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EXTREME DRIVING CHARACTERISTICS ESTIMATION FOR ESP-EQUIPPED PASSENGER CAR

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ABSTRACT−As the vehicle becomes bigger and faster, the importance of vehicle stability in an extreme driving condition caused by sudden steering, road condition or unexpected case has been emphasized. The ESP system is being utilized to improve the handling performance and the vehicle stability. In this study, we implemented various tests and proposed estimation methods for ESP characteristics in extreme driving situations. The estimation methods for ESP proposed in this paper are expected to facilitate developing the control logic and improving the performance of the ESP system.

KEY WORDS : ESP(Electric stability program), Vehicle stability, Handling stability, Extreme driving situation

1. INTRODUCTION

Passenger cars become bigger and faster recently since the driver's demand for a safe leisure has been increased. This implies the drastic needs of vehicle stability and handling performance. Hence, the role and importance of ESP has been emphasized, which recognizes the movement of the vehicle in a sudden steering situation or an extreme driving condition and allows to have a safe and smooth driving by controlling the braking system (Bosch, 2000).

ESP is effective in environments to associate with the lateral acceleration including low frictional roads such as snowy and extreme driving conditions in which excessive slip angle occurs due to the sudden steering (Kazuhico and Yasuji, 1994; Ken *et al.*, 1996).

The motion of a vehicle in an extreme driving condition can be categorized into two cases; a drift when a vehicle inclines outwards, and a spin out when a vehicle inclines inwards regardless of driver's intention. It displays that a vehicle moves excessively in extreme driving condition, and this can be eased by producing yaw moment of a vehicle through the external brake and actuator control ability (Kwak and Lee, 2003).

Vehicle stability estimation is to evaluate a control system for the improvement of the steering performance and stability relative to lateral and longitudinal forces of a tire. It is necessary to study vehicle dynamics and characteristics to estimate vehicle stability (Yoshimi and Masato, 1997; Gillespie, 2002).

No accurate estimation method of ESP characteristics in extreme driving conditions has been developed since it depends on the analytical estimation method or the test drivers' subjective estimation, in which is difficult to guarantee reproducibility and efficiency in a driving test. Consequently, the accurate and objective test methods using accurate instruments are under an investigation. Inagaki *et al.* (1994) tested the vehicle stability by analyzing vehicle movement by using a phase plane method of slide angle and controlling yaw moment created by braking force. Shibahata *et al.* (1992) tested vehicle stability using handling, slide angle, and variation in yaw moment in an extreme driving condition. Although the researches have been dealing with the improvement of vehicle stability, these have difficulties in analyzing a real vehicle movement and estimating the ESP characteristics.

In this study, driving tests using two ESP-equipped vehicles are accomplished under various extreme driving conditions, and the vehicle motion and brake characteristics are analyzed. Moreover, the ESP- equipped vehicle's driving characteristics are estimated by analyzing the production mechanism of the vehicle's compensation moment generated by ESP.

2. CHARACTERISTICS OF ESP

ESP assists a driver to perform a safe maneuver in an

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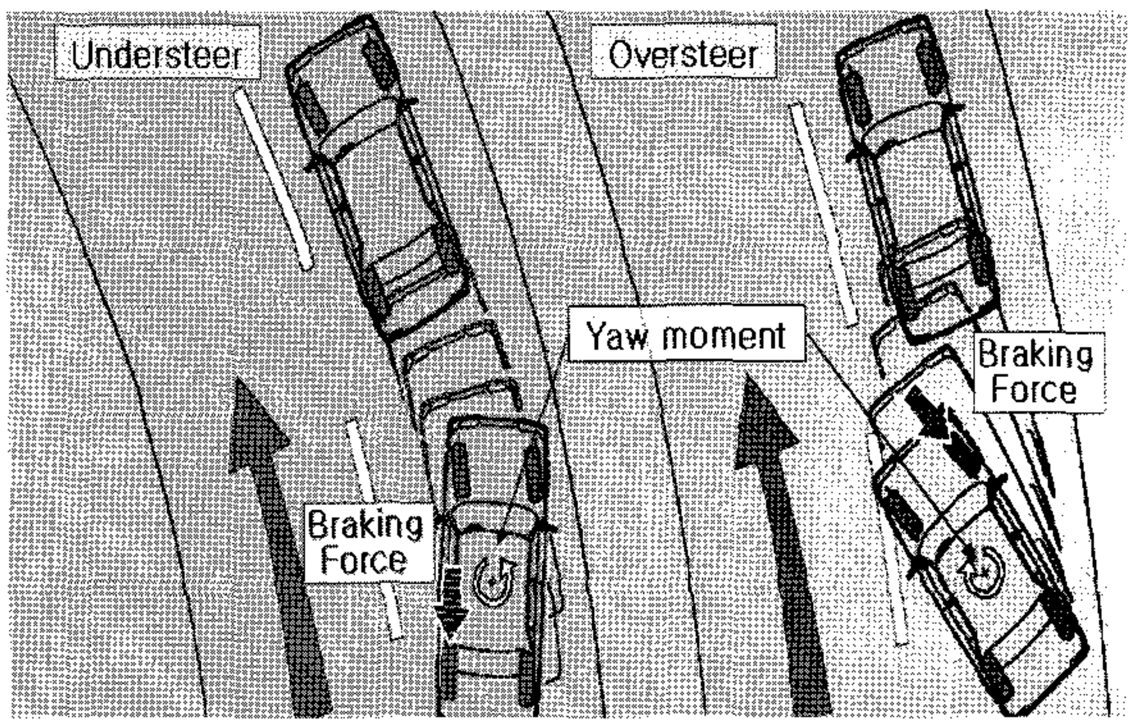
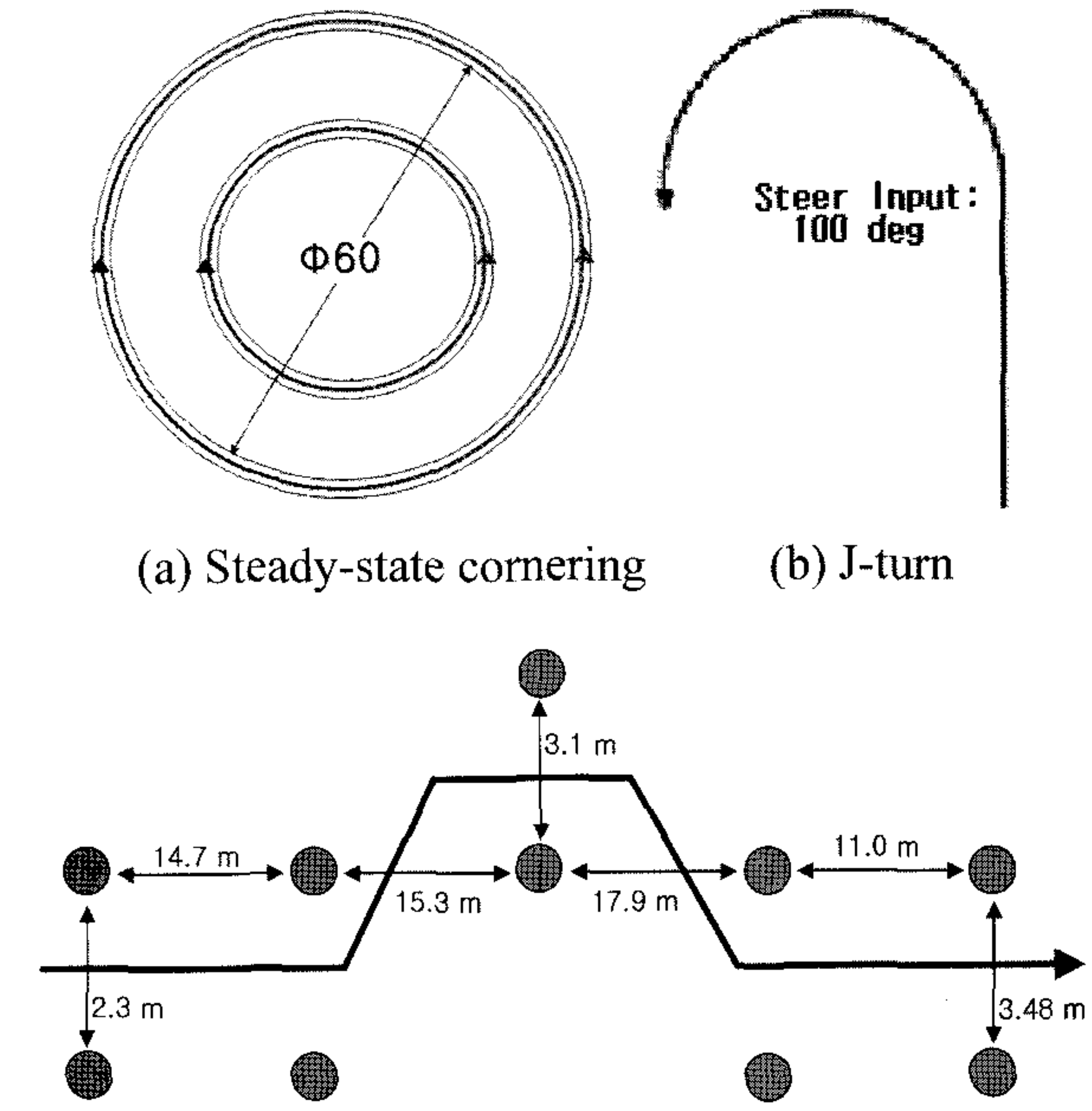


Figure 1. Critical situation with ESP controls.



