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A Study on Shared Control between the Driver and an Active Steering Control System in Emergency Obstacle Avoidance Situations

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Abstract: Recently, automatic steering systems for emergency obstacle avoidance have been studied extensively. The control input of such active steering control systems can be classified into the steering angle and the steering torque input. The steering torque based control provides some degree of freedom for drivers to control the vehicle motion, thus it has potential for development as steering assistance system. This paper describes the evaluation of shared control characteristics between human drivers and the active steering system for obstacle avoidance assistance system based on steering torque input. The shared control characteristics between the driver and the active steering system are investigated by using the driving simulator reconstructing a dangerous scenario.

Keywords: Automobile, Collision Avoidance, Active Steering System, Shared Control, Driving Simulator

1. INTRODUCTION

Recently, automatic steering systems for emergency obstacle avoidance have been studied extensively in order to reduce collision accidents (Keller et al., 2011, and Isermann et al., 2008). Among these contributions, there is a research issue how the autonomous steering assistance function should be designed in order to get good acceptance from the human driver when both human and machine conduct the driving task simultaneously.

There is a report that more than fifty percent of drivers use a steering manoeuvre to avoid collisions in emergency situations (Lechner, et al., 1991). However, the control effect on the driving characteristics of the driver when both the driver and the active steering system conduct the avoidance manoeuvre simultaneously has not been clarified. In addition, there is a possibility of false-positive steering intervention in the case of an autonomous steering system and the interaction between the system and the human driver needs to be investigated (Braeuchle, et al., 2013). Therefore, from the viewpoint of man-machine system, it is essential to investigate the shared control law for enhancing the collision avoidance performance while minimizing the conflicts between the control action of the driver and the system and ensuring the driver acceptance when the control intervention is conducted.

This study investigates the shared control characteristics between the driver and the active steering control system for collision avoidance assistance by using the driving simulator reconstructing a critical scenario that the obstacle suddenly appears from occlusions. From the viewpoint of human-machine interface, there is a report that the steering torque control provides some degree of freedom in permitting the driver to steer the vehicle (Nagai, et al., 2002). Therefore, the active steering control for collision avoidance assistance is designed based on the steering torque input, which enables the driver to perform an override manoeuver. This paper examines the effectiveness of the active steering system for collision avoidance assistance on the driver-vehicle system among different level of the steering intervention by using the driving simulator.

The rest of the paper is organized as follows. Section 2 describes the design of the active steering system for collision avoidance based on the steering torque input. Section 3 describes the experimental setup of the driving simulator experiments to examine the effectiveness of the system. Section 4 shows the results obtained from the driving simulator study, followed by Section 5 discussing the shared control characteristics of the system and the driver. Finally, Section 6 summarizes the major understandings and findings obtained from the study.

2. COLLISION AVOIDANCE STEERING ASSISTANCE SYSTEM DESIGN

Figure 1 shows the block diagram of the collision avoidance steering assistance system with the steering torque as an input.

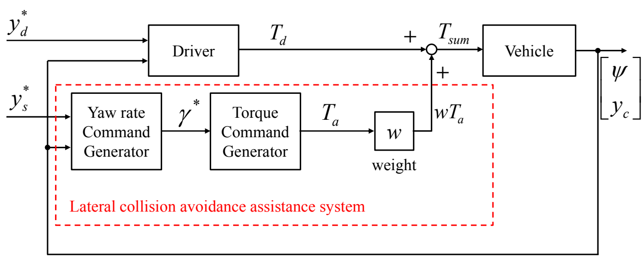


Fig. 1. Block diagram of the collision avoidance steering assistance system with the steering torque input.

If the system detects an obstacle ahead and finds that the collision cannot be avoided by braking only, the assistance system actively changes its driving lane to avoid collision with the obstacle based on the assumption that there is no object existing in the adjacent lane. The system is composed of the yaw rate command generator, the steering torque command generator, and the weighting coefficient to determine the intervention level of the steering assistance.

2.1 Yaw rate command generator

Figure 2 shows the description of the planar motion of the vehicle in the earth-fixed coordinate system. Here, the desired yaw rate γ^* as a path generation is calculated based on the preview control, as similar to the general look-ahead driver model (Kondo et al., 1968).

