An electronic stability program (ESP) system for passenger cars can be utilized effectively to stabilize a skidding vehicle and thus make the vehicle more controllable to reduce the risk of traffic accidents and to improve driving safety. In this paper, a vehicle multi-body dynamic model constructed using MSC.ADAMS/Car is adopted to investigate the reliability of the ESP system. To improve control performances, controllers used in the ESP system are designed according to fuzzy logic and PID control theory. Then, a joint simulation model is established in a MATLAB/Simulink environment, in which the ESP control module is embedded into the vehicle dynamic model achieved from ADAMS/Car. After establishing the joint model in the ADAMS/Car environment, experimental simulations can be conducted by step steering, ISO emergency double lane change, and fish hook tests to study various vehicle behaviors with the developed ESP system. The simulation results demonstrate that the designed ESP system can improve vehicle handling and stability and assist in adapting to various roads and driving conditions.

Keywords: Electronic stability program, multi-body dynamics, fuzzy logic, PID controller.

1. INTRODUCTION

The demand for studies regarding system control strategies and vehicle performance optimization via an electronic stability program (ESP) system has increased for the purposes of enhancing vehicle stability control and improving driving safety [1-12]. The ESP system is based on an anti-lock brake system (ABS) and anti-slip regulation (ASR) system. It prevents vehicle wheels from locking or skidding when the vehicle brakes or steers. Additionally, by inhibiting an over-steering or under-steering trend, the ESP system can increase its ability for anti-skid. Shibahata [1] developed a simple method called the $\beta$-method to analyze the effect of a vehicle’s sideslip angle on its maneuverability. Anton [2] developed a system to help a driver keep his/her car under control. The developed system regulates the engine’s torque and wheel brake pressure using traction control components to minimize the error between actual and desired motions. In the automobile industry, a model based sensor monitoring system applied in the ESP system was developed, implemented, and produced in large volumes by Continental Teves, Inc. A basic component of the ESP system is an on-line sensor monitoring system using sensors, mainly used to detect faults as early as possible to prevent an erroneous control or system malfunction [3]. Anton summarized Bosch ESP experiences [4] and showed that the vehicle slip angle is a crucial indicator of the maneuverability of an automobile. BMW has developed a dynamic stability control (DSC) system, which is essentially a stability and traction control system, based on the simulation of the vehicle dynamics and actual measurement of the driving situations. A comparison of the actual and nominal vehicle situations results in a set of control commands which can be used for vehicle stabilization [13]. Huiyi [14] has derived a vehicle dynamic model with 16 DOF by a verification using MATLAB/Simulink, where after completing the simulation under a normal mode, a real-time window target model under the external mode is produced. Jia [15] has built another vehicle dynamic model and control logic for active yaw control by adding anti-braking and traction control systems in the ESP controller.
Since a vehicle is a complex nonlinear system, using common 2-DOF- and 7-DOF-models of a vehicle dynamic system will not completely suffice to reflect vehicle movements in various extreme conditions. Therefore, in this paper, we first construct a multi-body dynamic vehicle model using MSC.ADAMS/Car. Then we embed the designed ESP control module with the developed fuzzy logic PID controllers in MATLAB/Simulink into the established multi-body dynamic model. Finally, we carry out joint simulations under the ADAMS/Car to inspect the reliability of the ESP system in various experimental conditions.

2. ESTABLISHMENT OF CAR MULTI-BODY DYNAMIC MODEL

2.1 Car Multi-body Dynamic Model

Using ADAMS/Car, we construct a multi-body dynamic car model, which consists of the vehicle body, the power train, front and rear suspension, braking, steering, and tire systems; we further establish external constraints provided by ADAMS/Car, such as road conditions [16]. Notice that the tire system used in development adopts a PACEJKA model [17] and the brake system employs the disc brake with a 4-channel ABS. Other subsystems are constructed according to the required vehicle parameters.

Furthermore, in the ADAMS/Car simulation, the driving conditions are controlled by File Driven Events in ADAMS/SmartDrive, which includes the driver’s open-loop and closed-loop control of the accelerator, the steering wheel, the clutch and transmission, and so on.

