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A Preview Predictor Driver Model with Fuzzy Logic for the Evaluation of Vehicle Handling Performance

퍼지로직을 기초로한 차량 조종안정성 평가를 위한 예측 운전자 모델

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ABSTRACT

A fuzzy driver model based on a preview-predictor and yaw rate is developed. The model is used to investigate the handling performance of two wheel steering system(2WS) and four wheel steering system(4WS) vehicles. The two degree-of-freedom model which has yaw and lateral motion predicts the path of the vehicles. Based upon the yaw rate and lateral deviations, the fuzzy engine describes the human driver's complicated control behavior which is adjusted for the driving environment. Both typical single lane change maneuver and double lane change maneuver are adopted to demonstrate the feasibility of fuzzy driver model.

1. Introduction

During the last two decades, a number of vehicle models for 2WS or 4WS have been developed to study the handling performances of the vehicles. Simulations of the models include sophisticated expressions of the vehicle suspensions, tires, and sprung mass motions and are able to predict nonlinear and limit vehicle response. these vehicle simulations are, however, by themselves inadequate to study many handling problems for the automobile safety. the problem is that the simulations must have steering control inputs that are supplied by the user as a function of time. This is difficult to do for the complex maneuvers used by drivers to avoid accidents. An additional complication is that the driver is adaptive. As a result the control inputs used by a driver to successfully perform a maneuver change whenever the vehicle parameters, speed or maneuver conditions vary. The best way to generate these complicated maneuver dependent control inputs is through a closed loop computer simulation of the driver.

The most common man-machine system in use today is a driver and an automobile, but

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little is known about the details of driver dynamic responses and how they interact with the vehicle dynamic characteristics. The control scheme used in this paper is a fuzzy logic which includes preview control strategies for regulation or tracking tasks. A common example of this type of control strategy occurs during normal automobile path following in which drivers "look-ahead" to follow a desired path. Human operators, as part of various man-machine systems, typically employ preview control strategies to control and stabilize such systems. It is widely recognized that human operators are capable of controlling and adapting to a wide variety of dynamic systems, many of which are vehicles with a preview-oriented control requirement.

There are two kinds of driver models which are compensation tracking models and preview tracking models. The preview tracking models take into account future path information, but the compensation tracking models do not.

Iguchi[1] presented a PID compensation for driver model shown in Fig.1. Asahkens and Mcrure[2] presented a model based on a compensation tracking model which considered driver response time delay, driver action delay, leading time constant and lag time constant. Kondo and Yoshimoto[3,4] proposed a preview tracking model which uses the future path information as shown in Fig.2. This model gives better tracking accuracy than the compensation tracking model. MacAdam and Sheridan[5,6] derived and optimal preview control model in which the driver is always looking at a finite interval of the future path and driving his vehicle aiming at a goal that is to minimize the tracking error. To gain more understanding about the dynamic property of the system, Guo[7,8] presented an algorithm to perform the modeling of the closed loop driver-vehicle directional control system from a mathematical point of view and preview follower theory.

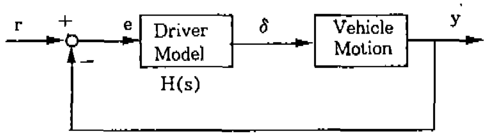

Fig.1 The Compensation Tracking Models

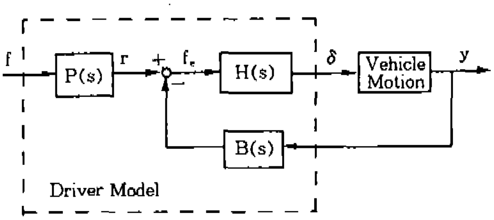

Fig.2 Preview Tracking Models

In this paper a fuzzy driver model based on the preview-predictor and yaw rate is developed. The model is used to investigate the handling performance of 2WS and 4WS vehicles. The two degree-of-freedom model which has yaw and lateral motion predicts the path of the vehicles. In the design stage of vehicle suspension, this fuzzy driver model can be used as a tool to estimate vehicle's handling performance.