By assuming that the yaw rate is proportional to the lateral deviation of preview point, the relationship between the yaw rate and the lateral deviation of preview point can be expressed as follows:

$$\gamma = k\left(y_s^* - y_s\right) = k\left\{y_s^* - \left(y_c + l_s\psi\right)\right\}\ , \tag{1}$$

where, γ indicates the yaw rate, k indicates the gain factor, y_s^* indicates the desired lateral displacement of preview point, y_s indicates the lateral displacement of preview point, y_c indicates the lateral displacement of centre, ψ indicates the yaw angle and l_s indicates the preview distance.

In addition, by assuming that the side slip angle is negligible, the relationship between the lateral velocity and the yaw angle can be expressed as follows:

$$\psi = \frac{\dot{y}_c}{V}, \tag{2}$$

where, V indicates the velocity.

Moreover, the following relationship can be obtained by differentiating the Eq. (2).

$$\dot{\psi} = \gamma = \frac{\ddot{y}_c}{V}. \tag{3}$$

Therefore, the following relationship can be obtained by substituting Eqs. (2)-(3) into Eq. (1).

$$\ddot{y}_c = kV\left\{y_s^* - \left(y_c + \frac{l_s}{V}\dot{y}_c\right)\right\}. \tag{4}$$

From Eq. (4), the transfer function from the desired lateral displacement of preview point to the lateral displacement of centre can be expressed as the following expression.

$$\frac{Y_c}{Y_s^*} = \frac{kV}{s^2 + kl_s s + kV} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}. \tag{5}$$

Here, ω_n indicates the natural frequency and ζ indicates the damping ratio of the reference tracking response.

In this paper, the damping ratio is set to 1 to prevent the overshoot of the collision avoidance path. Therefore, the following relationships can be obtained.

$$2\omega_n = kl_s. \tag{6}$$

$$\omega_n^2 = kV. \tag{7}$$

Moreover, the following relationship can be obtained by substituting Eq. (6) into Eq. (7).

$$k = \frac{4V}{l_s^2}. \tag{8}$$

As a result, the desired yaw rate can be expressed the following equation.

$$\gamma^* = \frac{4V}{l_s^2}\left(y_s^* - y_s\right). \tag{9}$$

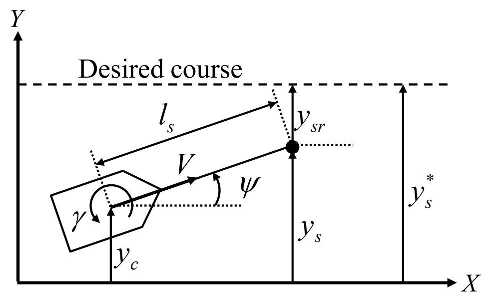


Fig. 2. Vehicle model in earth-fixed coordinate system.

2.2 Steering torque command generator

To simplify the steering control law, the steering assistance torque T_a is calculated by assuming the equation of motions of the steering system model and the equivalent two-wheel vehicle model in steady state, and additionally determining the relationship between the steering torque and the yaw rate.

Figure 3 shows the equivalent two-wheel vehicle model in general. The equivalent two-wheel vehicle model can be expressed as follows:

$$mV\left(\dot{\beta} + \gamma\right) = 2C_f\left(\delta_f - \frac{l_f}{V}\gamma - \beta\right) + 2C_r\left(\frac{l_r}{V}\gamma - \beta\right), \tag{10}$$

$$I_z\dot{\gamma} = 2l_fC_f\left(\delta_f - \frac{l_f}{V}\gamma - \beta\right) - 2l_rC_r\left(\frac{l_r}{V}\gamma - \beta\right), \tag{11}$$

where, m indicates the vehicle mass, I_z indicates the yaw inertia moment of vehicle, C_f (C_r) indicates the front (rear) cornering stiffness, l_f (l_r) indicates the distance between the vehicle centre and the front (rear) axle, β indicates the vehicle body side slip angle, γ indicates the yaw rate, and δ_f indicates the front steering angle.

