Received 5 July 2022, accepted 6 August 2022, date of publication 10 August 2022, date of current version 19 August 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3197885

RESEARCH ARTICLE

Does Shared Mode Improve Steering and Vehicle Motions During Control Transition From Automated to Manual Driving in Real Passenger Car?

KOHEI SONODA[1], KIO OKADA[1], KENJI SATO[2], GENYA ABE[2], AND TAKAHIRO WADA[1,3], (Member, IEEE)

[1]Graduate School of Information Science and Engineering, Ritsumeikan University, Kusatsu, Shiga 525-8577, Japan
[2]Japan Automobile Research Institute, Tsukuba, Ibaraki 305-0822, Japan
[3]Division of Information Science, Nara Institute of Science and Technology, Takayama, Ikoma, Nara 630-0192, Japan

Corresponding author: Takahiro Wada (t.wada@is.naist.jp)

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ritsumeikan University Ethics Review Committee for Medical and Health Research Involving Human Subjects, as well as the JARI Ethics Review Committee.

ABSTRACT Drivers occasionally need to resume vehicle control when an automated driving system (ADS) cannot handle a situation. However, a lack of driver readiness can prevent a smooth transition. For example, in an obstacle avoidance situation, a method to transfer the vehicle control based on the driver's input of the steering angle can be adopted where rapid steering operation by the driver is required immediately after resuming control. It was observed from the previous studies based on a fixed-based driving simulator that the discontinuity in control due to a sudden disengagement of the control torque of the ADS resulted in steering instability. In addition, the previous studies had proposed a shared mode, in which haptic shared control (HSC) was placed between the automated and manual driving. It was demonstrated that steering stability could be improved through the shared mode. However, in the previous studies, the observation of steering instability and verification of HSC effectiveness of the shared mode were limited to fixed-based driving simulator experiments, in which there was no vehicle motion. In addition, for practical applications, a method using a torque sensor in the previous method is expected to be replaced by a more robust method, because it may introduce noise and the use of a lowpass filter leads to some time lag. Therefore, in this study, we developed a new control transition method that uses only the steering angle. We conducted experiments using a real car, in which the participants were instructed to resume steering control from the automated driving mode. The results demonstrate that the discontinuity in control during the control transition deteriorates the steering stability and vehicle motion, and the shared mode can improve them.

INDEX TERMS Automated vehicles, control transition, haptic shared control, shared mode.

I. INTRODUCTION

The development of automated driving (AD) technology has been actively conducted worldwide. Various types of automated driving systems (ADSs), including those assumed to interact with human drivers, are considered because it is difficult to produce a system that works appropriately in various situations. For example, in Level 3 driving automation by the Society of Automotive Engineers (SAE) [1], the driver is expected to resume vehicle control when necessary. Many human factor studies related to AD have been conducted to address the concern regarding humans being able to respond appropriately when they have not been driving, and control needs to transition from AD to manual.

The associate editor coordinating the review of this manuscript and approving it for publication was Xiaojie Su.

Control transfer from AD to manual driving is classified into user-initiated and system-initiated transitions [2], [3]. A user-initiated transition occurs when the driver decides to assume driving control upon detecting the silent failure of the automated system or because of other reasons. System-initiated transition is triggered by the ADS's request to intervene (RTI), and the driver is expected to assume control. Research on a series of driver behaviors, starting from RTI, is necessary for safe and smooth control transition because intervention may be requested at unintended times by the vehicle.

We focus on the system-initiated control transition because driver reaction to the RTI significantly affects driving safety during and after the control transition. Let us consider the general process of system-initiated control transition. When the ADS decides to hand over control to the driver for any reason, it issues an RTI to the driver via auditory, visual, and/or other signals. After the driver notices it, he/she regains the driving posture and gathers information from the surrounding traffic environment to gain appropriate situation awareness. Then, after the driver judges that he or she is ready to drive, the driver expresses his/her intent to start driving to the ADS by either pushing a button, turning a steering wheel, pushing a pedal, or an alternative method, which triggers the ADS to transfer control to the driver. Then, the ADS turns off the automated vehicle control to enter the manual driving mode.

Many studies have been conducted on reaction time to RTI and subsequent driving behavior because it is necessary for drivers to notice the issuance of an RTI and respond to it appropriately within a certain time to ensure safety. [4], [5], [6], [7], [8], [9], [10], [11], [12]. Such research studies include vibration or other multimodal RTIs to reduce reaction time and improve situation awareness and trust [13], [14], [15], [16]. Furthermore, there are studies related to the judgment of the appropriate timing of control transfer to manual driving based on the estimation of the driver's controllability or readiness for driving [17], [18].

Even after a driver judges oneself as ready to drive, he/she may not immediately be an effective controller. Namely, there are some difficulties in the control transition related to the human motor control aspect. For example, studies have suggested that the accuracy of visually perceived velocity deteriorates during AD [19] and the drivers' mental models for the vehicle may not be appropriately selected during AD [20]. In addition, some research studies suggest that disengagement of the ADS control results in discontinuity of control. Furthermore, it was observed from the previous studies employing fixed-based driving simulators that steering and vehicle instability occurred immediately after the control transition from AD to fully manual driving when the transition was triggered by the driver's steering input [21], [22]. To overcome such difficulties in the human motor control aspect, a method that places a shared mode between the fully AD and fully manual driving, wherein a human and vehicle drive together, has been proposed [21], [22], [23], [24], [25]. Haptic shared control (HSC) is utilized in the shared authority mode [26], [27], [28], [29], [30] wherein the human and ADS exert force/torque on a single input device, such as the steering wheel, to achieve a collaboration between the two agents. The HSC achieves a smooth control transition from the automated to manual driving at the human motor control level by gradually reducing the strength of the ADS control. Studies employing the fixed-based driving simulators have demonstrated that the control transition method based on the shared authority mode using the HSC could improve the steering and vehicle stability on a straight highway [21] and curved road [22].

However, the observation of the steering and vehicle instabilities and the effectiveness of the shared mode in reducing the instability have been limited to the fixed-based driving simulator experiments. For a better understanding of the influence of the control transition method on motion control performance, such as steering stability and vehicle stability, it is essential to evaluate it as a human–vehicle system based on the reaction of the driver under the influence of vehicle motion with a real passenger car. In addition, in previous research, the steering torque signal as well as the steering wheel angle was used for control transition with the shared authority mode. For practical applications in a real vehicle, the method using a torque sensor in the previous study is expected to be replaced by a more robust method, because it may introduce noise and the use of a lowpass filter leads to some time lag. Therefore, we developed a simpler alternative method that uses only the steering angle. The proposed method was implemented in a passenger car, and experiments were conducted with participants to investigate its effectiveness.