2. Preview Error by Predictor Models

In order to identify a driver's behavior, a preview-predictor model is used. The driver model samples the vehicle states regularly to determinde vehicle position and yaw rate. From these quantities the driver predicts what the future path will be. The predicted quantities are then compared to their desired values. The yaw rate and the errors between the predicted and the desired path are used as the basis for changes in control inputs to the vehicle. Fig.3 illustrates the basic idea.

The model uses feedback loops on the average front wheel steering angle and on the vehicle state variables. The output of the predictor and the current yaw rate are used to calculated a correction to the average front wheel steering angle. The fuzzy rule determines the steering input angles to correct the path. As Fig.3 shows, the predicted path is determined at 3 points at each time, including the current position. The points on the path are equally spaced in time, separated by t_{ppt} as follows :

$$t_{pred}=(i-1)t_{ppt}, \qquad i=1,\ 2,\ 3 \tag{1}$$

In this study, $t_{ppt}=0.5$ seconds and there are three t_{ppt} intervals. For a vehicle speed of 27.7m/sec(100km/hr), this corresponds to a look ahead distance of 41.55m.

The predicted path is governed by a two degree-of-freedom predictor vehicle model. The two degree-of-freedom predictor model has the vehicle's yaw and lateral velocities. The perceived vehicle kinematics at the sampling time is used as initial conditions for the differential equations, and the control commands δ. The dynamics of the prediction model are

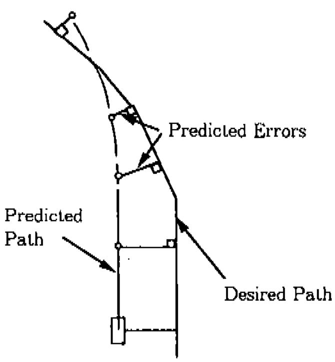

Fig.3 The Predicted Errors by Preview Model

$$mu(\frac{d\beta}{dt}+r)=2F_{yf}+2F_{yr} \tag{2}$$

$$I\frac{dr}{dt}=2aF_{yf}-2bF_{yr} \tag{3}$$

where m is the predictor vehicle's mass, u is longitudinal velocity, β is slip angle, γ is yaw rate, a ad b are wheel locations, and I is the mass moment of inertia. the cornering forces of the front and rear tire are

$$F_{yf}=-C_f(\beta+\frac{a}{u}r-\delta_f) \tag{4}$$

$$F_{yr}=-C_f(\beta-\frac{b}{u}r) \tag{5}$$

where C_f and C_f are the cornering coefficients for front and rear tires respectively. These equations are integrated numerically. The orientation of the vehicle is

$$v_x=u \tag{6}$$

$$v_y=u(\beta+\phi) \tag{7}$$

$$x=\int(v_x\cos(\phi)-v_y\sin(\phi))dt \tag{8}$$

$$y=\int(v_x\sin(\phi)+v_y\cos(\phi))dt \tag{9}$$

$$\phi=\int r dt \tag{10}$$

wher ϕ is the yaw angle, and x and y are the displacements in the global coordinate. Once the vehicle's predicted path has been determined, the preview-predictor model proceeds in and identical way to calculate the steering control inputs with fuzzy reasoning.

One of two inputs for the fuzzy engine is the weighted average of the errors between the predicted and desired positions at three preview points. The perpendicular distance to the desired path, D_{pi}, is calculated for each predicted path point. This distance is ideally along a line perpendicular to the desired path closest to the vehicle by a search procedure. The steering error can be calculated as :

$$ERR = \sum_{i=1}^{3} WT_i K_{pi} D_{pi} \tag{11}$$

$$K_{pi} = \frac{2(a+b)}{3}(1+KD(u_{pi}^2+v_{pi}^2))/S_{pi}^2 \tag{12}$$

where S_{pi} is the distance from the current vehicle position to the i-th predicted point, u_{pi} and v_{pi} are the vehicle's predicted longitudinal and lateral velocities at i-th predicted point, respectively, a+b is wheel base, WT_i is the weighting factor, and KD is its understeer/oversteer coefficient.

