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DEVELOPMENT OF HARDWARE-IN-THE-LOOP SIMULATION SYSTEM AS A TESTBENCH FOR ESP UNIT

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ABSTRACT–As the vehicle electronic control technology quickly grows and becomes more sophisticated, a more efficient means than the traditional in-vehicle driving test is required for the design, testing, and tuning of electronic control units (ECU). For this purpose, the hardware-in-the-loop simulation (HILS) scheme is very promising, since significant portions of actual driving test procedures can be replaced by HIL simulation. The HILS incorporates hardware components in the numerical simulation environment, and this yields results with better credibility than pure numerical simulations can offer. In this study, a HILS system has been developed for ESP (Electronic Stability Program) ECUs. The system consists of the hardware component, which that includes the hydraulic brake mechanism and an ESP ECU, the software component, which virtually implements vehicle dynamics with visualization, and the interface component, which links these two parts together. The validity of HIL simulation is largely contingent upon the accuracy of the vehicle model. To account for this, the HILS system in this research used the commercial software CarSim to generate a detailed full vehicle model, and its parameters were set by using design data, SPMD (Suspension Parameter Measurement Device) data, and data from actual vehicle tests. Using the developed HILS system, performance of a commercial ESP ECU was evaluated for a virtual vehicle under various driving conditions. This HILS system, with its reliability, will be used in various applications that include durability testing, benchmarking and comparison of commercial ECUs, and detection of fault and malfunction of ESP ECUs.

KEY WORDS : Hardware-in-the-loop simulation (HILS), Electronic stability program (ESP), Real-time simulation

1. INTRODUCTION

As the vehicle electronic control technology quickly grows and becomes complicated, a more efficient means than the traditional in-vehicle driving test is required for extensive testing of ECUs. For this purpose, the hardware-in-the-loop simulation (HILS) scheme is very promising, since it can replace significant portions of actual driving test procedures (Lee *et al.*, 2003; Park *et al.*, 2003; Suh *et al.*, 1998; Zanten, 1996). HILS incorporates hardware components of prime concern in a numerical simulation environment, yielding results with better credibility than pure numerical simulations can offer. HILS runs in real time and provides time- and cost-effectiveness over actual driving test. It also makes possible test procedures that are difficult or even impossible in actual driving tests.

The goal of this research is to develop a HILS system for testing and benchmarking commercial ESP ECUs. The reliability of the HIL simulation results is directly affected by the accuracy of the vehicle model. The HILS system in this research used the commercial software CarSim to generate a detailed full vehicle model, and its parameters were set by using design data, SPMD (suspension parameter measurement device) data, and data from actual vehicle tests.

In the ESP HILS environment, the vehicle model and the hardware brake mechanism must be simulated in real time in synchronization. In this research, the PC-based real-time simulation environment, RT-Lab and QNX operating system, were employed. The HILS system developed in this research is also equipped with real-time visualization of the driver's view so that the operator can respond interactively with HILS while the simulation is being carried out in real time. Using the developed HILS system, performance of a commercial ESP ECU was evaluated for a virtual vehicle under various driving conditions.

2. ELECTRONIC STABILITY PROGRAM

The ESP is an electronic chassis control system whose objective is to maintain the lateral vehicle stability in

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critical cornering situations (Zanten, 2000; Tseng *et al.*, 1999; Park and Heo, 2000; Matsumoto *et al.*, 1992; Zhang *et al.*, 2006).

A critical lateral motion of a vehicle occurs when tire-road contact cannot be sustained. When this occurs, the body sideslip angle grows and the sensitivity of the yaw moment with respect to the steer angle suddenly diminishes. Addition of the steer angle can no longer increase the yaw moment that is necessary to restore the vehicle stability. In such situations, the ESP system tries to make the vehicle's lateral motion behave as closely as the driver's steering intention. To this end, the ESP generates a compensating yaw moment to restore stability by distributing asymmetric brake forces to the wheels.

The ESP control logic first computes the reference yaw rate. This is the steady state yaw rate at current values of the vehicle speed and steer angle input, and is given below.

$$\gamma_{ref} = \frac{v_x}{L\left(1 + \frac{v_x^2}{v_c^2}\right)}\delta_f \tag{1}$$

In the above, γ_{ref} is the reference yaw rate, v_c the characteristic speed, v_x the vehicle speed, δ_f the front steer angle, and L the wheel base.

