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EVALUATION OF FOUR-WHEEL-STEERING SYSTEM FROM THE VIEWPOINT OF LANE-KEEPING CONTROL

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ABSTRACT–This paper evaluates the effectiveness of four-wheel-steering system from the viewpoint of lane-keeping control theory. In this paper, the lane-keeping control system is designed on the basis of the four-wheel-steering automobiles whose desired steering response is realized with the application of model matching control. Two types of desired steering responses are presented in this paper. One is zero-sideslip response, the other one is steering response which realizes zero-phase-delay of lateral acceleration. Using simplified linear two degree-of-freedom bicycle model, simulation study and theoretical analysis are conducted to evaluate the lane-keeping control performance of active four-wheel-steering automobiles which have different desired steering responses. Finally, the evaluation is conducted on straight and curved roadway tracking maneuvers.

KEY WORDS : Four-wheel-steering, Lane-keeping control, Active safety, Model matching control, Vehicle dynamics, Optimal control

1. INTRODUCTION

As recent advance in automatic steering, researches on lane-keeping control are being carried out extensively in the field of automated vehicles as well as driving assistance systems (Hedrick, 1994; Tsugawa, 1998; Fujioka, 1999). At the beginning of our research, a lane-keeping controller based on conventional front-wheel steering vehicle (2WS) was designed to regulate lateral deviation at the center of gravity with the application of optimal control theory. As a result, the lateral deviation is well regulated with satisfactory dynamics, while yaw dynamics tends to have undesirable damping behaviour (Mouri, 1994). From the viewpoint of vehicle dynamics and control, however, it is impossible to achieve desirable lane-keeping performance in both lateral and yaw directions by using the only front-wheel steering angle as control input. Thus, additional control input is necessary to overcome this problem.

From a viewpoint of control theory, four-wheel-steering system (4WS) seems to be an attractive alternative in enhancing lane-keeping control performance. In the field of active safety, four-wheel-steering system (4WS) has been studied extensively for a long time and regarded as an effective tool to enhance vehicle handling performance and active safety. In the last decade, various types of four-wheel-steering vehicles have been developed and appeared on market. Many control algorithms of four-wheel-steering system have been developed for various desirable control objectives such as reduction of phase-lag of acceleration and yaw rate, reduction of side slip angle, etc. (Furukawa, 1989). As a representative report of 4WS for ITS, Alleyne proposed a control strategy of four-wheel-steering for unintended roadway departure prevention and proved its effectiveness by computer simulation (Alleyne, 1997). However, our main interest, here, is not only from the viewpoint that, what type of 4WS is the most effective in lane-keeping control performance, but also how 4WS can be objectively evaluated by using lane-keeping control theory.

Based on these backgrounds, this paper applies lane-keeping control theory to evaluate 4WS that is designed for enhancing active safety. This paper employs 4WS which applies the model matching control technique to realize the desired steering response (Nagai, 1989). Two representative desired steering responses are presented in this paper. Computer simulations are carried out to verify the effectiveness of each control law on lane-keeping control performance.

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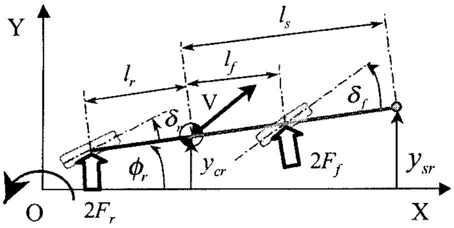

Figure 1. Equivalent 2 DOF bicycle model.

2. VEHICLE MODEL

This paper mainly focuses on the normal lane-keeping behavior of vehicle which the body side slip angle is so small that the velocity is approximately constant. The effects of roll, heave, and pitch motions as well as the dynamic characteristics of tire and steering system are also neglected. The side slip angle of right and left tires are in the region that the linear tire model is valid. Based on these assumptions, this paper employs an equivalent bicycle model as shown in Figure 1 to describe the vehicle dynamics. The equations of motions can be expressed as follows:

$$m\ddot{y}_c = mV(\dot{\beta} + \dot{\phi}) = 2F_f + 2F_r \tag{1}$$

$$I\ddot{\phi} = 2l_fF_f - 2l_rF_r \tag{2}$$

$$F_f = C_f\left(\delta_f - \frac{l_f}{V}\dot{\phi} + \phi_r - \frac{\dot{y}_{cr}}{V}\right) \tag{3}$$

$$F_r = C_r\left(\delta_r - \frac{l_r}{V}\dot{\phi} + \phi_r - \frac{\dot{y}_{cr}}{V}\right) \tag{4}$$

where m denotes the vehicle mass, I the yaw moment of inertia, y_c the lateral displacement at center of gravity, ϕ the yaw angle (Subscript r denotes the variable relative to reference line.), V the vehicle velocity, β the body side slip angle, l_f and l_r the distances from the front and rear axles to the center of gravity, respectively, F_f and F_r the front and rear cornering forces, respectively, C_f and C_r the front and rear cornering stiffnesses, respectively, δ_f and δ_r the front and rear steering angles, respectively.

