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IMPROVEMENT OF DRIFT RUNNING PERFORMANCE BY STEERING SYSTEM WHICH ADDS DIFFERENTIATION STEER ASSISTANCE

H. NOZAKI*

Department of Mechanical Engineering, Faculty of Science and Engineering, Kinki University, 3-4-1 Kowakae, Higashiosaka-shi 577-8502, Japan

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ABSTRACT−In this research, an effective technique was examined to improve the drift running performance. Concretely, the driver model by which the counter steer was done was assumed to the model by which the vehicle body slip angle (and the vehicle body slip angle velocity) was feed back. Next, the effectiveness of the system which added the assist steer angle corresponding to the steering wheel angle velocity to a front wheel steer angle was clarified as a drift running performance improvement technique of the vehicle. As a result, because the phase advances when the differentiation steer assistance is added, it has been understood to be able to cover the delay of the counter steer when the drift running. Therefore, it has been understood that the drift control does considerably easily. Moreover, it has been understood that the differentiation steer assistance acts effectively at the drift cornering by which the drift angle is maintained in cornering and the severe lane change with a drift at a situation. That is, it was understood to be able to settle to the drift angle of the aim quickly at the time of the drift cornering because the delay of the control steer angle of the counter steer was improved. Moreover, it was understood for the transient overshoot of the vehicle tracks to be able to decrease, and to return to the state of stability quickly at the severe lane change.

KEY WORDS : Motion control, Automobile, Vehicle dynamics, Steering system, Maneuverability, Stability, Simulation, Driver model

NOMENCLATURE

m : vehicle mass {1500 kg}
I : yaw moment of inertia {240 kg·m^2}
l : wheel base {2.62 m}
l_f, l_r : distance from vehicle center of gravity to front and rear axles {1.18, 1.44 m}
N : overall steering gear ratio {15.4}
δ_H : steering wheel angle
δ_f : front wheel steer angle ($\delta_f = \delta_H/N$)
r : yaw rate
$\dot{r}$: yaw angle acceleration
β : vehicle body side-slip angle
β_f, β_r : side-slip angle of front and rear wheel
V : vehicle forward speed
F_f, F_r : cornering force of front and rear wheel
W_f, W_r : vertical load of front and rear wheel
$W_{f\text{-}in}$, $W_{f\text{-}out}$, $W_{r\text{-}in}$, $W_{r\text{-}out}$: vertical load of inside and outside wheels (front and rear wheel)
Δw_f, Δw_r : vertical load movement of inside and outside wheels (front and rear wheel)
μ : coefficient of friction of road
F_t : tire cornering force
β_t : tire slip angle
K_t : tire cornering power
y_{OL} : lateral displacement of target course
L : distance to eye point
ε : lateral displacement difference between eye point and target course.
k : proportion constant

**Corresponding author.* e-mail: nozaki@mech.kindai.ac.jp

1. INTRODUCTION

A general driver often did the counter steer in the provinces where it snows much. Therefore, we are about to see a lot of appearances to which the drift cornering is done. That is, the direction of the vehicle can be freely changed even in the state which cannot be controlled in the steering wheel operation by running by which the rear wheel is slipped. Moreover, there is a case to need the counter steer for no aim it either to avoid spin in the state which should be avoided in the emergency. Then, an effective technique which was able to facilitate controlling even if entering this state of the drift was examined. The research of the steer system which contained the differentiation term named "Differentiation steering wheel" in general was done by Hirao O., and, in addition, the best range was researched by Nakaya H. These researches show the effect about grip area. Here, the grip area is an area where the rear wheel does not exceed the maximum cornering force. On the other hand, the four-wheel steering system (4WS) is thought to be effective in the stability improvement in the grip area compared with the differentiation steering wheel, and the 4WS has already been used now. However, the 4WS cannot also demonstrate the effect in the drift area. On the other hand, because the differentiation steer assistance was able to improve the delay of the counter steer, it was thought that it was a very effective improvement technique in the drift area.

Moreover, nowadays there are many active steering systems and safety systems. For instance, when over-steering, "Active steering wheel system" of BMW has the method to operate a reverse-steering wheel by the yaw ratio regulator. That is, the system which comes to stabilize in counter steer with the yaw ratio regulator in case of the braking on the split μ road for instance has been developed. However, though these controls are the methods to control yaw angle stabilizing, it is thought that the driver might not be able to become familiar because there is a case where the operation is done in the direction opposite to the operation of the driver. On the other hand, The direction of the differentiation steer assistance is equal to the direction where the driver is operated. Therefore, because it is the one to improve the delay of the reaction of the driver, there is not being steered in the direction opposite to the driver operation like an active steering wheel of BMW. Therefore, it is thought that the differentiation steer assistance becomes the one which becomes familiar easily for the driver. Moreover, because the differentiation steer assistance does not do a complex control, it can be judged that the problem's that the control does not act in a certain situation occurring is not, and is also high that reliability.