In addition, fig. 4 shows the steering system model. In this study, the complicated power steering mechanism and the torsional stiffness of the steering model are not considered. Moreover, the self-aligning torque is transferred from the front wheels to the steering wheel directly through the steering gear. Therefore, the equation of motion of the steering system model which is used in this study can be expressed as follows:

$$J_s \ddot{\delta}_{sw} = -C_s \dot{\delta}_{sw} - \frac{2\xi C_f}{n}\left(\frac{\delta_{sw}}{n} - \frac{l_f}{V}\gamma - \beta\right) + T_a, \tag{12}$$

where, J_s indicates the moment of inertia of the steering system, C_s indicates the viscous damping coefficient of steering system, ξ indicates the trail of front tyre, n indicates the overall steering gear ratio, and δ_{sw} indicates the steering wheel angle.

As mentioned before, in order to simplify the steering control law, the steering assistance torque T_a is calculated by assuming the equation of motions of the steering system model and the equivalent two-wheel vehicle model in the steady state, and additionally determining the relationship between the steering torque and the yaw rate. Therefore, the steering assistance torque can be expressed by rearranging Eqs. (10)-(12) and neglecting the derivative terms as follows:

$$T_a = \frac{\xi m l_r V}{nl}\gamma^*, \tag{13}$$

where, l indicates the wheel base.

2.3 Shared control between the system and the driver

The shared control which is equivalent to the intensity of the steering assistance torque is determined by the steering assistance torque multiplied by the weighting coefficient w. Here, the weighting coefficient w is a constant value and is varied from 0 to 1. Therefore, when the value of the weighting coefficient w is zero, it refers to the case without assistance. On the other hand, when the value of the weighting coefficient w is one, it refers to the case with full assistance. Figure 5 (a) and (b) show the simulated lateral displacement and the steering torque, for different values of weighting coefficient w. As can be noticed from the fig. 4, the assistance torque increases with increasing the weighting coefficient w and the avoidance performance improves.

3. EXPERIMENT CONDITION

The experiment was conducted by employing six subject drivers to evaluate the shared control characteristics of the drivers and the collision avoidance steering assistance system with steering torque input by using driving simulator.

3.1 TUAT driving simulator

Figure 6 shows the TUAT driving simulator used in the experiments. The TUAT driving simulator consists of a host computer, a visual system, an audio system, a steering system and a motion controller. The driving simulator is equipped with the same driver interfaces as real vehicle. The host computer calculates the vehicle behaviour based on input of driver interfaces and delivers the signals to driver interfaces based on the calculated vehicle dynamics state. In addition, any scene or traffic situation is reconstructed by setting the road environment and the traffic flow of other vehicles.

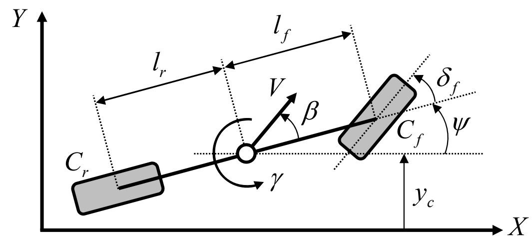


Fig. 3. Equivalent two-wheel vehicle model.

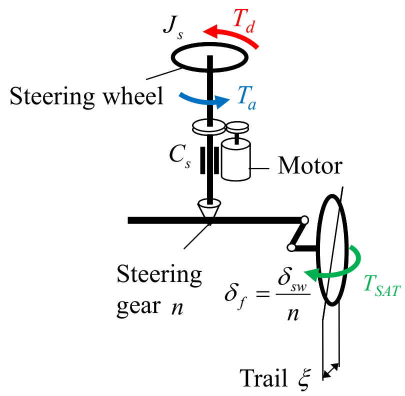
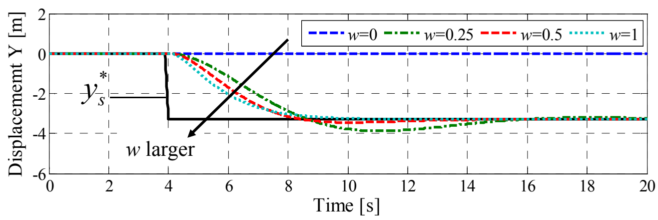
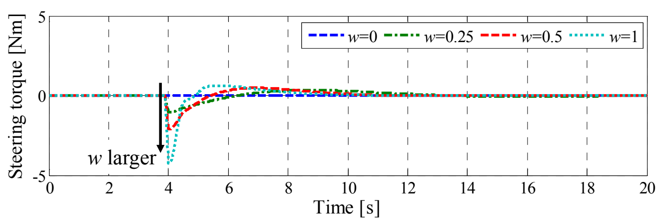


Fig. 4. Steering system model.