2.2 Brake Subsystem Structure

A brake subsystem is key in the entire control system for constructing a multi-body dynamic model. Since the ESP system fully relies on the ABS system, a precise control of the braking force on each wheel is required for better control performance. In this paper, we use four-channel ABS disc brakes (each channel is controlled independently) as shown in Figure 1, where the brake caliper is connected to the column of suspension while the brake disc is mounted on the wheel through the input communicator. The brake pressure is determined by a quantitative relationship between brake pedal force and brake pipe pressure. According to the location of the brake caliper as well as its other factors, a braking torque is determined and applied to the vehicle axle. The wheel slide rate is then controlled by a trigger signal through the ABS system.

![Figure 1: ABS braking system template](image)
Taking the left front wheel as an example, the brake torque is determined as the following:

\[
\text{ABS}_{4\text{disk}}.\text{front_left_brake_torque}_{\text{VAR}} = 2 \cdot \text{ABS}_{4\text{disk}}.\text{pvs_front_piston_area} \times \text{VARVAL}(\text{ABS}_{4\text{disk}}.\text{left_front_brake_line_pressure} + \text{ABS}_{4\text{disk}}.\text{front_left_add_brake}) \cdot \text{ABS}_{4\text{disk}}.\text{pvs_front_brake_mu} \cdot \text{ABS}_{4\text{disk}}.\text{pvs_front_effective_piston_radius} \times \text{STEP}(\text{VARVAL}(\text{ABS}_{4\text{disk}}.\text{left_front_wheel_omega})) - 0.0175, 1, 0.0175, -1) \times \text{VARVAL}(\text{ABS}_{4\text{disk}}.\text{front_left_trigger_signal})
\]  

(1)

where the applicable parameters are defined below:

"2": double sides
piston_area: brake cylinder piston area
brake_line_pressure: pressure of the brake line
add_brake: the brake pressure increment caused by the sliding rate increment
brake_mu: brake pad friction coefficient
effective_piston_radius: brake effective radius
wheel_omega: wheel speed
STEP: brake torque when a wheel is doing positive & negative switch continuously
trigger_signal: switching signal of the ABS sliding rate controller.

In Equation (1), the parameter of brake_line_pressure is calculated by the following formula:

\[
\text{left_front_brake_line_pressure} = \text{_brake_system_4Wdisk.pvs_front_brake_bias} \times \text{VARVAL(._brake_system_4Wdisk.cis_brake_demand_adams_id)} \times \text{(_brake_system_4Wdisk.force_to_pressure_cnvt)}
\]  

(2)

where

pvs_front_brake_bias: distribution of the brake force of the front brake
VARVAL(_BRAKE_ABS_4disk.cis_brake_demand_adams_id): brake pedal driving force
_brake_system_4Wdisk.force_to_pressure_cnvt: conversion factor by which the brake pedal force is directly converted into the pressure of the fluid medium (air or brake fluid) in the brake master tube.

Constructing the brake system model leads to five system variables for each wheel. Two used in achieving the ESP function are add_brake and trigger_signal while the rest include line_pressure, brake_torque and wheel_omega, designated for the brake system. These system variables are used to define and construct a simulation platform (control_palette in ADAMS/Controls) to carry out a joint simulation using both ADAMS/Car and MATLAB/Simulink.

2.3 Selection of Input and Output Variables in the Joint Simulation

The ADAMS/Controls module in ADAMS plays a fundamental step in building a complex mechanical system model, performing simulations, and analyzing. In order to use this module, the MATLAB/Simulink-based control module, which serves as a plug-ins function in ADAMS as shown in Figure 2, is established first. Then through the ADAMS/Controls interface, the ADAMS car model is imported to the established MATLAB/Simulink control module using the MATLAB S-function. Using the constructed control platform obtained from the ADAMS/Controls module, eight (8) input variables (actuation variables) and nine (9) output variables (sensor variables) are created via the plant Export template shown in Figure 2, where the definitions of the input and output variables are illustrated.
3. DESIGN OF THE ESP SYSTEM

