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Development of HILS Systems for Active Brake Control Systems

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Abstract: As the vehicle electronic control technology grows fast and becomes more sophisticated, a more efficient way than the traditional in-vehicle driving test is demanded for design, test, and tuning of electronic control units. For this purpose, HILS(Hardware-In-the-Loop simulation) scheme is very promising since significant portions of actual driving test procedures can be replaced by HIL simulation. The HILS method incorporates hardware components in the numerical simulation environment, and this yields results with better credibility than pure numerical simulations. In this study, HILS systems have been developed for active brake control systems: ABS(Anti-lock Brake System), TCS(Traction Control System), and ESP(Electronic Stability Program). The system consists of the hardware part that includes the hydraulic brake mechanism and the ECUs, the software part that virtually implements the vehicle dynamics with visualization, and the interface part that links these two parts together. The HILS system in this research uses the commercial software CarSim to generate a detailed full vehicle model. Using the developed HILS system, the performance of a virtual vehicle was evaluated with commercial ECU modules under various driving conditions.

Keywords: Hardware-In-the-Loop Simulation(HILS), Anti-lock Brake System(ABS), Traction Control System(TCS), Electronic Stability Program(ESP)

1. INTRODUCTION

During the past 20 years, active brake control technologies have been growing rapidly producing ABS, TCS, and ESP (Fig. 1).

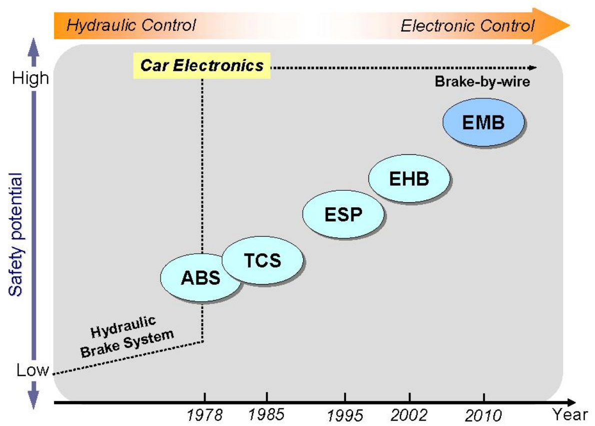


Fig. 1 Development history of brake control systems.

Since brake control systems are directly related with the vehicle safety, strict and extensive testing is always demanded before their debut in the customer's market. To this end, many automakers test prototypes and verify control logics by actual driving test. Computer simulation is also used for verification but only in a limited way, due to its low reliability.

The driving test for evaluating brake control ECUs are often time consuming, expensive and not reproducible. The HILS, by incorporating actual ECUs in its simulation environment, can provide a better time- and cost- effectiveness over the test. The reliability of the simulation results would lie somewhere in the middle of that of the vehicle test and the pure simulation. The HILS also makes possible a dangerous maneuver that could lead to an accident in a real situation.

The HILS system consists of the hardware, software and interface parts. The software part includes a virtual vehicle dynamic model and the hardware part includes the actual brake system including the commercial ECUs. Two parts are linked by the interface part in a real time simulation environment.

In this research, a HILS system has been developed to test commercial ABS, TCS, and ESP ECUs. Using the developed HILS system, performance of commercial brake ECUs were evaluated for a virtual vehicle under various driving conditions. The system has been built in a laboratory providing convenient and reliable means for testing multiple ABS, TCS and ESP modules. In addition to performance evaluation of the ECU modules, the HILS system in this study can be used to perform human-in-the-loop simulation to investigate responses of the driver under various driving conditions including dangerous conditions that could lead to an accident in the real situation.

2. ACTIVE BRAKE SYSTEMS

The ABS system was originally developed to prevent wheels from locking during hard braking. Modern ABS systems, however, not only prevent wheels from locking but also maximize the braking forces generated by the tires by preventing the longitudinal slip ratio from exceeding an optimum value. The basic mechanism of the ABS is to either hold or release the braking pressure on the wheels if there is a danger of wheel locking. It could also hold or release the braking pressure in order to keep the slip ratio at the wheel from exceeding an optimum value.

TCS is another active brake control device for car safety designed to improve acceleration performance and stability of vehicles on slippery road conditions. TCS, is also called ASR(Acceleration Slip Regulation), is a functional extension of ABS. Its objective is to gain maximum longitudinal force and lateral force during the accelerating period of a car.