(a) Lateral displacement.



(b) Steering torque.

Fig. 5. Simulation result of autonomous collision avoidance by steering (without driver).

3.2 Experimental scenario

The driving scenario is shown in fig. 7. The experiment was conducted under the condition that the vehicle was running at a constant speed of 60 km/h on a two-lane straight road and there was an obstacle which randomly darted out from a number of occlusions located on the left side of the road. The obstacle darted out at the front side of the vehicle at a time instant that the time-to-collision is lower than 2 s. The assistance system is activated at the same time instant of the obstacle appearance. At this condition setting, the vehicle cannot avoid the collision by only braking due to the limited braking capability. The subjects were instructed to avoid the obstacle and change the lane by steering without brake pedal operation to focus the attention on the steering behaviour of the drivers when the obstacle darted out, although common drivers might also avoid the obstacle by brake pedal operation or gas pedal operation besides steering. Additionally, after avoidance, the subjects were instructed to keep on running in the adjacent lane. The above experiment was conducted four times for a subject under the condition that the value of weighting coefficient w was changed at a value of 0, 0.25, 0.5, and 1. During the experiments, the subjects were not informed about the changed value of weighting coefficient w.

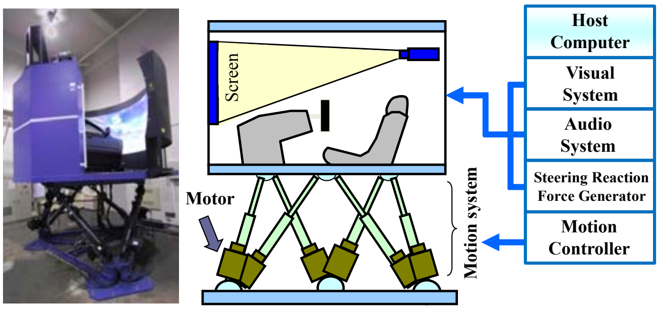


Fig. 6. TUAT Driving simulator.

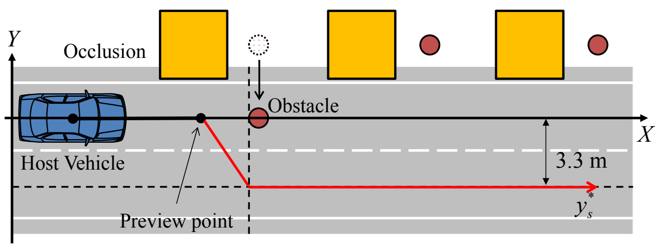
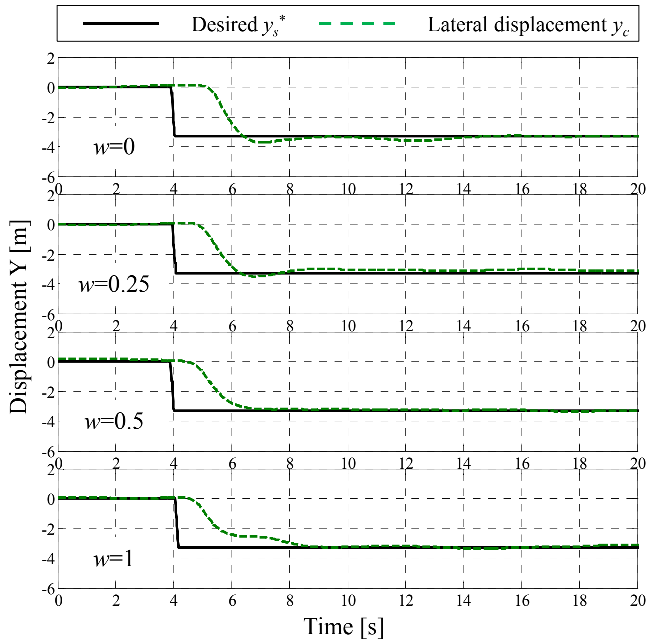


Fig. 7. Pictorial diagram of experiment scenario.

