Development of ABS ECU for a Bus using Hardware In-the-Loop Simulation

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Abstract: Antilock Brake System (ABS) is indispensable safety equipment for vehicles today. In order to develop new ABS ECU suitable for pneumatic brake system of a bus, a Hardware In-the-Loop Simulation (HILS) System was developed. In this HILS, the pneumatic brake system of a bus and antilock brake component were used as hardware. For the computer simulation, the 14-Degree of Freedom (DOF) bus dynamic model was constructed using the Matlab/Simulink software package. This model was compiled and downloaded in the simulation board, where the Power PC processor was used for real-time simulation. Additional commercial package, the ControlDesk was used to monitor the dynamic simulation results and physical signal values. This paper will focus on the procedure and results of evaluating the ECU in the HILS simulation. Two representative cases, wet basalt road and split-μ road, were used to simulate real road conditions. At each simulated road, the vehicle was driven and stopped under the help of the developed ECU. In each simulation, the dynamical behavior of the vehicle was monitored. After enough tests in the laboratory using HILS, the parameter-tuned ECU was equipped in a real bus, which was driven and stopped in the real test field in Korea. And finally, the experiment results of ABS equipped vehicle's dynamic behavior both in HILS test and in test fields were compared.

keywords: Antilock Brake System(ABS), Hardware In-the Loop Simulation(HILS), in-vehicle test, Electronic Control Unit(ECU)

1. Introduction

Recently Antilock Brake System becomes the most essential and indispensable equipment for safety when driving a vehicle. It has become popular in passenger cars after BOSCH developed the first electronically controlled system in late 1960's. Lately it becomes popular also in commercial vehicles and about 15 % of commercial vehicles with air brakes in Western Europe were equipped with ABS in early 1990's. [1] Today almost every vehicle has equipped its own ABS for safety. ABS is mainly composed of ECU, wheel speed sensors and Pressure Control Valves (PCVs). Wheel speed sensors on wheels detect the speed of each wheel. And PCVs modulate the braking pressure according to the control signals from the ECU, the ABS controller. The ECU monitors the wheels' speeds and estimates states of vehicle and determines when the anti-lock braking action is applied. Passenger cars use hydraulic pressure for generating braking force, but commercial vehicles use pneumatic pressure for it. So the main difference between antilock brake controller of commercial vehicle and that of passenger car is due to brake system itself. For heavy vehicles such as trucks and bus braking pressure modulators, PCVs are the type of pneumatic solenoid valves. For passenger cars pressure modulators are hydraulic proportional valves. Thus pressure modulator for commercial vehicle is more sluggish than that of passenger car.

An antilock brake control algorithm and ECU for pneumatic brake system in a commercial vehicle has been studied in Korea [2][3]. In this paper, the procedure for developing the control logic and ECU itself will be omitted. But how to construct the experimental environment for evaluating the control logic and ECU will be focused on. For this purpose, HILS was constructed. A commercial vehicle under braking, pneumatic brake system of it, test roads and antilock brake components can be substituted for it [4][5]. Recently Hardware In-the-Loop Simulation methods are becoming popular especially in automotive industry because it can reduce development time and costs. The Hardware In-the Loop (HIL) environment provides a real-time coupling of the physical hardware and computer simulation. In this framework, hardware components are interchangeable with software models allowing experiments to be run to study a particular subsystem without requiring a vehicle to run the real tests.

The simulated vehicle was driven and stopped in the simulated road conditions. Three typical road conditions are considered. - dry asphalt road, wet basalt road and split-μ road. Each road condition was represented by the tire-road adhesion curve. Finally the ECU was used to generate the braking pressure and the 14-DOF vehicle dynamics was downloaded to simulator. But in some ways, we can not make sure that the software models - the developed vehicle dynamics model and constructed Hardware In-the-Loop Simulator - are correct enough to imitate real world. In order to make sure, the finally confirmed algorithm and controller was tested in the real field – a real bus under braking, test roads, a real brake system, and test driver was used in the test. For field tests, data acquisition system for the test vehicle was constructed, which will monitor the vehicle's dynamic behavior when emergency brake action is applied to it. The test results of ABS controller in the Hardware In-the-Loop Simulator and in the real test field will be presented and compared. After that, the HILS can be considered to be constructed correctly and to simulate the vehicle, tire, test road and brake system.

2. HILS for Pneumatic Brake System

2.1 Real-time simulation using HILS

A *system* is a synergistic combination of components, which perform a specific objective. A *real-time system* is one where the present output depends on the past input, and as a result, the output changes within specified time so as to affect correct responses in the surrounding system. Modeling time and simulating events in time are difficult issues to address in synthesis, and happen to be essential to the analysis of the real-time response of several ABS controller calculations.

In order to perform real time simulation, many hardware are required including a real-time simulator, host PC, I/O interface, A/D converter and so on. In the host PC, modeling of dynamics is performed. This modeling can be implemented using the Matlab/ Simulink Program Package. This dynamics models are compiled to downloadable C-code and downloaded to real-time simulator using the Realtime Workshop Program Package. DSP and alpha-chip processor board was used as a real-time simulator. After downloaded to a real-time simulator, the dynamics model can be run. The ControlDesk Program Package, running in the host PC can control the simulation states and monitor and modify the simulated parameters in real-time.

2.2 Practical Implementation of HILS for ABS

The designed HILS is shown in Fig. 1. The HILS can be divided into hardware parts and software parts. Software parts are implemented in a real-time simulator. Any hardware of real system can be substituted by software model in the design of HILS, and vice versa. The more hardware are used, the more likely to be real world. But additional hardware requires extra expenses. In this paper, the full-air brake system of real bus and ABS components were used as hardware, and the others are substituted by software.