3. The Steering Input by Fuzzy Logic

In this section, a fuzzy-logic control scheme is introduced to a driver model, and the feasibility is studied. In fact, fuzzy logic lies in the formulation of the fuzzy rules that use linguistic adjectives and interrelations similar to a natural language. These characteristics make the understanding and modification of a fuzzy logic based control much easier than is possible with conventional techniques. This fuzzy control describes the human driver's complicated control behavior which is adjusted for the driving environment. In order to apply fuzzy logic, the fuzzy set values of the input and output variables are specified as Table 1.

Fig.4 illustrates the membership functions

Table 1 Fuzzy-Set Values for the Driver Model

Error(ERR)	Yaw Rate(r)	Steering Input δ
LB (Left Big : Negative)	NB (Negative Big)	PB (Positive Big)
L (Left : Negative)	NM (Negative Medium)	PM (Positive Medium)
ZE (Zero)	ZE (Zero)	PS (Positive Small)
R (Right : Positive)	PM (Positive Medium)	ZE (Zero)
RB (Right Big : ositive)	PB (Positive Big)	NS (Negative Small)
		NM (negative Medium)
		NB (Negative Big)

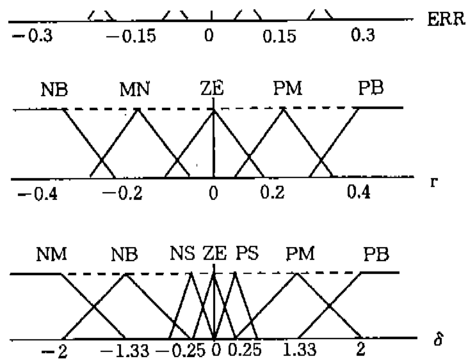

Fig.4 Fuzzy Membership Function for the Driver Model

		ERR				
		LB	L	ZE	R	RB
	NB	PB	PB	PM	PS	ZE
Yaw	NM	PB	PM	PS	ZE	NS
rate	ZE	PM	PS	ZE	NS	NM
	PM	PS	ZE	NS	NM	NB
	PB	ZE	NS	NM	NB	NB

Fig.5 Fuzzy Associative Memory for the Driver Model

of the input and output variables. Next, the fuzzy rule base or bank of Fuzzy associative memory(FAM) rules(Kong and Kosko[9]) are specified as shown in Fig.5. FAM rules draw the output fuzzy set from the imput fuzzy

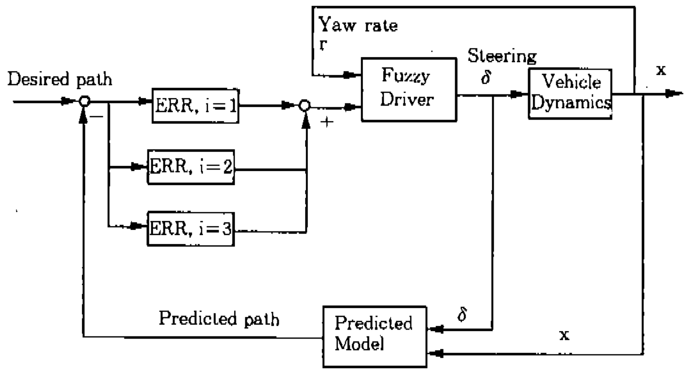

Fig.6 The Overall View of the Driver Model with Fuzzy Reasoning

sets. In other words, these FAM rules are just the compact expression of all possible fuzzy rules. By the fuzzy reasoning methods, the fuzzy outputs are determined by the fuzzy inputs which are the predicted error and yaw rate.

Fig.6 shows the overall view of the driver model with fuzzy reasoning, which simulates the double lane change maneuver for 2WS and 4WS. Just as a human driver would, this driver model evaluated the handling performance of the vehicles.

4. A Vehicle Dynamic Model for the simulation

In order to evaluate vehicle handling performance, a nonlinear bicycle model having 3 degrees-of-freedom(lateral velocity, yaw rate, and roll motion) was used. Although a 3 degree-of-freedom model was originally proposed by Segel[10], the model in this study has different descriptions of external forces and inertia terms. Many papers descrbed vehicle dynamics with just 2 degrees-of-freedom or simple 3 degrees-of-freedom without suspension compliance effect, but this model adds the roll motion with suspension compliance ef-

