First International Symposium on
Future Active Safety Technology
toward zero-traffic-accident
September 5-9,2011, Tokyo, JAPAN

20117374

Study of Effects of Steering Assist Control Considering Driver Characteristics in Curve Situation

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ABSTRACT: In recent years, a lot of research regarding steering assist controls has been studied with aims of reducing driver's steering workload and improving vehicle performance. Meanwhile, the performance as man-machine system may not always improve by intervention of the steering assist control because driver's steering is essential. Therefore, the design of the system considering driver's characteristics is necessary. In this research, we designed the steering assist control by applying the optimal regulator for the closed-loop system including the driver, and control inputs of this system are both the steering angle and the steering torque in order to take driver's characteristics into account. In addition, we verified the control effects by using the driving simulator.

KEY WORDS: Automobile, Steering Assist Control, Optimal Control, Driving Simulator, Curve Situation,

1. Introduction

When road friction decreases in curve situation, a vehicle becomes unstable and might spin. In this research, we aimed to achieve excellent handling and stability by the steering assist control that taking driver's characteristics into account.

In recent years, varied steering assist controls are proposed and improve the handling and the stability of vehicle by electric power steering and steer by wire technology [(1)~(3)]. The steering system of vehicle is deeply related to driver's feeling because it has the important role that is not only reflecting driver's intention in vehicle motion but also conveying vehicle motion to driver through a steering wheel. Therefore, when intervention of the assist control opposes to the operational intention of driver, it gives uncomfortable feeling to him, and he can't steer according to his intention. Thus, the performance as man-machine system may not always improve by intervention of the assist control, and the assist control should be realized that it is easy to drive for driver and gives good feeling to him.

In previous studies, authors designed the steering assist control by applying the optimal regulator for the closed-loop system including the driver, and examined with assumptions of the crosswind disturbance in lane following situation and the sudden change of road friction in curve situation [(4),(5)]. As a result, they suggested that it is possible to design the optimal steering assist control for driver by above-mentioned design method. Meanwhile in curve situation, the steering reaction force that arises from the self aligning torque (hereafter SAT) becomes important information for driver to understand the vehicle behavior and the road condition. Thus, the steering torque is also deeply related to driver's feeling, and the further improvement of the performance as man-machine system can be expected by adding the steering torque to control input.

In this paper, we designed the steering assist control that both the steering angle and the steering torque are control inputs in order to take driver's characteristics into account. In addition, we verified the effect of newly designed control by the experiment using the driving simulator (hereafter DS).

The signs to use in this paper are as follows.

M	:	Vehicle mass
I_z	:	Yaw moment of inertia
l_f, l_r	:	Distance from center of gravity to front and rear axles
F_f, F_r	:	Cornering force of front and rear tires
C_f, C_r	:	Cornering power of front and rear tires
N	:	Steering gear ratio
ξ	:	Caster trail
C_s	:	Equivalent viscous friction coefficient of front wheels
I_s	:	Moment of inertia of steering wheel
V	:	Vehicle velocity
β	:	Vehicle body slip angle
y	:	Lateral deviation
φ	:	Yaw angle
y_r	:	Lateral deviation to the target trajectory
φ_r	:	Yaw angle to the target trajectory
θ	:	Driver's steering wheel angle
T_d	:	Driver's steering torque
u_θ	:	Assist angle
u_T	:	Assist input torque
ρ	:	Road curvature
L_x	:	Driver's preview distance
ε	:	Deviation from the driver's preview point to the target trajectory
K_e	:	Driver gain
T_h	:	Time constant of first-order lead
T_k	:	Time constant of first-order lag
τ	:	Dead time of driver

2. Steering Assist Control Setup

The steering assist control designed in this study is the lane following control that assists the driver's steering to follow the center of the driving lane by the state quantity feedback of vehicle. Driver's characteristics are reflected in the system by using a closed-loop system consisting of models of the driver, the steering system and the vehicle. Control inputs that are added to the steering as assist are calculated by the optimal regulator that is one of optimal control theories.