In the case of curved trajectory with constant radius of curvature ρ, the relative variables with respect to the desired course are expressed as follows:

$$\dot{\phi}_r = \dot{\phi} - \rho V \tag{5}$$

$$\ddot{y}_{cr} = \ddot{y}_c - \rho V^2 . \tag{6}$$

3. CONTROL SYSTEM DESIGN

The objective of the control system is to regulate the lateral deviation at the center of gravity and yaw deviation of the vehicle to be zero. The control system, as shown in Figure 2, consists of the model matching controller which makes the vehicle follow the desired vehicle response by making use of the active front and rear steering angle, and the lane-keeping controller designed by linear quadratic control theory.

3.1. Model Matching Controller

The purpose of model matching control is to make the outputs of 4WS vehicle follow the outputs of desired model which has the ideal steering response. The model matching controller consists of feedforward controller which depends on steering wheel angle input from optimal lane-keeping system, and feedback controller which is designed to compensate the state deviations of side slip angle and yaw rate.

3.1.1. Feedforward controller

By deriving the inverse model of the equations of the 2 DOF motions, Equations (1), (2), (3), (4), the control law of front and rear steering angles can be determined as the following transfer functions.

$$\frac{\delta_f(s)}{\delta(s)} = \frac{1}{2lC_f}\left[ml_rVs + 2lC_f\frac{\beta(s)}{\delta(s)}\right.$$

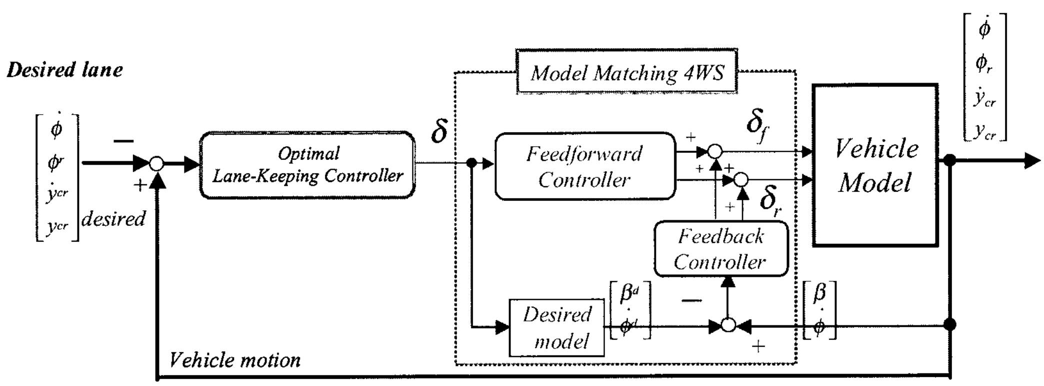

Figure 2. Description of lane-keeping system with active four-wheel-steering vehicle.

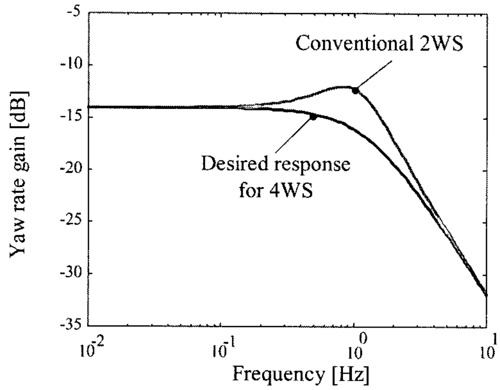

Figure 3. Approximated desired yaw rate response.

$$+\left(Is + ml_rV + \frac{2l_f lC_f}{V}\right)\frac{\dot{\phi}(s)}{\delta(s)}\Bigg] \quad (7)$$

$$\frac{\delta_f(s)}{\delta(s)}=\frac{1}{2lC_f}\Bigg[ml_rVs + 2lC_f\frac{\beta(s)}{\delta(s)}$$

$$+\left(Is - ml_rV + \frac{2l_f lC_f}{V}\right)\frac{\dot{\phi}(s)}{\delta(s)}\Bigg] \quad (8)$$

From the above equations, the feedforward control law of 4WS is determined according to the steering responses of desired model which can be determined in many ways. This paper discusses the following two types of steering responses, those are:

(1) zero-side-slip-angle response which will be referred as "**4WS-A**" and,

(2) steering response which has no phase-lag in lateral acceleration which will be referred as "**4WS-B**".