Therefore, the purpose of this study was to confirm the effect of the control transition from automated to manual driving, triggered by the driver's steering operation, on the steering and vehicle motions, and to verify the effectiveness of the proposed shared mode without any torque sensors for control transition in a real passenger car on a test track.

The remainder of this paper is organized as follows. Section II describes the proposed control transfer method from automated to manual driving based on the shared authority mode. Section III presents the experimental method to investigate the effectiveness of the proposed method. Section IV presents the results. Section V presents the discussion of the results. Finally, the paper is concluded in Section VI.

II. CONTROL TRANSFER METHOD TRIGGERED BY STEERING INTERVENTION

A. OVERVIEW

The present study considered a situation wherein steering control is transferred from the ADS to manual driving by human steering action when rapid steering is required. In some cases, the control transition to manual driving can be triggered by operating pedals or buttons. However, there are cases in which the driver wants to trigger the control transition

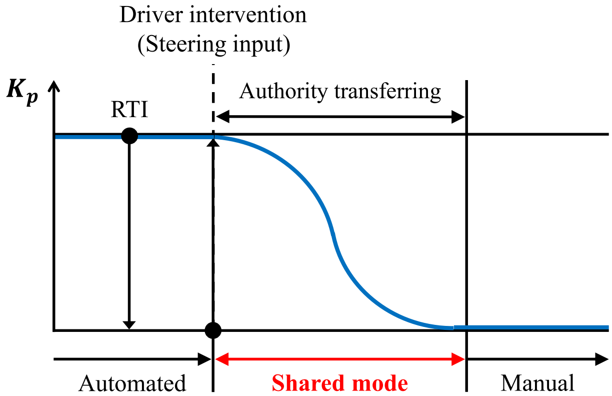

FIGURE 1. Conceptual diagram of the control transfer method via shared mode. The vertical axis, the gain K_p, denotes the strength of the automated vehicles. The gain is tuned in the shared mode to achieve a smooth connection between the automated and manual modes.

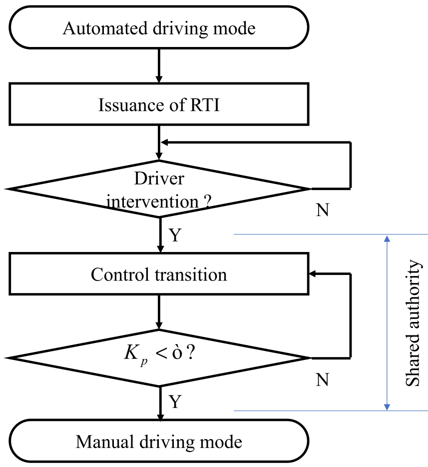

FIGURE 2. Flowchart of the proposed method for control transfer.

by operating a steering wheel when rapid steering is needed, which can deteriorate the steering stability. Therefore, the present research focuses on the cases wherein the steering operation triggers the control transition. If a driver's steering intervention deviates from the desired steering angle of the ADS, the ADS torque is applied in the opposite direction of the driver's steering action. In such situations, the sudden disengagement of the ADS may cause control discontinuity and steering instability [21]. Judgment of the driver's intent to intervene at an earlier stage, when the driver steering input is small, could be one solution to this problem. However, this may cause false detection of the intervention intention and lead to an unexpected control transition. An intermediate state could be produced between fully automated and fully manual driving using the shared mode proposed in [21].

A schematic and flowchart of the method for the transfer of steering control from AD to manual driving via the shared mode are shown in Figs. 1 and 2, respectively. First, we assume that the vehicle is driven by the ADS without any human intervention. Thereafter, we suppose that the ADS encounters a situation to which it cannot respond, such as an obstacle appearing in front of the vehicle, and issues an RTI. Hence, the driver needs to intervene immediately after the RTI is issued. With this method, when the driver intervenes in the ADS operation by using the steering wheel, the system shifts from AD mode to shared authority mode. The strength of the control gradually decreases in shared authority mode and finally shifts to manual driving mode when the strength is sufficiently close to zero.

B. STEERING CONTROL OF THE ADS

We assume the ADS employs a proportional-differential (PD) controller as the lateral controller to maintain the lane, expressed as [21]:

$$\tau_{ads} := -K_p(\theta(t) - \theta_d(t)) - K_d\dot{\theta}(t), \tag{1}$$

where τ_{ads} denotes the torque exerted on the steering shaft by the ADS. Scalars $\theta(t)$ and $\theta_d(t)$ are the current values of the steering angle and its desired value determined by the ADS to track the vehicle trajectory, respectively.

C. DETECTION OF THE DRIVER INTERVENTION INTENTION

The driver's intention to intervene in the steering operation is determined by the following inequality:

$$\int_{t_{RTI}}^{t} \theta(\tau)d\tau \geq W_0 \quad \text{or} \quad \int_{t_{RTI}}^{t} \theta(\tau)d\tau \leq -W_0, \tag{2}$$

where t_{RTI} denotes the time at which the RTI was issued. The threshold $W_0 = 32[\deg \cdot s]$ was chosen based on trial and error, such that when the driver rotated the steering wheel to take over the ADS control and change the lane, the ADS would neither interfere with the steering action of the driver nor decrease the steering smoothness. When inequality (2) is satisfied, the driving mode is changed from automated to shared authority.

Note that torque and angle sensors were used in previous studies [21], [28], whereas only the angle sensor is used in the present study.

D. CONTROL TRANSFER METHOD USING GAIN TUNING

When inequality (2) is satisfied, the system enters the authority sharing mode. In this mode, the control strength of the ADS, or K_p in (1), decreases smoothly based on the gain adjustment method, expressed as:

$$\frac{dK_p}{dt} := -G \cdot \mathrm{sgn}(K_p(t))|K_p(t)|^p, \tag{3}$$

where $p = 0.5$ is used such that the gain K_p converges to zero within a finite time [31]. Note that the time course of the gain K_p is determined only by time because (3) does not include any parameters related to the driver actions, such as steering angle or torque, and K_p converges to zero in 0.85 s.

