both wrists while in the vehicle. In the shared authority mode, vibration was applied to the driver, in which the voltage applied to the vibrator was determined as $v = AK_p$, where the proportional constant A was determined by trial and error. The driver was expected to be continuously aware of any change in the status of authority.

IV. EXPERIMENTAL METHOD

A. Scenario

As an experimental scenario, assume a situation in which a driver exits an expressway for any reason such as the intent of the driver has been changed (see Fig. 3). The driver must take control authority from the ADS before reaching the exit.

B. Conditions

We set two experimental factors: a two-level G gain condition for the gain-tuning method as a between-subject factor and a four-level method condition as a within-subject factor. The two levels of the gain condition are $G = 0.006$ and 0.014, while the four levels of the method condition are as follows: 1) manual driving, 2) no-gain-tuning, 3) gain-tuning, and 4) gain-tuning + vibration administration, which are described as follows:

1) In the manual driving condition, a driving trial was conducted in which the subjects were to drive without the ADS.
2) In the no gain-tuning condition, K_p was not calculated but was abruptly reduced to zero upon the detection of an opposing steering intention of the driver; this is described as State II.
3) In the gain-tuning condition, K_p was tuned according to the proposed gain-tuning formula in (6) when the steering intention of the driver was determined as State II; this occurred in the absence of wristband vibration.
4) The gain-tuning + vibration condition is an extension of Condition 3, the gain-tuning condition, that implemented wristband vibration that was directly proportional to the amplitude of K_p, as explained in Section III-E.

Conditions 2, 3, and 4 have been designated as the automated driving conditions.

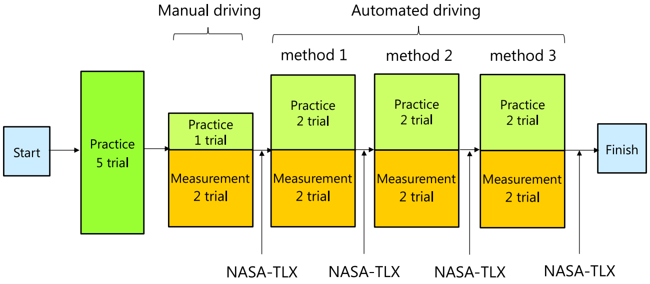


Fig. 4. Experimental procedure.

C. Procedure

Fig. 4 illustrates the experimental procedure. Five manual driving trials were performed by each subject to ensure accustomization to the driving simulator. Then, each subject performed an additional manual driving session, followed by three driving sessions that each corresponded to a single automated driving condition described above. The order of the three automated driving sessions was randomized among subjects. The manual driving session comprised one practice trial followed by two measured trials. Each of the automated driving sessions consisted of two practice trials followed by measured trials. Following each session, the subjective workload was assessed via the Japanese-language version of the NASA task load index (NASA-TLX) [33], [34], in which the weighted workload (WWL) was calculated as the weighted average of six subjective subscales: mental demand, physical demand, temporal demand, performance, frustration, and effort, which ranged between 0 and 100; a higher score means a higher subjective workload.

In the manual driving trials, the subject manually drove the vehicle. Conversely, in the automated driving trials, the subject was instructed to gaze ahead at the road with their hands placed on their thighs as they rode in the ego vehicle driven by the ADS.

During both the manual and automated driving trials, after passing a few expressway exits, a beep was administered for a period of 1 s when the ego vehicle reached a distance of 380 m before Point A, which corresponded to an exit. This beep represented the sudden change in driver intention to exit the expressway.

During the manual driving trials, the subject promptly steered to change lanes and exit the expressway upon hearing the beep.

Fig. 5. Driving simulator.

However, during the automated driving trials, the subjects were required to push the button near the steering wheel to enter into the shared authority mode prior to steering towards the exit.

D. Participants

The subjects participating in this experiment were 23 males and one female aged 20 to 24 who possessed a driver's license and provided written informed consent. Groups of twelve subjects were assigned to perform trials for each gain condition. As compensation for participation, a 500-yen prepaid card to purchase books was provided to each subject.