[4WS-A Vehicle]

First, for 4WS-A vehicle, the desired steering response can be expressed as follows:

$$\frac{\beta(s)}{\delta(s)}=0\,; \quad (9)$$

$$\frac{\dot{\phi}(s)}{\delta(s)}=\frac{k_r}{1+\tau_r s}\,; \quad (10)$$

where, δ indicates the steering wheel angle input. As shown in Figure 3, k_r and τ_r are the steady-state gain and the time constant of yaw rate response respectively which are determined from conventional front-wheel steering vehicle as follows:

$$k_r=\frac{1}{1-\dfrac{m(C_f l_f - C_r l_r)V^2}{2l^2 C_f C_r}}\cdot\frac{V}{l}\cdot\frac{1}{i_{st}}\,; \quad (11)$$

$$\tau_r=\frac{k_r I}{2l_f C_f}\,. \quad (12)$$

where, l indicates the vehicle wheelbase, i_{st} the steering gear ratio. To realize the desired responses of 4WS-A, substituting Equations (9), (10) into Equations (7), (8), the active front and rear steering law can be obtained as follows:

$$\frac{\delta_f(s)}{\delta(s)}=\frac{k_r}{2lC_f}\left[\frac{I}{\tau_r}+\left(ml_rV+\frac{2ll_fC_f}{V}-\frac{I}{\tau_r}\right)\frac{1}{1+\tau_r s}\right]; \quad (13)$$

$$\frac{\delta_f(s)}{\delta(s)}=\frac{k_r}{2lC_f}\left[-\frac{I}{\tau_r}+\left(ml_rV-\frac{2ll_rC_r}{V}+\frac{I}{\tau_r}\right)\frac{1}{1+\tau_r s}\right]. \quad (14)$$

[4WS-B Vehicle]

In the case of 4WS-B vehicle, the desired steering response can be expressed as follows:

$$\frac{\ddot{y}_c(s)}{\delta(s)}=k_rV\,; \quad (15)$$

$$\frac{\dot{\phi}(s)}{\delta(s)}=\frac{1}{1+\tau_r s}\,. \quad (16)$$

Note that the yaw rate response is set identical to 4WS-A vehicle. According to this desired steering response, the side slip angle response becomes 1st order lag response as follows:

$$\frac{\beta(s)}{\delta(s)}=\frac{1}{V}\left(\frac{\ddot{y}_c(s)}{\delta(s)}\right)-\frac{\dot{\phi}(s)}{\delta(s)}=\frac{k_r\tau_r}{1+\tau_r s}\,. \quad (17)$$

To realize the desired responses of 4WS-B, substituting Equations (16), (17) into Equations (7), (8), the steering law for active front and rear steering angle can be obtained as follows:

$$\frac{\delta_f(s)}{\delta(s)}=\frac{k_r}{2lC_f}\left[\frac{1}{\tau_r}+ml_rV\left(\frac{2ll_fC_f}{V}+2lC_f\tau_r-\frac{I}{\tau_r}\right)\frac{1}{1+\tau_r s}\right]; \quad (18)$$

$$\frac{\delta_r(s)}{\delta(s)}=\frac{k_r}{2lC_f}\left[\frac{1}{\tau_r}+ml_fV\left(-\frac{2ll_rC_r}{V}+2lC_r\tau_r-\frac{I}{\tau_r}\right)\frac{1}{1+\tau_r s}\right]. \quad (19)$$

3.1.2. Feedback controller

In addition to feedforward controller, feedback controller is used to compensate the influence of external disturbances or dynamic uncertainties. With the application of optimal control theory, the feedback controller is designed as the following way.

When the controlled variables are defined to be the errors of side slip angle and yaw rate, the equation concerning the error variables is derived as follows:

$$\begin{bmatrix}\Delta\dot{\beta}\\ \Delta\ddot{\phi}\end{bmatrix}=\begin{bmatrix}A_{11} & A_{12}\\ A_{21} & A_{22}\end{bmatrix}\begin{bmatrix}\Delta\beta\\ \Delta\dot{\phi}\end{bmatrix}+\begin{bmatrix}B_{11} & B_{12}\\ B_{21} & B_{22}\end{bmatrix}\begin{bmatrix}\delta_{fb}\\ \delta_{rb}\end{bmatrix} \quad (20)$$

where, all elements in the matrix are determined from equations of 2DOF motions as follows:

$$A_{11}=-\frac{2(C_f+C_r)}{mV},\quad A_{12}=-1-\frac{2(l_fC_f+l_rC_r)}{mV^2},$$
$$A_{21}=-\frac{2(l_fC_f-l_rC_r)}{I},\quad A_{22}=-\frac{2(l_f^2C_f+l_r^2C_r)}{IV},$$
$$B_{11}=\frac{2C_f}{mV},\ B_{12}=\frac{2C_r}{mV},\ B_{21}=\frac{2l_fC_f}{I},\ B_{22}=-\frac{2l_rC_r}{I}.$$