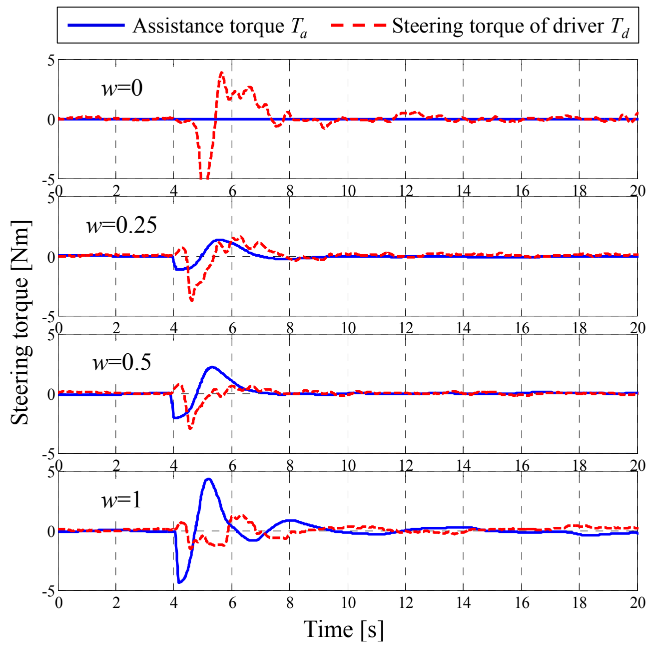
4. EXPERIMENT RESULTS

Figure 8 (a) and (b) show the experiment results by a subject driver indicating the lateral displacement and the steering torque respectively.

As can be seen in fig. 8 (a), the lateral displacement of the vehicle centre of gravity shows the overshoot with respect to the desired avoidance path in the case without the steering assistance, while the overshoot of the lateral displacement is effectively reduced in the case of the steering assistance.



(a) Lateral displacement.



(b) Steering torque.

Fig. 8. Experiment results by a driver with the steering assistance system (Subject A).

In addition, fig. 8 (b) presents that the driver steering torque is reduced when the steering assistance system is activated, compared to the case without assist.

However, the phase difference of the steering torque of the driver and the assistance torque increases as increasing the intensity of assistance. Additionally, the assistance torque is applied in the opposite direction with the driver steering torque when the value of the weighting coefficient is 1. In the other words, the assistance system operates against the steering intention of driver when the weighting coefficient is increased.

From experimental data observation, the following interaction between the driver and the system in the primary evasive steering manoeuvre phase and the return steering phase was found. In the primary evasive steering phase by the assistance system, the driver applied the steering torque in the opposite direction with the assistance torque to dampen the steering movement for a duration shorter than 1 s, since the assistance system operates earlier than the driver as there is a certain reaction time from when the driver recognizes an obstacle until the driver steers. As a result, the driver has tendency to dampen the steering wheel movement to keep the vehicle go straight until the driver intends to conduct evasive manoeuvre.

In the return steering phase, the driver applied the steering torque in the opposite direction with the steering assistance for about 2 s. Especially in the case of full assistance (w=1), the conflict between the driver and the steering assistance continued even after the vehicle completed the lane change manoeuvre for obstacle avoidance. This implies that the driver intended to fix the steering wheel which was turned automatically.

5. DISCUSSIONS

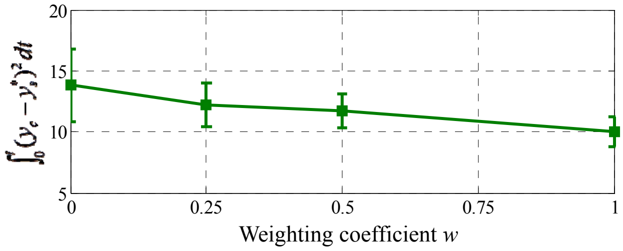
This section discusses the experimental results obtained in the previous section in quantitative manner.

5.1 Avoidance path tracking performance and steering effort

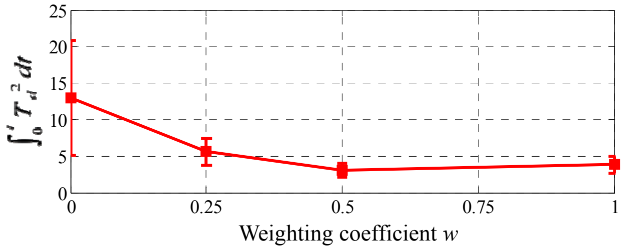
The increasing or decreasing in the driver's steering torque and the avoidance performance are respectively evaluated quantitatively by the steering effort of the driver which is defined by the integral squared value of the steering torque of the driver and the avoidance path error which is defined by the integral squared value of the difference between the lateral displacement of centre of gravity and the lateral displacement of preview point. The integral time interval is 20 s from the position with respect to the obstacle of 100 m.