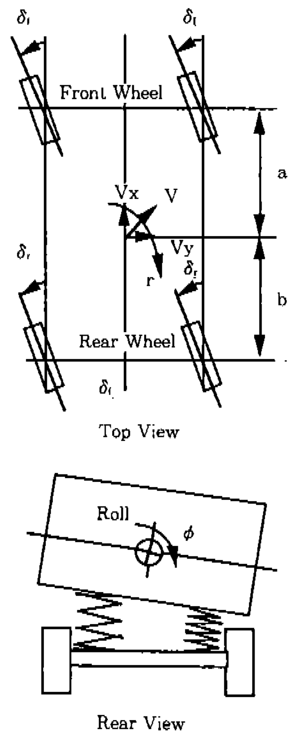

Fig.7 Top and Rear Views of 3DOF Vehicle

fect. In order to validate the fuzzy driver model, two kinds of steering system are compared. One is two wheel steering system (2WS), the other is four wheel steering system(4WS). Meanwhile the 2WS system is the conventional front wheel steering system, the 4WS is the steering system in which rear wheel as well as front wheel are steered. The control schemes for 4WS is described in[12]. Top and rear views of this system are shown in Fig.7. The side slip angle, β is the angle between the vehicle's center line and the velocity vector of the center of gravity(c. g.). The command input is the steer angle for the reference model.

Neither braking nor steering system dynamics were considered in this study. The dynamics of the vehicle system is described as :

Yaw motion :

$$(I_{szz}+I_{uzz})\dot{r}+(-I_{sxz}+I_{uzz}\tan\varepsilon)\dot{p} = 2(a\cdot y_f - b\cdot y_f + N_f + N_r) \tag{13}$$

Lateral motion :

$$(u\cdot m_t)\dot{\beta}+(-m_s z_s + m_u x_u \tan\varepsilon)\dot{p} = 2(y_f + y_r)-(u\cdot m_t)r \tag{14}$$

Roll motion :

$$\begin{aligned}(&-I_{sxz}+I_{uzz}\tan\varepsilon + m_{uf}h_{uf}a\cdot\Gamma_{\phi f} + m_{uf}h_{uf}b\cdot\Gamma_{\phi r})\dot{r} \\ &+u(-m_s z_s - m_s x_s \tan\varepsilon + m_{uf}h_{uf}a\cdot\Gamma_{\phi f} \\ &+m_{ur}h_{ur}a\cdot\Gamma_{\phi f})\dot{\beta}+\{I_{sxx}+I_{sxz}\tan\varepsilon \\ &+(m_{uf}h_{uf}a\cdot\Gamma_{\phi f}+m_{uf}h_{uf}b\cdot\Gamma_{\phi r})\tan\varepsilon\}\dot{p} \\ &=-(d_f+d_r)p-(K_f+K_r+m_s\cdot g\cdot z_s)\phi \\ &+2L_f\Gamma_{\phi f}-2L_r\Gamma_{\phi r}-u(-m_s z_s - m_s x_s\tan\varepsilon \\ &+m_{uf}h_{uf}a\cdot\Gamma_{\phi f}+m_{uf}h_{uf}b\cdot\Gamma_{\phi r})r\end{aligned} \tag{15}$$

where

$$a=\frac{m_r}{m_t}L,\quad b=\frac{m_f}{m_t}L$$

$$x_s=\frac{am_{sf}-bm_{sr}}{m_f},\quad x_u=\frac{am_{uf}-bm_{ur}}{m_f},$$

$$z_s=\frac{bh_f-ah_r}{L}+\frac{m_{uf}h_f-m_{ur}h_r}{m_f}-\frac{m_t h_t}{m_s}$$

$$z_0=\frac{bh_f+ah_r}{L},\quad \tan\varepsilon=\frac{h_f-h_r}{L}$$

The nomenclatures for the parameters are listed in Appendix A. The data which are used in the simulation are accquisited from sub-compact car of Hyundai. Fig.8 shows the schematic of the 3 DOF vehicle that shows the roll motion axis. the kinematic relations between the state variables are expressed as follows :

$$\dot{\phi}=p,\quad \dot{y}=u(\beta+\theta),\quad \dot{\theta}=r \tag{16}$$

The tire forces and moments can be written in general as :

$$y_f=f_{af}(\alpha_f,\ \gamma_f,\ F_{zf}),$$

$$y_r=f_{ar}(\alpha_r,\ \gamma_r,\ F_{zr}), \tag{17}$$

where α is side slip angle, γ is cambe angle, F_z is the normal force applied, and subscripts f and r represent front and rear wheels, respectively. The detail characteristics of tire is described in[13]. But, for simplicity, the following linear tire model is used in this study :