Then, the effectiveness of the system which added assisted a front wheel steer angle corresponding to the steer angle velocity to a usual front wheel steer angle was examined as a drift running performance improvement technique idea of the vehicle. The reason is that the delay of the driver steer can be improved by the steer assistance proportional at the steer angle velocity. Here, the drift area is an area where the rear wheel exceeded the maximum cornering force. That is, it is an area where counter steer is needed. Here, the drift cornering shows that cornering is done by the rear wheel's exceeding the maximum cornering force, and controlling counter steer in the state of the drift. Here, the drift angle shows the body slip angle at the time of the drift cornering.

2. DESCRIPTION OF VEHICLE MOVEMENT

2.1. Equation of Motion

The analysis of the movement in the vehicle used the vehicle model of two degree of freedom (Figure 1).

The equation of motion is as follows.

$$mV(\dot{\beta}+r) = F_f + F_r \tag{1}$$

$$I\dot{r} = l_f F_f - l_r F_r \tag{2}$$

Moreover, when the tire slip angle of a right and left wheel is assumed to be equal to facilitate analyzing, the front and rear side-slip angle is as follows.

$$\beta_f = \delta_f - \beta - l_f r / V \tag{3}$$

$$\beta_r = -\beta + l_r r / V \tag{4}$$

The normal load of a right and left wheel which considered the load movement by a lateral acceleration becomes a type as below.

$$\left.\begin{aligned} W_{f-in} &= W_f/2 - \Delta w_f \\ W_{f-out} &= W_f/2 + \Delta w_f \\ W_{r-in} &= W_r/2 - \Delta w_r \\ W_{r-out} &= W_r/2 + \Delta w_r \end{aligned}\right\} \tag{5}$$

To clear a qualitative character, the vehicle model makes two-wheel model a base. However, because the limit area where the drift is accompanied has been treated, it is necessary to consider the vertical load movement between an inside and outside wheel. Therefore, four wheels for each were considered in the expression (5). A dynamic load movement cannot be calculated by the vehicle model of two degree of freedom. Then, this is calculated from static balance by using height of center of gravity and the relation of the inertia force and so on.

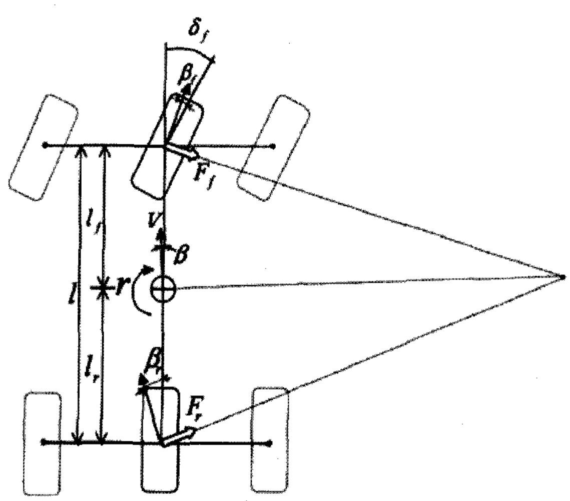

Figure 1. Vehicle model (bicycle model).

Moreover, a right and left wheel is calculated at the body center in Figure 1.

And, the effect of a right and left wheel considers the friction coefficient of an individual tire to the load. And, the cornering force is calculated, and it is added right and left.

The cornering force characteristic of the front and rear wheel is obtained as a function of the slip angle and the vertical load of the front and rear wheel. The cornering force characteristic of the tire was based on the expression of Fiala.

$$\left.\begin{array}{l} F_t = f(\varphi)(\mu W) \\ \text{where:} \\ f(\varphi) = \varphi - |\varphi|\varphi/3 + \varphi^3/27 \quad (|\varphi| \le 3) \\ \varphi = K_t \tan\beta_b/\mu W \end{array}\right\} \quad (6)$$

Tire cases were set in φ of 3 or more (Figure 2). The equation was set as follows.

$$f(\varphi) = 1 - 1/87(|\varphi| - 3) \quad (7)$$

That is, the maximum value was exceeded and it was assumed the decreasing characteristic. By lowering μ of the rear wheel a little than the front wheel, the maximum cornering force of the rear wheel was lowered a little compared with the front wheel. That is, it was assumed the condition setting for the drift to do easily.

2.2. Steer Model in Drift Cornering

Result of recording eye point of driver in drift cornering with eye camera, it has been understood that the eye point of the driver is forward diagonal correspond to body slip angle (Figure 3). That is, it has been understood that the driver perceives the progress direction vector of the body, and controls the counter steer angle in the state to maintain the drift angle. Accordingly, the driver steer model in drift cornering was assumed to be a model by which the vehicle body slip angle and vehicle body slip angle velocity were feedback.