3.1 Determination of Nominal Values

If the tire’s lateral-stiffness is considered to be a fixed value, the lateral force would be linear with the wheel sideslip angle. Furthermore, if the vehicle is simplified into a 2-DOF linear model with only the lateral movement along Y-axis and the yaw movement about the Z-axis, then the linear relationship among the steering input $\delta$, yaw rate $\gamma$, lateral acceleration $u_y$, sideslip angle $\beta$, and vehicle velocity $u_x$ can be described in Equation (3) which is shown below [18]:

\[
\begin{align*}
(k_1 + k_2)\beta + \frac{1}{u_x}(ak_1 - bk_2)\gamma - k_1\delta &= m(u_y + u_x\gamma) \\
(ak_1 - bk_2)\beta + \frac{1}{u_x}(a^2k_1 + b^2k_2)\gamma - ak_1\delta &= I_x\gamma
\end{align*}
\]

Therefore, the nominal values of the yaw rate and the sideslip angle required by the ESP control algorithm can be obtained by solving Equation (3).

3.2 Structure of the ESP System

The ESP control algorithm is designed to have the hierarchical structure shown in Figure 3. It is divided into three control layers: (1) yaw torque control; (2) wheel slip-rate control (braking pressure); and (3) control of pumps and valves. The first control layer uses the vehicle posture as its control object. The ESP control unit (ECU) constantly calculates $\Delta\omega_y$ and $\Delta\beta$, which are designated as the differences between the nominal values and the actual values of the yaw rate and sideslip angle, respectively. If both differences are in their allocated ranges, the ESP system will take no actions. Otherwise, the ESP system will be...
activated according to the following steps: the first layer will calculate the required yaw-torque-increment \( \Delta M \) according to \( \Delta \omega \gamma \) and \( \Delta \beta \) and proceed to use the obtained \( \Delta M \) to determine an optimal slip-rate for each wheel and to pass the slip-rate increment \( \Delta \lambda \) to the second control layer. The second control layer will then use each vehicle wheel as its control object. According to the slip-rate increment \( \Delta \lambda \) from the first control layer and the actual slip-rate \( \lambda \), the ESP system will calculate the suited brake force for each wheel and then determine the brake pressure as well as switch time for all the brake solenoid valves. Finally, the third layer will incorporate the hardware control of valves, pumps and so on.

![Diagram of the designed ESP control algorithm](image)

**Figure 3: The structure of the designed ESP control algorithm**

### 3.3 Design of the Fuzzy PID Controller

Two fuzzy-PID controllers are designed for the ESP control module. One is a sideslip angle PID controller and the other yaw rate PID controller; each adjusts its control parameters \( K_p \) (proportional constant) and \( K_i \) (integration constant) adaptively using a fuzzy logic control technique [19]. Figure 4 shows the sideslip angle fuzzy logic PID controller as an illustrative example. Note that the control principles for the two fuzzy logic PID controllers are the same.

![Diagram of the fuzzy logic PID controller for sideslip angle control](image)

**Figure 4: The fuzzy logic PID controller for sideslip angle control**
The principles of the fuzzy logic PID controller for the control of sideslip angle are described below:

1. Input and output variables

As shown in Figure 4, the fuzzy logic sub-controller takes the difference between the yaw rate and its nominal value as the input while the other PI sub-controller determines the difference between the sideslip angle and its nominal value as another input. Note that the fuzzy logic sub-controller adjusts two control parameters $K_p$ and $K_i$ for the PI sub-controller. The controller finally generates an output control variable, which is the yaw-torque-increment.

2. Fuzzy logic rules

The fuzzy controller utilizes the normalized variables. The basic domains for normalized variables of the yaw rate error, $E\left(\Delta \omega_r\right)$ and error rate of change, $EC\left(\frac{d(\Delta \omega_r)}{dt}\right)$, are [-1, 1] and [-1, 1], respectively. The normalized control variable has the range [0, 1]. The fuzzy sets are defined as follows:

- The fuzzy set for the observable variable $E$ or $EC$: {NB, NM, NS, ZO, PS, PM, PB}
- The fuzzy set for the control variable $U$: {Z, PS, PM, PG, PB}

Notice that NB, NM, NS, ZO, Z, PS, PM, PG, PB designate negative big, negative medium, negative small, zero, positive small, positive medium, positive gradient and positive big, respectively. Considering that the Gaussian membership function is adopted for each input linguistic variable and each output linguistic variable, $E$ and $EC$, each having seven fuzzy linguistic variables, result in 49 fuzzy rules. The fuzzy controller is devised using the MAMDANI model with the max-min method for inference. The centroid method is employed for defuzzification [19]. Each fuzzy logic rule is expressed as “if ... then ...”, and is listed in Table 1.