III. EXPERIMENTAL METHOD

A. PARTICIPANTS

Twelve licensed drivers (ten men and two women) aged between 26 and 58 years (average = 40.0, SD = 8.9) participated in the experiment. Their driving experience ranged from 8 to 40 years (average = 20.8, SD = 9.1) and annual mileage from 150 to 30000 km (average = 9596, SD = 8273). All participants were employees of the Japan Automobile Research Institute (JARI) and received no financial compensation.

B. EXPERIMENTAL VEHICLE

The experimental vehicle was a commercially available minivan that was converted to drive with the AD mode in longitudinal and lateral directions, as shown in Fig. 3.

Vehicle trajectory control is achieved in ADS with steering control (1), in which the desired steering angle is determined so that the vehicle follows the desired path. This is based on the relationship between a given desired vehicle path, which is described in advance in terms of the earth-fixed coordinate system, and the current vehicle position and orientation. The vehicle position was estimated using the measured signal of velocity and yaw rate of the vehicle from real-time kinematic global navigation satellite system (RTK-GNSS) positioning information.

The following safety measures were configured for the experimental vehicle. First, the driver's operation of the brake pedal immediately deactivated the ADS and the driver could drive the vehicle in full manual driving mode under any circumstance. Second, pushing the emergency button, which was directly connected to the ECU, immediately deactivated the ADS to enable full manual driving. Third, an emergency auxiliary brake was installed in the rear passenger seat where the experimenter was seated, enabling the experimenter to activate the vehicle's brake regardless of the activation state of the ADS.

FIGURE 3. A photograph of the experimental vehicle.

During the AD mode, the vehicle was operated as a Level 3 driving automation of SAE J3016 (2016), in which the longitudinal and lateral directions of the vehicle were entirely controlled by automation. The participant was instructed not to grasp the steering wheel and not to step on the brake or acceleration pedals during the AD mode. The participants were also not required to monitor the road ahead during this mode while no subtasks or mental tasks were given explicitly. The velocity of the vehicle in the ADS was set to 30 km/h.

C. EXPERIMENTAL COURSE

The experiment was conducted at a test course called the V2X urban area in JARI, as shown in Fig. 4. The measurement driving trial started from the point depicted as "1" in Fig. 4, continued in the numerical order, and then returned to 1.

The driving test was conducted as follows: 1) begin the trial from 1 in manual mode; 2) drive manually through a circumferential road 2; 3) stop at point 3; 4) after activating the ADS, restart to drive through road 4; 5) RTI is issued around 5; 6) driver intervenes through steering action to change lanes to avoid collision with obstacles, which changes the mode to shared authority mode; and finally, 7) the control authority is entirely transferred to the human driver to reach the manual driving mode, and the trial is ended at the starting point 1.

Here, Fig. 5 shows an enlarged view of points 3 to 7 from Fig. 4. Light-emitting objects imitating an obstacle were placed on the surface of the road and appeared in the same lane where the participant drove the vehicle at 30 km/h in the AD mode. Next, the ADS issued an RTI to request the driver to take over the control. The driver grasped the steering wheel and steered to change lanes to avoid collisions with the obstacles.

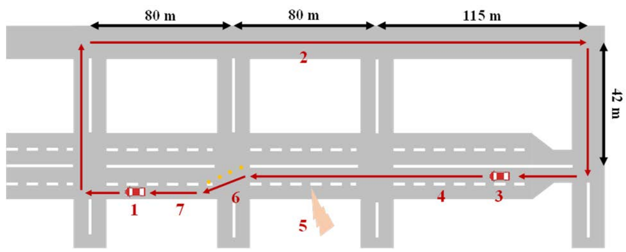

FIGURE 4. Experimental course. 1: Start, 2: Long, straight with manual driving, 3: Stop and restart to activate ADS, 4: Automated driving, 5: RTI issued, 6: Steering intervention by driver to change lane, 7: Manual driving.

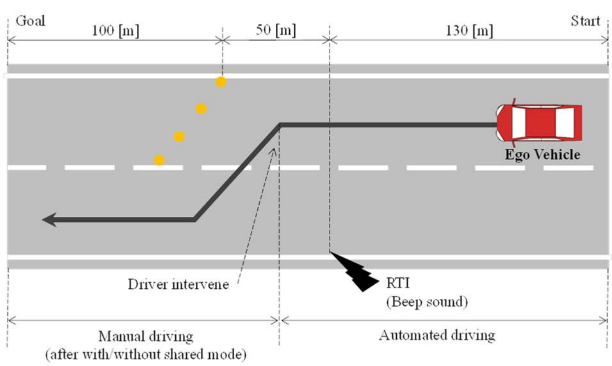

FIGURE 5. Enlarged view of the experimental course showing the control transition area details.

The time required for each trial was approximately 2 min. Signboards were installed to make it easier for the drivers to understand where to turn and stop. The traffic lights on the test course were deactivated throughout the experiments.

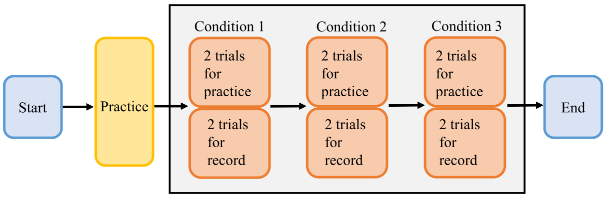

FIGURE 6. Diagram of the experimental procedure.

D. EXPERIMENTAL FACTOR

The driving method was considered as the main factor in the experiment. The experiment employed a within-subject design, in which each participant experienced the following three driving methods:

1) manual driving, in which the participants manually drove the vehicle throughout the test course,
2) without shared mode, in which the ADS suddenly deactivated when the participant intervened, and
3) with shared mode, in which the proposed method of control transition with the shared authority mode was used.

E. EXPERIMENTAL PROCEDURE

Here, Fig. 6 illustrates the experimental procedure. First, the participants were informed about the experimental conditions and procedures, which were approved by the Ritsumeikan University Ethics Review Committee for Medical and Health Research Involving Human Subjects and the JARI Ethics Review Committee.

Then, the participants provided written informed consent and answered a questionnaire regarding age, driving history, and driving frequency. The participants then rode in the experimental vehicle and drove on the test course twice to become accustomed to the experimental course, operation of the vehicle, and methods to activate and deactivate the ADS. Subsequent experiments were divided into blocks corresponding to the three levels of the experimental factor, and the order of each level was changed for each subject to ensure counterbalance. Each block or condition consisted of two trials for practice, followed by two additional trials for measurement. The participants were not informed whether the control method they were using was with shared or without shared mode.