(a) Steady-state cornering (b) J-turn

(c) Double lane change

Figure 2. Test courses.

emergency situation by selectively controlling each wheel, actuating braking and driving systems repeatedly (controls in driving direction). The ESP-equipped vehicle stays on the lane in an extreme driving condition; when it tries to avoid an obstacle instantly, when it suddenly changes lanes, and when the driver is exposed to a critical situation such as wrong recognition of the road curvature etc.

ESP operates when the desired path of a vehicle is deviated from the actual path. The ESP operation controls the braking force so that understeer (drift) and over-steer (spin out) are prevented; understeer is that the front part of a vehicle leans outwards, and oversteer is that the rear part of vehicle leans outwards. As it is shown in Figure 1, ESP controls the braking system of a vehicle to follow the desired trace using data measured by sensors attached to the vehicle, and guarantees the driving and steering stability (Gillespie, 2002).

3. DRIVING TEST FOR ESP ESTIMATION

To estimate ESP characteristics in extreme driving conditions, the driving test is carried out on a dry road (high μ).

The characteristics of ESP is estimated by analyzing the result data such as ESP control factors including yaw rate, lateral acceleration, brake pressure, steering angle, and tires force measured by 6-axis wheel force transducers in the driving test. Table 1 illustrates measurement systems that were used in the driving test.

Table 1. Measurement system.

Measurement system	Measurement
Gyro-platform	3-axis Acc., Roll, Pitch, Yaw
Steering wheel sensor	Steer angle, Angular velocity, Torque
Speedometer	Speed, Body slip angle
Wheel force transducer	6-axis Wheel force, Rotation speed
Brake pressure sensor	Brake pressure

3.1. Test Courses and Methods

To test the extreme driving characteristics of ESP-equipped vehicle, the test courses in Figure 2, which are steady-state cornering, j-turn, and double lane change, are selected to generate an extreme condition associated with a vehicle slip.

4. TEST RESULT ANALYSIS AND ESTIMATION METHODS

4.1. Steady-State Cornering

In the steady-state cornering test, dynamic characteristic data such as lateral acceleration, side slip angle, yaw rate, steering angle, and brake line pressure are measured under an ESP operation. Consequently, the initial control speed of ESP operation is calculated.

From the steady-state cornering test, two methods to estimate ESP characteristic are proposed. One is the under-steer gradient curve method that estimates an extreme driving condition using lateral acceleration and steering angle as shown in Figure 3.

In Figure 3, the under-steer gradient preserves almost the same value below 0.7 g of lateral acceleration, and it drastically increases over 0.7 g when ESP is turned off. On the other hand, there is a relatively steady increase in gradient when ESP is on. This means that the range over 0.7 g of lateral acceleration is an extreme driving condition and ESP should be operated and deliver the braking force to the wheels so that yaw moment compensation

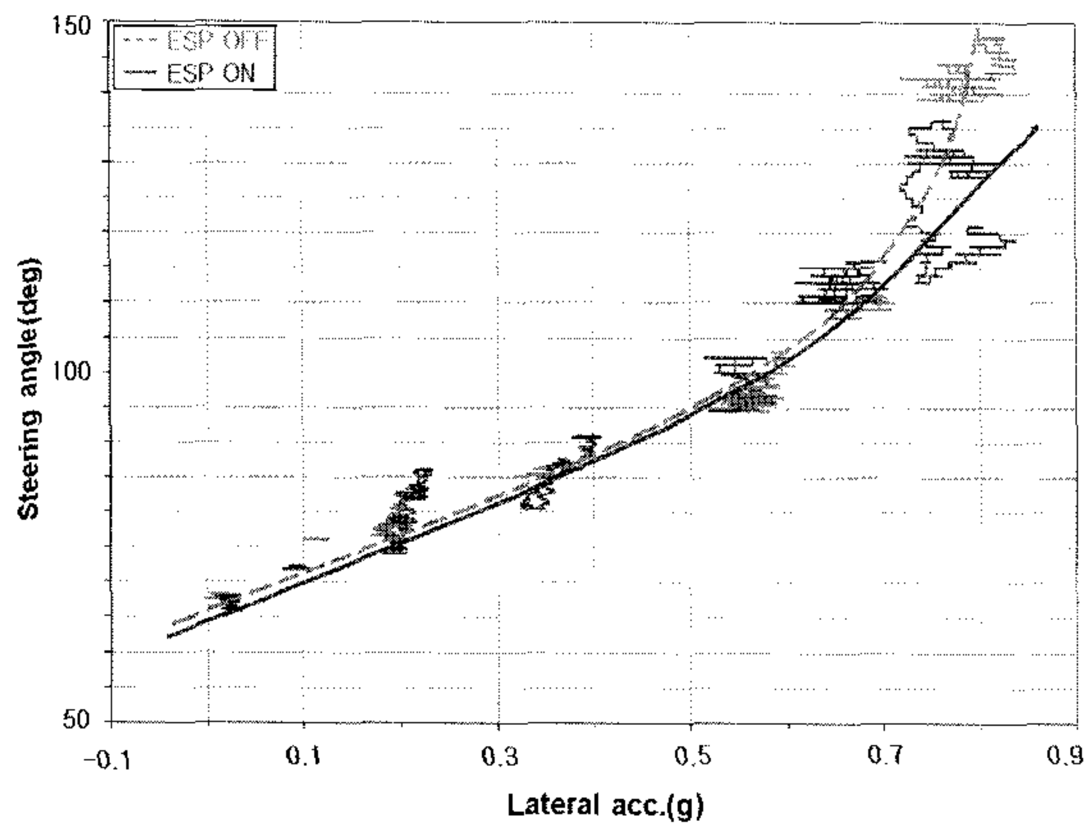


Figure 3. Understeer gradients (Test car A).