2.1. Vehicle model

The vehicle model is the equivalent two-wheel model shown in Figure 1. Parameters of the vehicle are set to values of the passenger car. Here, it is necessary to consider the road geometry of the driving course in the situation that the target trajectory changes continuously like a curve road. Thus, the road geometry is included in motion equations of the vehicle by using the road curvature.

If the vehicle follows the curve road that the curvature is ρ, the lateral acceleration and the yaw rate to the target trajectory are shown by equations (1) [6]. The change of curvature is approximated as shown by equation (2). The coefficient λ is decided according to how many times per second the vehicle passes curve. From Figure 1 and equations (1), motion equations of the vehicle are obtained as shown by equations (3). The front wheel angle is approximated by proportional to the steering angle.

$$\ddot{y}_r = \ddot{y} - \rho V^2, \quad \dot{\varphi}_r = \dot{\varphi} - \rho V \tag{1}$$

$$\dot{\rho} = -\lambda \rho \tag{2}$$

$$\begin{cases} M\ddot{y} = F_f + F_r \\ I_z \ddot{\varphi} = l_f F_f - l_r F_r \end{cases} \tag{3}$$

Here,

$$\begin{cases} F_f = -2C_f \left(\dfrac{\dot{y} - V\varphi + l_f \dot{\varphi}}{V} - \dfrac{\theta}{N} - \dfrac{u_\theta}{N} \right) \\ F_r = -2C_r \left(\dfrac{\dot{y} - V\varphi - l_r \dot{\varphi}}{V} \right) \end{cases}$$

2.2. Steering model

The steering model is the linear model shown by equation (4). It is not considered the complex power steering model and the tensional rigidity of steering system, and assumes that the SAT of front wheels directly transmitted to the steering wheel through the steering gear. The assist torque is added to the driver's steering torque, and the SAT increased by adding the assist angle was not transmitted to the steering wheel.

$$I_s \ddot{\theta} = -C_s \dot{\theta} - \frac{\xi C_f}{N} \left(\frac{\theta}{N} - \frac{l_f (\dot{\varphi}_r + \rho V)}{V} + \varphi_r - \frac{\dot{y}_r}{V} \right) + T_d + u_T \tag{4}$$

2.3. Driver model

The driver model is the second order preview model shown in Figure 2. This model steers in response to the deviation ε from the driver's preview point to the target trajectory, and is shown by equation (5). It is the model consisting of the driver gain, the first-order lead, the first-order lag and the dead time. The deviation ε is approximated as shown by equation (6).

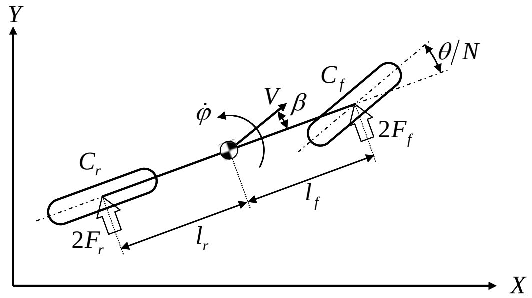

Fig. 1 Equivalent two-wheel model

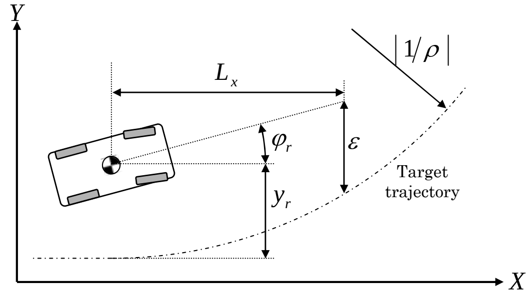

Fig. 2 Second order preview model

$$T_d = K_e \frac{T_h s + 1}{T_k s + 1} \frac{1 - \tau/2\, s}{1 + \tau/2\, s} \varepsilon \tag{5}$$

$$\varepsilon = y_r + L_x \varphi_r - \frac{L_x^2}{2} \rho \tag{6}$$

2.4. Design of control System

The state equation of the system is set up. The state equation shown by equation (7) is provided from the above-mentioned equations.