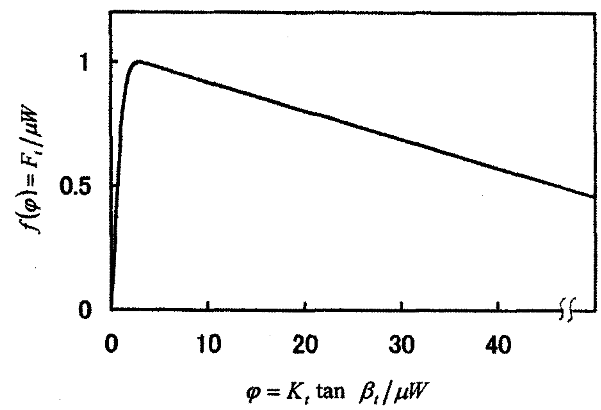

Figure 2. Tire model.

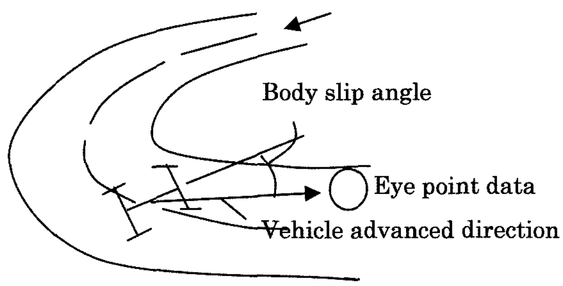

Figure 3. Eye point of driver at the drift cornering.

The steer model of the drift running to maintain an intentional drift angle in cornering was examined. The step steer angle at time when cornering was started did as follows. (This setting is up to time that the vehicle body slip angle β does not exceed 10 deg)

$$\delta_f = k_0 step(t) \quad (|\beta| \le 10) \quad (8)$$
$$(\delta_H = N\delta_f)$$

δ_H is the one that δ_f and N of overall steering gear ratio were multiplied ,that is, the steering wheel angle.

Next, the steer angle for the vehicle body slip angle β to have exceeded 10 degree was assumed to be equation (9). This shows the control steer angle by which the drift angle in the drift region was maintained. That is, the steer model of the driver was assumed to be a model by which the vehicle body slip angle and vehicle body slip angle velocity were feedback. The steer model of the driver was quoted from the research thesis which the author had presented in AVEC'02. Here, forecast term where body slip angle velocity $\dot{\beta}$ was feed back was excluded. (That is $k_3 = 0$). That is, the model of an inexperienced driver that the forecast steer is not so done here was set.

$$\delta_f = (k_1 + \beta) \times k_2 + \dot{\beta} \times k_3 \quad (|\beta| \ge 10) \quad (9)$$
$$(\delta_H = N\delta_f)$$

Where, k_1 shows the constant which controls the target drift angle, and k_2 shows the gain constant of the feedback steer.

The drift control steer angle of Equation (9) is shown in Figure 4.

The inclination of the control steer angle changes when k_2 is changed as shown in the dotted line of Figure 4.

Moreover, the dotted line shifts up and down overall when k_1 is changed. The solid line of Figure 4 shows the relation between the vehicle body slip angle and the front wheel steer angle when the front and rear wheel does the balance by the counter steer in cornering. Therefore, if the steer angle intersects with the solid line by periodi-

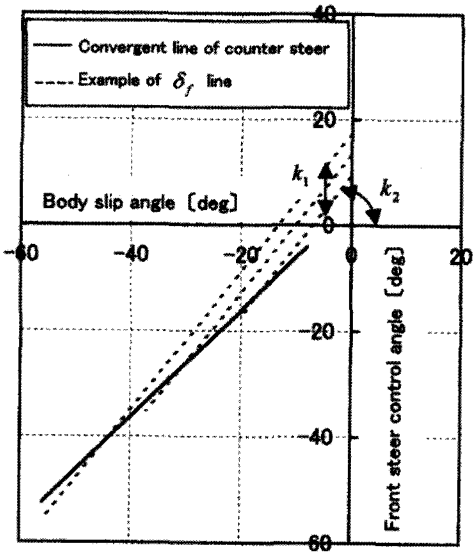

Figure 4. Counter steer model.

cally going and coming and settles on the line of a dotted line drift control steer angle to the point to do the balance, the drift angle can be maintained while turning.

Moreover, because the delay was caused in the feedback steer when it was only a steer of proportion to the vehicle body slip angle β, the forecast feedback steer by coefficient at the vehicle body slip angle velocity $\dot{\beta}$ was added as a differentiation element.