This equation means that the stability of the error can be compensated by the state feedback controller as follows:

$$\begin{bmatrix}\delta_{fb}\\ \delta_{rb}\end{bmatrix}=-\begin{bmatrix}K_{11} & K_{12}\\ K_{21} & K_{22}\end{bmatrix}\begin{bmatrix}\Delta\beta\\ \Delta\dot{\phi}\end{bmatrix}. \tag{21}$$

By using LQR control design theory, the gain matrix of the feedback controller can be determined to minimize the following performance index.

$$J_{MMC}=\int_0^\infty\left[\left(\frac{\Delta\beta}{\beta_{\max}}\right)^2+\left(\frac{\Delta\dot{\phi}}{\dot{\phi}_{\max}}\right)^2+\left(\frac{\delta_{fb}}{\delta_{f\max}}\right)^2+\left(\frac{\delta_{rb}}{\delta_{r\max}}\right)^2\right]dt \tag{22}$$

where, the denominators of each term indicate the allowable values of state errors and control inputs.

3.2. Lane-Keeping Controller Design

In the design of lane-keeping controller, all state feedback control to steering wheel angle is employed by assuming that all state variables are measurable or observable by estimator. Mouri proposed Extended Kalman Filtering technique to estimate vehicle states and road configuration for front-wheel-steering vehicle based on information from CCD camera (Mouri, 2002). The same configuration of estimator is also applicable for active four-wheel-steering vehicle. To examine how 4WS improves lane-keeping performance, this paper applies that 4WS vehicle to a simple lane-keeping control task. Since the steering responses of vehicle are expressed in vehicle-fixed coordinate system, they must be transformed into the earth-fixed coordinate system in lane-keeping control design.

In the case of 4WS-A, the vehicle body side slip angle is zero, hence the lateral velocity becomes proportional to the heading angle as follows:

$$\dot{y}_{cr}=V(\beta+\phi_r)=V\phi_r \tag{23}$$

From the yaw rate response in Equation (10), yaw motion can be expressed as follows:

$$\ddot{\phi}=-\frac{1}{\tau_r}\dot{\phi}+\frac{k_r}{\tau_r}\delta \tag{24}$$

From Equation (24) and Equation (25), the state-space equation of 4WS-A vehicle in lane-keeping control can be obtained as follows:

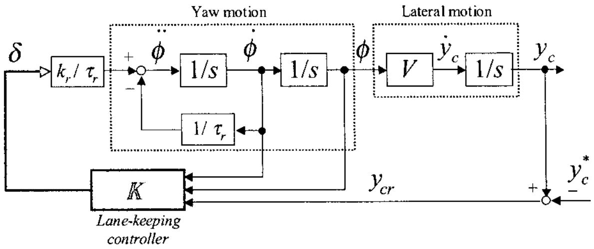

Figure 4. Block diagram of lane-keeping system by 4WS-A vehicle (sideslip zeroing 4WS).

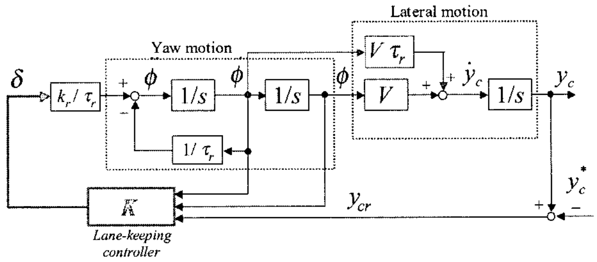

Figure 5. Block diagram of lane-keeping system by 4WS-B vehicle (lateral acceleration phase-lag zeroing 4WS).

***4WS-A vehicle*:**

$$\begin{bmatrix}\ddot{\phi}\\ \phi_r\\ \dot{y}_{cr}\end{bmatrix}=\begin{bmatrix}-1/\tau_r & 0 & 0\\ 1 & 0 & 0\\ 0 & V & 0\end{bmatrix}\begin{bmatrix}\dot{\phi}\\ \phi_r\\ y_{cr}\end{bmatrix}+\begin{bmatrix}k_r/\tau_r\\ 0\\ 0\end{bmatrix}\delta \tag{25}$$

On the other hand, body side slip angle of 4WS-B is not zero but it is proportional to the yaw rate as follows:

$$\dot{y}_{cr}=V(\beta+\phi)=V(\tau_r\dot{\phi}+\phi_r)=V\tau_r\dot{\phi}+V\phi_r \tag{26}$$