$$\dot{X} = AX + BU \tag{7}$$

Here,

$$X = \begin{bmatrix} y_r & \dot{y}_r & \varphi_r & \dot{\varphi}_r & \theta & \dot{\theta} & T_d & \dot{T}_d & \rho \end{bmatrix}^T, \quad U = \begin{bmatrix} u_\theta & u_T \end{bmatrix}^T$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{22} & a_{23} & a_{24} & a_{25} & 0 & 0 & 0 & a_{29} \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{42} & a_{43} & a_{44} & a_{45} & 0 & 0 & 0 & a_{49} \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} & a_{67} & 0 & a_{69} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ a_{81} & a_{82} & a_{83} & a_{84} & a_{85} & 0 & a_{87} & a_{88} & a_{89} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\lambda \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & b_{61} & 0 & 0 & 0 \\ 0 & b_{21} & 0 & b_{41} & 0 & 0 & 0 & b_{81} & 0 \end{bmatrix}^T$$

$$a_{22} = -2\frac{C_f + C_r}{MV}, \quad a_{23} = 2\frac{C_f + C_r}{M}, \quad a_{24} = -2\frac{l_f C_f - l_r C_r}{MV},$$

$$a_{25} = 2\frac{C_f}{MN}, \quad a_{29} = a_{24}V - V^2, \quad a_{42} = -2\frac{l_f C_f - l_r C_r}{I_z V},$$

$$a_{43}=2\frac{l_f C_f - l_r C_r}{I_z},\quad a_{44}=-2\frac{l_f^2 C_f + l_r^2 C_r}{I_z V},\quad a_{45}=2\frac{l_f C_f}{I_z N},$$

$$a_{49}=a_{44}V,\quad a_{62}=\frac{\xi C_f}{I_s N V},\quad a_{63}=-\frac{\xi C_f}{I_s N},$$

$$a_{64}=\frac{\xi C_f l_f}{I_s N V},\quad a_{65}=-\frac{\xi C_f}{I_s N^2},\quad a_{66}=-\frac{C_s}{I_s},$$

$$a_{67}=\frac{1}{I_s},\quad a_{69}=a_{64}V,\quad a_{81}=\frac{K_e}{T_k \tau/2},$$

$$a_{82}=\frac{K_e\left(T_h-\tau/2\right)-K_e T_h \tau/2\left(a_{22}+a_{42}L_x\right)}{T_k \tau/2},$$

$$a_{83}=\frac{K_e L_x - K_e T_h \tau/2\left(a_{23}+a_{43}L_x\right)}{T_k \tau/2},$$

$$a_{84}=\frac{K_e L_x\left(T_h-\tau/2\right)-K_e T_h \tau/2\left(a_{24}+a_{44}L_x\right)}{T_k \tau/2},$$

$$a_{85}=-\frac{K_e T_h \tau\left(a_{25}+a_{45}L_x\right)}{T_k \tau/2},\quad a_{87}=-\frac{1}{T_k \tau/2},$$

$$a_{88}=-\frac{T_k+\tau/2}{T_k \tau/2},$$

$$a_{89}=-\frac{K_e\frac{L_x^2}{2}\left\{1-\lambda\left(T_h-\tau/2\right)\right\}+T_h \tau/2\left(a_{24}V-V^2+a_{44V}L_x\right)}{T_k \tau/2},$$

$$b_{21}=a_{25},\quad b_{41}=a_{45},\quad b_{62}=a_{67},$$

$$b_{81}=-\frac{K_e T_h \tau/2\left(a_{25}+a_{45}L_x\right)}{T_k \tau/2}$$

Control inputs are calculated by the optimal regulator. The performance function shown in equation (8) was defined. Characteristics assumed to be targets and measures for the driver to steer were used for the performance function of the optimal regulator. The first term of the performance function is the deviation from the driver's preview point to the target trajectory, and aims to improve the stabilization of the vehicle. The second and third terms are followings of the yaw rate and the lateral acceleration to the steering torque, and both of them aim to improve the responsibility of the vehicle motion to the driver's steering. Both the fourth and fifth terms are control input quantities. Each coefficient of terms (g_1, g_2, g_3, g_4, g_5) is the weight coefficient of the performance function, and K_1 and K_2 are the steering gains. The assist characteristic is configured by changing values of these coefficients.