Figure 1 shows the control scheme of the ESP. When the vehicle understeers during cornering, the yaw rate becomes less than the reference yaw rate. The ESP then applies braking force selectively to the inner rear wheel. Then, due to unbalanced braking forces between the two rear wheels, oversteering yaw moment is generated. Decrease of lateral force in the inner rear wheel further increases the oversteering yaw moment. When the vehicle oversteers during cornering, the yaw rate becomes greater than the reference yaw rate. The ESP then applies braking force to the outer front wheel. Unbalanced braking forces between the two front wheels generate understeering yaw moment, and this is further increased by a decrease in lateral force in the outer front wheel.

The ESP has been already commercialized for passenzger vehicles, and is referred to by various names: VDC (Vehicle Dynamics Control), DSC (Dynamic Stability Control), ASC (Active Stability Control), etc. The ESP system has a good potential of becoming one of the chassis control necessities since it can be produced with little additional cost on top of the ABS/TCS system which has already become a standard chassis part in most vehicles.

3. ESP HILS SYSTEM

The hardware-in-the-loop simulation scheme is being widely adopted in the automotive industry. It integrates the actual ECU and its peripheral hardware with the virtual vehicle model, forming a closed loop to be simulated in real time. The result of the HIL simulation has better credibility than does pure numerical simulation. HILS provides better time- and cost-effectiveness over actual driving test. It also makes possible test procedures that are difficult or even impossible in actual driving tests. Such advantages are especially favorable for brake control ECUs, since their in-vehicle tests are characterized by high cost, a long test period, and potential danger.

Figure 2 shows the configuration of the ESP HILS system constructed in this research. It consists of the software component, the hardware component, and the interface component. The software component includes a vehicle dynamics model, an EMS (Engine Management System) model, a TCU (Transmission Control System) model and a real-time simulation environment. The hardware component consists of the hydraulic brake mechanism and a commercial ESP unit. The interface component links these two components together. Figure 3 shows a photo of the HILS system developed in this research. The following sections describe each component in detail.

3.1. Software Component

The main role of the software component is to define a vehicle model and to carry out real-time simulation. For this, CarSim was used for vehicle modeling and RT-Lab was used for real-time simulation; they were linked by

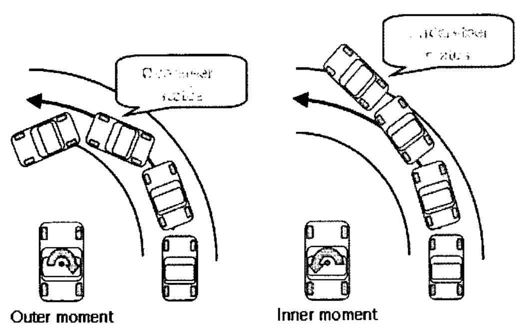


Figure 1. The concept of ESP.

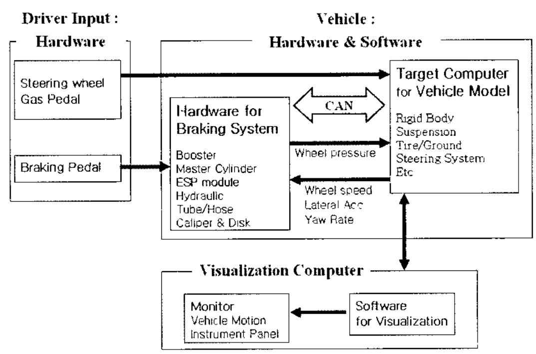


Figure 2. Overall configuration of ESP HILS system.

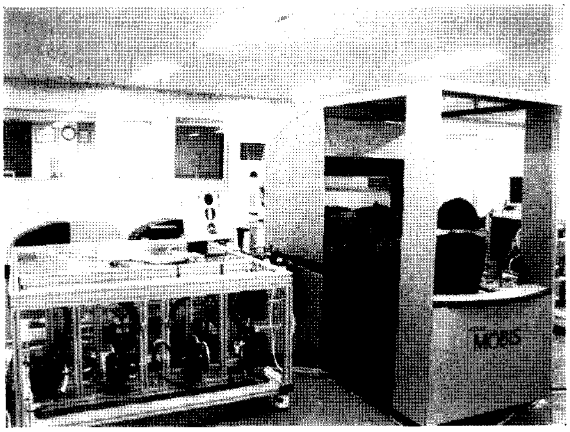


Figure 3. Photo of the ESP HILS system.