E. Apparatus

A stationary driving simulator (DS) was used for the experiments (see Fig. 5). A brushless DC motor (Maxon Corporation) was attached to the steering shaft to generate a torque about the axis; additionally, a torque sensor (Kyowa Electronic Instruments Co., Ltd.) was also installed on the steering wheel to measure the torque applied to the steering shaft by the human subject. Furthermore, computer graphs were generated via Unity 3D (Unity Technologies, Inc.), and vehicular motion was calculated by utilizing Carsim (Mechanical Simulation Corp.).

F. Evaluation Method

The root mean squares (RMSs) of the angular velocity of the steering wheel and the maximum value of the steering wheel angle were used as the indices of stability of steering operation. The RMS of the yaw rate was used as the index of stability for vehicular motion. Additionally, the RMSs of the driver torque and WWL, as determined via the NASA-TLX, were used as the indices of the driver workload.

The RMS of the angular velocity of the steering wheel was calculated using the angular velocity of the steering wheel measured during the period between the cooperative status switching to State II and the angular velocity initially satisfying the condition of $\dot{\theta} \leq -5$ rad/s. The maximum steering wheel angle was calculated using the steering angle measured during the period from the cooperative status switching to State II to the angle initially satisfying the condition of $\theta \leq 0$. The yaw rate implemented in the RMS calculation was taken as the yaw rate measured during the period of time when it initially exceeded and fell below 0.8 rad/s. In addition, the RMS-implemented driver torque was measured during the following period of time: the first instance of $\tau_c \geq 0.5$ N·m to $\tau_c \leq 0$. These analysis boundary conditions were established to obtain the values of the respective RMSs corresponding to the time period between the initiation and completion of a driver steering action.

V. EXPERIMENTAL RESULTS

A. Times Series Pattern of the Measured Signals

Fig. 6(a) and (b) show examples of the measured signals for the no-gain-tuning and gain-tuning conditions, respectively, with $G = 0.014$ near the point where the expressway was exited. As seen in Fig. 6(a) K_p rapidly decreased to zero without the gain-tuning method when the cooperative status was judged as 2, which means state II, and a large and rapid steering angular velocity and yaw rate were observed around that time. In contrast, as shown in Fig. 6(b) with the proposed gain-tuning method, K_p gradually decreased to zero after the cooperative status was judged as 2, and a smaller and milder steering wheel angular velocity and yaw rate were observed.