F. EVALUATION METHOD

The maximum value of the steering angle and root mean square (RMS) value of the steering angular velocity were used as evaluation indices of steering stability. The RMS values of the yaw rate and lateral acceleration of the vehicle were used as indices of the rapidness of vehicle motion, and the RMS value of the driver torque was used as the index of the driver load. The indices related to the steering stability and rapidness of vehicle motion were evaluated 2 s from the start of the shared authority mode. The index of the driver load was evaluated from the time when the driver torque first exceeded 0.2 Nm to the time when it became less than 0 Nm in order to analyze the torque data from the instant when the counterclockwise turning of the steering began to the instant when the clockwise turning of the steering began.

IV. EXPERIMENTAL RESULTS

A. TIME SERIES DATA

Fig. 7 shows the time series signals of the control gain, steering angle, steering angular velocity, vehicle yaw rate, lateral acceleration, and torque applied to the steering for each condition for each participant, in the order from the top. Note that the vehicle yaw angle and lateral acceleration were measured by the inertial measurement unit sensors attached to the vehicle, that is, the signals were expressed in the vehicle-fixed coordinate system. Each row illustrates the results with manual, without shared, and with shared modes from the left column.

The time series data of the vehicle yaw rate were calculated using the time differentiation of the yaw angle, which was derived from the position measured from two RTK-GNSSs attached to the front and rear of the vehicle. The filtered value was obtained by applying a moving average filter with a 0.25 s time window.

The blue and red solid lines show the torque exerted on the steering by the driver and ADS, respectively.

B. MAXIMUM STEERING ANGLE

Fig. 8 shows the mean of the maximum steering angle for all subjects for each condition. The error bar shows the standard deviation. One-way analysis of variance (ANOVA) revealed the significance of the main effect of the driving method factors ($F(2, 46) = 77.1$, $p < 0.001$). A post-hoc test implementing the Bonferroni correction revealed that the maximum steering angle of the manual condition was significantly smaller than those of the without shared mode and with shared mode conditions. Additionally, the value observed in the without-shared mode was significantly greater than that observed in the with shared mode, as seen in Table 1.

C. RMS OF STEERING ANGULAR VELOCITY

Fig. 9 shows the mean RMS value of the steering angular velocity for all subjects for each condition. The error bar shows the standard deviation and one-way ANOVA revealed the significance of the main effect of the driving method factors ($F(2, 46) = 160.2$, $p < 0.001$). A post-hoc test implementing the Bonferroni correction revealed that the RMS steering angular velocity of the manual condition was significantly smaller than those of the without-shared and with-shared modes. Additionally, the value observed in the without shared mode was significantly greater than that observed in the with shared mode, as seen in Table 2, thereby demonstrating that the tendency was the same as that for the maximum angle shown in the previous subsection.

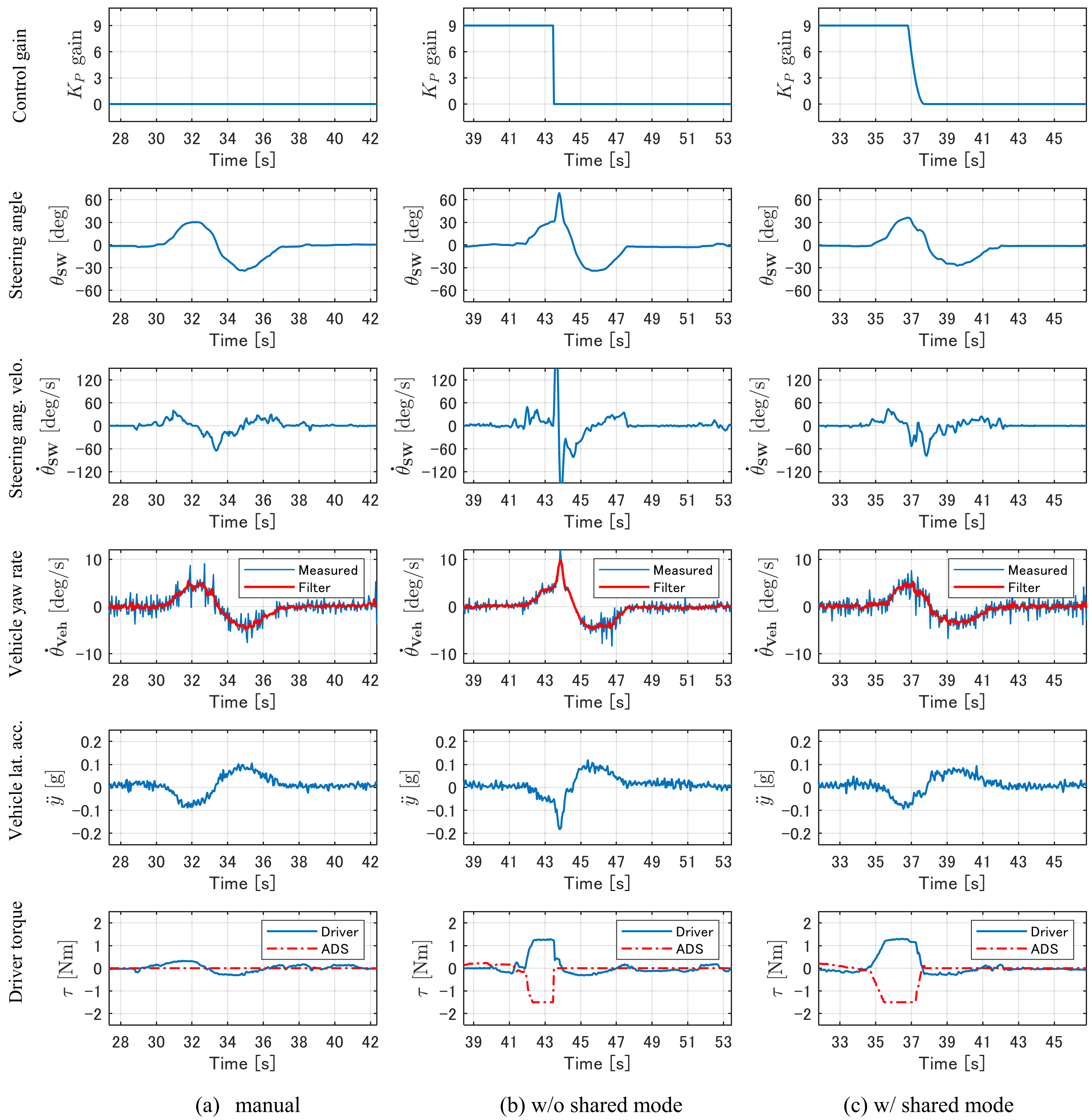

FIGURE 7. Examples of the measured signals under: (a) manual, (b) without shared mode, and (c) with shared mode conditions, extracted from when the participant intervened after the issuance of an RTI.