The average and the standard deviation of the avoidance path error and the steering effort in the case of all six subject drivers are shown in fig. 9 (a) and (b) respectively.

Figure 9 (a) shows that the average of the avoidance path error decreases with the increasing value of the weighting coefficient. The overshoot of the lateral displacement of the centre of gravity is reduced by the steering assistance, as well as the reaction time of the driver is compensated by the early intervention of the assistance system. In addition, the standard deviation of the avoidance path error decreases as the increase of the weighting coefficient since the steering assistance applied full torque assist to the driver-vehicle system in controlling the vehicle motion. As can be noticed from fig. 9 (b), the average of the steering effort of the driver is reduced when the steering assistance system operates compared to the case without assist. However, the average of the steering effort of the driver increases when the value of the weighting coefficient is 1 compared to the case that the value of the weighting coefficient is 0.5. The reason that the driver applied larger steering torque is the assistance torque was applied in opposite direction which the driver intended, or the driver intended to dampen the unexpected steering wheel movement which was turned by the active steering system. As a result, the shared control characteristic of the assistance system is not satisfactory, as the steering effort of driver is large when the intensity of the steering assistance is excessively large.



(a) Avoidance path error.



(b) Steering effort of driver.

Fig. 9. Average and standard deviation of integral squared values.

5.2 Handling quality

To evaluate the handling quality during the obstacle avoidance manoeuvre, the Lissajous diagram steering torque of the driver and the yaw rate of all subject drivers are depicted in fig. 10 when the weighting coefficient w is set at 0.5 and 1. The X axis indicates the steering torque of driver and the Y axis indicates the yaw rate. The second quadrant and the fourth quadrant show the region of bad handling quality, as the yaw rate is generated in the opposite direction with the driver steering torque. This implies that the drivers were attempting to dampen the steering movement caused by the active steering system.

Figure 10 shows that the Lissajous diagram existing in the second quadrant or the fourth quadrant increases when the weighting coefficient is 1, compared to the case when the weighting coefficient is 0.5. Therefore, the handling quality becomes worse when the full assistance by the active steering system is applied.

6. CONCLUSIONS

This paper examined the effectiveness of active steering for collision avoidance assistance on the driver-vehicle system for different intervention levels of the active steering by using a driving simulator.

According to the driving simulator study, the overshoot of the

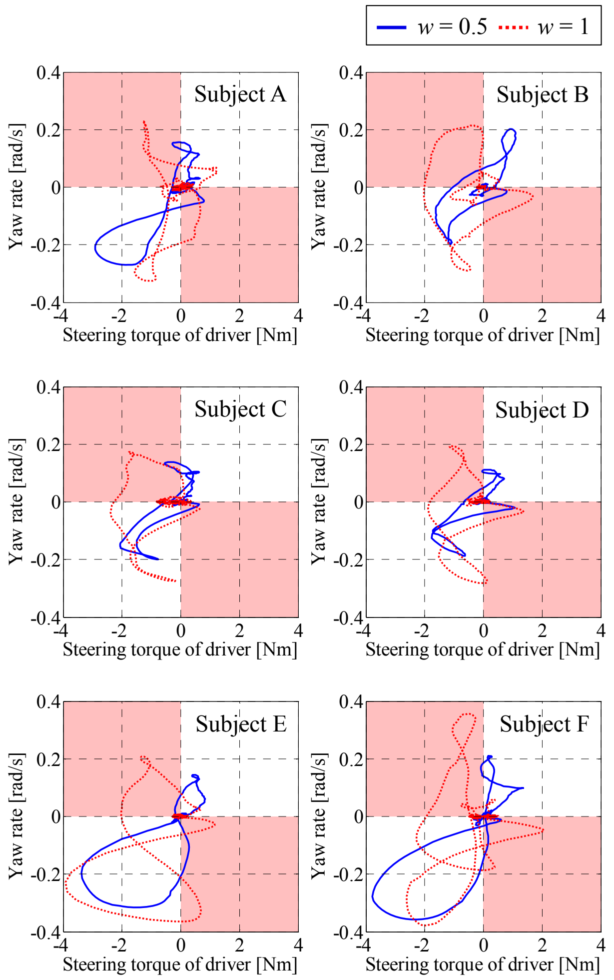


Fig. 10. Lissajous diagram of the steering torque of the driver and the yaw rate (all subject drivers).