$$J=\int_0^\infty\left[g_1\left(y_r+L_x\varphi_r-\frac{L_x^2}{2}\rho\right)^2+g_2\left(K_1T_d-\dot{\varphi}_r\right)^2+g_3\left(K_2T_d-\ddot{y}_r\right)^2+g_4u_\theta^2+g_5u_T^2\right]dt \tag{8}$$

The feedback gain F is calculated to minimize this performance function, and the optimal control input U is calculated as shown by equation (9).

$$U=-FX \tag{9}$$

3. Examination by the Simulation

3.1. Driving Task

To examine the steering assist control in usual drive, the simulation of driving on curve road was executed assumed the winding. The curvature radius was set to two conditions of R90 and R60 shown in Figure 3. The crossing angle of curve was set to 30deg, and the vehicle speed was set to 50km/h. In addition, the low frictional section was setup on the curve road to make it easy to evaluate the stability of the control system. The frictional coefficient of road was set to 0.18 on the low frictional road, and that of usual road was set to 1.00.

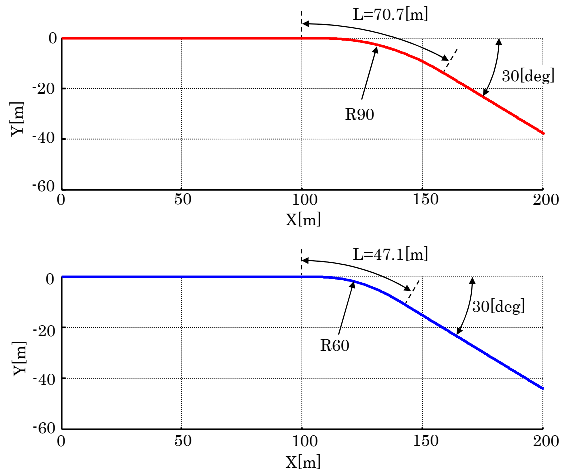

Fig. 3 Curve road task

3.2. Simulating Condition

The composition of the simulation model is shown in Figure 4. The full vehicle model (CarSim by MSC Ltd.) was used for the simulation and moreover the equivalent two-wheel model was used for the control system design. As assist conditions, each value of weight coefficients (g_1, g_2, g_3, g_4, g_5) of the performance function was changed form 10^{-2} to 10^3. In each condition, all weight coefficients excepted changed weight coefficient were 10^0.

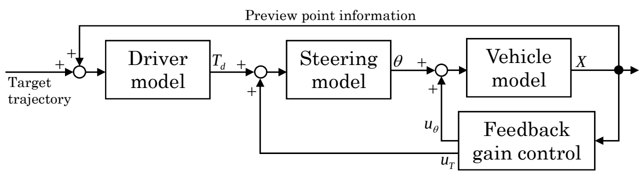

Fig. 4 Composition of the simulation model

3.3. Results of Simulation

Figure 5 shows simulation results in the case of curve road (R90). These are time-series graphs of the steering torque and the yaw rate when each weight coefficient g_i of the performance function is changed form 10^{-2} to 10^3. By the low frictional section, responses of the steering torque and the yaw rate change, and the vehicle behavior is disturbed. Especially, the influence appears strongly when the vehicle is returning from the low frictional road to the usual road.