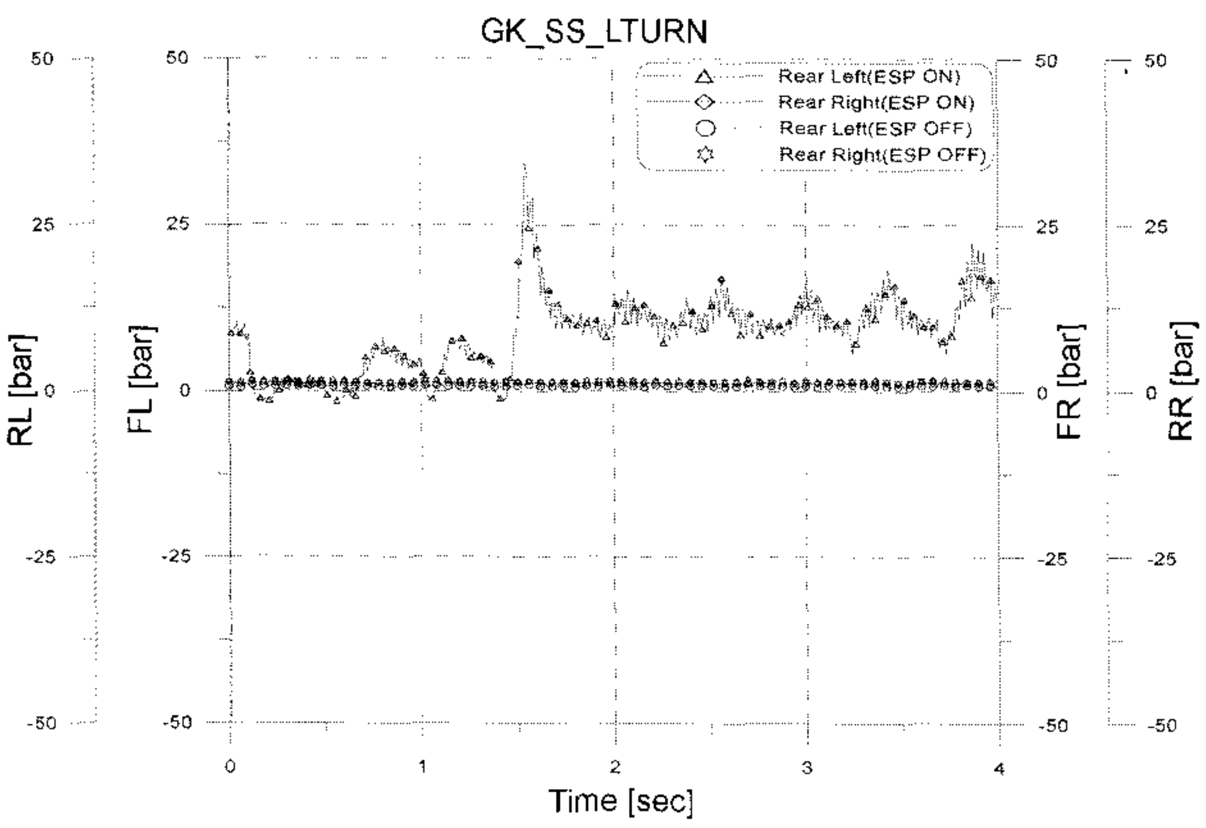
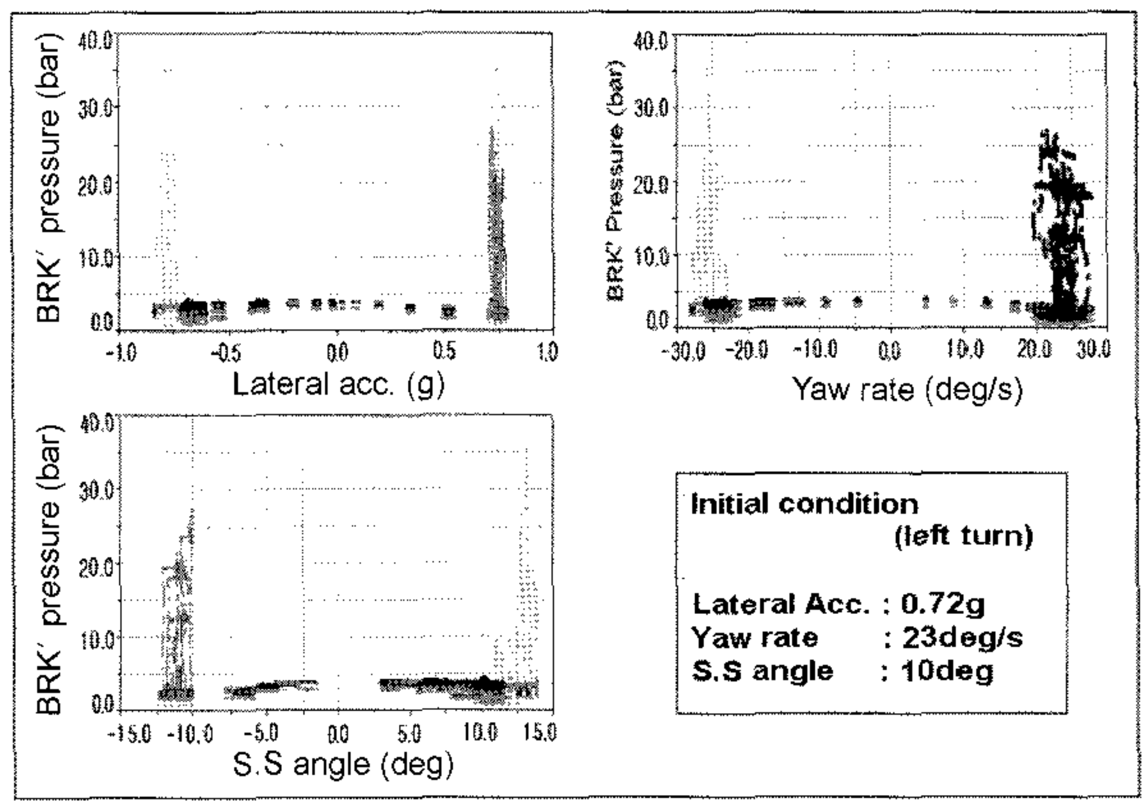
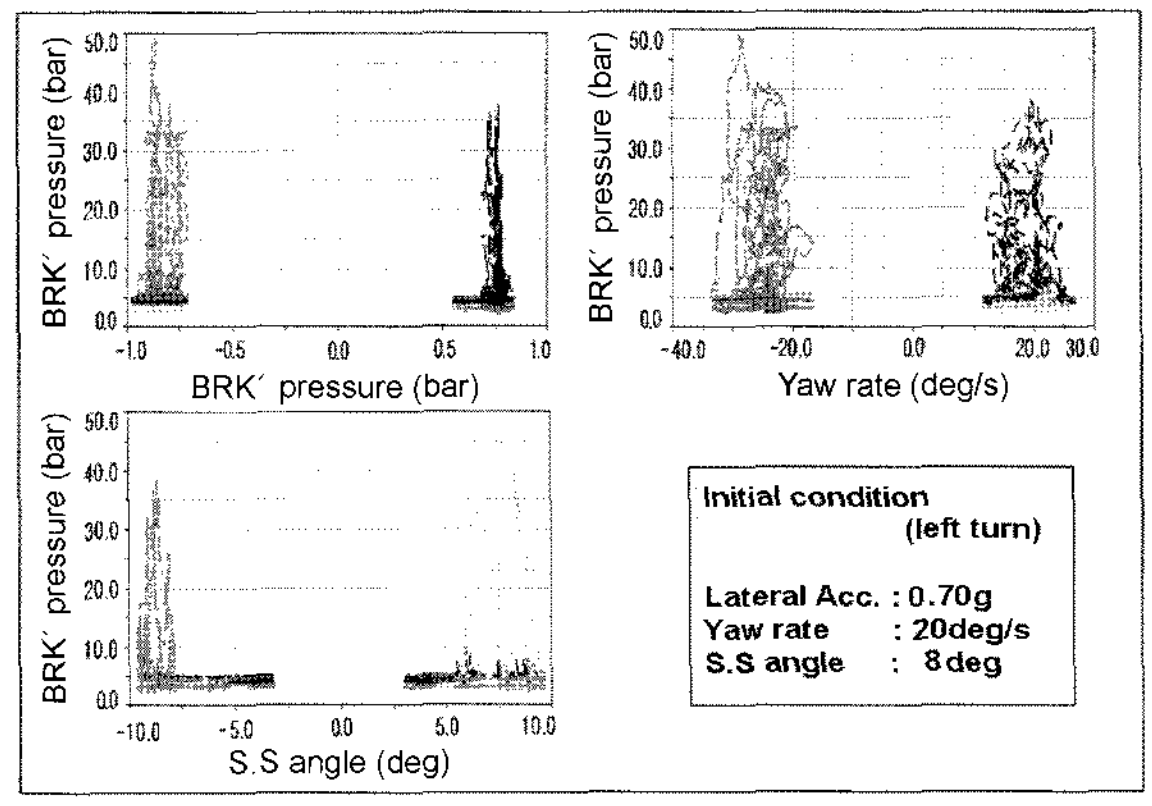


Figure 4. Brake pressure when ESP was ON/OFF.



(a) Test car A



(b) Test car B

Figure 5. Vehicle dynamic characteristics and braking pressure when ESP starts to operate.

guarantees vehicle stability as shown in Figure 4.

Another is to estimate the initial control moment and the starting point to the extreme driving condition by analyzing dynamic characteristic values when ESP begins to operate.

Figure 5 shows the distribution of braking pressures with respect to the main ESP control factors including lateral acceleration, yaw rate, and side slip angle, which are categorized into Test car A and Test car B. Table 2 displays the results of initial control point of each case. The results are used to determine a starting time to an extreme driving condition and the initial control point to operate the brake system for the vehicle stability.

Table 2. Vehicle dynamic characteristics value at control starting point.