2.3. Steer Method of Vehicle (Differentiation Steer Assistance)

Next, the steer method of the vehicle was assumed to be a method to add the differentiation steer assistance to a usual steering wheel as shown in Figure 5. That is, the assistance front wheel steer angle ($P \cdot \dot{\delta}_H$) by which constant P was multiplied at the steer angle speed $\dot{\delta}_H$ was obtained. Next, the assistance front wheel steer angle ($P \cdot \dot{\delta}_H$) was assumed to be a method added to a general front wheel steer angle (δ_H/N). It is possible to show by the following expression.

$$\delta_f = \delta_H/N + P \cdot \dot{\delta}_H \quad (|\beta| > 10) \tag{10}$$

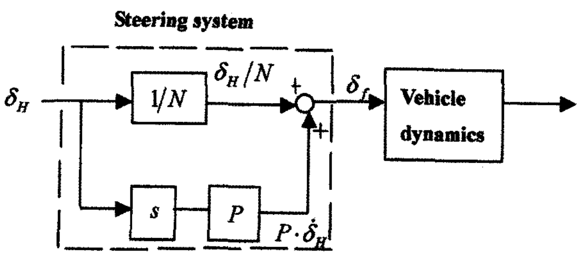

Figure 5. Block diagram of differentiation steer assist system.

To understanding the effect of the differentiation steer assistance in the drift control area, the differentiation steer assistance was made to act since point by which the body slip angle exceeded 10 deg.

3. DRIFT RUNNING SIMULATION RESULT

The influence of differentiation steer assistance constant P was simulated in the steer method of the vehicle. Because the rear wheel does the skid when the turn starts by adding the steer of the step, counter steer acts according to equation (9) of driver steer model, and is controlled. And the turn by which the drift angle is maintained is done in the simulation. The vehicle velocity is 100 km/h. When differentiation steer assistance constant P is 0 (case without the differentiation steer

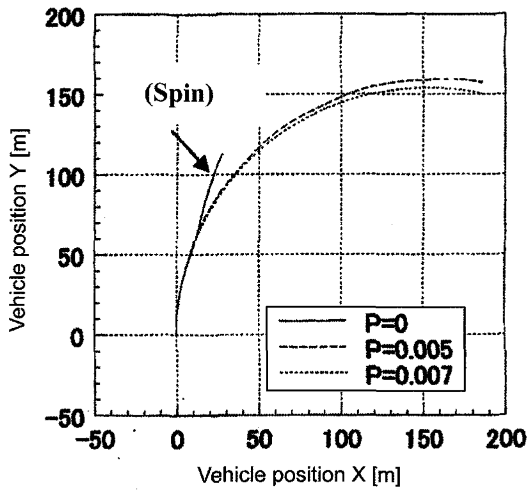

Figure 6. Running trajectory.

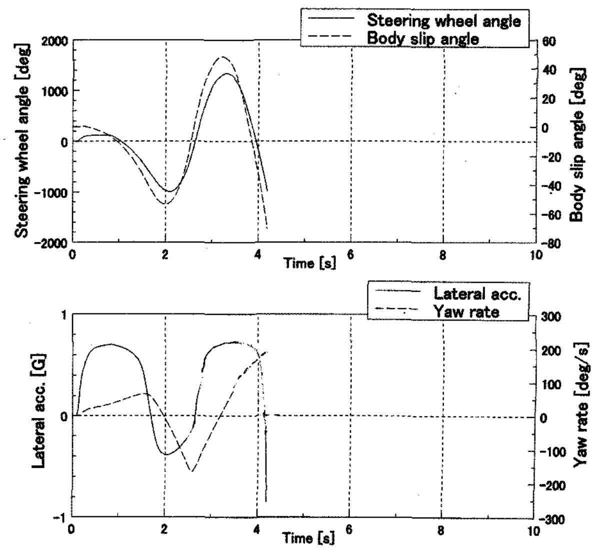

Figure 7. Simulation results (P=0).

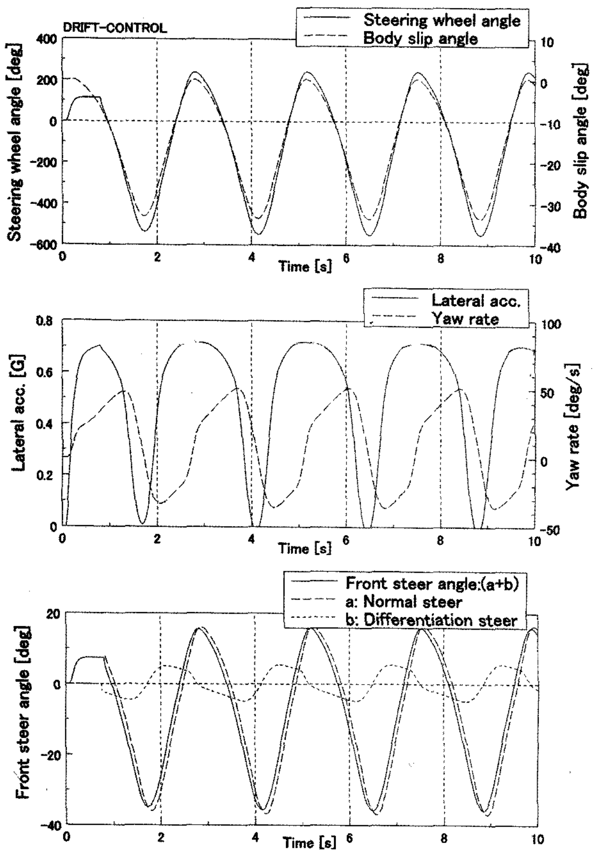

Figure 8. Simulation results (P=0.005).