lateral displacement of the vehicle centre of gravity during the obstacle avoidance manoeuvre is reduced when increasing the intervention level of the steering assistance, and the driver steering torque is also reduced. These control effects refer to the vehicle stability enhancement and the steering effort reduction during obstacle avoidance manoeuvre. However, when the intensity of the steering assistance becomes larger, the steering assistance torque was applied in the opposite direction with the driver steering torque which means that there was conflict between the driver and the steering assistance. As a result, the steering effort of the driver increases when the intensity of the steering assistance becomes larger. In addition, the handling quality as well as the steering feeling is unsatisfactory in the case of full assistance, as the driver steering torque and the yaw rate are not in the same direction. Therefore, the shared control characteristics of the driver and the assistance system proposed in this study should be optimized with a weighting coefficient of 0.5 in terms of the vehicle stability and the handling quality.

As the next step of the study, the adaptation of the intervention level depending on the driver state and the collision risk as well as the override characteristics will be studied.

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REFERENCES

Braeuchle, C., Flehmig, F., Rosenstiel, W. and Kropf, T. (2013). Driver Influence on Active Pedestrian Protection Systems with Combined Braking and Steering. *Proceedings of 2nd International Symposium on Future Active Safety Technology towards Zero-Traffic Accident (FAST-zero'13)*, TS1-1-6, No. JSAE 20134608, pp.1-6.

De Winter, J.C.F., et al. (2011). Preparing drivers for dangerous situations, a critical reflection on continuous shared control. *IEEE International Conference on Systems, Man and Cybernetics*, pp.1050-1056.

Hartmann B., Eckert A., Rieth E., Sevenich M.. (2011). Emergency Brake & Steer Assist - The Integration of Emergency Brake and Steer Assistance Taking Driver Behaviour in Emergency Situation into Account. *20th Aachen Colloquium Automobile and Engine Technology*, pp.1527-1544.

Isermann, R., Schorn, M. and Stahlin, U. (2008). Anticollision system PRORETA with automatic braking and steering. *Vehicle System Dynamics*, Vol.46, Supplement, pp.683-694.

Katzourakis, D., Olsson, C., Lazic, N. and Lidberg, M. (2013). Driver Steering Override Strategies for Steering Based Active Safety Systems. *Proceedings of 2nd International Symposium on Future Active Safety Technology towards Zero-Traffic Accidents (FAST-zero'13)*, OS2-1-2, No. JSAE 20134592, pp.1-6.

Keller, C.G., Dang, T., Fritz, H., Joos, A., Rabe, C. and Gavrila, D.M. (2011). Active Pedestrian Safety by Automatic Braking and Evasive Steering. *IEEE Transactions on Intelligent Transportation Systems*, Vol.12, No.4, pp.1292-1304.

Kondo, M. and Ajimine, A. (1968), Driver's Sight Point and Dynamics of the Driver-Vehicle System Related to It, *Proceedings of the SAE Automotive Engineering Congress*, Detroit, MI.

Nagai M., Shitamitsu K., Yoshida H., and Mouri H. (2001). Over-ride Characteristics of Lane-Keeping Control System Using Steering Torque Input (Driving Simulator Study on Lateral Wind Response). *Proceedings of Society of Automotive Engineers of Japan Autumn Congress (Abstract in English)*, No.82-01, pp.9-12.

Nagai, M., Mouri, H. and Raksincharoensak, P. (2002). Vehicle Lane Tracking Control with Steering Torque Input. *Vehicle System Dynamics*, Vol.37, Supplement, pp.267-278.

Nagiri, S. (1995). An Experimental Analysis of Avoidance Manoeuvre in Emergency Condition. *Toyota Central R&D Labs Review*, Vol.30, No.3, pp.71-75.