Dynamic characteristics	Control starting point	
	Test car A	Test car B
Lateral acc.	0.72 g	0.70 g
Yaw rate	23 deg/s	20 deg/s
Side slip angle	10 deg	8 deg

4.2. J-turn

The purpose of J-turn test is to estimate the response characteristics of a vehicle in a transient state. It is proposed to estimate the ESP response and the path of vehicle by analyzing the result of ESP on/off test.

First, Figure 6 shows the extreme driving condition of J-turn test. It shows that each test vehicle generates the braking pressure in a certain period according to the ESP-equipped vehicle, after the lateral acceleration is increased significantly in an extreme driving condition. Consequently, the ESP control response characteristics are calculated based upon it.

The control response rate is computed at 90% of lateral acceleration, one of criteria, during the steady-state. The difference of response time for two vehicles is shown on Table 3.

Second, general passenger vehicles as well as ESP-equipped test vehicle have understeer characteristics, and a drift is observed in an extreme driving condition when the ESP system is turned off. However, it provides the braking force to the rear LH wheel to compensate the effect of a drift.

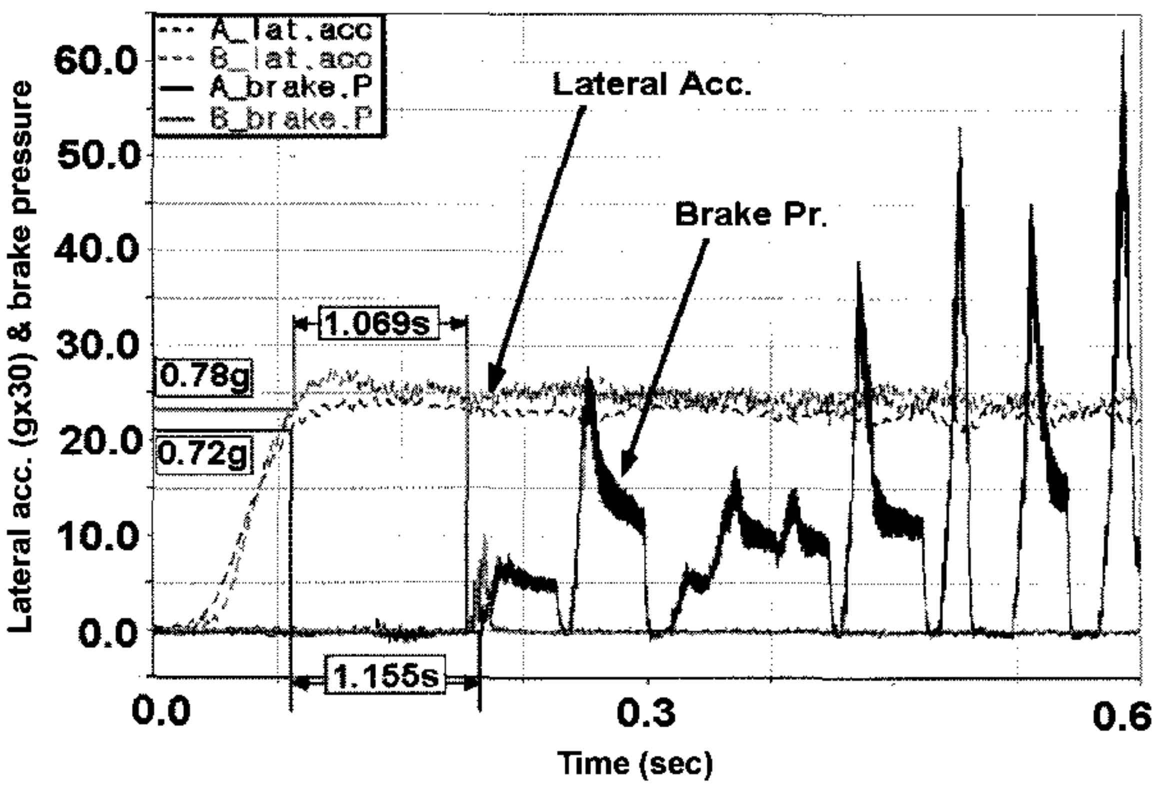


Figure 6. ESP response speed.

Table 3. Control response speed of two test vehicles.

Dynamic characteristics	Control response speed	
	Test car A	Test car B
Lateral acceleration	1.155 sec (0.72 g)	1.069 sec (0.78 g)