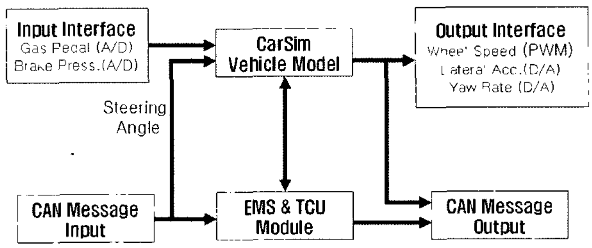


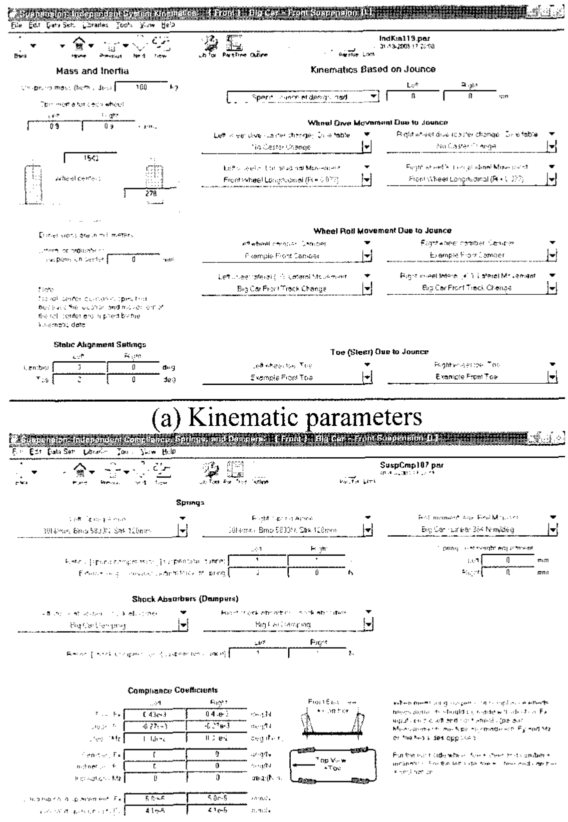
Figure 4. Basic structure of Simulink diagram of ESP HILS.

Simulink (MSC, 2001; Opal RT, 2002; MathWorks, 2002).

Figure 4 shows the Simulink diagram for the ESP HILS system. The diagram consists of the following parts: a CarSim vehicle model block, an interface block processing input and output sensor signals, an EMS (Engine Management System) module, a TCU (Transmission Control Unit) module, and a CAN (Controller Area Network) message block for CAN communication between each module and the ESP ECU.

The validity of the HIL simulation result is largely contingent upon the accuracy of the vehicle model. To account for this, the HILS system in this research used the commercial software CarSim to generate a detailed full vehicle model. This vehicle model has 23 degrees of freedom and can be simulated in real time as a parametric model. Figure 4 shows the input and output quantities of the vehicle model.

The CarSim vehicle model consists of a rigid body, drive system, steering system, suspension system, and tire. For HILS operation, the transmission and engine modules of CarSim were replaced by those made in this research. To enhance the reliability of the vehicle model, the parameters for each component were set by using design data, SPMD (suspension parameter measurement device) data. For the tires, the Pacejka tire model in CarSim was used. The tire parameters were set using measurement data that reflect a used tire with some modification. Figure 5 shows the windows for entering parameters for suspension in CarSim.



(a) Kinematic parameters

(b) Compliance parameters

Figure 5. Window for entering suspension parameters.

To confirm the validity of the mathematical vehicle model, various actual vehicle tests were performed and the response of the model was compared using steady state driving test on a circular road and J-turn tests.

Figure 6 shows the results for J-turn test with 0.7 g lateral acceleration. The vehicle was steered by 70 degrees at 100 km/h. Figure 6 compares the actual vehicle test result with the pure simulation result. The overall comparison reveals that the response of the vehicle model agrees well with that of the actual vehicle. The vehicle data as shown in Figure 6 will be used as inputs to the ESP ECU in the HILS system, and considering the results, it can be expected that the HILS results give good credibility.