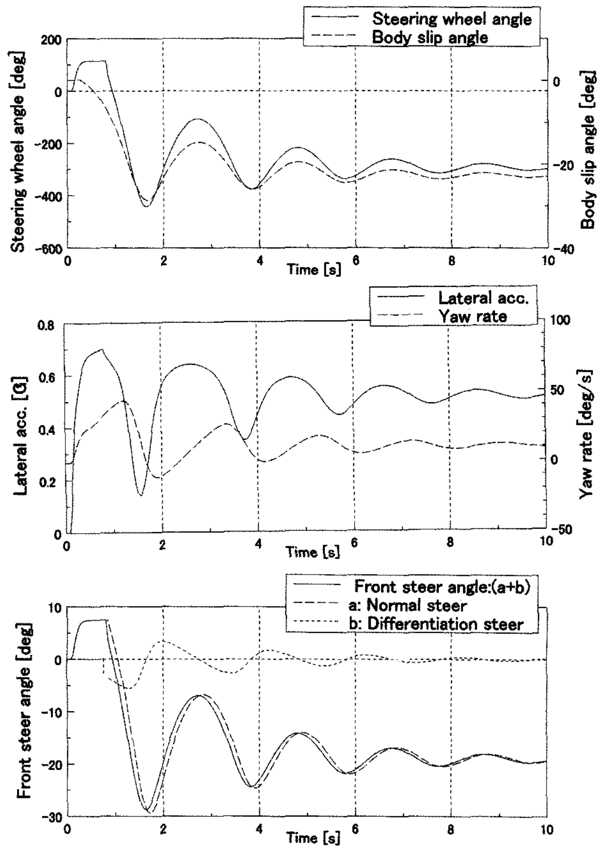

Figure 9. Simulation results (P=0.007).

assistance), and is 0.005, and 0/007, the turn tracks in the drift cornering shows in Figure 6. Though P=0 has arrived at spin, P=0.005 and 0.007 cases are cornering by which the drift angle is maintained. Figure 7 shows the result of the turn simulation by which the drift angle is maintained in case of P=0. The step steer of about 100 deg has been done for the first about one second. Afterwards, the counter steer is applied, too much, the counter steer is returned, the steer angle is returned too much, the counter steer is applied, and the state which arrives at spin after the emanation tendency is shown. Moreover, the state of the body slip angle, lateral acceleration, and yaw rate is shown. On the other hand, Figure 8 and Figure 9 show the case to add the differentiation steer assistance. Figure 8 indicates the case of P=0.005. In this case, the vehicle behavior does not arrive easily at spin, and the counter steer and the return steer are repeated by almost the same amplitude. Moreover, because differentiation steer angle (b) becomes the tendency to the phase advancement for usual steer angle (a), front wheel steer angle (a+b) became a tendency to which the phase was a little advanced compared with usual steer angle (a) (Figure 8). Figure 9 indicates the case of P=0.007. The amplitude when the

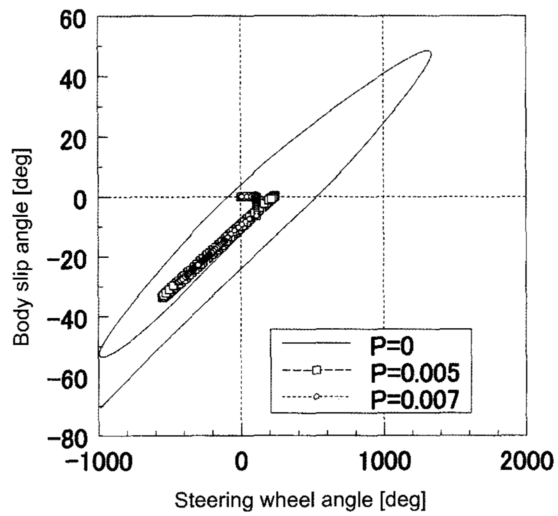

Figure 10. Phase plane trajectory of steering wheel angle – body slip angle.

counter steer is applied and returned decreases. It shows that the drift control is a settling tendency.°°Moreover, the case with P=0.007 showed the tendency same as in the case of P=0.005. That is, front wheel steer angle (a+b) became a tendency to which the phase was a little advanced compared with usual steer angle (a). It has been understood that the phase delay of the steer in the drift control is improved by adding the differentiation steer assistance. And, it has been understood to settle to the drift angle of the aim quickly consequentially. (Here, it is k_1=10, and k_2=1.5 in the constant of the steer model of the driver) Next, it has been understood that the counter steer and the return steer are done delaying the phase to the body slip angle a little for P=0 as shown in Figure 10. On the other hand, it has been understood to hardly cause the phase delay for P=0.005 and P=0.007.