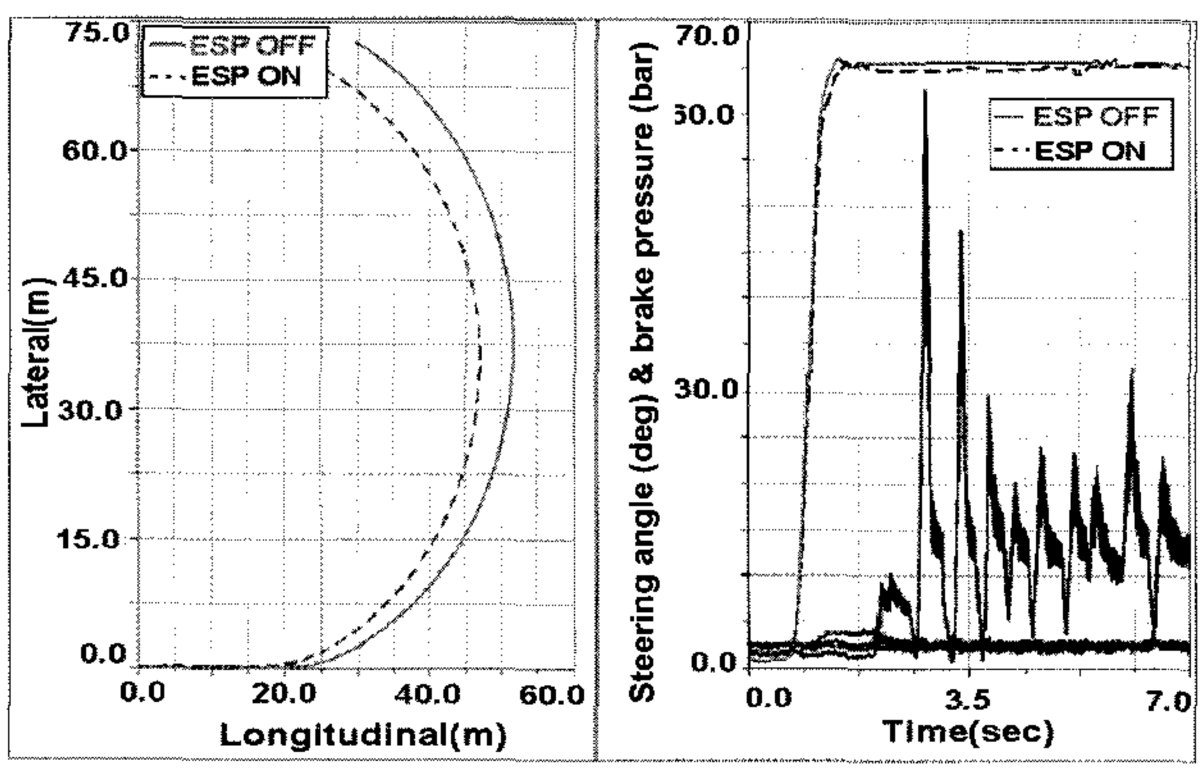


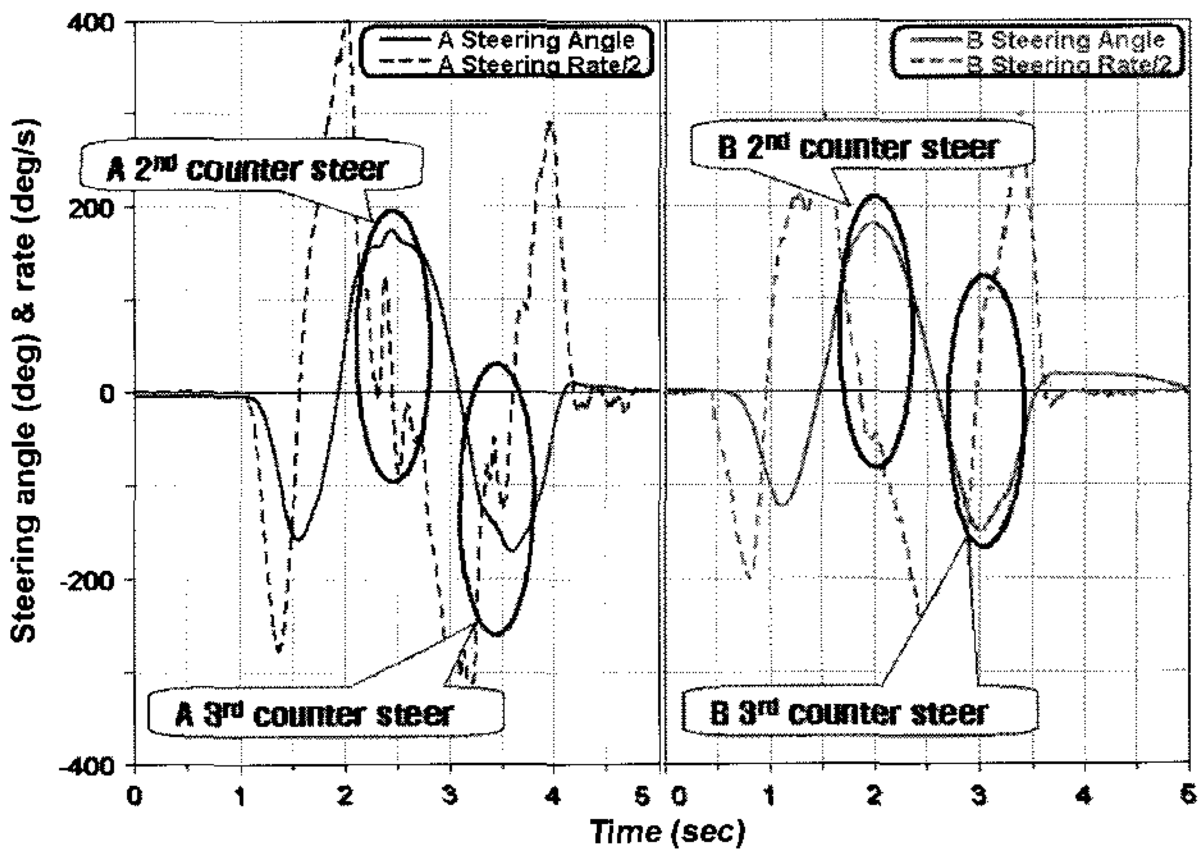
Figure 7. Vehicle trace in J-turn test.

Consequently, the vehicle remains stable and keeps the track of driving course. The drifted trace of a wheel relative to the driving course was reduced compared to the status of the vehicle under the condition that ESP is not operated, and the vehicle has also a smooth steering characteristic.

4.3. Double Lane Change

4.3.1. Estimation based on steering response

It is hard to estimate vehicle movement based on measured numerical data since most of the vehicle motions in an extreme driving condition do appear in a complicate and continuous type rather than in discrete one. An estimation method of the double lane change test is able to analyze the driver's steering characteristic in an extreme driving condition so that the instaneous moment



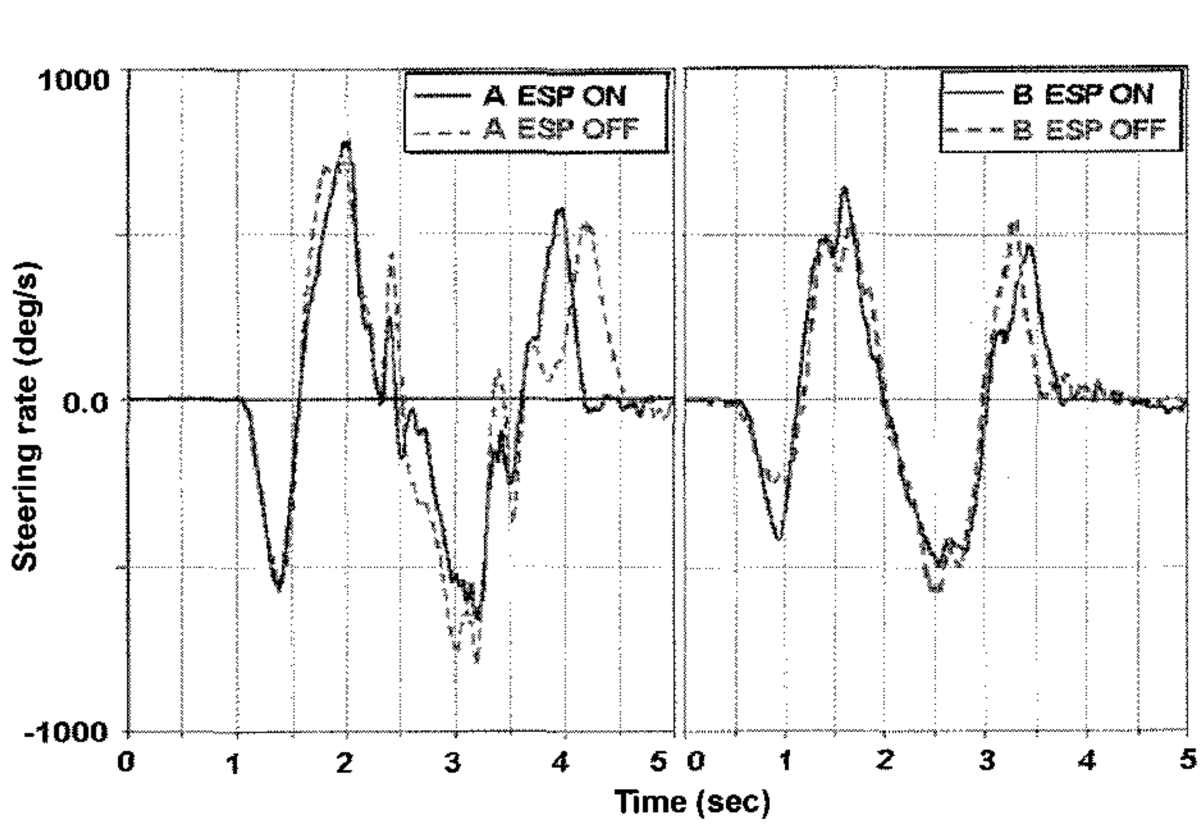
(a) Test car A (b) Test car B

Figure 8. Steering angle and its rate when ESP is on/off.

of the vehicle motion can be analyzed indirectly, but it is relatively precise.

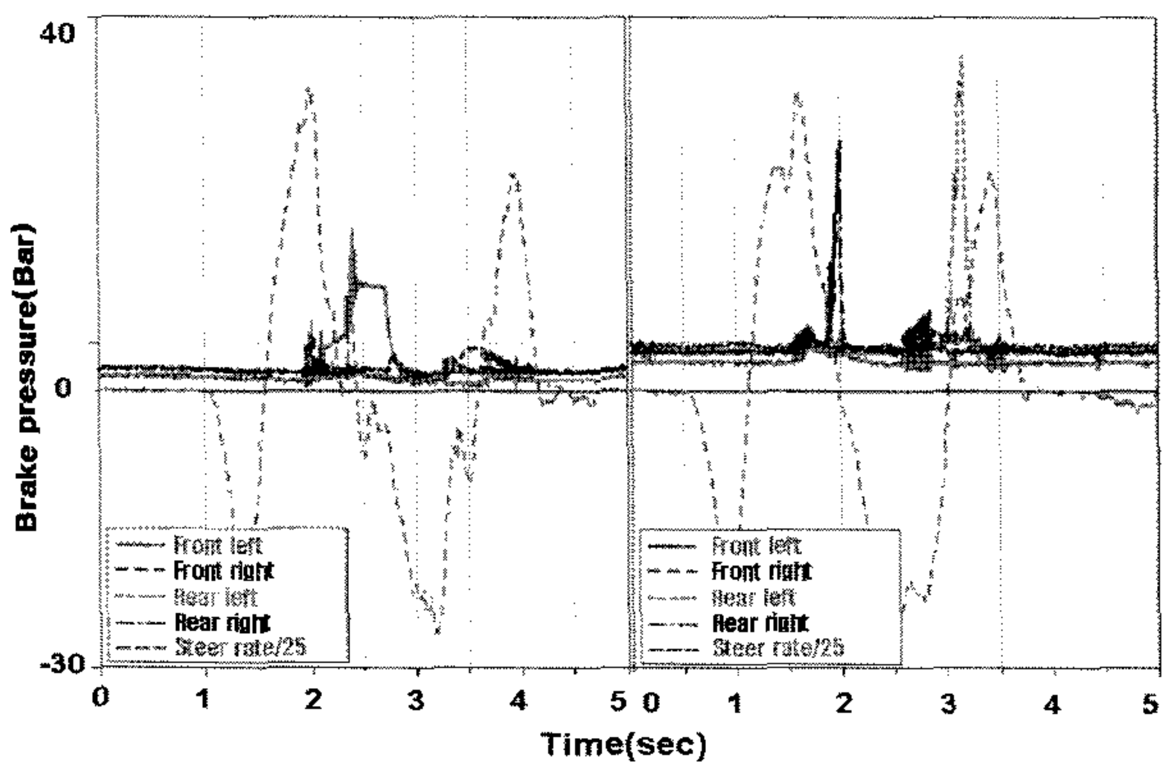
Figure 8 shows the steering angle and its rate of two test vehicles. The elliptical area in Figure 8 shows ESP operation range. Either before or after ESP is operated, it can be observed that there are changes in the steering angle and its rate near the maximum point of the steering angle. In case of Test car A, there is a sudden counter steer at the maximum point of the steering angle, which shows a large change in the slope of the steering angle rate. On the other hand, Test car B data shows a smooth slope of the steering angle rate and a smooth steering handling.