In the HILS environment, the software vehicle model must be synchronized with the hardware brake system, and they must run in real time. To achieve this, the real-time simulation environment RT-Lab was employed. In this environment, the vehicle model developed using CarSim and Simulink on a host computer gets downloaded and executed on a target PC in real time. The target computer runs under the QNX operating system.

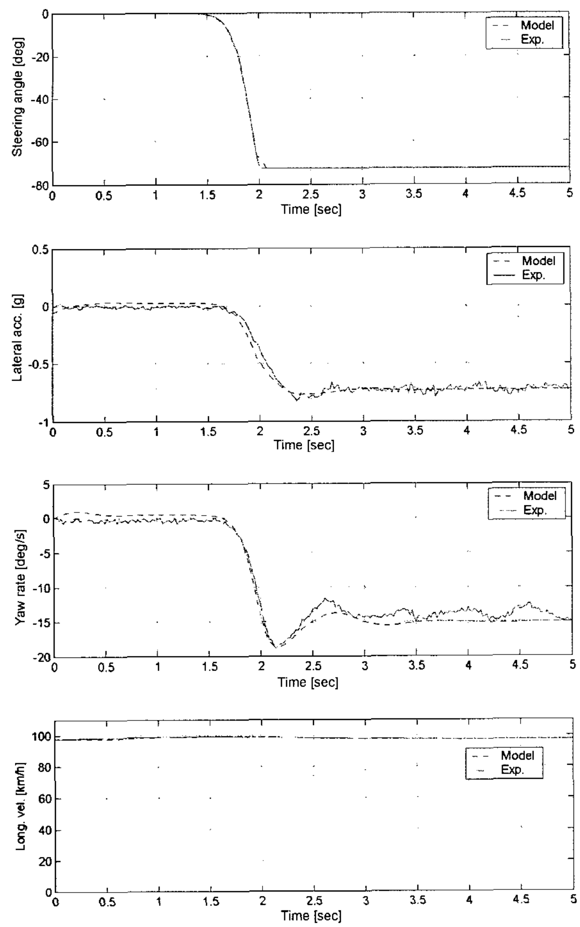


Figure 6. Comparison between vehicle model simulation and actual vehicle test.

3.2. Hardware Component

The hardware component of the ESP HILS system is composed of the ECU, the hydraulic brake system, the steering wheel, pedals, sensors, computers for simulation and visualization, and the wheel speed sensor emulator.

Commercial ESP units are manufactured with ECU (Electronic Control Unit) and HCU (Hydraulic Control Unit) integrated together in a single package. The presence of the HCU demands that the ESP HILS system should have a hydraulic brake mechanism similar to the one used in the actual vehicle. The hydraulic brake mechanism includes the brake pedal, booster, master cylinder, hydraulic tubes and hoses, and the calipers and brake disks for each wheel. In addition, a vacuum pump is needed to provide vacuum to the booster in the absence of an engine.

The computer in the hardware component carries out real-time simulation of the 23 DOF vehicle model. In this study, three Pentium-4 PCs were used in host-target configuration as shown in Figure 7. The two target PCs were linked via IEEE 1394 and communication between the host and target PCs was accomplished by TCP/IP.

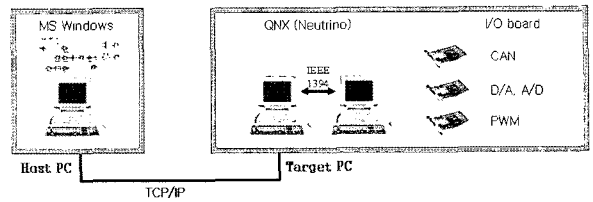


Figure 7. Configuration of host and target PCs.

The ESP HILS system has a brake pedal, an accelerator pedal, and a steering wheel, which can be applied by the operator. In addition, a real-time visualization system was constructed so that the operator could respond interactively to the vehicle response while the HIL simulation is being performed. The visualization window also provides the operator with the capability of selecting different test conditions such as straight split friction road, road for obstacle avoidance, circular road, handling circuit, etc.