B. Angular Velocity of the Steering Wheel

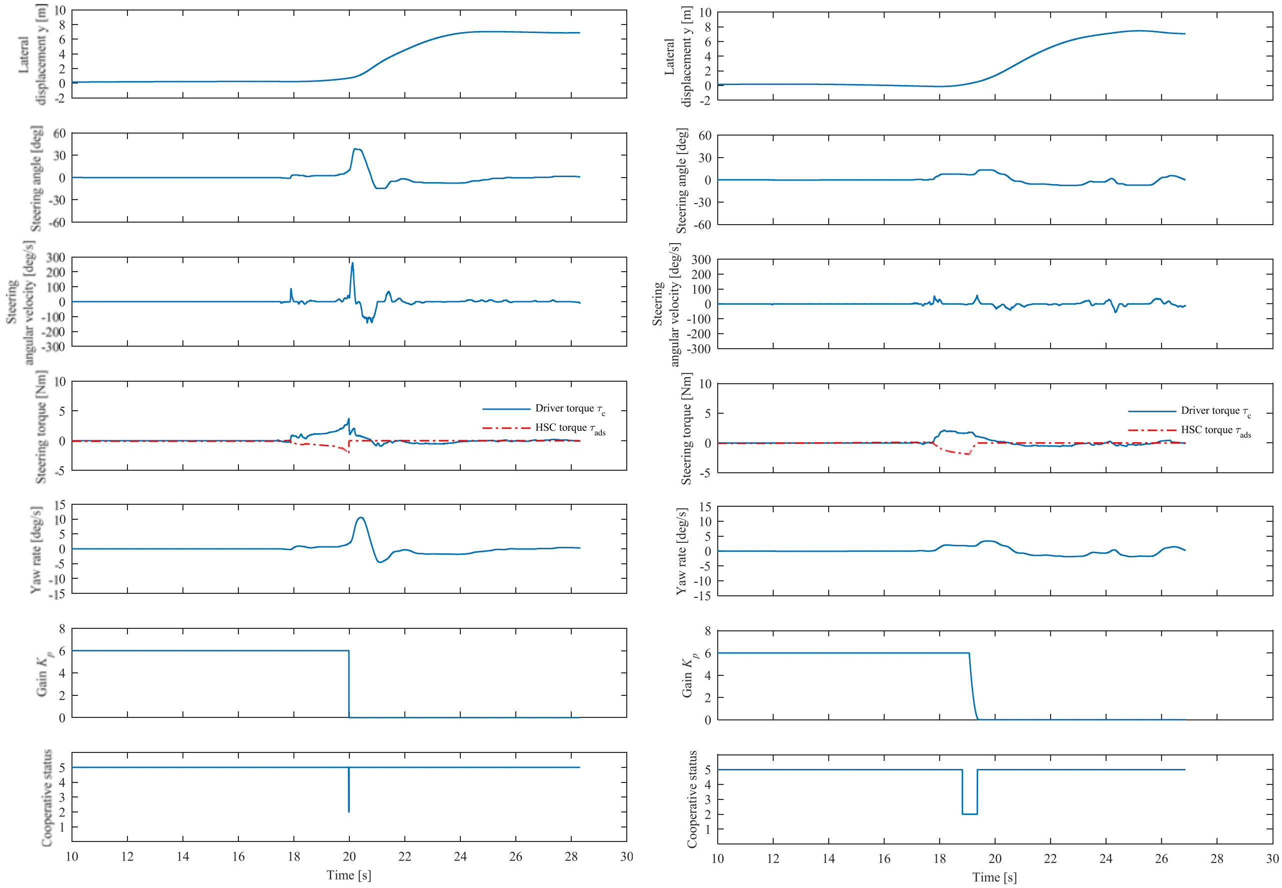
Fig. 7 illustrates the average RMS values of the angular velocity of the steering wheel for each driving condition; the error bars show the standard deviation. Although a two-way analysis of variance (ANOVA) revealed the significance of the main effects of the method $(\mathrm{F}(3, 138) = 163.6, \mathrm{p} = 0.000)$ and gain conditions $(\mathrm{F}(1, 46) = 5.772,\ \mathrm{p} = 0.020)$, no significance was found for the interaction $(\mathrm{F}(3, 138) = 1.76, \mathrm{p} = 0.184)$.

A post-hoc test implementing the Bonferroni correction for the method factor revealed that the angular velocity measured under the no-gain-tuning condition was significantly larger than that measured during manual driving (p = 0.000), gain-tuning (p = 0.000), and gain-tuning + vibration (p = 0.000). There was no significant difference between the gain-tuning and gain tuning + vibration conditions (p = 1.000). Furthermore, no significant differences were found between every other pair, including those between the gain-tuning and gain tuning + vibration conditions (p = 1.000).

C. Maximum Steering Wheel Angle

Fig. 8 shows the average of the maximum values of the steering wheel angle for each driving condition; the error bars show the standard deviation. A two-way ANOVA revealed the significance of the main effects of the method $(\mathrm{F}(3, 138) = 39.92, \mathrm{p} = 0.000)$, while no significance was found for the gain factor $(\mathrm{F}(1, 46) = 1.50, \mathrm{p} = 0.227)$ or interaction $(\mathrm{F}(3, 138) = 1.78, \mathrm{p} = 0.154)$.

A post-hoc test implementing the Bonferroni correction for the method factor revealed that the steering wheel angle during manual driving was significantly smaller than that during the automated driving conditions with no gain-tuning $(\mathrm{p} = 0.000)$, gain-tuning $(\mathrm{p} = 0.007)$, and gain-tuning + vibration $(\mathrm{p} = 0.038)$. In addition, the angles measured under the



(a) (b)

Fig. 6. Examples of measured signals with $G = 0.014$. (a) No gain-tuning condition. (b) Gain-tuning condition.

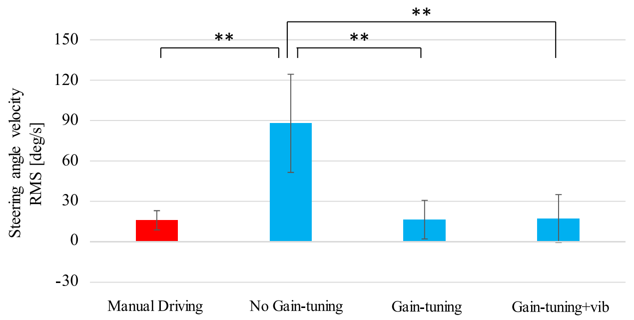


Fig. 7. RMS of steering angular velocity.