4. EXPERIMENT RESULT BY DRIVING SIMULATOR (DRIFT RUNNING)

The running examination was done by using driving simulator made by the virtual mechanics company shown in Figure 11. Driving simulator installs the software (vehicle model) made by Mechanical Simulation Corporation. Please refer to the paper by Watanabe Y. of Mechanical Simulation Corporation of the reference. Figure 12 and Figure 13 show the examination result. The examination method depresses the accelerator in cornering of a high lateral acceleration when 75m in radius turns, slides the rear wheel intentionally, and the driver applies the counter steer. Afterwards, the driver controlled the amount of the counter steer angle, and the driver kept controlling the drift turn of 75m in radius while maintaining the drift angle (Figure 12). Moreover, when the driver intentionally depressed the accelerator, and the rear wheel skid was generated, the accelerator was returned a little, and the state was maintained as

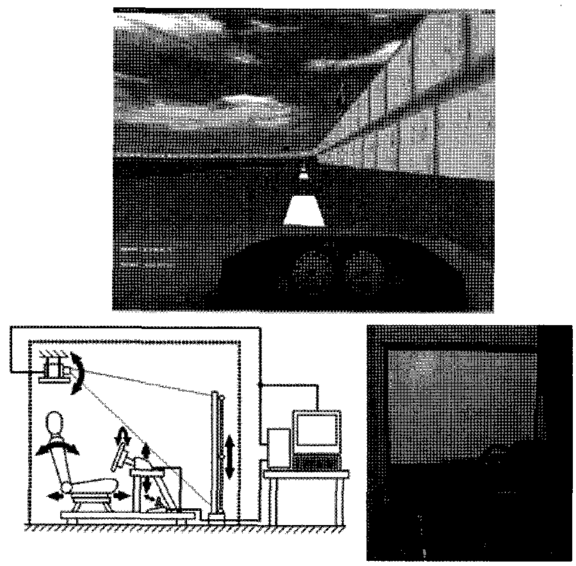

Figure 11. Driving simulator.

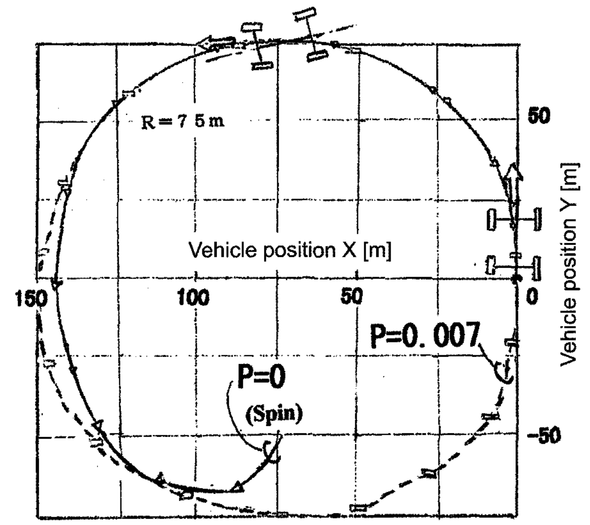

Figure 12. Experiment result of running trajectory using the driving simulator.

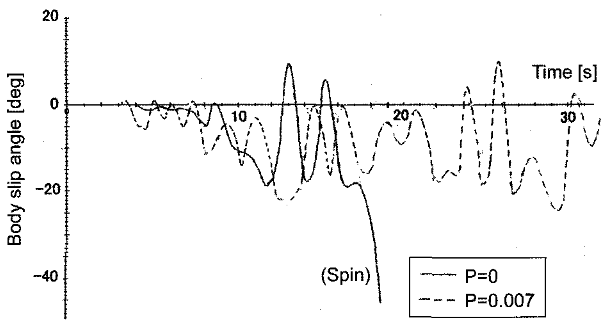

Figure 13. Experiment result of body slip angle using the driving simulator.

much as possible concerning the accelerator operation. As a result, the vehicle velocity of the drift cornering kept within the range at 85–95 km/h. That is, it was assumed the drift control by which counter steer was frequently done as an experiment condition. The test used the panelist in the stage which had comparatively become accustomed to the drift control operation in driving simulator. As a result, the maintenance control of the drift angle became difficult with spin in differentiation steer assistance constant P=0. On the other hand, the drift angle was able to keep controlling maintaining, and the drift control was far easier in differentiation steer assistance constant P=0.007 case. Figure 12 shows running trajectory of the drift turn. Figure 13 shows the change in the body slip angle into the elapsed time. The driver is emanated in differentiation steer assistance constant P=0 vibrating. On the other hand, it was able to be confirmed that the drift angle was able to control maintaining while repeating the counter steer and the return of the counter steer in differentiation steer assistance constant P=0.007case.