3.3. Interface Component

Described in this section are the devices that were used for interface of the hardware and software components in the HILS system. Interface is needed to provide linkage between the actual brake system and the virtual vehicle model. This was accomplished by measuring the wheel cylinder pressures at four wheels and by feeding them to the vehicle model. To achieve this, pressure sensors and an A/D board were used. The pressure of the master cylinder was also measured for validation of measured pressures.

In actual vehicles, the wheel speeds are measured by the wheel speed sensors and they enter the ESP ECU as input. In the HILS system, however, there are no rotating wheels; hence, electric signals compatible with the wheel speed sensor outputs must be generated from wheel speed values computed from the vehicle dynamic model. For this, a wheel speed sensor emulator was constructed in this study and its configuration is shown in Figure 8.

The ESP ECU implements functions of ABS and TCS,

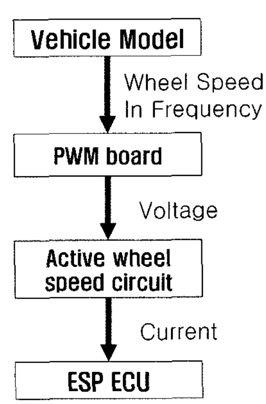


Figure 8. Wheel speed sensor emulator.

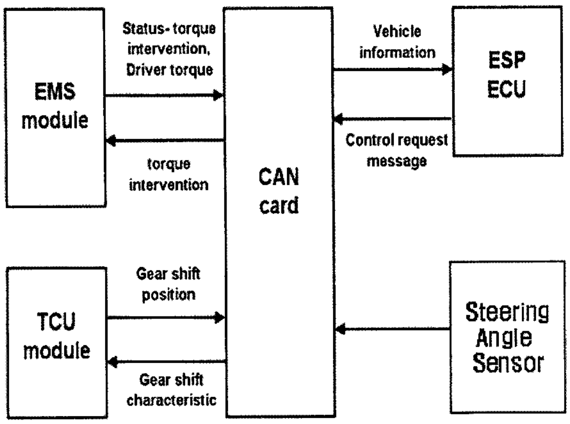


Figure 9. Communication done via CAN.

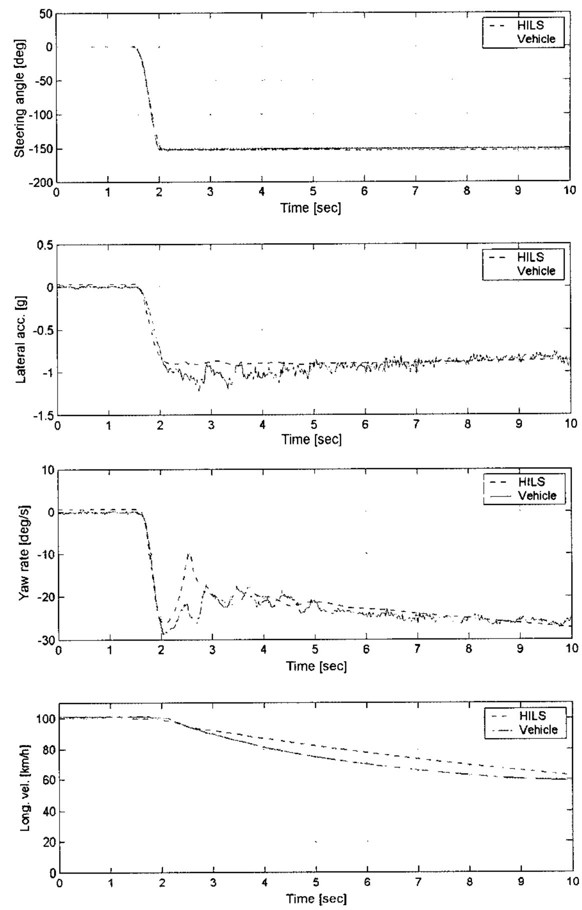
as well as the vehicle dynamics control. Hence, it requires the rotational torque, rotational speed and throttle angle of the engine, and gear position. To generate these signals without actual powertrain hardware, EMS and TCU modules were constructed. The ESP ECU communicates with these modules via the CAN communication protocol. The vehicle model also receives the torque required by the engine, the operational status of TCS, and other information by the CAN protocol. The steering angle sensor also communicates with the ESP ECU via CAN. Figure 9 shows the information flow accomplished via CAN communication.