<table>
<thead>
<tr>
<th>Ec</th>
<th>PB</th>
<th>PM</th>
<th>PS</th>
<th>ZO</th>
<th>NS</th>
<th>NM</th>
<th>NB</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
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<tr>
<td></td>
<td>PM</td>
<td>PB</td>
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<td>PM</td>
<td>PM</td>
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</tr>
<tr>
<td></td>
<td>PS</td>
<td>PB</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td></td>
<td>ZO</td>
<td>PM</td>
<td>PM</td>
<td>PS</td>
<td>Z</td>
<td>PS</td>
<td>PM</td>
</tr>
<tr>
<td></td>
<td>NS</td>
<td>PB</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td></td>
<td>NM</td>
<td>PB</td>
<td>PG</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>PB</td>
<td>PG</td>
<td>PG</td>
<td>PB</td>
<td>PG</td>
<td>PB</td>
</tr>
</tbody>
</table>

Described above is the design principle for the sideslip angle PI controller; the same design principle is applied to the yaw rate controller, where the fuzzy logic controller input variables are the sideslip angle error and its error change rate. The fuzzy logic controller outputs control variables $Ki$ and $Kp$ adaptively, which will be used by the PI controller to achieve yaw rate feedback control. Figure 5 shows each established PID controller model based on MATLAB/Simulink. As shown in Figure 5, $Ke$ and $Kec$ are the normalization factors of the error $E$ and error change $EC$. Note that the fuzzy controller first outputs the integration constant $Ki$ directly; the
proportional constant $K_p$ is obtained by multiplying $K_i$ and a constant gain $K_u$. Finally, the PI controller output is produced.

The joint controller structure is also detailed in Figure 5. The lower part depicts the sideslip angle controller, which contains a fuzzy logic control module (Fuzzy Logic Controller 1) and a sideslip PI controller; the upper part is the yaw rate controller, which includes a fuzzy logic control module (Fuzzy Logic Controller 2) and a yaw rate PI controller. The final control output is the weighted result of the two sub-controllers.

![Figure 5: The fuzzy-PID controller model](image)

### 3.4 Integrated ESP Control System

In this paper, all the functions of the ESP system module are simplified to an integration, which contains the vehicle dynamic controller (VDC) and ABS modules as depicted in Figure 6. The ECU module in the ESP system is a basic control logic unit of VDC. After comparing the collected four wheel speed signals, body yaw rate, and sideslip angles along with their corresponding 2 DOF nominal values and so on, the yaw moment increment required to balance under-steering or over-steering actions can be calculated. Then the ECU chooses the wheel to control according to its control logic and directly transmits a calculated sliding rate increment to ABS. The ABS unit issues orders to its brake system, which in turn exerts “add_brake” to the wheel in order to increase the balance to ensure the vehicle steering stability. Meanwhile, the ABS unit constantly switches the brake through “trigger_signal” to keep the sliding rate in its ideal range. The system adopts a simple and reliable logic threshold value for control of the sliding rate, which is set between 0.15–0.2.
4. JOINT SIMULATION AND DISCUSSION

4.1 Joint Simulation Model

To carry out experimental simulations to investigate a vehicle’s handling stability in various extreme conditions, the ESP system module is assembled to a car multi-body dynamic model with MATLAB/Simulink shown in Figure 7. Now, we can verify the ESP control effects on the vehicle reliability in various experimental conditions by simulation tests.

4.2 Simulation Test

Based on vehicle test standards, we conduct step steering, ISO emergency double lane change, and fish hook tests to study the control performances. Specifically, our simulation tests include the scenarios in which a car is steering, braking and turning continuously, changing lanes abruptly, evading obstacles and so on [20-21]. These simulation conditions are listed in Table 2.
(1) Step steering angle

The vehicle’s transitional characteristics can be obtained by simulating a step steering angle. In our simulations, the test uses the driver open-loop control when the driver turns the steering wheel sharply at the second seconds and finishes it at the third seconds. The steering wheel turns 100 degrees during the process. As shown in Table 2, there are 4 different step steering angle tests in total.