ESP is an electronic chassis control system of which the objective is to maintain the lateral vehicle stability in critical cornering situations. A critical lateral motion of a vehicle occurs when tire-road contactness 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 which is necessary to restore the vehicle stability. In such situations, the ESP system tried 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 the stability by distributing asymmetric brake forces to the wheels. Fig. 2 shows the control scheme of the ESP.

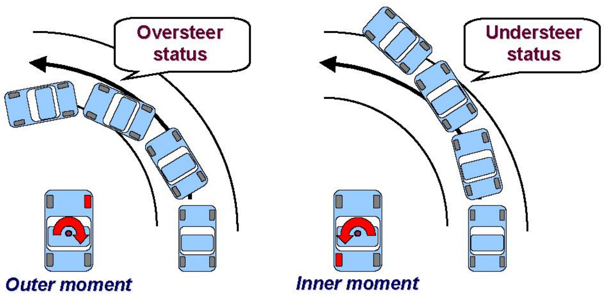


Fig. 2 The concept of ESP.

3. COMPOSITION OF HILS SYSTEMS

3.1 Software part

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

Fig. 3 shows the Simulink diagram for the 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 message block for CAN communication between each module and ECU. Validity of the HIL simulation result is largely contingent upon 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 27 degrees of freedom and can be simulated in real time as a parametric model. Fig. 4 shows the input and output quantities of the vehicle model.

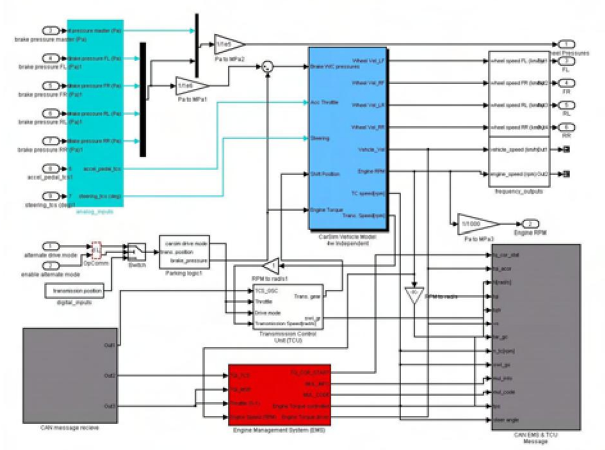


Fig. 3 Simulink diagram of HILS.

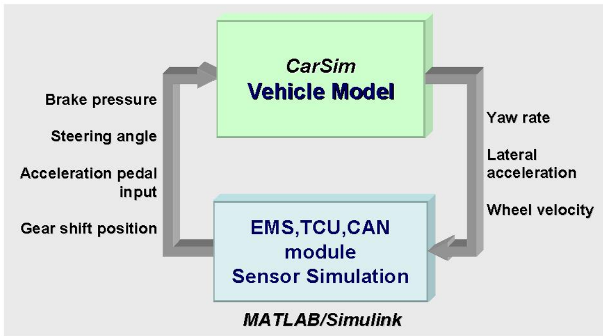


Fig. 4 Input and output data of vehicle model.

In this 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.

3.2 Hardware part

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

Commercial ABS, TCS and ESP modules consist of ECU(Electronic Control Unit) and HCU(Hydraulic Control Unit) integrated together in a single package. Presence of the HCU demands that the HILS system should have a hydraulic brake mechanism similar to the one in the actual vehicle. The hydraulic brake mechanism includes the brake pedal, booster, master cylinder, hydraulic tubes and hoses, and 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 part carries out real-time simulation of 27 DOF vehicle model. In this study, two Pentium 4 PC's were used in host-target configuration as shown in Fig. 5. The two PC's communicate by TCP/IP.

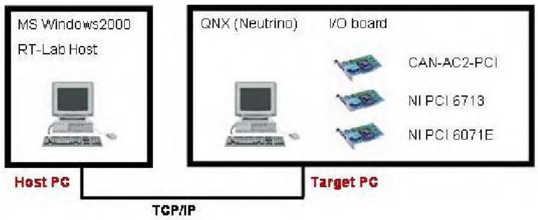


Fig. 5 Configuration of host PC and target PC.