The yaw rate and G sensor signals are calculated in the vehicle model and transferred to the ESP ECU through a DA board. Since the sensor signals have their own diagnostics functions, the diagnostic signals are transferred to the ESP ECU as well.

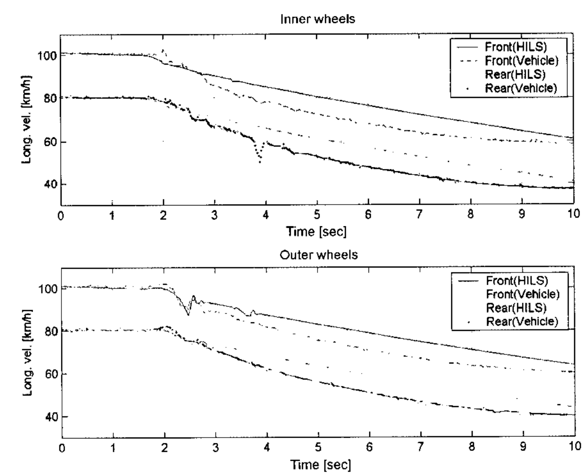
4. VALIDATION OF HILS SYSTEM

This chapter shows results of the HIL simulation and actual vehicle test that were been conducted for performance validation of the ESP HILS system constructed in this research. Since the ESP system in practice operates near critical driving situations, simulation was performed for potentially dangerous situations. Various J-turn tests with large steering angles were carried out, and one of the results is given here.

Figure 10 shows results for a J-turn test in the HIL simulation and actual vehicle test. The initial vehicle speed was 100 km/h and the steering wheel angle changed by 150 degrees. Shown in Figure 10 are the time histories of the steering wheel angle, lateral acceleration, yaw rate, longitudinal speed of the vehicle, and wheel speeds. In the plot of the wheel speeds, the rear wheel speeds are lowered by 20 km/h for visual distinction. It can be seen that the yaw rates from the HIL simulation agrees well with those from the actual vehicle test, except



(a) Variables of sprung mass



(b) Wheel speeds

Figure 10. J-turn test results in HILS and vehicle test.

for a slightly larger undershoot in HILS case.

The wheel speed results show the operation of the ESP unit. If the pressure at a particular wheel builds, the velocity of the wheel decreases abruptly, and if the pressure disappears, the wheel velocity increases again. In

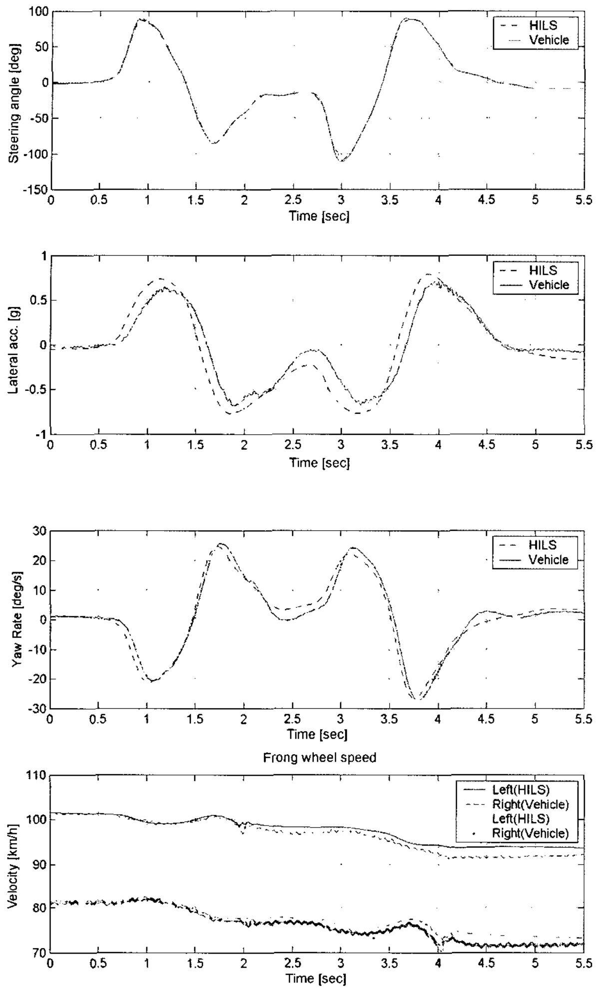


Figure 11. Double Lane Change results in HILS and vehicle test.

this test, ESP operation occurred mainly in the outer wheel, which means that the oversteering situation occurred.