D. RMS OF VEHICLE YAW ANGULAR VELOCITY

Fig. 10 shows the mean RMS value of the vehicle yaw angular velocity for all subjects for each condition. The error bar shows the standard deviation and one-way ANOVA revealed the significance of the main effect of the driving method factors ($F(2, 46) = 22.2$, $p < 0.001$). A post-hoc test implementing the Bonferroni correction revealed that the RMS vehicle yaw angular velocity without shared mode was significantly larger than those of the manual and shared mode conditions, and no significant difference was observed between the manual and shared mode conditions (Table 3).

E. RMS OF VEHICLE LATERAL ACCELERATION

Fig. 11 shows the mean RMS value of the lateral acceleration of the vehicle over all subjects for each condition.

The error bar shows the standard deviation. One-way ANOVA revealed the significance of the main effect of the driving method factors ($F(2, 46) = 62.2$, $p < 0.001$).

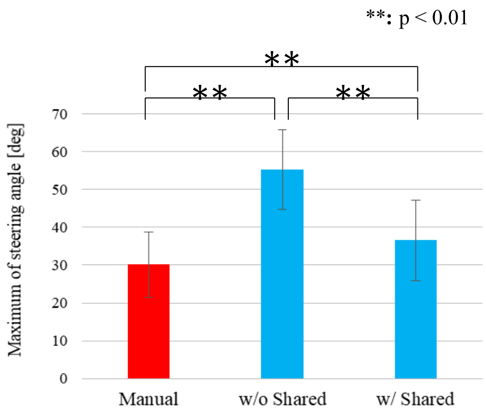

FIGURE 8. Maximum of steering wheel angle.

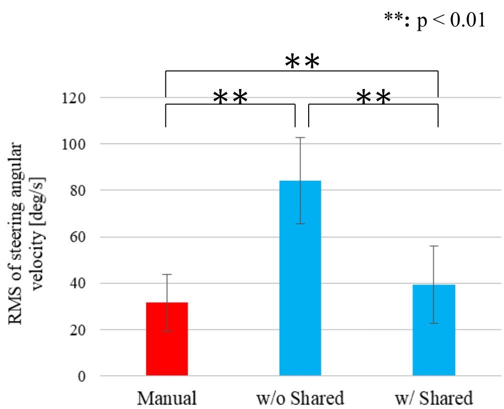

FIGURE 9. RMS of steering wheel angular velocity.

TABLE 1. Differences in maximum steering wheel angle between driving method conditions.

	Manual	w/o shared	w/ shared
Manual	-	-	-
w/o shared	.000**	-	-
w/ shared	.007**	.000**	-

**: p < 0.01, -: not applicable

A post-hoc test implementing the Bonferroni correction revealed that the RMS vehicle lateral acceleration of the without shared mode was significantly larger than those of the manual and shared mode conditions. No significant difference was observed between the manual and shared mode conditions, as shown in Table 4, thereby demonstrating that the tendency was the same as that for the maximum angle shown previously.

F. RMS OF DRIVER TORQUE

Fig. 12 shows the mean RMS value of the driver steering torque over all subjects for each condition and the error bar shows the standard deviation. One-way ANOVA revealed the significance of the main effect of the driving method factors

TABLE 2. Differences in RMS steering angular velocity between driving method conditions.

	Manual	w/o shared	w/ shared
Manual	-	-	-
w/o shared	.000**	-	-
w/ shared	.002**	.000**	-

**: p < 0.01, -: not applicable

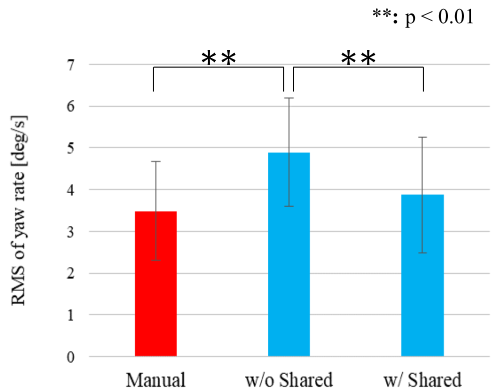

FIGURE 10. RMS of vehicle yaw angular velocity.

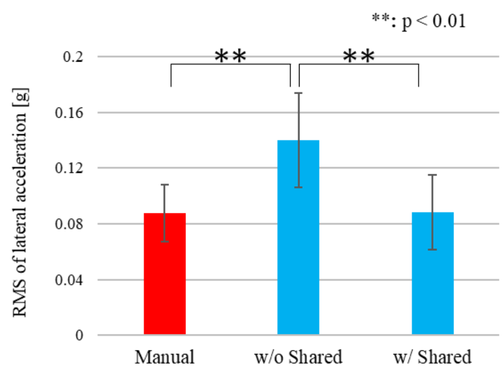

FIGURE 11. RMS of lateral acceleration.

TABLE 3. Differences in RMS vehicle yaw angular velocity between driving method conditions.

	Manual	w/o shared	w/ shared
Manual	-	-	-
w/o shared	.000**	-	-
w/ shared	n.s.	.001**	-

**: p < 0.01, -: not applicable, n.s.: not significant

TABLE 4. Differences in the RMS of lateral acceleration between driving method conditions.

	Manual	w/o shared	w/ shared
Manual	-	-	-
w/o shared	.000**	-	-
w/ shared	n.s.	.000**	-

**: p < 0.01, -: not applicable, n.s.: not significant

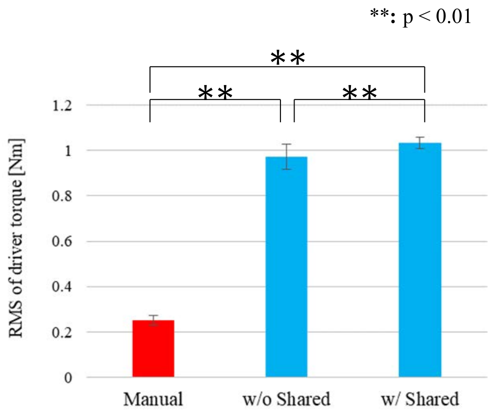

FIGURE 12. RMS of driver torque.