From Equation (25) and Equation (27), the state-space equation of 4WS-B in lane-keeping control can be expressed as:

***4WS-B vehicle*:**

$$\begin{bmatrix}\ddot{\phi}\\ \phi_r\\ \dot{y}_{cr}\end{bmatrix}=\begin{bmatrix}-1/\tau_r & 0 & 0\\ 1 & 0 & 0\\ V\tau_r & V & 0\end{bmatrix}\begin{bmatrix}\dot{\phi}\\ \phi_r\\ y_{cr}\end{bmatrix}+\begin{bmatrix}k_r/\tau_r\\ 0\\ 0\end{bmatrix}\delta \tag{27}$$

The control input of lane-keeping controller is determined by using linear quadratic control theory. All state variables of vehicle are fed back to determine the steering wheel angle as the following expression.

$$\delta=-K_{\dot{\phi}}\dot{\phi}-K_{\phi}\phi_r-K_{yc}y_{cr} \tag{28}$$

where, the state feedback gains, $K_{\dot{\phi}}$, K_{ϕ}, K_{yc}, are determined to minimize the performance index which regards only lateral deviation from the desired lane as follows:

$$J=\int_0^{\infty}(q_{yc}y_{cr}^2+r\delta^2)dt. \tag{29}$$

where, q_{yc} indicates the weighting coefficient of lateral deviation which refers to the level of the control achievement and r indicates the weighting coefficient of steering wheel angle which refers to the lane-keeping controller effort.

3.3. Road Curvature Estimation Using Kalman Filter

In the case of curved roadway, road curvature is treated as a disturbance which reflects in steady-state error. To deal with this problem, this section proposes a control algorithm, with the application of Kalman filter, for estimating road curvature by detecting only the vehicle's lateral deviation, without requiring feedforward of road curvature.

The change in road curvature is approximated as the first-order system disturbed by Gaussian white noise, which can be expressed as:

$$\dot{\rho}=-\lambda\rho+w \tag{30}$$

where, w indicates the process noise of the control plant, λ indicates the dynamic characteristics of curvature variation. The lateral deviation at the sensor near the front bumper, employed for estimating vehicle states together with curvature, can be expressed as follows:

$$y_{sr}=y_{cr}+l_s\phi_r-\frac{l_s^2}{2}\rho+v \tag{31}$$

where, l_s indicates the distance from CG to front bumper, and v indicates observation noise. Determining the covariances of process noise and observation noise, the Kalman filter can be designed. To construct the lane-keeping controller with curvature estimation, the curvature will be included as a state variable so that the state-space equation of each type of vehicle can be rewritten as follows:

4WS-A vehicle:

$$\begin{bmatrix}\ddot{\phi}\\ \dot{\phi}_r\\ \dot{y}_{cr}\\ \dot{\rho}\end{bmatrix}=\begin{bmatrix}-1/\tau_r & 0 & 0 & 0\\ 1 & 0 & 0 & -V\\ 0 & V & 0 & 0\\ 0 & 0 & 0 & -\lambda\end{bmatrix}\begin{bmatrix}\dot{\phi}\\ \phi_r\\ y_{cr}\\ \rho\end{bmatrix}+\begin{bmatrix}k_r/\tau_r\\ 0\\ 0\\ 0\end{bmatrix}\delta+\begin{bmatrix}0\\ 0\\ 0\\ 1\end{bmatrix}w \tag{32}$$

4WS-B vehicle:

$$\begin{bmatrix}\ddot{\phi}\\ \dot{\phi}_r\\ \dot{y}_{cr}\\ \dot{\rho}\end{bmatrix}=\begin{bmatrix}-1/\tau_r & 0 & 0 & 0\\ 1 & 0 & 0 & -V\\ V\tau_r & V & 0 & 0\\ 0 & 0 & 0 & -\lambda\end{bmatrix}\begin{bmatrix}\dot{\phi}\\ \phi_r\\ y_{cr}\\ \rho\end{bmatrix}+\begin{bmatrix}k_r/\tau_r\\ 0\\ 0\\ 0\end{bmatrix}\delta+\begin{bmatrix}0\\ 0\\ 0\\ 1\end{bmatrix}w \tag{33}$$

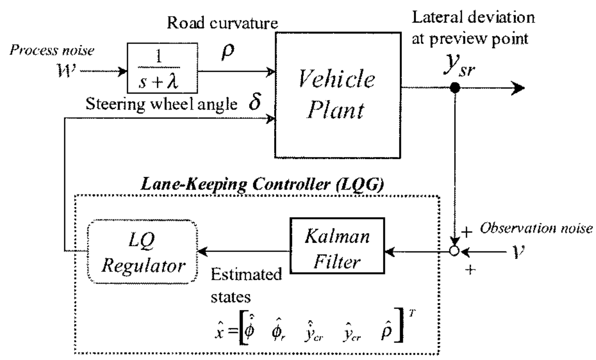

Figure 6. Description of lane-keeping system coupled with curvature estimation by Kalman filter.