Table 2. Simulation Conditions

<table>
<thead>
<tr>
<th>Simulation Conditions</th>
<th>Initial Vehicle Speed</th>
<th>Road Adhesion Coef</th>
<th>Pilot control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step steering angle (1)</td>
<td>40 m/s</td>
<td>0.8</td>
<td>Open loop</td>
</tr>
<tr>
<td>Step steering angle (2)</td>
<td>30 m/s</td>
<td>0.5</td>
<td>Open loop</td>
</tr>
<tr>
<td>Step steering angle (3)</td>
<td>20 m/s</td>
<td>0.6</td>
<td>Open loop</td>
</tr>
<tr>
<td>Step steering angle (4)</td>
<td>20 m/s</td>
<td>0.2</td>
<td>Open loop</td>
</tr>
<tr>
<td>ISO Emergency double lane change (1)</td>
<td>30 m/s</td>
<td>0.6</td>
<td>Closed loop</td>
</tr>
<tr>
<td>ISO Emergency double lane change (2)</td>
<td>30 m/s</td>
<td>0.4</td>
<td>Closed loop</td>
</tr>
<tr>
<td>ISO Emergency double lane change (3)</td>
<td>20 m/s</td>
<td>0.5</td>
<td>Closed loop</td>
</tr>
<tr>
<td>Fish hook (1)</td>
<td>30 m/s</td>
<td>0.8</td>
<td>Closed loop</td>
</tr>
<tr>
<td>Fish hook (2)</td>
<td>20 m/s</td>
<td>0.6</td>
<td>Closed loop</td>
</tr>
<tr>
<td>Fish hook (3)</td>
<td>20 m/s</td>
<td>0.4</td>
<td>Closed loop</td>
</tr>
</tbody>
</table>

(a) Movement tracks

(b) Yaw-rate
(c) Sideslip angle

(d) Front wheel steering angle

(e) Lateral acceleration
(f) Longitudinal velocity

(g) Lateral displacement

(h) Four-wheel sliding rate
Figure 8 shows the results from one of our steering angle step tests. For this testing scenario, the car’s initial speed is set to 40 m/s and the road friction coefficient \(\mu\) of 0.8 is used. Without using the ESP control, the car will spin or drift when the driver turns his steering wheel sharply at a high speed. According to our simulated result, the car would be totally out of control within three seconds as depicted in Figure 8a. However, with the ESP system, the car yaw-rate, sideslip angle, and front steering angle are greatly improved (see Figs. 8b, c, and d). In addition, the response of the lateral acceleration is also greatly improved with a regular curve (Figure 8e). The sliding rate from each wheel is kept within 20% when the car travels on the high friction-coefficient road (Figure 8h). In this case, the triggered signal controlling the sliding rate is not activated, but the brake force of the right front wheel increases (see Figure 8i). Finally, the car is able to turn sharply and keep its sideslip angle and yaw-rate in a steady scope while maintaining stability.

The other tests confirm that, without the ESP control, the car on a wet road or iced-over road will spin or drift (out of control at 2.6 seconds for a wet road and 2 seconds for an iced-over road). With the ESP, the car remains under control. Although there are still some sideslips of wheels and fluctuations of the sliding rate on the front right wheel, the control effect can further be improved by adding an auxiliary control wheel.

(2) ISO emergency double lane change

In ADAMS/car, we simulate an ISO emergency double-lane-change condition to investigate the occurrences of overtaking and the motion of a vehicle in order to avoid obstacles. During simulations, the car model is controlled using the driver closed-loop control across a course specified in ISO-3888 [16] with a moving line capacity of 3.586m. We conduct 3 different double lane change tests as listed in Table 2.
(a) Movement tracks