Theoretical results show that the body slip angles of P=0 are greater than those of P=0.007. But, experimental results show that the body slip angles of P=0 are smaller than those of P=0.007 before the vehicle goes into the spin status. The reason for this difference is explained as follows.

In the experiment result, as for the P=0.007 case, even if the slip angle grows a little by the operation mistake of the driver than the P=0 case, the P=0.007 case shows that it is possible to cover because the delay of counter steer is small.

5. ADDITIONAL EXAMPLE OF SIMULATION FOR SEVERE LANE CHANGE WITH DRIFT

In the preceding clause, it was an examination when the drift angle was maintained at the time of cornering. Here, the drift is controlled by the counter steer when the side-slip is caused in the rear wheel to the severe lane change, and the case to do the follow running to the target course is indicated. The steer model of the driver does horizontal displacement of the vehicle of becoming advanced as present vehicle posture (yaw angle: θ) forward L[m] L/V time, and the deflection ε subtracted from horizontal displacement of the target course is done and feedback control is done (Figure 14).

$$\varepsilon = y + L\sin\theta - y_{OL} \tag{11}$$

$$\delta_H = N \times (k \times \varepsilon) \tag{12}$$

(Here, it was assumed $L = 14$m and $k = -1.5$.)

Next, the steer method of the vehicle was assumed to be a method to add the differentiation steer to a usual steering wheel assisting as well as equation (10). That is, it was assumed the method to add the assistance front wheel steer angle by which the constant was multiplied at the steer angle speed to a usual front wheel steer angle.

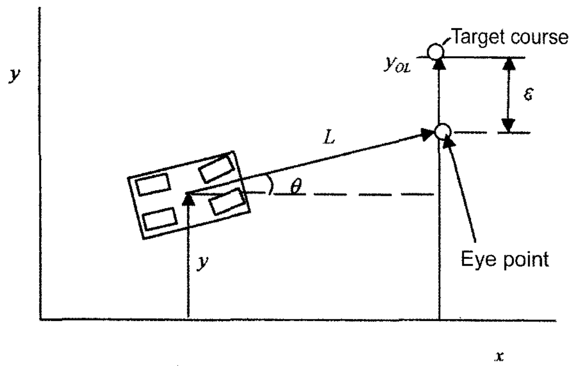

Figure 14. Driver steer model.

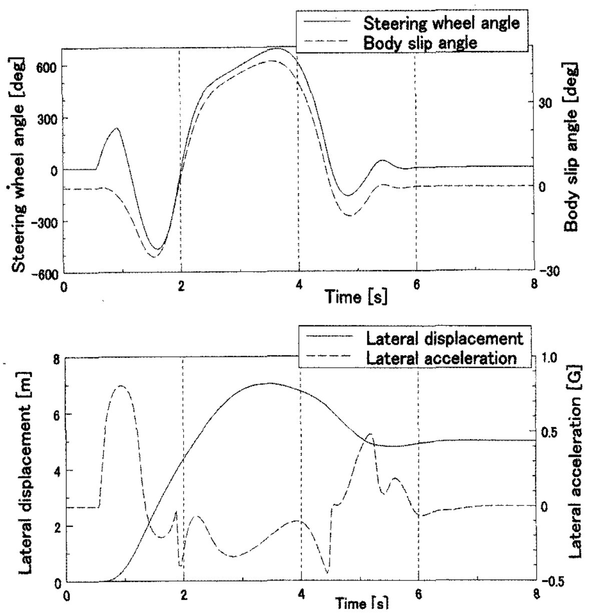

Figure 15. Simulation results of lane change (P=0).