TABLE 5. Differences in the RMS of driver torque between driving method conditions.

	Manual	w/o shared	w/ shared
Manual	-	-	-
w/o shared	.000**	-	-
w/ shared	.000**	.000**	-

**: p < 0.01, -: not applicable, n.s.: not significant

($F(2, 46) = 3448.0$, $p < 0.001$). A post-hoc test implementing the Bonferroni correction revealed that the RMS driver torque of the manual condition was significantly smaller than those of the without shared and shared mode conditions. Additionally, the value observed in the without shared condition was smaller than that observed in the with shared mode condition, as seen in Table 5.

V. DISCUSSION

Many methods of driver intervention to trigger the control transition from automated to manual driving have been studied, including button operation, pedal operation, steering operation, and time from RTI issuance. Intervention by steering operation may be used in situations where immediate steering is required, such as obstacle avoidance. Among them, the present study focused on the control transfer method based on the steering action of the driver. The purpose of the present study was to verify the occurrence of the instabilities in the steering and vehicle motions during control transition by a steering action and the effectiveness of the shared mode as a method to solve the instability of the steering and vehicle motion by using a real passenger car.

The results for the RMS steering angular velocity and maximum steering angle showed that the values were significantly larger in the two conditions with control transfer from the ADS than for manual driving. Additionally, the values were significantly lower in the shared mode than in the without shared mode. These results indicate that the conventional method, in which the ADS immediately disengages the steering control during the transition, causes a decrease in the steering stability when compared with the manual method; however, the introduction of the shared mode can improve the stability.

The results for the yaw rate and lateral acceleration of the vehicle showed that the values were significantly larger for the driving without shared mode than for manual driving and driving with shared mode. Furthermore, no significant difference was observed between the results for manual driving and driving with shared mode. These results strongly suggest that the conventional method, in which the ADS immediately disengages the control during the transition, causes rapid vehicle motion when compared with the manual method; however, the utilization of the shared mode can decrease this phenomenon. The significant increase in the driver torque during the control transfer, with and without shared mode, when compared with manual driving is considered to be due to the torque needed for drivers to compete with the ADS torque until the ADS judges the intent of the intervention.

In summary, we demonstrated through experiments with a real passenger car that instability in steering and rapid vehicle motions could occur when the control transition was made using the conventional method, in which the ADS is immediately disengaged by a steering action, and the shared mode could improve the steering stability. The shared mode reduces the rapidness of vehicle motion, as in manual driving. These tendencies align with the results observed in previous studies employing a fixed-based driving simulator [21], [22] and shared mode for control transition.

In the proposed control transition mode, the time required for the gain K_p to reach 0, that is, the duration of the shared mode, is 0.85 s. However, as seen from Fig. 7 (c), the time series pattern of the steering angle was similar to that in Fig. 7 (a), which is a manual driving case. In Fig. 7 (b), where the automatic control was suddenly cut off, the steering angle pattern was almost the same, including before and after control transition, with the only difference that the steering angular velocity changed significantly when the control was suddenly turned off. These results suggest that the shared mode does not interfere with the human steering operation; however, it has the effect of alleviating the steering instability when the control is cut off. One of the contributions of the present study is that it utilizes the steering angle information but not torque information for judging the driver's intention to intervene and the gain tuning process for control transition, whereas the previous studies [21], [22], [28] had used both the steering angle and driver torque information. Another contribution of the present study is the demonstration of the effectiveness of the shared mode for control transition using a real car driven on a test course, whereas several related works [18], [19], [20], [21] demonstrated their effectiveness only through simulator experiments. In the previous studies [21], [22], [28], the cooperative status between the driver and ADS was determined based on the pseudo-works performed by the driver and ADS on the vehicle, which was calculated using the torques and steering or vehicle velocity. The pseudo-works were used for the judgment of the driver's intention to intervene and gain tuning for the control transition. The present research demonstrates that the proposed method works effectively without a torque sensor.

There exist many possibilities for methods to tune the ADS strength, including immediately disengaging the ADS control, reduction of the control torque over time, and reduction of weighting in the objective function for the optimal regulator with the prediction of driver behavior [21]. A detailed comparison among methods, including the control algorithm and parameters used in the proposed method, should be conducted as future work.

The limitations of the present study are that the proposed method was evaluated at 30 km/h and in a straight line only. Demonstrating that the proposed method was effective at such a low velocity could also be regarded as another contribution of the present study because the simulator experiments of the previous studies [21] assumed driving on an expressway at 80 km/h. However, it is necessary to verify the effectiveness of the proposed method in various scenarios, including various velocity ranges and road shapes such as curved roads [22]. Comparing the performance of the existing control methods in different environments is also an important topic for research. Assuming a case where rapid steering operation is required immediately after RTI, such as when avoiding obstacles, a shared mode has been introduced for solving problems in the control transition from automated driving to manual driving by human steering action. For this reason, the evaluation of the proposed method was limited to the scenario shown in Fig. 5, in which rapid lane changing is required in this paper. Small steering angles are input in cases where a lane change is performed over a long period. In this case, satisfying inequality (2) takes time. Additionally, as pointed out in [22], driver steering behaviors due to different traffic environments during or immediately before the control transition affects the effectiveness of the method. Therefore, for future work, the driver steering behaviors to which the proposed method can be applied must be clarified. In addition, developing a systematic manner to determine the parameter due to the traffic environment must be investigated. Another limitation of this study is that the effect of the mental status of the participants just before and during the control transition was not evaluated. It is known that the operator's mental status just before the control transition significantly affects the quality of the transition [9], [10]. To maintain the mental load as low as possible, no subtask was explicitly given to the participants during the experiment. In addition, because the participants were aware of the point where the RTI would be issued through the practice trials conducted before the measurement trials, it appears that the drivers were prepared for the RTI just before its issuance. Consequently, the participants always focused on the road ahead. Therefore, it is unlikely that there was a large difference in the mental status of the participants. However, in future, the effectiveness of the proposed method under various mental states should be investigated for a better understanding.

VI. CONCLUSION

The purpose of this study was to confirm the effect of the control transition from automated to manual driving triggered by the driver's steering operation on the steering stability and vehicle motion, and the effectiveness of the shared mode in improving the steering stability and vehicle motion in a real passenger car on a test track.