The changes of responses by differences of assist characteristics are examined. By enlarging g_1, the driver's steering and the vehicle motion become stable and the control effect improves after passing the low frictional section, and there is no big difference while the vehicle is going into the curve. And there is not a difference by lessening g_1. When g_2 or g_3 is changed, the responsibility of the vehicle motion is improved by enlarging each value. In addition, by enlarging g_2, the responsibility of the vehicle motion is greatly improved compared with the conditions of enlarging g_3. Moreover, when g_4 is changed, there is no big difference of the control effect by differences of assist characteristic. When g_5 is lessened, the wobble of the vehicle behavior becomes suppressed. However, when g_5 is too small, the steering torque and the yaw rate vibrate after passing the low frictional section.

The tendency of the control effect aimed by each term of the performance function appears in the simulation results. However, the yaw rate is almost the same pattern while the driving on the low frictional section in all assist conditions. Therefore, it can be said that the effect of this assist control on the stabilization of the vehicle motion during the low frictional section is not so achieved.

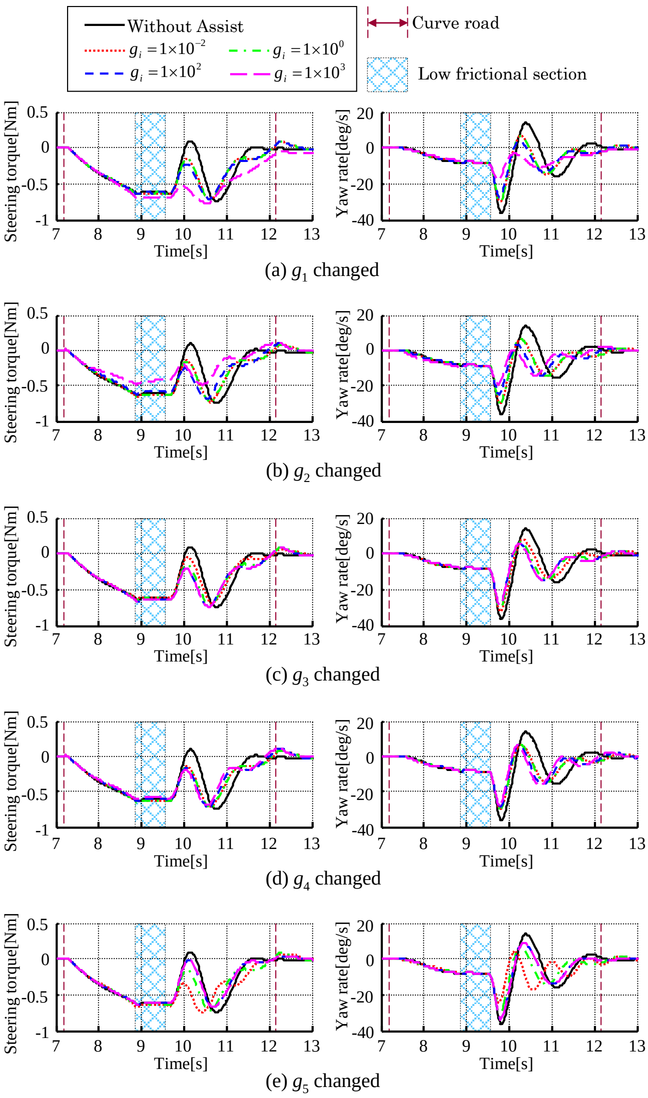

Fig. 5 Simulation results in the case of curve road (R90)

4. Driving Simulator Experiment

4.1. Driving Simulator

Figure 6 shows the appearance of DS used in the experiment. It has a steering torque simulator and can ingenerate an arbitrary steering reaction force. In addition, it also has a lateral motion system.

Figure 7 shows the system configuration of DS. First, the driver's steering angle that added the assist angle is input to the vehicle model. Next, the SAT is calculated according to it. Here, when the assist angle directly powers a steering wheel, the balance of the assist angle added and SAT increased by it can be taken. However, both SAT by the driver's steering and the assist are directly fed back to the driver because this system adds only the signal of steering angle. Thus, the steering wheel model calculates SAT only by the driver's steering, and this is added the assist torque and then fed back. At the same time, the motor of the motion system is driven to simulate the lateral motion.