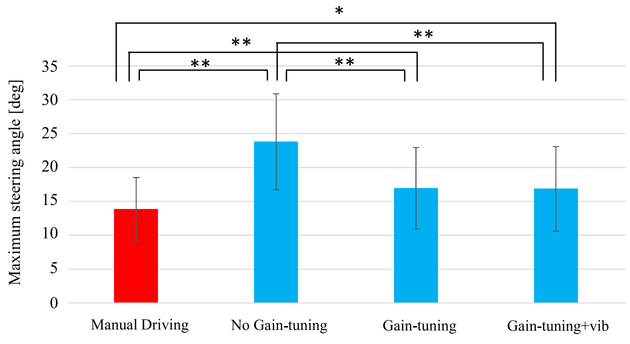


Fig. 8. Maximum steering wheel angle.

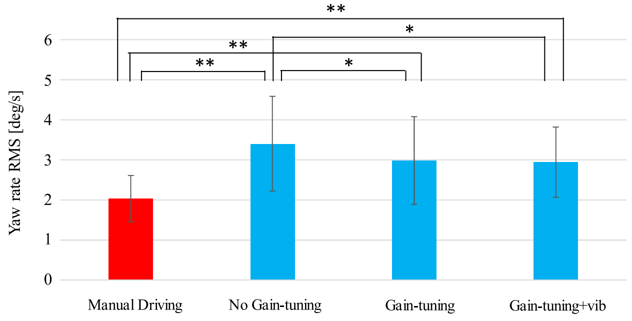


Fig. 9. RMS yaw rate.

gain-tuning and gain tuning + vibration conditions were significantly smaller than that measured during the no-gain-tuning condition ($p = 0.000$ and $p = 0.000$). Furthermore, there was no significant difference between the gain-tuning and gain tuning + vibration conditions ($p = 1.000$).

D. Yaw Rate

Fig. 9 shows the average RMS values of the vehicle yaw rate for each driving condition; the error bars show the standard deviation. A two-way ANOVA revealed the significance of the main effect of the method factor $(F(3, 138) = 34.13, p = 0.000)$,

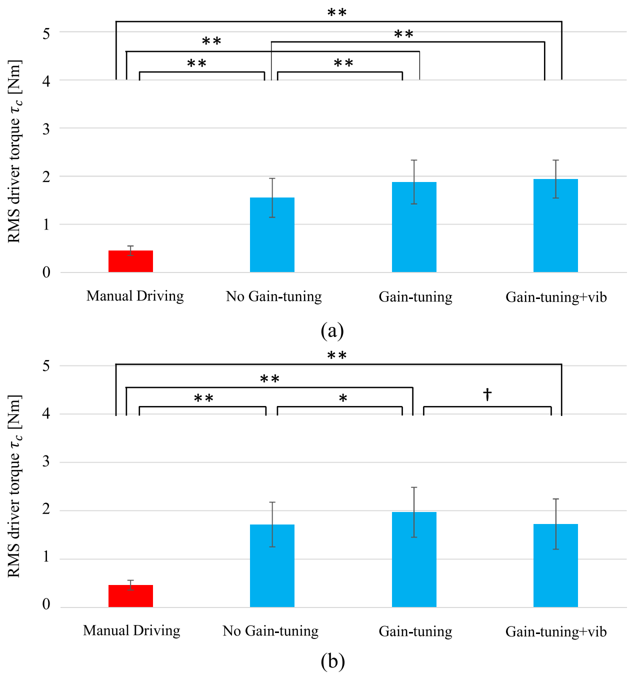


Fig. 10. RMS driver torque. (a) $G = 0.006$ (b) $G = 0.014$.

while no significance was found for that of the gain factor $(\mathrm{F}(1, 46) = 1.039, \mathrm{p} = 0.315)$ or interaction $(\mathrm{F}(3, 138) = 1.422, \mathrm{p} = 0.239)$.