The 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 has been constructed so that the operator can respond interactively to the vehicle response while the HIL simulation is being performed. The visualization window provides the operator with capability of selecting different test conditions such as straight split friction road, road for obstacle avoidance, circular road, handling circuit, etc.

3.3 Interface part

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 done 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.

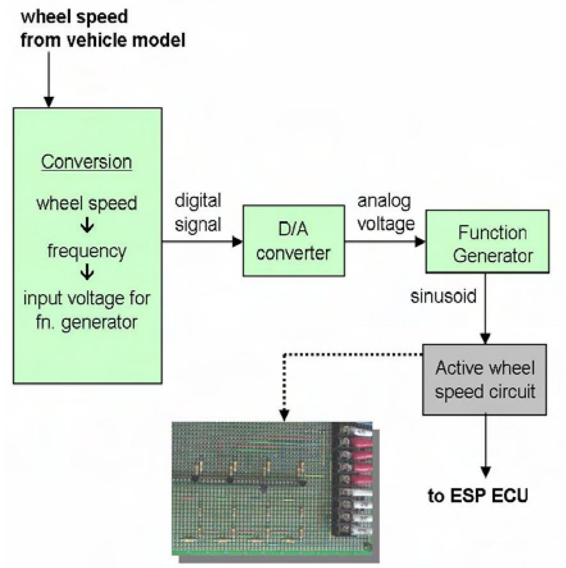


Fig. 6 Wheel speed sensor simulator.

In actual vehicles, the wheel speeds are measured by the wheel speed sensors and they enter the ECU as input. In the HILS system, however, there are no rotating wheels, and hence electric signals similar to the wheel speed sensor outputs must be generated from wheel speed values computed from the vehicle dynamic model. For this, a PWM signal generation module was made in this study and its configuration is shown in Fig. 6.

In the case of ESP HILS, the ECU implements functions of ABS and TCS 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 as shown in Fig. 3. The ESP ECU communicates with these modules via CAN(Controller Area Network) communication protocol. The vehicle model also receives the torque required by the engine, the operational status of TCS, and other information by CAN communication protocol.

The yaw rate and G sensor also communicates with the ECU via CAN, and it has its own diagnostics functions. The ESP ECU issues code bits that are exchanged cyclically between ESP ECU and yaw angular velocity & G sensor. Fig. 7 shows the information flow done via CAN communication.

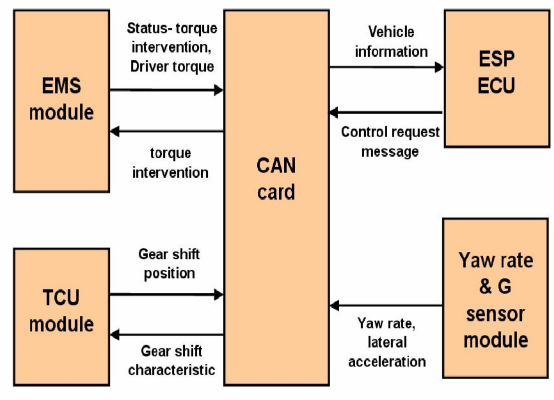


Fig. 7 Communication done via CAN

4. TEST RESULTS

4.1 ABS simulation

The performance of the ABS HILS system was tested under the following driving conditions. The road has split friction coefficient: the left friction coefficient is 0.8 and the right friction coefficient is 0.3. The initial vehicle velocity was 100km/h. During braking, the steering wheel can be manually operated if necessary to keep the vehicle on intended track. The test was also conducted without operation of the ABS ECU for performance comparison.

Fig. 8 shows the velocities of each wheel and vehicle during braking. Fig. 9 shows the pressure of the wheel cylinders and the master cylinder. From these figures, it can be seen that the ABS HILS system developed in this research is performing well providing a testbench for extensive tests of the ABS module. Fig. 10 shows the vehicle trajectory in the plane during braking. The vehicle with the ABS can stay on its lane in a μ-split condition while the vehicle without the ABS deviates and rotates significantly from the lane to the side of high frictional road.