Then, applying all state feedback control to the steering wheel angle, the control input can be calculated as follows:

$$\delta=-K_{\dot{\phi}}\dot{\phi}-K_{\phi}\phi_r-K_{yc}y_{cr}-K_{\rho}\rho \tag{34}$$

where, feedback gains are determined by optimal control theory to minimize the same performance index shown in Equation (30).

4. SIMULATIONS

4.1. Lane-Keeping Control on Straight Roadway

The lateral desired course, step input with magnitude of

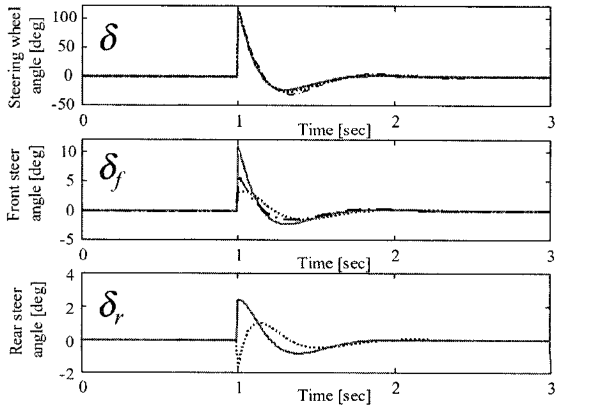

Figure 7. Lane-keeping responses on straight lane (Weights of lane-keeping controller: $q_{yc}=10^2$, $r=1$).

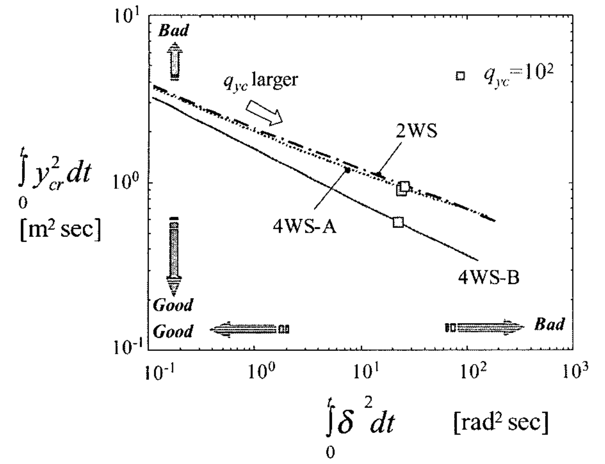

Figure 8. Trade-off curves of lane-keeping system on straight lane (Weights of lane-keeping controller: $q_{yc}=10^{-1}$ to 10^3, $r=1$, simulation time $t=5$ sec.).

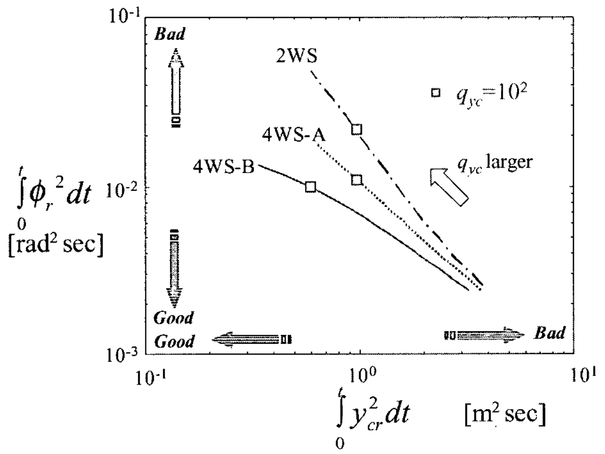

Figure 9. Lane-keeping performance curves on straight lane (Weights of lane-keeping controller: $q_{yc}=10^{-1}$ to 10^3, $r=1$, simulation time $t=5$ sec.).

0.2 meter, is applied to the vehicle running at constant speed of 100 km/h, at 1 second after simulation started. The simulation result is shown in Figure 7.

Figure 7 compares the step desired lane-keeping responses in the case of 4WS-A, 4WS-B, and 2WS vehicle. Clearly, both 4WS-A and 4WS-B vehicles provide the better damping behaviour of both lateral and yaw motions comparing with 2WS vehicle. Especially, in the case of 2WS vehicle, the yaw angle has dominantly oscillatory response. Moreover, the 4WS-B vehicle also provides better responsiveness and damping behaviour in lane-keeping response when comparing with the 4WS-A vehicle.