A post-hoc test implementing the Bonferroni correction for the method factor revealed that the yaw rate during manual driving was significantly smaller than that during the automated driving conditions of no gain-tuning $(\mathrm{p} = 0.000)$, gain-tuning $(\mathrm{p} = 0.000)$, and gain-tuning + vibration $(\mathrm{p} = 0.000)$. In addition, the yaw rates measured under the gain-tuning and gain tuning + vibration conditions were significantly smaller than that measured under the no-gain-tuning condition $(\mathrm{p} = 0.020$ and $\mathrm{p} = 0.015)$. Furthermore, there was no significant difference between the gain-tuning and gain tuning + vibration conditions $(\mathrm{p} = 1.000)$.

E. Driver Torque

Fig. 10 shows the average RMS values of the torque exerted on the steering wheel by the driver; the error bars show the standard deviation. A two-way ANOVA revealed the significance of the main effect of the method factor $(\mathrm{F}(3, 138) = 241.9, \mathrm{p} = 0.000)$ and interaction $(\mathrm{F}(3, 138) = 3.491, \mathrm{p} = 0.017)$ but not of the gain factor $(\mathrm{F}(1, 46) = 0.013, \mathrm{p} = 0.911)$.

A one-way ANOVA for $G = 0.006$ revealed the significance of the simple main effect of the method factor $(\mathrm{F}(3, 69) = 141.6, \mathrm{p} = 0.000)$. Moreover, a post-hoc test implementing the Bonferroni correction for the method factor for $G = 0.006$ revealed that the torque exerted during manual driving was significantly smaller than that measured during each applied condition of automated driving $(\mathrm{p} = 0.000$ for Conditions 2–4). In addition, the torque corresponding to the no-gain-tuning condition was significantly smaller than that measured during the application of the gain-tuning $(\mathrm{p} = 0.002)$ and gain tuning + vibration $(\mathrm{p} = 0.000)$ conditions. No significant difference was observed between the no-gain-tuning and gain tuning + vibration conditions $(\mathrm{p} = 1.000)$.

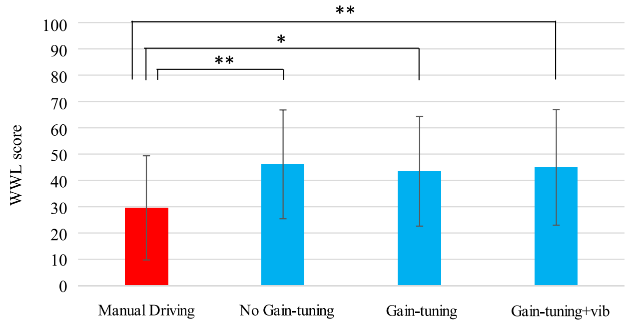


Fig. 11. WWL.

A one-way ANOVA for $G = 0.014$ also revealed the significance of the simple main effect of the method factor $(\mathrm{F}(3, 69) = 107.9, \mathrm{p} = 0.000)$. A post-hoc test implementing the Bonferroni correction for the method factor applying the $\mathrm{G} = 0.014$ condition revealed that the manual driving torque was significantly smaller than that measured during each condition of automated driving $(\mathrm{p} = 0.000$ for Conditions 2–4). In addition, the torque measured during the implementation of the gain-tuning condition was found to be significantly larger than that of the no-gain-tuning condition $(\mathrm{p} = 0.033)$, while the difference between that of the gain-tuning and gain tuning + vibration conditions was only marginally significant $(\mathrm{p} = 0.091)$.

F. Weighted Workload

Fig. 11 shows the mean WWL score, where the error bars indicate the standard deviation. A two-way ANOVA revealed the significance of the main effects of the method $(\mathrm{F}(3, 66) = 10.39, \mathrm{p} = 0.000)$ but not of the gain factor $(\mathrm{F}(1, 22) = 0.831, \mathrm{p} = 0.372)$ or interaction $(\mathrm{F}(3, 66) = 0.874, \mathrm{p} = 0.459)$.

A post-hoc test implementing the Bonferroni correction for the method factor revealed that the WWL for manual driving was significantly smaller than that for each of the automated driving conditions (no-gain-tuning, $\mathrm{p} = 0.003$; gain-tuning, $\mathrm{p} = 0.025$; gain-tuning + vibration, $\mathrm{p} = 0.009$). No significant differences were found between every other pair.