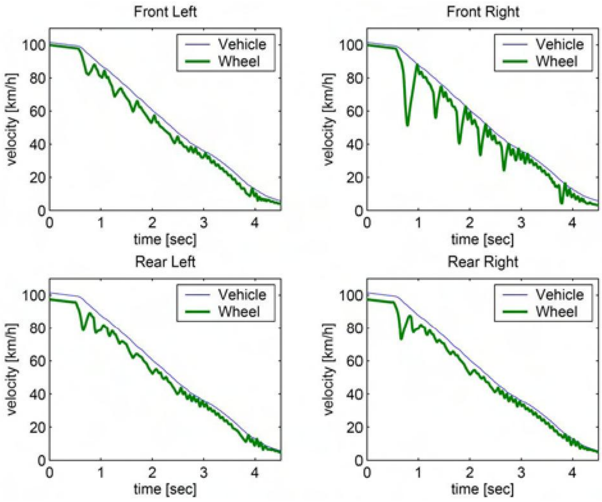


Fig. 8 Vehicle speed and wheel speed in panic braking.

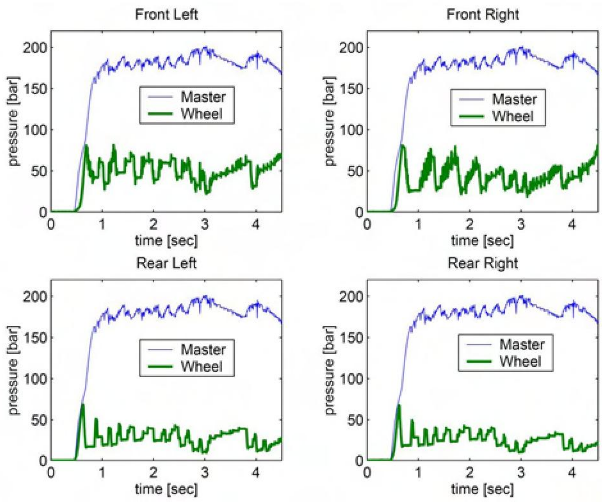


Fig. 9 Brake pressure in panic braking.

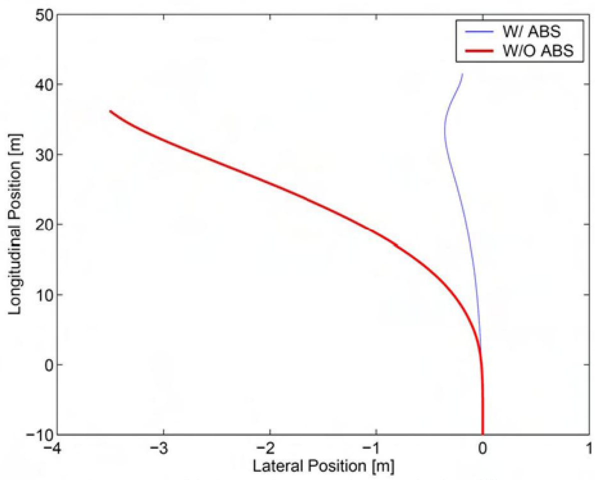


Fig. 10 Vehicle trajectory in panic braking.

4.2 TCS simulation

FTCS(Full Traction Control System) including engine TCS and brake TCS was employed for in this research. The virtual vehicle was accelerated up to 70km/h while the acceleration pedal was fully pushed. At this condition, the operation of TCS was shown in Fig. 11. At around 0.5 sec, the front left and right wheel speeds start to increase over the vehicle speed. At around 0.8 sec, the braking pressures of the front left and right wheel cylinders start to increase, which shows that the brake TCS starts to operate at that time. Also, at the same time, the torque required by engine starts to decrease under the torque required by driver's acceleration pedal input, which means the operation of engine TCS. By this operation, the front wheel speeds decrease up to the vehicle speed. This shows that the objective of TCS operation was attained.