In the case of Test car A, after a sudden counter steering, a sharp change in a slope of the steering angle rate indicates a spin motion of vehicle (Figure 10). It can be analyzed that the driver gives a sudden steering change to reduce yaw moment. In the case of Test car B, there is a stable steering after a smooth counter steering preserving normal driving conditions. To analyze the drivers' steering reaction in these vehicle driving situ-



(a) Test car A (b) Test car B

Figure 9. Steering rate when ESP is ON and OFF.



(a) Test car A (b) Test car B

Figure 10. The steering rate change and control wheel.

ations, the steering angle rate of each case in the condition that ESP is both on and off is compared and shown on Figure 9. In the case of Test car A, there is a significant decrease of the driver's unstable steering when ESP is on, comparing to the case that ESP is off. In the case of Test car B, the slope of steering angle rate is smooth when ESP is on.

Once the motion of vehicle is demonstrated either a spin or a drift, the ESP commences to control the target wheel. The results of this are shown in Figure 10. In the case of Test car A, it is shown that the braking is applied on the 2nd and 3rd outer wheels, which shows that the vehicle is in a spin out. On the other hand, in the case of Test car B, it is shown that the braking is applied on the inner wheel, which shows that the vehicle is in a drift.

The main function of ESP is to maximize the driving stability in order that the vehicle can avoid dangerous situations without any additional control from the driver. Therefore, the ESP control logic can be improved so as to reduce driver's additional handling in a viewpoint of results of the ESP on and off, and the ESP performance will be able to be estimated and improved by not only professional drivers but also general drivers.

4.3.2. Compensation moment generation mechanism analysis by ESP

The compensation moment generated by ESP during an extreme driving test can be calculated based upon the vehicle specifications and the measured wheel load. The center of gravity in the vehicle, which is required to calculate yaw moment, is computed by vertical loads when the vehicle is in driving. The effect of load distribution change during turn is neglected and the compensation moment is calculated from double lane change test of Test car A.

The moment of the whole vehicle produced by tires is shown in (1).

$$M_{tire}=M_{FY_f}+M_{FY_r}+M_{BF_l}+M_{BF_r}$$

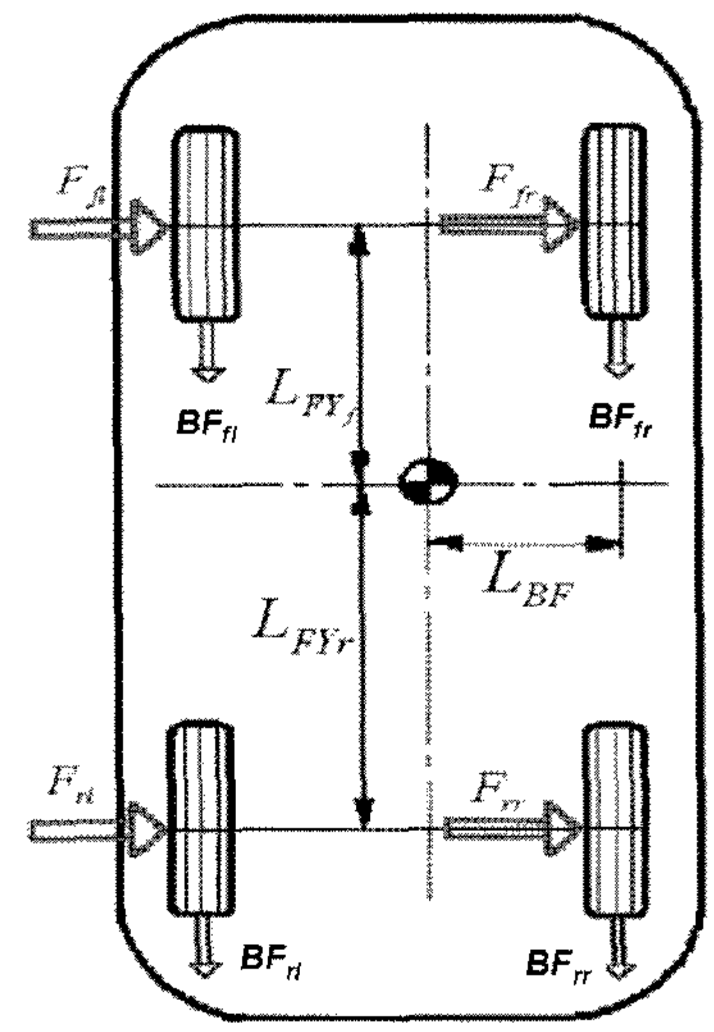


Figure 11. Calculation of yaw moment of the vehicle.

$$=-\{(F_{fl}+F_{fr})\times L_{FY_f}\}+\{(F_{rl}+F_{rr})\times L_{FY_r}\}$$
$$+\{(BF_{fl}+BF_{rl})\times L_{BF}\}-\{(BF_{fr}+BF_{rr})\times L_{BF}\} \quad (1)$$

Where, M_{tire} : Operation moment of the whole vehicle produced by tires

F_{xx} : Lateral force of wheel xx

BF_{xx} : Vehicle longitudinal force by driving control

L_{xx} : Moment arm of lateral and longitudinal force

Among 6-axis forces produced on wheels when the vehicle is in motion, the most effective factors to the vehicle yaw moment are lateral and longitudinal forces. Figure 11 shows each wheel force produced during turning. The yaw moment of a vehicle can be calculated as Equation (1). The compensation moment of a vehicle when ESP is on and off can be measured as shown in Figure 12. The area of sudden change in the yaw moment after and before ESP is on can be considered as the total compensation moment.

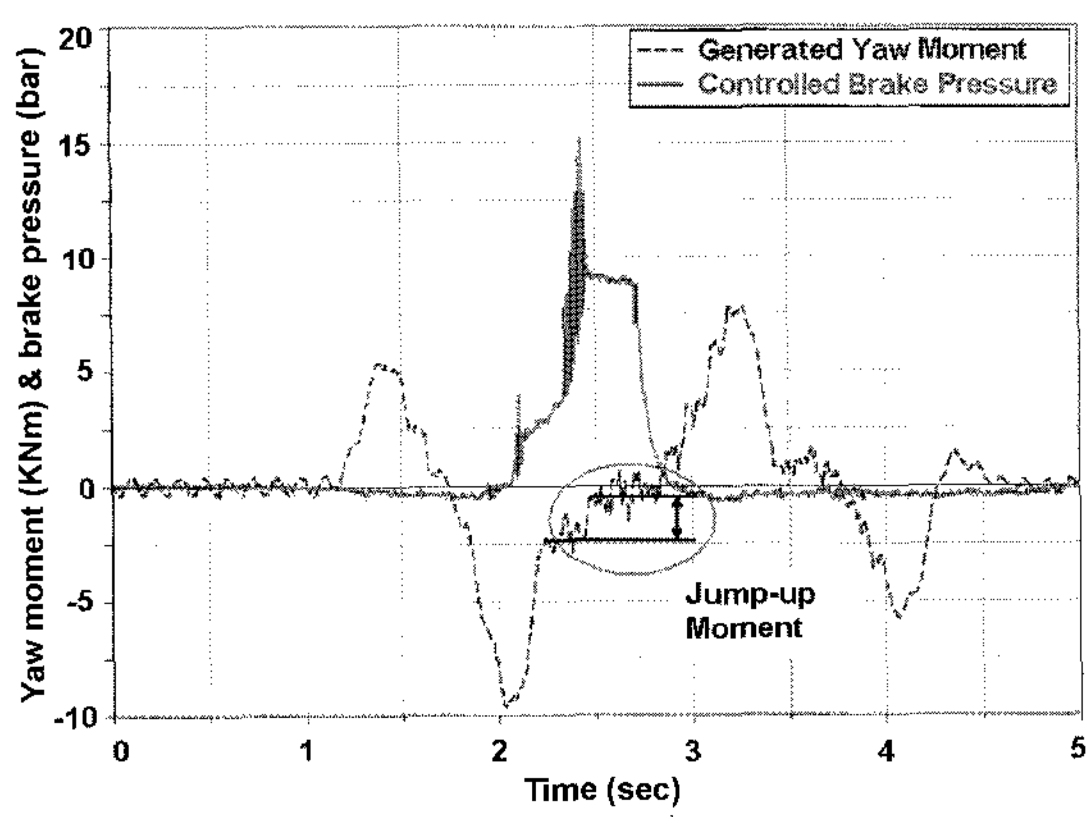


Figure 12. Change in the whole vehicle moment when ESP is on and off.