VI. DISCUSSION

A. Steering Operation Stability

The steering angular velocity during manual driving was significantly smaller than that measured during the applied no-gain-tuning condition but not significantly different from that of the gain-tuning and gain tuning + vibration conditions. These results suggest that transfer of control authority to the human can lead to unstable steering irrespective of the driver acknowledging the transfer, and this instability can be eliminated by implementing our proposed gain-tuning method. The tendency of the maximum steering wheel angle supports this. The implementation of vibration was found to yield no significant effects.

B. Vehicular Motion Stability

The results demonstrating that the yaw rate measured during manual driving was significantly smaller than that observed during the implementation of each of the automated driving conditions suggest that control transfer from the ADS to a human driver can lead to vehicular motion that is less stable than that observed during manual driving. Moreover, the results indicating a significantly lower yaw rate during the gain-tuning and gain tuning + vibration implementation than that during the implementation of the no-gain-tuning condition indicate that the utilization of our proposed gain-tuning method decreases this instability. The implementation of vibration was found to yield no significant effects.

C. Driver Workload

The significantly lower driver torque observed during manual driving as compared to that measured during the implementation of each of the automated driving conditions implies that control transfer from the ADS to a human driver can increase the driver load, which is assumed to occur when switching off the lane-keeping function of the ADS. Furthermore, the fact that the torque measured during the gain-tuning trials is significantly larger than that of the no-gain-tuning trials implies that the utilization of our proposed gain-tuning method could increase the load. The reason for this increased load is presumed to be the slower gain change observed in our proposed method. The marginally significant decreases in the torque during the gain tuning + vibration trials with a high gain as compared to that during the gain-tuning trials suggest that the implementation of vibration might have some effect in reducing the driver workload. Vibration is thought to act as a warning signal, and it might lead to this result. However, the other indices do not show any changes when adding vibration. Therefore, this result must be interpreted carefully.

Furthermore, the significantly lower WWL during manual driving as compared to that during the automated driving trials corresponds to the driver torque results.

D. Overall

The results above indicate that transfer of control authority from the ADS to a human driver can degrade the stability of the steering operation and vehicle behaviors in addition to increasing the driver workload relative to the stability observed during manual driving. This finding is in agreement with the results of previous studies [9], [13], which report that unstable driver operation and vehicular motion were observed during or immediately after the transition to manual driving in the case of ADS-initiated transition. Thus, one contribution of this paper is its demonstration of similar unstable operation being found in both ADS- and human-driver-initiated transitions, as is reported in [17].

The main contributions of this paper are as follows. The proposed gain-tuning method with and without vibration increases the steering stability to a level that is comparable to that observed during manual driving, and it significantly improves the vehicle stability relative to that observed without the implementation of the proposed gain-tuning method or without the conventional method.

Many research studies have focused on the driver performance centered around the transition with respect to aspects of cognition or decision-making such as the appropriate timing of RTI issuance to achieve a smooth transition [2], [9], [13] and driver situation awareness [11], [4] in an ADS-initiated transition. Moreover, in terms of operation, the steering wheel angle, pedal operation, or a button are mainly used as the user interface for authority transition [2], while some papers did not mention the method for disengaging the ADS or regaining manual control [16]. In contrast to previous studies, this paper elaborates on the operational level for both ADS- and human-driver-initiated transfers, demonstrating that the implementation of an operational or low-level controller can yield a smoother authority transfer. Note that the authors of [16] also focus on the operational level; however, the focus is on the effects of a change in the mental model of vehicle dynamics that is built in a human driver's central nervous system while using the ADS on the performance in control transitions.

Since HSC and cooperative control can change the control strength, it is expected to be applied to a control law connecting fully automated driving and manual driving. In fact, methods for dynamically changing the control strength have been proposed, such as gain-tuning control methods from the lane-keeping assist system using HSC to manual lane changing by the driver's steering input only [35], [25]. A method to expand haptic guidance to evasive maneuvers for collision avoidance has been proposed by shaping the stiffness including the negative stiffness around the neutral position [36]. However, there is no method for applying such an adaptable feature to a concrete method for control authority transfer between ADSs in Level 2 or 3 in SAE [1] and human drivers. In other words, the contribution of this research is to propose a concrete method for smooth and secure control transfer from an ADS to a human driver by adjusting the strength of HSC by focusing on the readiness at the operational level, which has not attracted much attention so far.