The lane-keeping performances of three types of vehicles are evaluated by using Trade-off curves. The trade-off curves, shown in Figure 8, plot the square of lateral error along the vertical axis and plot the square of steering wheel angle along the horizontal axis. Simulation result shows that under the same steering angle control input, the 4WS-B vehicle shows the best performance in lane-keeping with smallest deviation. On the other hand, as can be noticed from the graph, lane-keeping control performance by 4WS-A vehicle is not significantly improved from 2WS vehicle. Moreover, to make the

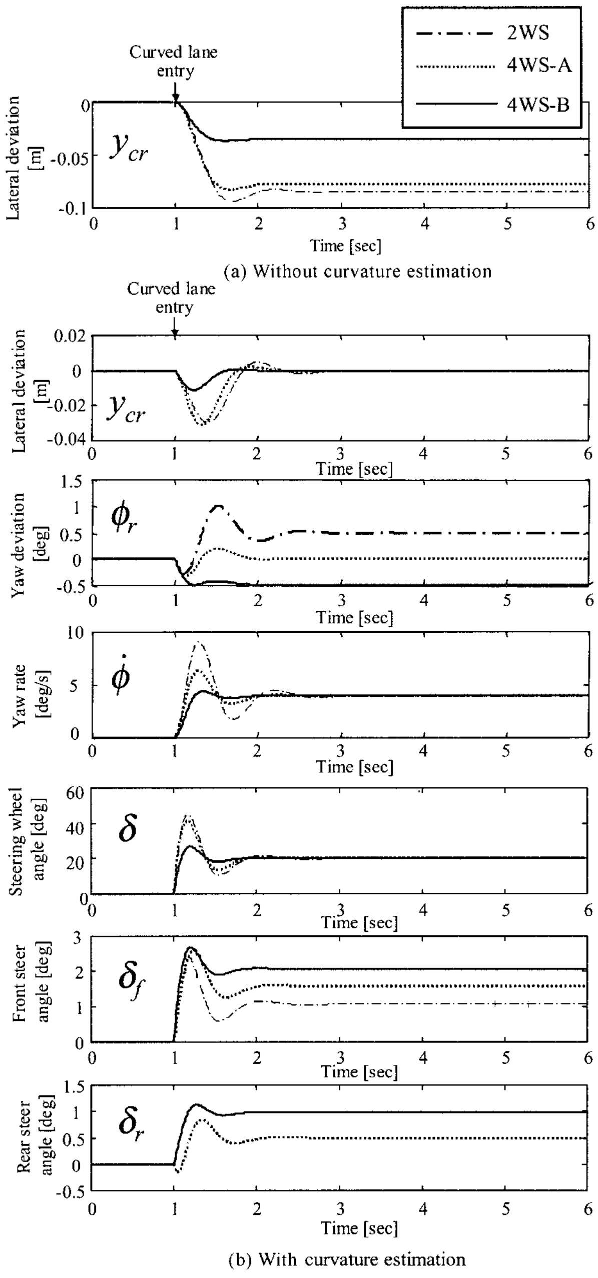

Figure 10. Lane-keeping response on curved lane (Weights of lane-keeping controller: $q_{yc}=10^2$, $r=1$).

better understanding in the improved lane-keeping response of yaw direction, Figure 9 plots the square of the lateral deviation along the horizontal axis and the square of the yaw deviation along the vertical axis. Clearly from the graph, 4WS-B vehicle shows the best performance in lane-keeping control with smallest lateral and yaw deviations.

4.2. Lane-Keeping Control on Curved Roadway

The simulation under the condition, that vehicle runs straightly at constant speed of 100 km/h for 1 second and enters to the curved trajectory with constant radius of 400 m, is conducted.

Figure 10 shows the curved lane-keeping responses of three types of vehicle. Since the curvature estimation is conducted, the lateral deviation is regulated to be zero in steady-state. 4WS-B vehicle provides the satisfactory response of both yaw and lateral directions in transient state whereas the 4WS-A and 2WS still have oscillatory response. 4WS-B also provides the smallest lateral deviation in tracking the curved lane with satisfactory response. However, 4WS-B vehicle has its drawback about the heading error due to its own desired model. On the other hand, 4WS-A vehicle, regulating the side slip angle during cornering, is superior in tracking performance of yaw direction.