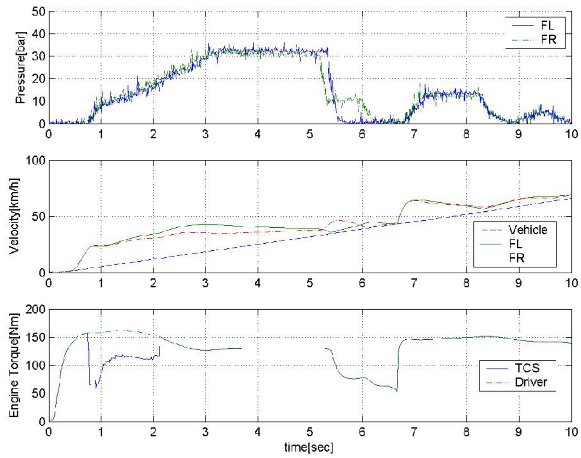
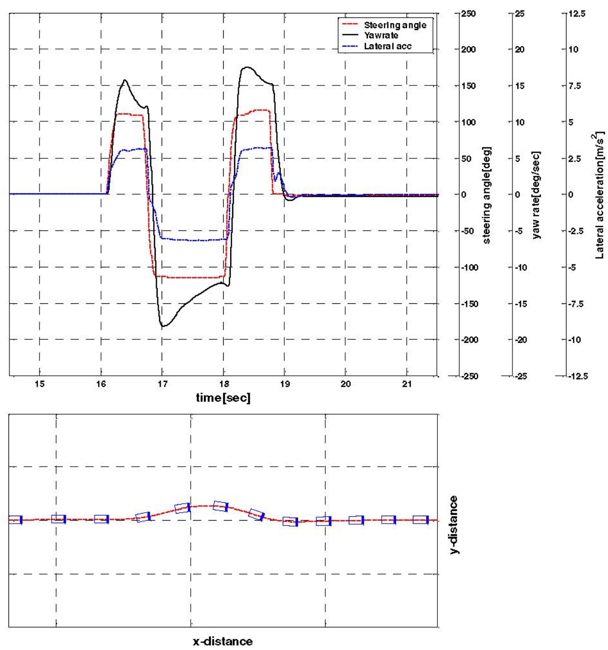


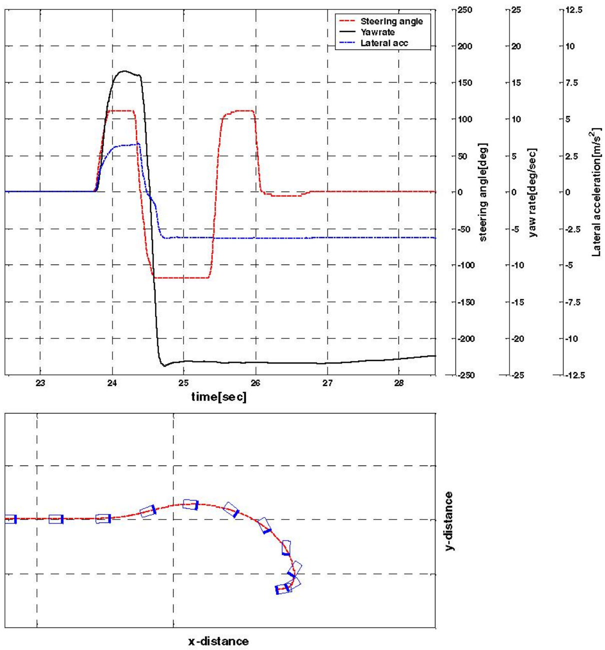
Fig. 11 Result of FTCS operation.

4.3 ESP simulation

The performance of the ESP HILS system was tested under slippery road. The road friction coefficient is 0.3. The initial vehicle velocity was 50km/h.



(a) with ESP



(b) without ESP

Fig. 12 Simulation results for double lane change test.

Fig. 12 shows simulation results for double lane change. It can be seen that, with ESP on, the vehicle successfully completes double lane change. But with ESP off the vehicle loses stability shortly after it enters the new lane and spins. This happens because the vehicle, on the current slippery road condition, cannot follow sudden big change of the steering angle.

5. CONCLUSION

In this study, a HILS system has been developed for commercial brake ECUs. The system consists of the hardware part that includes the hydraulic brake mechanism and commercial brake ECUs, the software part that virtually implements vehicle dynamics with visualization, and the interface part that links these two parts together. The validity of HIL simulation is largely contingent upon 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.

Using the developed HILS system, the performance of a virtual vehicle was evaluated with the commercial brake ECU modules under various driving conditions. It is seen that, the vehicle equipped active brake system can successfully complete all the tests on a slippery road. The HIL simulation results showed appropriate vehicle response for each test condition, which validated reliability of the brake HILS system.

The HILS system in this study will be used to perform human-in-the-loop simulation to investigate responses of the driver under various handling situations including dangerous ones that could lead to accidents in real situations.

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