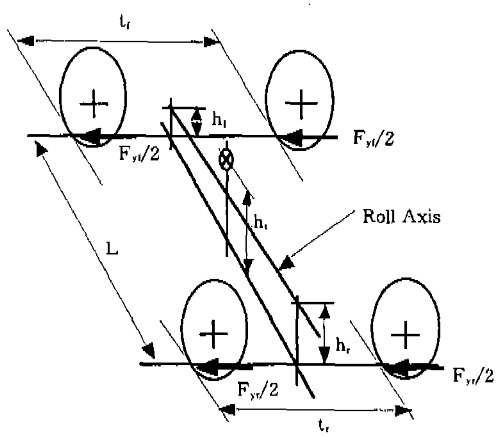

Fig.8 Schematic of the 3DOF Car

$$y_f = -C_{\alpha f}\alpha_f + C_{\gamma f}\gamma_f,\ y_r = -C_{\alpha r}\alpha_r + C_{\gamma r}\gamma_r \quad (18)$$

$$N_f = -N_{\alpha f}\alpha_f + N_{\gamma f}\gamma_f,\ N_r = -N_{\alpha r}\alpha_r + N_{\gamma r}\gamma_r$$

$$L_f = -L_{\alpha f}\alpha_f + L_{\gamma f}\gamma_f,\ L_r = -L_{\alpha r}\alpha_r + L_{\gamma r}\gamma_r$$

which are the function of tire side slip angles and camber angles

$$\alpha_f = b + \frac{a}{u}(r + p\tan\varepsilon) - E_{\phi f}f + E_{yf}y_f - E_{Nf}N_f - \frac{1}{2}E_{yf}m_{uf}a_{uf} - \delta_f$$

$$\gamma_f = \Gamma_{\phi f}f - \Gamma_{yf}y_f + \Gamma_{Nf}N_f + \frac{1}{2}\Gamma_{yf}m_{uf}a_{uf} \quad (19)$$

$$\alpha_r = b + \frac{b}{u}(r - p\tan\varepsilon) - E_{\phi r}f + E_{yr}y_r - E_{Nr}N_r - \frac{1}{2}E_{yr}m_{ur}a_{ur} - \delta_r$$

$$\gamma_r = \Gamma_{\phi r}f - \Gamma_{yr}y_r + \Gamma_{Nr}N_r + \frac{1}{2}\Gamma_{yr}m_{ur}a_{ur}$$

Notice in (19) the control inputs, the front wheel steer angle, δ_f, and the rear wheel steer angle, δ_r. Also, in(19), a_{uf} and a_{ur} are the components of the front and rear accelerations due to yaw, side slip and roll. They can be expressed as :

$$a_{uf} = u(\dot{\beta} + r) + a\cdot\dot{r} + a\tan\varepsilon\cdot\dot{p},$$

$$a_{ur} = u(\dot{\beta} + r) - b\cdot\dot{r} - b\tan\varepsilon\cdot\dot{p} \quad (20)$$

The lateral acceleration equation at any arbitrary location on body are given by

$$y_{pt} = u(\dot{\beta} + r) + (a - x_{pt})\dot{r} - \{(a - x_{pt})\tan\varepsilon + (z_0 - z_{pt})\}p \quad (21)$$

where the subscript pt denotes the point where accelerometer is attached. x_{pt} is the rear directional distance from the axle to the center of mass and z_{pt} is the height from the ground.