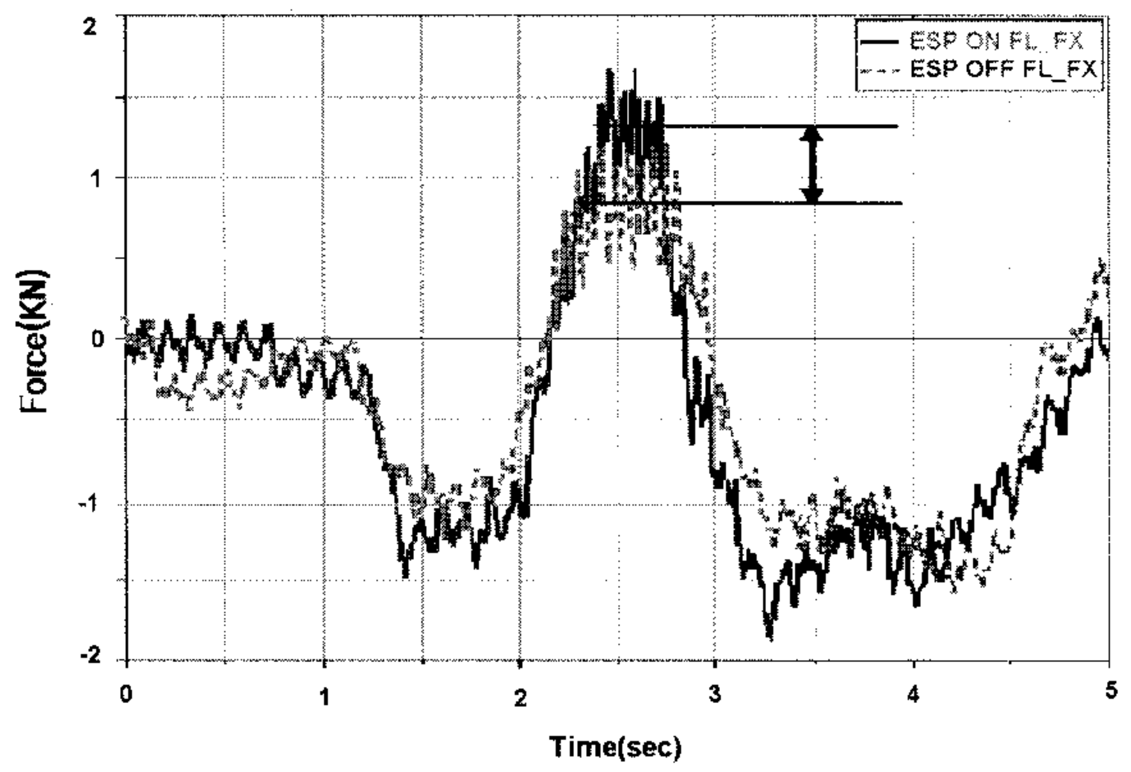


Figure 13. Change in longitudinal force on a controlled wheel by braking.

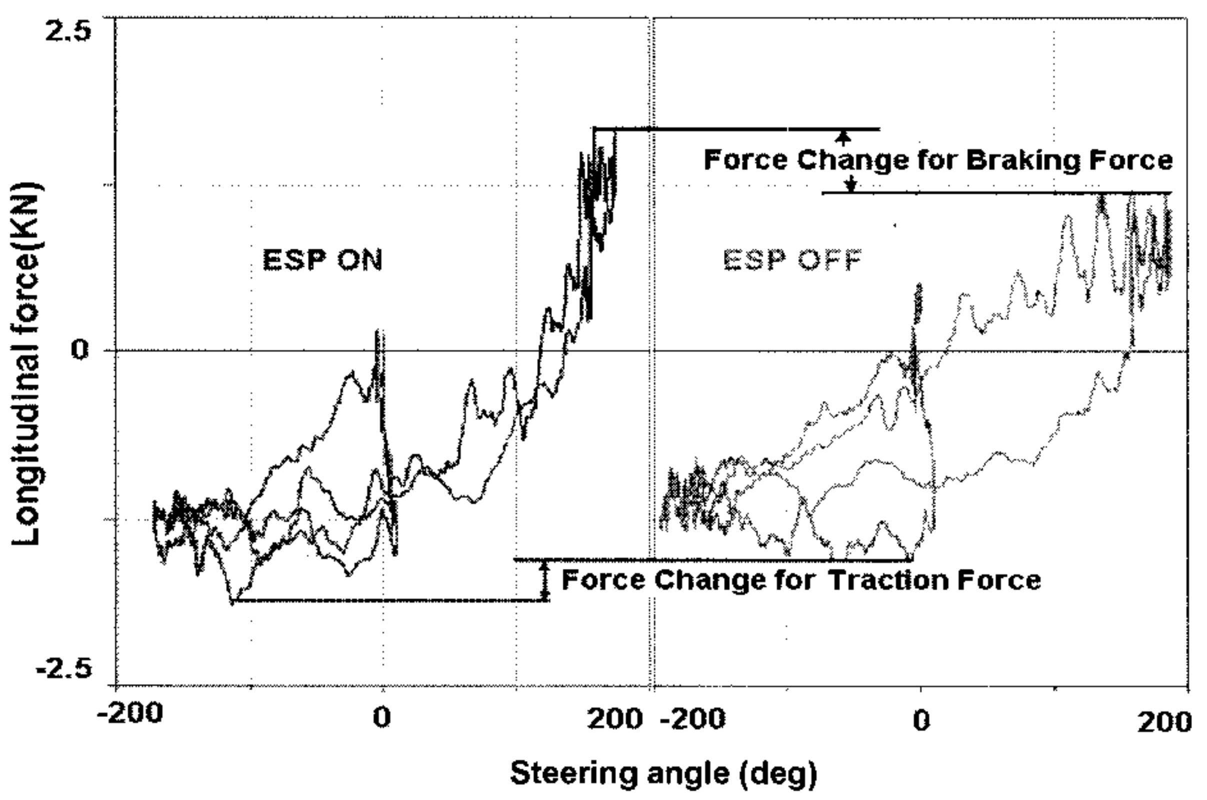


Figure 14. Change in longitudinal force -the control by driving and braking.

Figure 13 shows that the braking force is generated, and there is a large increase in the longitudinal force when ESP is on. It implies the compensation moment. Figure 14 shows the longitudinal force with respect to the steering angle when ESP is on and off. The upper difference represents a change in the braking force when ESP is on, and the lower difference represents a change in the longitudinal force according to the increase of the engine acceleration power.

In Figure 12, the total compensation moment of the test car is about 1,800 Nm and the compensation moment of a braking wheel by ESP operation can be calculated as below.

Compensation moment
$\neq$ Longitudinal force (0.6 kN) $\times$ Moment arm (0.745 m) (2)

The computational result of the right side of equation (2) is 447 Nm.

As shown in equation (2), the total compensation moment of a vehicle cannot be explained with the only braking force. This implies indirectly that there is another compensation moment unaccounted and also shows that these differences are related to the change in a lateral force on each wheel.