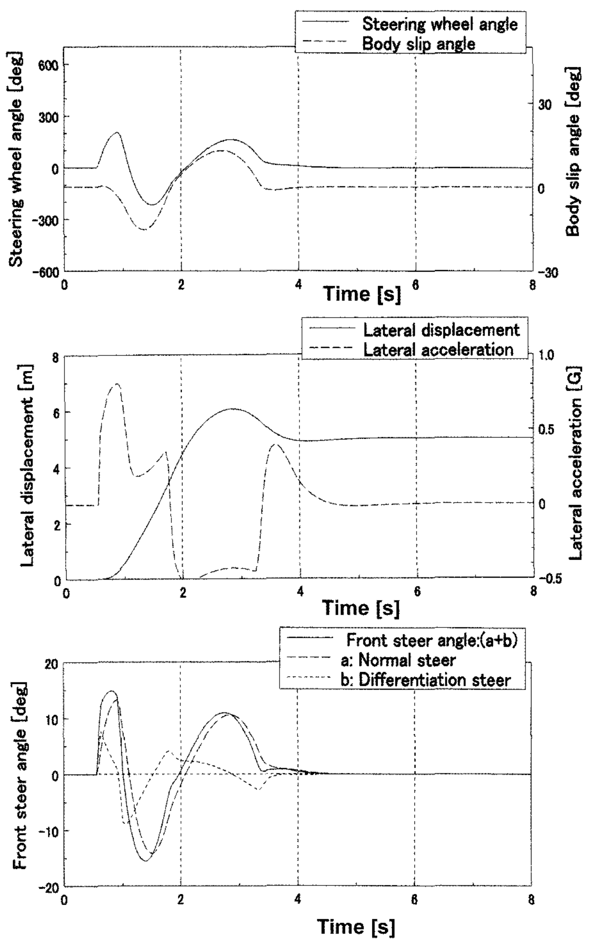

Figure 16. Simulation results of lane change (P=0.007).

The expression becomes the following.

$$\delta_f = \delta_H/N + P \cdot \dot{\delta}_H \quad (12)$$

The condition of the simulation is the vehicle velocity 100 km/h, and 5m in lane change width. As a result, case (P=0.007) understood the transient overshoot decreased compared with case (P=0), and stability rose (Figure 15 and Figure 16). Moreover, because differentiation steer angle (b) becomes the tendency to the phase advancement for usual steer angle (a) as shown in Figure 16, front wheel steer angle (a+b) became a tendency to which the phase was a little advanced compared with usual steer angle (a).

Though some the steer angles are the operations of ±300 deg in Figure 15 during 0.7–1.7 seconds in the simulation time, this is a initial steer for beginning of the lane change and a return steer because along the lane of it. 2–4.5 seconds are counter steer angles.

6. EXPERIMENT RESULT BY DRIVING SIMULATOR (SEVERE LANE CHANGE WITH DRIFT)

The running experiment for differentiation steer assistance constant P=0 and P=0.007 case was confirmed by using driving simulator shown in Figure 11.

Because the experiment on driving simulator becomes a condition with low vehicle velocity by restricting the course compared with the case of the simulation, It was assumed the condition which became a severe lane change with a drift same as the simulation by assuming the width of the lane change to be 10m.

The side-slip behavior of the rear wheel when a severe lane changed became calm for P=0.007 case compared with P=0. In addition, the counter steer operation was in time, and settling was also good in P=0.007 case. The vehicle behavior changed by side-slip of the rear wheel is rapid in P=0.007 case, and on the other hand, the transient overshoot of the vehicle and settling are considerably inferior, and have arrived at spin for P=0 even if the counter steer is done ahead of time. Figure 17 and Figure 18 shows the experiment result for differentiation steer assistance constant P=0 and P=0.007 case (Vehicle velocity goes at 80 km/h). Therefore, the confirmation by

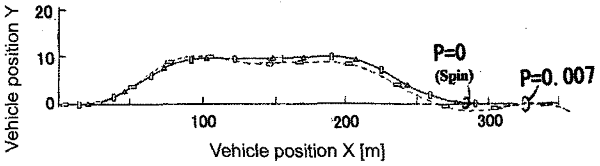

Figure 17. Experiment result of running trajectory with driving simulator.

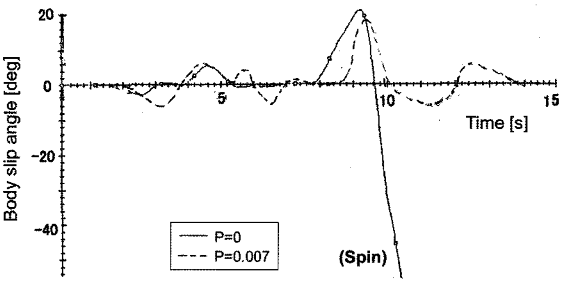

Figure 18. Experiment result of body slip angle with driving simulator.

which the simulation result was proven can have been experimental done.

7. CONCLUSIONS

The effect which the differentiation steer assistance caused for the drift running performance was examined. As a result, the following conclusion was obtained.

(1) Because the phase advances when the differentiation steer assistance is added, it has been understood to be able to cover the delay of the counter steer when the drift running. Therefore, it has been understood that the drift control become easy.

(2) It has been understood that the differentiation steer assistance acts effectively at the drift cornering by which the drift angle is maintained in cornering and the severe lane change with a drift. That is, it was understood to be able to settle to the drift angle of the aim quickly at the time of the drift cornering because the delay of the control steer angle of the counter steer was improved. Moreover, it was understood for the transient overshoot of the vehicle tracks to able to decrease, and to return to the state of stability quickly at the severe lane change.

In this research, the differentiation steer assistance examined the mechanism of the effect caused for the drift running performance. And, the direction of an effective improvement technique is examined in addition.

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