Here, while the vehicle is running in the curve road, it always moves laterally for the ground fixed coordinates. To simulate the lateral motion on a driving simulator, very wide range of operation is necessary. Therefore, this motion system uses the method that the pseudo lateral body sensory information based on the lateral jerk of vehicle model was given to the driver, and then return to the original position by washout algorithm.

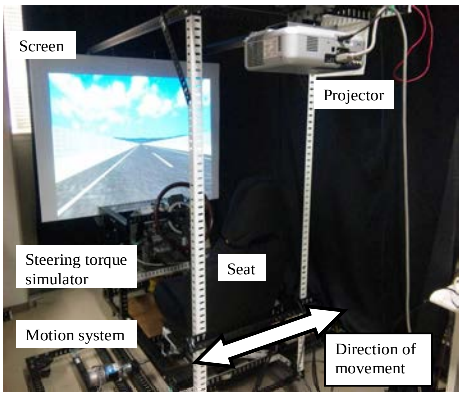

Fig. 6 Motion based driving simulator

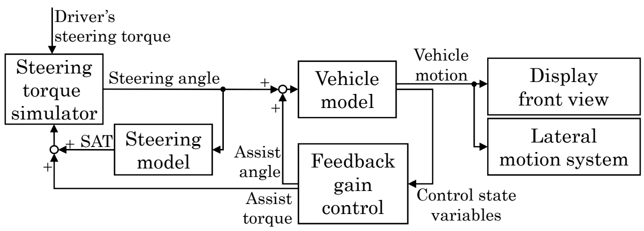

Fig. 7 System configuration of DS

4.2. Experimental Conditions

The effectiveness of the assist control designed was verified with the above-mentioned driving simulator. The curvature radius was set to two conditions of R90 and R60, and the vehicle speed was set to 50km/h similar to the simulation. The assist conditions were twelve added 'Without Assist' to eleven conditions shown in

Table 1 that values of weight coefficients of the performance function were changed. The detail of the assist control was not told to subjects, and it was told only that it assists the driver by steering to follow the center of the driving lane. The assist conditions were presented at random. Subjects were six students aged 22.0 years old (average) and given informed consent.

Table 1 Assist conditions that weight coefficients were changed

Condition	Weight coefficients of the performance function				
	g_1	g_2	g_3	g_4	g_5
(a)	1	1	1	1	1
(b)	100	1	1	1	1
(c)	1	100	1	1	1
(d)	1	1	0.01	1	1
(e)	1	1	10	1	1
(f)	1	1	1000	1	1
(g)	1	1	1	100	1
(h)	1	1	1	1000	1
(i)	1	1	1	1	0.1
(j)	1	1	1	1	10
(k)	1	1	1	1	1000

4.3. Experimental Results

In the experimental results, there was no big difference by the assist characteristic while the vehicle was going into the curve. Moreover, the influence on the vehicle motion by the steering did not appear while the driving on the low frictional section similar to the simulation. Therefore, we focused attention on the driver's steering and the vehicle behavior after passing the low frictional section. Because the difference by the driving task is only wavy size and because wavy shapes were similar, results in R90 are used for consideration.

Figure 8 shows average integration values of squared steering torque, squared steering angle velocity and squared yaw rate calculated from all subjects' results of seven seconds after passing the low frictional section in condition R90. These are used as the index of the driver's steering load, the steering stability and the vehicle stability, respectively.

First, condition (a) is compared to ‘Without Assist’. It is thought that the steering and the vehicle motion were stable by the assist control because of the decrease of the average integration value of the squared steering angle velocity and the squared yaw rate.