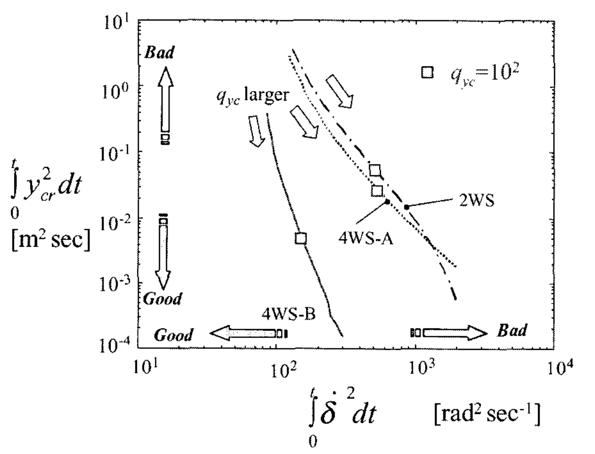

Figure 11. Trade-off curves of lane-keeping system on curved lane (Weights of lane-keeping controller: $q_{yc}=10^{-1}$ to 10^4, $r=1$, simulation time $t=5$ sec.).

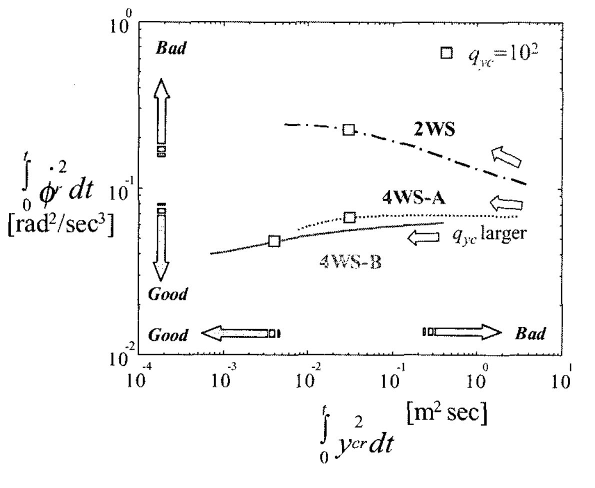

Figure 12. Lane-keeping performance curves on curved lane (Weights of lane-keeping controller: $q_{yc}=10^{-1}$ to 10^4, $r=1$, simulation time $t=5$ sec.).

To evaluate the performance of lane-keeping system, Figure 11 shows the trade-off curves which plots square of the steering wheel angular velocity along the horizontal axis and square of lateral deviation along the vertical axis. As can be noticed from the graph, 4WS-B vehicle provides the best performance of lane-keeping system with least steering effort and least deviation compared with other vehicles. Figure 12 shows lane-keeping performance in lateral and yaw directions by plotting the square of lateral deviation along horizontal axis and the square of yaw rate deviation along vertical axis. Clearly from the graph, 4WS-B provides superior lane-tracking performance to 4WS-A, and 2WS in both lateral and yaw motion.

5. CONCLUSIONS

This paper evaluates the vehicle dynamics of four-wheel-steering system, as an active safety technology, during lane-keeping task along straight and curved roadway by theoretical approach of lane-keeping control. The major conclusions to be drawn from the analysis in this paper are:

(1) By applying active 4WS system to lane-keeping task, the lateral and yaw dynamics during lane-keeping maneuver can be effectively controlled to have desirable characteristics, comparing with 2WS vehicle.

(2) It was proved that, comparing with conventional zero-sideslip 4WS (4WS-A), 4WS which makes the phase delay of lateral acceleration be zero (4WS-B) provides the best lane-keeping performance in both lateral and yaw directions during straight roadway and curved roadway.

(3) Compared to 4WS-A, it was clarified that 4WS-B effectively reduces steering effort in lane-keeping task during both straight roadway and curved roadway.

REFERENCES

Alleyne, A. (1997). A comparison of alternative intervention strategies for unintended roadway departure (URD) Control. *Vehicle System Dynamics* **27, 3,** 157–186.

Fujioka, T. and Omae, M. (1999). Overview of control for automatic driving system. *The Journal of the Robotics Society of Japan* **17, 3,** 18–23.

Furukawa, Y., Yuhara, N., Sano, S., Takeda, H., and Matsushita, Y. (1989). A review of four-wheel-steering studies from the viewpoint of vehicle dynamics and control. *Vehicle System Dynamics* **18,** 151–186.

Hedrick, J. K., Tomizuka, M. and Varaiya, P. (1994). Control issues in automated highway systems. *IEEE Control Systems* **12,** 21–32.

Mouri, H. and Furusho, H. (1997). Automatic path tracking control using linear quadratic control theory. *IEEE Conference on Intelligent Transportation Systems.*

Mouri, H., Shirato, R., Furusho, H. and Nagai, M. (2002). Investigation of automatic path tracking using extended kalman filter. *JSAE Review* **23, 1,** 61–68.

Nagai, M. (1989). Active four-wheel-steering system by model following control. *Proceedings of the 11th IAVSD Symposium*, Kingston, 428–439.