(b) Yaw-rate

(c) Sideslip angle
(d) Front wheel steering angle

(e) Lateral acceleration

(f) Lateral displacement
Figure 9 shows the results from one of our ISO emergency double-lane-change tests. In this test, the car’s initial speed was 30 m/s and the coefficient of friction $\mu$ of the road is set to 0.6. With the ESP control, the car can quickly turn using a smaller radius and complete the lane change accurately (see Figure 9a). The car sideslip angle without the ESP control has a significantly increased mutation after the steering wheel aligning (Figure 9c). Hence, the car can easily spin or drift if the tire road coefficient of friction diminishes or the car speed increases. With the ESP control, the car’s yaw-rate, sideslip angle and front steering angle are significantly improved (Figs. 9b, 9c, 9d). Furthermore, the lateral acceleration response is also enhanced, and its curve appears to be regular as shown in Figure 9e. Since the car doesn’t lose directional stability before being controlled, its longitudinal velocity and lateral displacement almost remain the same (Figs. 9f and 9g).

The other tests also show similar results. A vehicle sideslip angle and yaw rate without ESP control have obviously surpassed their steady values after the steering and aligning of the wheel. The car will easily lose its ease of steering due to its spinning and drifting. With ESP control, the vehicle yaw-rate, sideslip angle and front steering angle are kept in a small steady range. The response of lateral acceleration is also greatly improved with a regular curve. Each sliding rate from four wheels is kept around 20%. The longitudinal velocity and lateral displacement are maintained steadily under control by the driver.

(3) Fish Hook

The fish hook test is mainly used to estimate a transient response and roll stability of a vehicle. The simulation test is conducted using the driver closed-loop control. As listed in Table 2, we conduct 3 different fish hook tests.
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(a) Movement tracks

(b) Yaw-rate

(c) Sideslip angle
(d) Front wheel steering angle

(e) Lateral acceleration

(f) Longitudinal velocity
Figure 10 shows the results from one of our three fish hook tests, in which the car’s initial speed is set to 20 m/s and the coefficient of friction $\mu$ of the road is 0.4. Without ESP control, the car drifts and loses its ease of steering after the first time it returns from turning off and returning back to the road, as shown in Figure 10a. However, the car yaw-rate, sideslip angle, and front steering angle with ESP control are clearly improved (Figure 10b, 10c, 10d). Fig. 10e also shows a significant improvement of the lateral acceleration response. As shown in Figs. 10f and 10g, we also observe an improvement of the longitudinal velocity and lateral displacement. As a conclusion, the tested car is able to travel on the fish hook road with a rapid response, keep the sideslip angle and yaw-rate in a steady range, and maintain a good stability.

From the results of the other tests, it is evident that when the coefficient of friction $\mu$ of the road is 0.6, a car without ESP control runs off the road during the second returning and is in a dangerous state. With ESP control, when the coefficient of friction $\mu$ of the road is either 0.6 or 0.8, the car yaw-rate, sideslip angle, and front steering angle are improved. Similarly, the response of the lateral acceleration is also greatly enhanced. Furthermore, the ESP control can lead to an improvement of the longitudinal velocity and the lateral displacement.

The above simulation results demonstrate that a vehicle equipped with the ESP system can maintain its handling stability in various hazardous conditions. In addition, the ESP system can improve the car’s response in respect to the driver’s control to ensure safety within traffic. The ESP control effect is satisfactory if a car travels on a road with a medium or high coefficient of friction. When the coefficient of friction of a road is extremely low, control of the sliding wheels will be ineffective. It is also worth noting that since the speed has a strong influence on the ESP control effect, a reduction in control could occur when a car runs at a higher speed on a road with a medium coefficient of friction.

5. CONCLUSION

This paper has studied basic principles and control strategies for vehicle stability with an electronic systems program (ESP) control under a simulation environment. Two controllers in the ESP system were designed with fuzzy logic and PID control strategies. At the same time, by using MSC.ADAMS/Car, a multi-body dynamic car model was established and
integrated with the ESP system module for simulations. According to vehicle test standards, we conducted the step steering, ISO emergency double lane change, and the fish hook tests to investigate the ESP control performances for scenarios in which the car was steering, braking and turning continuously, changing lanes abruptly, evading obstacles and so on. The results demonstrate that our designed ESP system can improve vehicle handling and stability and assist the driver in adapting to a variety of roads and driving conditions.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of Foundation of State Key Laboratory of Automobile Dynamics Simulation, China (20071101).

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