In terms of the workload (WWL), the significant effects of the proposed method were not found. This may be because the instruction to use a button to initiate the shared authority mode to some extent conflicts with the requirement of the experimental scenario, which is initiating a steering action immediately after the transition. A similar authority transfer method as proposed here that does not require button depression has been reported to result in a quicker steering response [17], [31]; this method could be used as a basis to develop a technique to enhance the steering response in our proposed system.

As mentioned, the beep imitated the sudden change in driver intention to exit, which means driver-initiated transfer. However, these results could also be interpreted as a driver reaction to the ADS-initiated transfer because a beep could be also interpreted as an RTI. The differences between these two interpretations should be investigated, including evaluating how human drivers interact with the ADS after extended use of the system. The current study required drivers to look ahead without performing any subtasks. Therefore, the effectiveness of the proposed method when the driver engages subtasks or is distracted should be investigated, which is allowed in the Level 3 driving automation of J3016 [1]. In addition, the driver behavior or methods of interaction with a vehicle should be investigated using the proposed method with a variety of ages and sexes as well as in various scenarios in order to show the robustness of the proposed method.

VII. CONCLUSION

A method to transfer control authority from an ADS to a human driver by using HSC via a shared authority mode to connect automated driving and manual driving has been proposed to realize smooth authority transfer for ADSs. The driving simulator experiment demonstrated that, as compared to manual driving, even as a result of human-driver-initiated transfer, the steering stability and vehicle stability decreased, and the driver workload increased when authority was transferred from automated driving. The instability of the steering angular velocity was improved via the implementation of our proposed gain-tuning method. These results strongly suggest that our proposed authority transfer method for automated-to-manual driving transfer via a shared authority mode yielded an improved stability for steering operation and vehicular motion in driver-initiated transfer.

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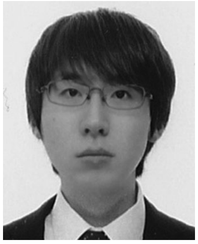

Takahiro Saito received the B.S. degree in engineering from Ritsumeikan University, Kusatsu, Japan, in 2017. Since 2017, he has been working toward the Master's degree at the Human Robotics Laboratory, where he has been a member since 2016. He has studied authority transfer between automated and manual driving via shared authority mode.

Takahiro Wada (M'99) received the B.S. degree in mechanical engineering, the M.S. degree in information science and systems engineering, and the Ph.D. degree in robotics from Ritsumeikan University, Kusatsu, Japan, in 1994, 1996, and 1999, respectively.

In 1999, he became an Assistant Professor with Ritsumeikan University. In 2000, he joined Kagawa University, Takamatsu, Japan, as an Assistant Professor with the Department of Intelligent Mechanical Systems Engineering as a faculty of engineering. He was promoted to Associate Professor in 2003. He has been a Full-Time Professor with the College of Information Science and Engineering, Ritsumeikan University, since 2012. In 2006 and 2007, he spent half a year with the University of Michigan Transportation Research Institute, Ann Arbor, MI, USA, as a Visiting Researcher. His current research interests include robotics, human machine systems, and human modeling. He is also interested in rehabilitation robotics, automotive safety via driver assistance systems, and various other areas of human–machine physical interactions.

Dr. Wada is a Member of the IEEE Intelligent Transportation Systems Society, the IEEE Systems, Man, and Cybernetics Society, the IEEE Engineering in Medicine and Biology Society, the IEEE Robotics and Automation Society, the Human Factors and Ergonomics Society, the Robotics Society of Japan, the Society of Automotive Engineers of Japan (JSAE), the Society of Instrument and Control Engineers, and the Japan Society of Mechanical Engineers. He was the recipient of the Best Paper Award from JSAE in 2008 and 2011 and the Outstanding Oral Presentation from the Society for Automotive Engineers in 2010, among other awards.

Kohei Sonoda received the Ph.D. degree in science from Kobe University, Kobe, Japan, in 2011. He is a Postdoctoral Fellow with the Human Robotics Laboratory, Ritsumeikan University, Kusatsu, Japan. His research interests include affordance and haptic shared control in driving assistance systems.