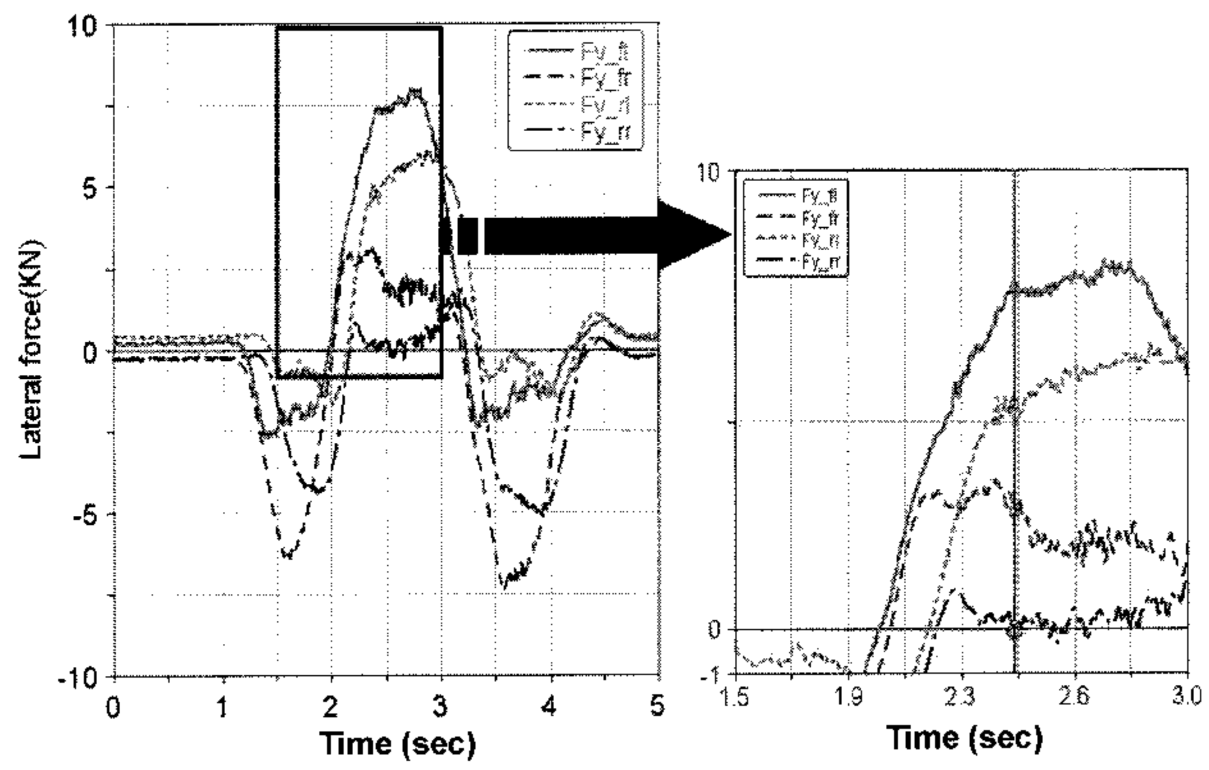
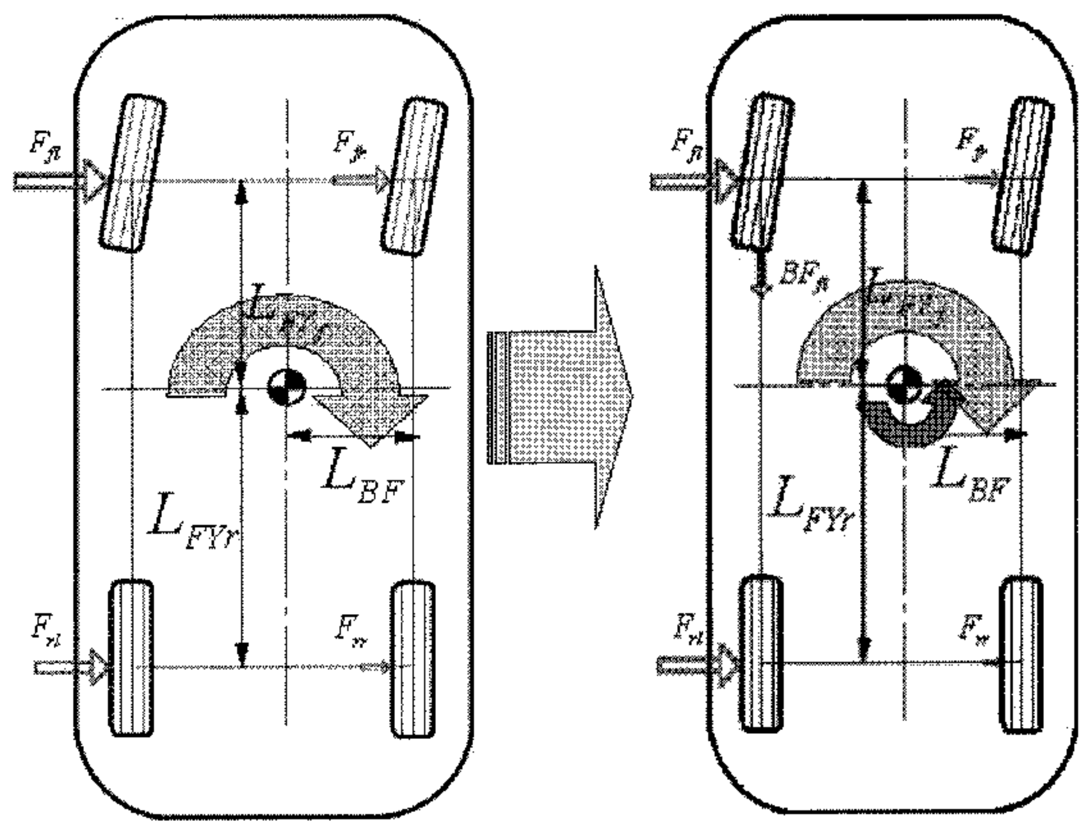


Figure 15. Lateral force changes on wheels when turning.

Figure 15 shows the change in a lateral force on each wheel when ESP is on. The vehicle lies at the maximum point of RH steering in the second turning of the double lane change test. It is the spin out.

The lateral force on the rear RH wheel at 2.4 second, when braking pressure starts to be applied, already drops to near '0' and does not affect on the vehicle motion anymore. The lateral force on the front LH wheel does not contribute to the compensation moment, since the lateral force remain constant due to the ESP operation. However, the lateral force on the rear LH wheel increases after ESP operation, which is a function as the counter-clockwise compensation moment. On the other hand, the lateral force on the front RH wheel decreases, and it reduces the total moment compared with the situation before the ESP is on so that it operates as the compensation moment.

Figure 16 shows the load of each wheel before and



(a) Before ESP operation (b) After ESP operation

Figure 16. The total compensation moment changes before and after ESP operation.

after ESP operation. Thus, the compensation moment can be calculated with each wheel force.

$$\text{The compensation moment} \fallingdotseq 447\ \text{Nm} + \{F_{rl}(0.6\ \text{kN}) \times L_{FYr}(1.5\ \text{m}) + F_{fr}(0.7\ \text{kN}) \times L_{FYf}(1.02\ \text{m})\} \quad (3)$$

The computational result of the right side of equation (3) is 2061 Nm.

It stands for the slightly greater compensation moment calculated in equation (3) than the actual compensation moment. If components of the lateral and longitudinal forces according to the steering angle and the load movement are considered, it is expected that more precise results can be obtained.

5. CONCLUSIONS

This paper presents various tests for ESP to estimate the extreme driving characteristics, proposed the estimation methods for ESP driving characteristics, and derived the following results.

(1) To estimate the ESP-equipped vehicle's extreme driving characteristics, the measurement system for the vehicle driving test was installed and the vehicle test modes were established to present an extreme driving condition.
(2) The estimation methods for the ESP extreme driving characteristic are proposed, such as the under steer gradient curve method, the estimation method with yaw rate, lateral acceleration, and slip angle curve on brake pressure, the dynamic characteristics estimation, the ESP response estimation, and the estimation method of the vehicle path.
(3) With the estimation methods for ESP using the steering angle and its rate and the analysis of changes in the lateral and longitudinal wheel forces generated by the braking pressure control, the compensation moment generated by ESP was calculated and the compensation moment generation mechanism by ESP was verified by the driving tests and proposed as an estimation method.

The estimation methods for ESP-equipped vehicle's extreme driving characteristic were proposed as above. This paper will be useful in not only developing the control logic of ESP, but also improving the performance of ESP.

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