The prescribed equations can be rewritten in matrix form which is convenient for computer implementation. The state vector for lateral vehicle dynamics is defined as

$$x = [r\ \beta\ p\ \phi]^T \quad (22)$$

The system can be described in a form of a general nonlinear system :

$$\dot{x}_p = f_p(x, u, t) \quad (23)$$

where $x_p(t) \in R^n$ and $u(t) \in R^m$. A more common form that is linear in input $u(t)$ is

$$\dot{x}_p = f(x, t) + B_p(x, t)u(t) \quad (24)$$

Note that some systems that are not linear in input u(t) can still be put in the form of by using an invertible input transformation. The linearized system is described as

$$\dot{x}_p = A_p x_p + B_p u(t) \quad (25)$$

In this paper the equation(11), which is linear in input, is used.

5. Reference Model

The desired vehicle handling performance is expressed in terms of a reference model, which gives the desired responses to a command signal. Relevant questions to be asked in developing a reference model for handling performances are : What are some criteria for evaluating vehicle handling performance?

What is the relationship between an objective estimation(Instrument measurement) and a subjective estimation(Jury estimation by expert driver)? Many works describe these issues with varied opinions. But, most of these agree on several points. A car which has shorter rise time for step steer can generally be regarded as having a better handling performance. Also, the shorter the settling time, the better the directional stability of the car. Moreover, the reference model should have zero slip angle at relatively low speed to reduce any unnecessary vehicle yaw motion. In order to realize a desired reference vehicle model based on these points, it has been determined that the tire cornering stiffness should be increased while yaw inertia moment is decreased. Based on these observations, the reference vehicle model is set up as

$$\dot{x}_m = A_m x_m + B_m r \tag{26}$$

where x_m is the 4×1 state vector which has the same dimension as x, B_m is the 4×1 control vector, and A_m is the 4×4 system matrix whose elements reflect the observations earlier.

6. A Simulation with the Driver Model

The driver model with fuzzy logic is used to investigate the handling performance of vehicles for a single lane change maneuver and a double lane change maneuver. A conventional 2WS vehicle and a 4WS vehicle which has control scheme proposed in this paper, were evaluated. Two vehicles are driven to follow a desired path by the fuzzy predictor driver model in Fig.9 for the single lane change maneuver. Overall, the maneuver is performed well and the vehcle is stabilized rapidly at the end of the maneuver. The trajectory seems quite reasonable and close to what would be expected from a real driver.

Fig.10 describes the two vehicles dynamic behavior for the double lane change. They are transient responses of two vehicles where those vehicles follow a desired course for the lane change at 30m/s. Although the two vehicles follow almost the same track, the yaw rate of 4WS is much less than that of 2WS. The rear wheel of 4WS steers such that the

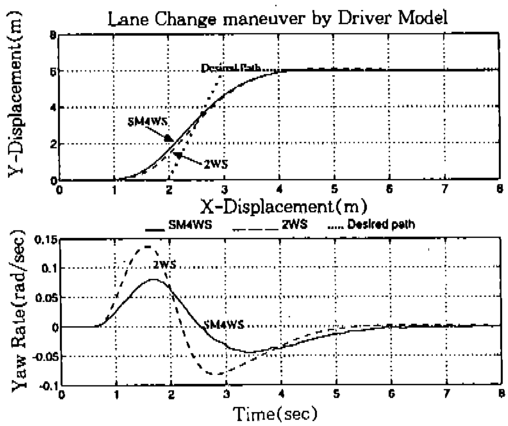

Fig.9 Lane Change Maneuver by Driver Model

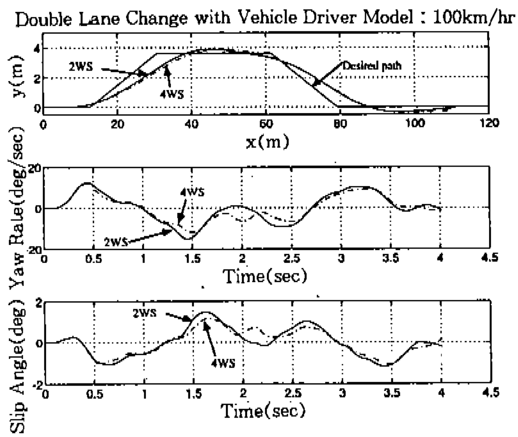

Fig.10 The Double Lane Change Maneuver for 2WS and 4WS by the Fuzzy Predictor Driver Model

unnecessary vehicle yaw rate is reduced. The initial speed was taken to 27.7m/sec(100km/hr). This is a relatively severe maneuver involving peak yaw rate levels of approximately 17 deg/sec. Although the two vehicles follow almost the same track in the double lane change maneuver, the peak yaw rate level of the 4WS was reduced by approximately 20% (3.4) under the 2WS system. For the 4WS vehicle, the peak of side slip angle as well as yaw rate has been reduced by 15% under that of the 2WS vehicle.