The results of the experiments with participants showed that the conventional method, in which the ADS immediately disengages the steering control during the transition, causes a decrease in the steering and vehicle stabilities when compared with manual driving. However, the control transition method using shared mode improved the steering stability and vehicle motion during the control transition. Thus, the introduction of the shared mode contributes to improving the automotive safety in automated driving systems.

ACKNOWLEDGMENT

The authors would like to thank Hiroki Kawashima of the Japan Automobile Research Institute and also would like to thank Kyohei Yamaguchi and Yuki Yano for their assistance with the experiments.

REFERENCES

[1] *Taxonomy and Definitions for Terms Related to Driving Automation Systems for on-Road Motor Vehicles*, SAE International, Warrendale, WA, USA, 2016.

[2] P. Wintersberger, P. Green, and A. Riener, "Am I driving or are you or are we both? A taxonomy for handover and handback in automated driving," in *Proc. 9th Int. Driving Symp. Hum. Factors Driver Assessment, Training Vehicle Design*, Montpelier, VT, USA, 2017, pp. 333–339, doi: 10.17077/drivingassessment.1655.

[3] Z. Lu and J. C. F. de Winter, "A review and framework of control authority transitions in automated driving," *Proc. Manuf.*, vol. 3, pp. 2510–2517, Jan. 2015, doi: 10.1016/j.promfg.2015.07.513.

[4] M. Blanco, J. Atwood, H. M. Vasquez, and T. E. Trimble, "Human factors evaluation of level 2 and level 3 automated driving concepts," Nat. Highway Traffic Saf. Admin., Washington, DC, USA, Tech. Rep. DOT HS 812 182, 2015. [Online]. Available: http://www.nhtsa.gov/DOT/NHTSA/NVS/CrashAvoidance/TechnicalPublications/2015/812182_HumanFactorsEval-L2L3-AutomDrivingConcepts.pdf

[5] N. Merat, A. H. Jamson, F. C. H. Lai, M. Daly, and O. M. J. Carsten, "Transition to manual: Driver behaviour when resuming control from a highly automated vehicle," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 27, pp. 274–282, Nov. 2014, doi: 10.1016/j.trf.2014.09.005.

[6] B. Mok, M. Johns, K. J. Lee, D. Miller, D. Sirkin, P. Ive, and W. Ju, ''Emergency, automation off: Unstructured transition timing for distracted drivers of automated vehicles,'' in *Proc. IEEE 18th Int. Conf. Intell. Transp. Syst.*, Sep. 2015, pp. 2458–2464, doi: 10.1109/ITSC.2015.396.

[7] S. S. Borojeni, L. Chuang, W. Heuten, and S. Boll, ''Assisting drivers with ambient take-over requests in highly automated driving,'' in *Proc. 8th Int. Conf. Automot. User Interfaces Interact. Veh. Appl.*, Lansing, MI, USA, Oct. 2016, pp. 237–244, doi: 10.1145/3003715.3005409.

[8] V. Melcher, S. Rauh, F. Diederichs, H. Widlroither, and W. Bauer, ''Take-over requests for automated driving,'' *Proc. Manuf.*, vol. 3, pp. 2867–2873, Jul. 2015, doi: 10.1016/j.promfg.2015.07.788.

[9] K. Zeeb, A. Buchner, and M. Schrauf, ''Is take-over time all that matters? The impact of visual-cognitive load on driver take-over quality after conditionally automated driving,'' *Accident Anal. Prevention*, vol. 92, pp. 230–239, Jul. 2016, doi: 10.1016/j.aap.2016.04.002.

[10] A. Eriksson and N. A. Stanton, ''Takeover time in highly automated vehicles: Noncritical transitions to and from manual control,'' *Hum. Factors*, vol. 59, no. 4, pp. 689–705, Jan. 2017, doi: 10.1177/0018720816685832.

[11] P. Wintersberger, D. Dmitrenko, C. Schartmüller, A.-K. Frison, E. Maggioni, M. Obrist, and A. Riener, ''S(C)ENTINEL: Monitoring automated vehicles with olfactory reliability displays,'' in *Proc. 24th Int. Conf. Intell. User Interfaces*, Los Angeles, CA, USA, Mar. 2019, pp. 538–546, doi: 10.1145/3301275.3302332.

[12] W. Morales-Alvarez, O. Sipele, R. Léberon, H. H. Tadjine, and C. Olaverri-Monreal, ''Automated driving: A literature review of the take over request in conditional automation,'' *Electronics*, vol. 9, no. 12, p. 2087, Dec. 2020, doi: 10.3390/electronics9122087.

[13] S. Petermeijer, P. Bazilinskyy, K. Bengler, and J. de Winter, ''Take-over again: Investigating multimodal and directional TORs to get the driver back into the loop,'' *Appl. Ergonom.*, vol. 62, pp. 204–215, Jul. 2017, doi: 10.1016/j.apergo.2017.02.023.

[14] K. Sonoda and T. Wada, ''Displaying system situation awareness increases driver trust in automated driving,'' *IEEE Trans. Intell. Vehicles*, vol. 2, no. 3, pp. 185–193, Sep. 2017, doi: 10.1109/TIV.2017.2749178.

[15] A. Telpaz, B. Rhindress, I. Zelman, and O. Tsimhoni, ''Haptic seat for automated driving: Preparing the driver to take control effectively,'' in *Proc. 7th Int. Conf. Automot. User Interfaces Interact. Veh. Appl.*, Nottingham, U.K., Sep. 2015, pp. 23–30, doi: 10.1145/2799250.2799267.

[16] S. M. Petermeijer, S. Cieler, and J. C. F. de Winter, ''Comparing spatially static and dynamic vibrotactile take-over requests in the driver seat,'' *Accident Anal. Prevention*, vol. 99, pp. 218–227, Feb. 2017, doi: 10.1016/j.aap.2016.12.001.

[17] J. Nilsson, P. Falcone, and J. Vinter, ''Safe transitions from automated to manual driving using driver controllability estimation,'' *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 4, pp. 1806–1816, Aug. 2015, doi: 10.1109/TITS.2014.2376877.

[18] M. Kaustubh, D. Willemsen, and M. Mazo, ''The modeling of transfer of steering between automated vehicle and human driver using hybrid control framework,'' in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Gothenburg, Sweden, Jun. 2016, pp. 808–814, doi: 10.1109/IVS.2016.7535480.