Figure 11 shows the results for a double lane change test in the HIL simulation and actual vehicle test. The initial vehicle speed was 100 km/h. Shown in Figure 11 are time histories of the steering wheel angle, lateral acceleration, yaw rate, and front wheel speeds. In the plot of the wheel speeds, the right wheel speeds are lowered by 20 km/h for visual distinction. The plot of the wheel speeds shows that ESP was activated to prevent oversteering situation at the instant of 2 sec and 4 sec. In the 4 plots of Figure 11, the HILS results agree very closely with the results from the actual vehicle test.

5. APPLICATION OF ESP HILS

The ESP HILS system of this research was developed for multiple purposes. First, the system can be used for durability test of ESP units. The ESP HILS system, providing an environment that resembles realistic driving conditions, enables one to carry out durability tests. This is possible only when the HILS system gained reliability above a certain level. In the test procedure, the ESP will be activated in a predefined test mode to forecast durability in the required lifetime. Test items will include operation of the motor and the valves, oil leakage, etc.

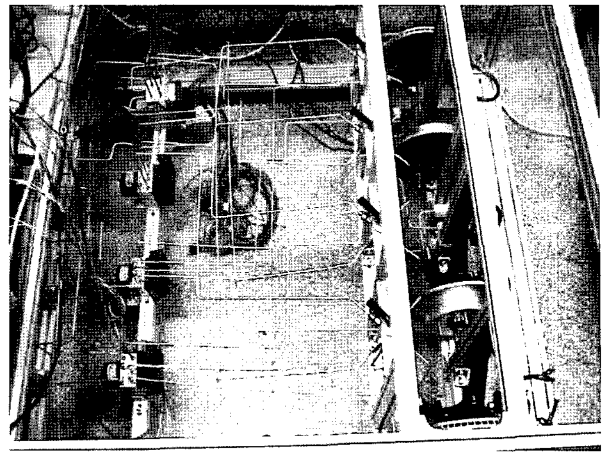


Figure 12. 4 ECUs installed in the HILS system.

Secondly, the HILS system developed in this research can be used to benchmark performance of the ESP units. It allows one to test not only a single unit, but also multiple units as many as four installed at the same time.

Figure 12 shows the HILS system with 4 ECUs installed. Selectivity among the multiple units is made by switches of five way valves. This unique feature is particularly advantageous when comparing performance of multiple ESP units since it provides identical test environments and allows time-efficient comparison.

Thirdly, the ESP HILS system developed in this research can be used to detect fault and malfunction of the ESP units. A variety of driving conditions can be tested under the HILS environment to check normal operation of the ESP unit. Test conditions that are too dangerous in the actual vehicle test impose no difficulty to the HIL simulation.

6. CONCLUSION

In this study, a HILS system was developed for ESP (Electronic Stability Program) ECUs. The system consists of the hardware component, which includes the hydraulic brake mechanism and an ESP ECU, the software component, which virtually implements vehicle dynamics with visualization, and the interface component, which links these two components together. The validity of HIL simulation is largely contingent upon the accuracy of the vehicle model. To account for this, the HILS system developed this research used the commercial software

CarSim to generate a detailed full vehicle model, and its parameters were set by using design data, SPMD data, and data from actual vehicle tests.

Using the developed HILS system, the performance of a commercial ESP ECU was evaluated for a virtual vehicle under various driving conditions. It can be seen that in the HIL simulation the vehicle with ESP follows the yaw rate that the actual vehicle yields in severe J-turn tests. Other data, such as the lateral acceleration and wheel velocities, are also similar in both HILS and actual vehicle tests. These results demonstrate the high reliability of the ESP HILS system.

The HILS system in this study can be used to examine the performance of various ESP ECUs and to perform the benchmarking for them. The system can also be used for investigating the possibility of the ECU's malfunction under critical handling situations that may lead to accidents in real situations.

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