The wheels of the 4WS vehicle were steered to reduce unnecessary yaw rate, result in improvement of the vehicle handling performance. To investigate the lane change handling performance of 4WS and 2WS, a closed-loop simulation with the driver model was simulated.

7. Conclusion

The computer model of drivers based upon fuzzy logic has been implemented through a sophisticated vehicle simulation. A number of simulation runs were made using the driver models to simulate two maneuvers, a single lane change and a double lane change. The result of these simulations showed that the fuzzy driver model could successfully perform both maneuvers. Just like a human driver, fuzzy engine steered vehicle's handle wheel and stabilized the dynamic behavior of the vehicles. The fuzzy driver model is used to investigate the handling performance of 2WS and 4WS vehicles. The two degree-of-freedom predictor model which has yaw and lateral motion predicts the path of the vehicles. In the design stage of vehicle suspension, this fuzzy driver model can e used as a tool to estimate vehicle's handling performance.

* This research has been supported by catholic univ. of Taegu-Hyosung.

Appendix A. Nomenclature for Handling Parameters

$C_{\alpha f}$: Front tire cornering stiffness per tire (positive)

$C_{\alpha r}$: Rear tire cornering stiffness per tire (positive)

$C_{\gamma f}$: Front tire camber stiffness per tire(positive)

C_{γ_r} : Rear tire camber stiffness per tire(positive)

d_f : Front roll damping coefficient

d_r : Rear roll damping coefficient

E_{Nf} : Front aligning torque deflection steer per wheel(positive understeer)

E_{Nr} : Rear aligning torque deflection steer per wheel(positive understeer)

$E_{\phi f}$: Front roll steer coefficient(positive understeer)

$E_{\phi r}$: Rear roll steer coefficient(positive understeer)

E_{yf} : Front lateral force deflection steer per wheel(positive understeer)

E_{yr} : Rear lateral force deflection steer per weel(positive understeer)

h_f : Front roll center height

h_r : Rear roll center height

h_t : Total mass c.g. height

h_{uf} : Front unsprung mass c.g.height

h_{ur} : Rear unsprung mass c.g.height

I_{sxx} : Sprung mass roll inertia

I_{szz} : Sprung mass yaw inertia

I_{uzz} : Unsprung mass yaw inertia

I_{sxz} : Sprung mass product inertia

K_f : Front roll stiffness

K_f : Rear roll stiffness

L : Wheel base

$L_{\alpha f}$: Front overturning moment/slip angle per tire(positive)

L_{ar} : Rear overturning moment/slip angle per tire(positive)

$L_{ar\gamma f}$: Front overturning moment/camber angle per tire(positive)

$L_{ar\gamma_r}$: Rear overturning moment/camber angle per tire(positive)

m_f : Mass on front wheels

m_r : Mass on rear wheels

m_s : Sprung mass

m_t : Total mass

N_{af} : Front tire aligning torque/slip angle per tire(positive)

N_{ar} : Rear tire aligning torque/slip angle per tire(positive)

$N_{\gamma f}$: Front tire aligning torque/camber angle per tire(positive)

N_{γ_r} : Rear tire aligning torque/camber angle per tire(positive)

p : Roll velocity

r : yaw velocity

y : Lateral displacement

β : Side slip angle

ϕ : Roll angle

θ : Yaw angle

Γ_{Nf} : Front aligning torque deflection camber per wheel(positive understeer)

Γ_{Nr} : Rear aligning torque deflection camber per wheel(positive understeer)

Γ_{af} : Front roll camber coefficient(positive understeer)

Γ_{ar} : Rear roll camber coefficient(positive understeer)

Γ_{yf} : Front lateral force deflection camber per wheel(positive understeer)

Γ_{yr} : Rear lateral force deflection camber per wheel(positive understeer)

u : Vehicle velocity

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