Secondly, results in conditions that g_1~g_3 were changed are considered. In condition (b), the average integration value of squared steering angle velocity decreases more than the value of condition (a), thus the steering was more stable. In condition (c), all of average integrated values were smaller than values of condition (a). Thus, the steering load was reduced in addition to the stabilization of the steering and the vehicle motion in this condition. And, in condition (d), the steering load was reduced though it was heavier than that of condition (c). In condition (e) and (f), the control effect was not seen in the steering and the vehicle motion, and the steering load becomes heavier by enlarged g_3. Therefore, it is thought that the assist characteristic of condition (c) is the most effective in the reducing the driver’s steering load and the improvement of the vehicle stability in these assist conditions.

Thirdly, results in conditions that g_4 and g_5 were changed are considered. In these conditions, there are differences at the average integration value of squared steering torque, squared steering angle velocity though there is no big difference in the vehicle motion. In condition (g) and (h), the average integration value of steering torque squared was decreased. However, the average integration value of steering angle velocity squared increases. Thus, the steering was unstable though the steering load was reduced by enlarging g_4. In condition (i), the steering load greatly increased, and questionnaire results of subjects showed uncomfortable feelings such as ‘the steering reaction force is too strong’ or ‘the steering by not the driver but the assist control is essential’. In condition (j), the steering load decreased, and the stability of the steering improved more than conditions (a). Therefore it was understood that the steering stability becomes unstable though the steering load decreases by suppressing the assist angle, and the steering stability is able to be improved without giving the driver the uncomfortable feeling by suppressing moderately the assist torque.

Finally, from these results, Figure 9 shows time-series graphs of subject A at ‘Without Assist’ and good conditions ‘(b), (c), (h) and (j)’. The effect is seen at convergences of the steering and the vehicle motion in time-series graphs, and the result similar to the average integration values of squared variables is obtained. Therefore it was suggested that it is good assist control that the weight coefficient value of the following of the yaw rate to the steering torque is enlarged in the curve situation. In addition, it was understood that the steering stability is able to be improved without giving the uncomfortable feeling to the driver by suppressing moderately the assist torque.

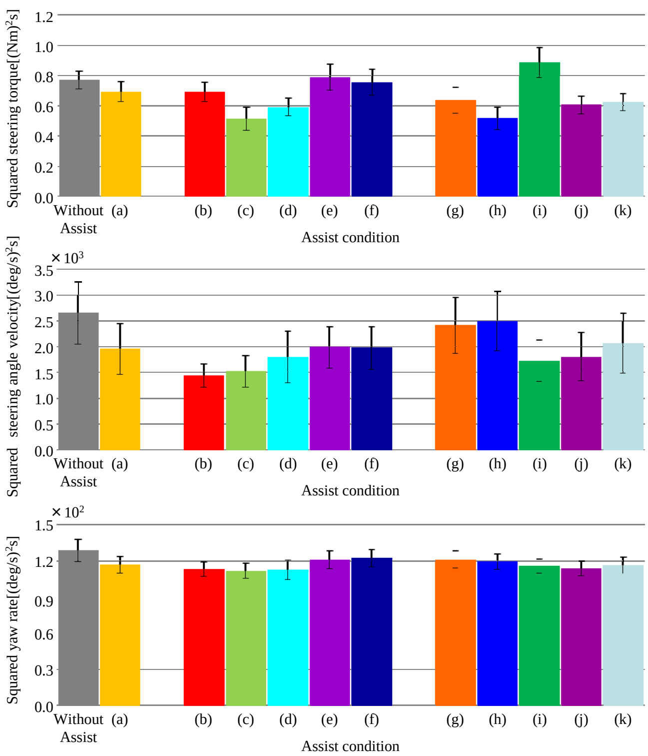

Fig. 8 Average integration values of squared variables of all subjects' results in the case of curve road (R90)