[19] C. Mole, G. Markkula, O. Giles, Y. Okafuji, R. Romano, N. Merat, and R. Wilkie, ''Drivers fail to calibrate to optic flow speed changes during automated driving,'' in *Proc. 10th Int. Driving Symp. Hum. Factors Driver Assessment, Training Vehicle Design: Driving assessment*, Des Moines, IA, USA, Jun. 2019, pp. 113–119.

[20] H. E. B. Russell, L. K. Harbott, I. Nisky, S. Pan, A. M. Okamura, and J. C. Gerdes, ''Motor learning affects car-to-driver handover in automated vehicles,'' *Sci. Robot.*, vol. 1, no. 1, Dec. 2016, Art. no. eaah5682, doi: 10.1126/scirobotics.aah5682.

[21] T. Saito, T. Wada, and K. Sonoda, ''Control authority transfer method for automated-to-manual driving via a shared authority mode,'' *IEEE Trans. Intell. Veh.*, vol. 3, no. 2, pp. 198–207, Jun. 2018, doi: 10.1109/TIV.2018.2804167.

[22] K. Okada, K. Sonoda, and T. Wada, ''Transferring from automated to manual driving when traversing a curve via haptic shared control,'' *IEEE Trans. Intell. Vehicles*, vol. 6, no. 2, pp. 266–275, Jun. 2021, doi: 10.1109/TIV.2020.3018753.

[23] T. Wada and R. Kondo, ''Shared authority mode: Connecting automated and manual driving for smooth authority transfer,'' in *Proc. Symp. Future Act. Saf. Technol. Toward Zero Traffic Accident (FAST-Zero)*, Nara, Japan, 2017, pp. 1–5.

[24] R. Kondo, T. Wada, and K. Sonoda, ''Use of haptic shared control in highly automated driving systems,'' in *14th IFAC/IFIP/IFORS/IEA Symp. Anal., Design, Eval. Human Mach. Syst.*, Tallinn, Estonia, 2019, vol. 52, no. 19, pp. 43–48.

[25] J. Ludwig, A. Haas, M. Flad, and S. Hohmann, ''A comparison of concepts for control transitions from automation to human,'' in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Miyazaki, Japan, Oct. 2018, pp. 3201–3206, doi: 10.1109/SMC.2018.00542.

[26] P. G. Griffiths and R. B. Gillespie, ''Sharing control between humans and automation using haptic interface: Primary and secondary task performance benefits,'' *Hum. Factors*, vol. 47, no. 3, pp. 574–590, 2005, doi: 10.1518/001872005774859944.

[27] D. A. Abbink, M. Mulder, and E. R. Boer, ''Haptic shared control: Smoothly shifting control authority?'' *Cogn. Technol. Work*, vol. 14, no. 1, pp. 19–28, Nov. 2012, 10.1007/s10111-011-0192-5

[28] R. Nishimura, T. Wada, and S. Sugiyama, ''Haptic shared control in steering operation based on cooperative status between a driver and a driver assistance system,'' *J. Hum.-Robot Interact.*, vol. 4, no. 3, pp. 19–37, Mar. 2015, doi: 10.5898/4.3.Nishimura.

[29] F. Flemisch, D. Abbink, M. Itoh, M.-P. Pacaux-Lemoine, and G. Weßel, ''Shared control is the sharp end of cooperation: Towards a common framework of joint action, shared control and human machine cooperation,'' *IFAC-PapersOnLine*, vol. 49, no. 19, pp. 72–77, 2016, doi: 10.1016/j.ifacol.2016.10.464.

[30] S. Cutlip, Y. Wan, N. Sarter, and R. B. Gillespie, ''The effects of haptic feedback and transition type on transfer of control between drivers and vehicle automation,'' *IEEE Trans. Human-Mach. Syst.*, vol. 51, no. 6, pp. 613–621, Dec. 2021, doi: 10.1109/THMS.2021.3107255.

KOHEI SONODA received the Ph.D. degree in science from Kobe University, Japan, in 2011. He is currently an Assistant Professor with the College of Information Science and Engineering, Ritsumeikan University, Japan. His research interests include affordance and haptic shared control in driving assistance systems.

KIO OKADA received the B.S. and M.S. degrees in engineering from Ritsumeikan University, Japan, in 2019 and 2021, respectively. He was a member of the Human Robotics Laboratory, Ritsumeikan University. His research interest includes automotive safety in driving assistance systems.

KENJI SATO received the B.S. degree in mechanical engineering from Tokai University, Kanagawa, Japan, in 2009. He has been a Researcher with the Japan Automobile Research Institute, Tsukuba, Japan, since 2009.

GENYA ABE received the B.S. degree in mechanical engineering from Mie University, Tsu, Japan, in 1997, the M.S. degree in information systems from the University of Electro-Communications, Chofu, Japan, in 1999, and the Doctor degree in human sciences from Loughborough University, Loughborough, U.K., in 2005. Since 1999, he has been a Researcher with the Japan Automobile Research Institute, Tsukuba, Japan. His research interests include understanding driver's trust in advanced driver assistance systems and automated driving systems.

TAKAHIRO WADA (Member, IEEE) 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, Japan, in 1994, 1996, and 1999, respectively. In 1999, he became an Assistant Professor at Ritsumeikan University. In 2000, he joined the Department of Intelligent Mechanical Systems Engineering, Faculty of Engineering Kagawa University, Takamatsu, Japan, as an Assistant Professor. He was promoted to an Associate Professor, in 2003. He joined the College of Information Science and Engineering, Ritsumeikan University, in 2012, as a Full Professor. Since 2021, he has been a Full Professor and the Director of the Human Robotics Laboratory, Division of Information Science, Nara Institute of Science and Technology (NAIST), Japan. In 2006 and 2007, he spent half a year at the University of Michigan Transportation Research Institute, Ann Arbor, as a Visiting Researcher. His current research interests include robotics, human–machine systems, and human modeling. He is a member of ITSS, SMC, EMBS, and RAS, the Robotics Society of Japan (RSJ), the Society of Automotive Engineers of Japan (JSAE), the Society of Instrument and Control Engineers (SICE), and the Japan Society of Mechanical Engineers (JSME). He received the Best Paper Award from JSAE, in 2008 and 2011, and the Outstanding Oral Presentation from the Society for Automotive Engineers (SAE), in 2010.