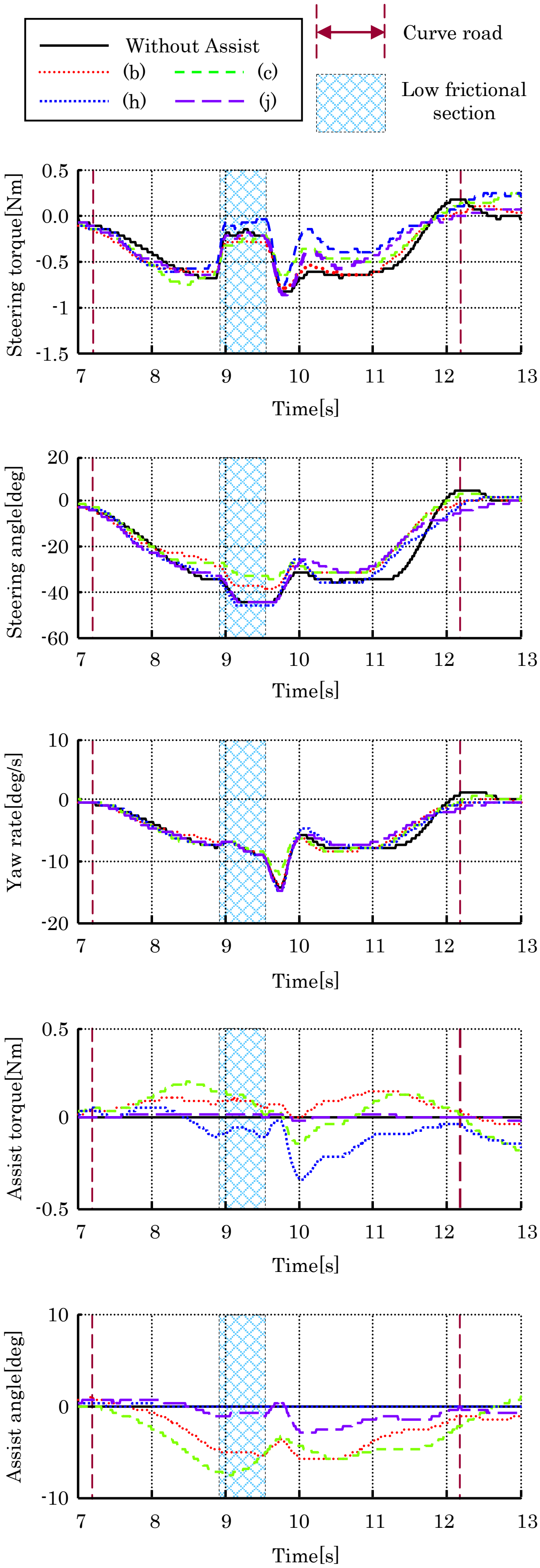

Fig. 9 Experimental results of subject A in the curve road (R90)

5. Conclusion

We assumed the situation that vehicle goes into the low frictional section while driving on the curve road, and designed the steering assist control. First, the driver was treated as a controller, and the assist steering control was constructed by applying the optimal regulator to a closed-loop system of driver, steering system and vehicle. In addition, characteristics assumed to be targets and measures for the driver to steer were used for the performance function of the optimal regulator. Secondly, the control effect of the steering assist control was predicted by using the simulation. Finally, the control effect constructed was verified by the experiment using the DS.

As a result, it has been understood to be able to construct the steering assist control that is appropriate for driving on the curve road by enlarging the weight coefficient value of the following of the yaw rate to the steering torque in the performance function of the optimal regulator. Moreover, it was suggested that the steering stability is able to be improved without giving the driver the uncomfortable feeling by suppressing moderately the assist torque.

The future problem is the improvement of the driver model used for the design of the assist control and the simulation. The driver model in this study steers in response to the deviation from the driver’s preview point to the target trajectory. However, it is thought that the driver steers based on the body sensory information such as the steering reaction force, the yaw rate and the lateral acceleration. Therefore it is necessary to examine a driver model and a performance function where driver's behavior is more considered.

Acknowledgment

The authors thank Mr. Hiroyuki Fuke very much for his valuable comments on designing the steering assist system in this study.

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Published in: FAST-Zero'11 Proceedings (No.TS2-8-1-5, 20117374)
Date of Conference: 5-9 Sep.2011
Publisher: Society of Automotive Engineers of Japan
Publication Year: 2011