The pneumatic pressure in air-tank is supplied by an external air compressor and is controlled near 8 ~ 8.5 [bar] like in a real bus. The pressures in the power/service brake chamber are measured using four pressure sensors. When the driver pushes the brake pedal, the braking pressures in each brake chamber are measured and fed to A/D converter of simulator. Then the real-time simulator calculate the vehicle dynamics according to these braking pressures and transmit the wheels' speeds to the wheel speed simulator. The wheel speed simulator is a substitute for wheel speed sensors on each wheel. It can generate four independent sinusoidal voltage signals proportional to wheel speeds. So the ECU can acquire wheel speed signals the same manner like in a real bus. When the ECU monitors the wheel speeds, it estimates the vehicle speed, calculates slips and accelerations in each wheel, makes reference braking forces and operates the pressure control valves in each wheel. The pressure control valves modulate the amount of air-flow to each brake chamber thus changes the braking pressures and torques in each wheel.

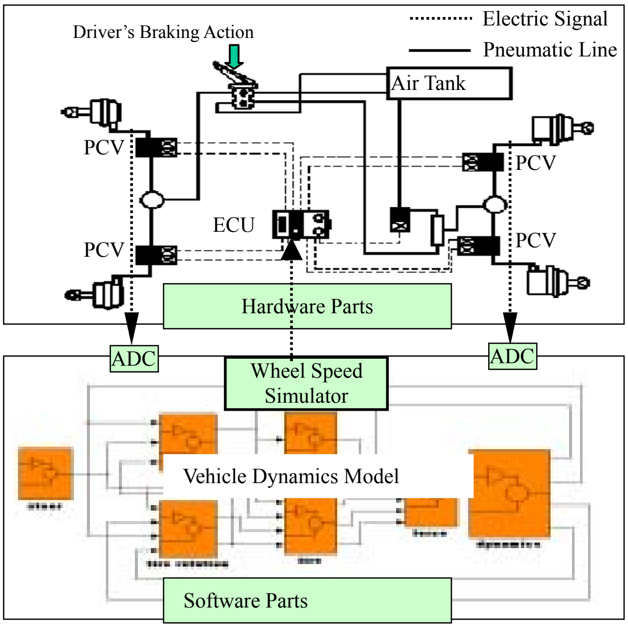

Fig. 1. Configuration of HILS system

The software parts of HILS are composed of a vehicle dynamics model and wheel speed simulation program. The vehicle dynamics model contains steering, tire-road relations, suspensions, chassis and so on. Detailed explanation is presented in next paragraph. The hardware configuration of developed ABS HILS for pneumatic brake system is shown in upper side of Fig. 1. Using actual brake system as a part of HILS, we can get rid of modeling errors due to linearization of the components. Human's behavioral style such as driver's braking action can also be included in the control input. These are the merits of using hardware In-the Loop simulator.

3. Vehicle Dynamics Model for Antilock Brake System

The bus dynamics model is composed of a vehicle dynamics model and tire dynamics model.

3.1 Vehicle Dynamics Model

In order to simulate the vehicle body and wheel dynamics, fourteen equations of motion have to be integrated [6]. Assume the vehicle body, shown in Fig. 3, is composed of three rigid bodies. The sprung mass, which represents the chassis of the vehicle have 3 DOF translational movement and 3 DOF rotational movement. The translational motion consists of longitudinal, lateral, and vertical motions. The rotational motion is composed of rolling, pitching, and yawing motions. The unsprung mass, which represents front and rear axles, have 4 DOF movement, namely the front and rear axle have vertical and rolling motions respectively. And the rotational movement of wheels was added in the vehicle model.

3.1.1 Dynamic equations of sprung mass

The dynamics equations of translational and rotational motions of sprung mass are represented by (1)~(6).

$$M\ddot{x} + M_s e\ddot{\theta} = \sum F_x - M(\dot{z}\dot{\theta} - \dot{y}\dot{\psi}) \\ - M_s e\dot{\phi}\dot{\psi} + M_{uf} l_f - M_{ur} l_r)\dot{\psi}^2 \tag{1}$$

$$M\ddot{y} - M_s e\ddot{\phi} + (M_{uf} l_f - M_{ur} l_r)\ddot{\psi} = \\ \sum F_y - M(\dot{x}\dot{\psi} - \dot{x}\dot{\phi}) - M_s e\dot{\theta}\dot{\psi} \tag{2}$$

$$M_s \ddot{z} = \sum F_{si} - M_s(-\dot{x}\dot{\theta} + \dot{y}\dot{\phi} - e\dot{\phi}^2 - e\dot{\theta}^2) \tag{3}$$

$$I_x\ddot{\phi} - (I_y - I_z)\dot{\theta}\dot{\psi} = M_s a_y e\cos\phi + M_s ge\sin\phi \\ + b\sum T_{yi} - t_{sf}(F_{s1} - F_{s2}) - t_{sr}(F_{s3} - F_{s4}) \\ - K_{rf}(\phi - \phi_{uf}) - K_{rr}(\phi - \phi_{ur}) \tag{4}$$

$$I_y\ddot{\theta} - (I_z - I_x)\dot{\phi}\dot{\psi} = l_f(F_{s1} - F_{s2}) - l_r(F_{s3} - F_{s4}) \\ - h\sum T_{xi} \tag{5}$$

$$I_z\ddot{\psi} - (I_x - I_y)\dot{\theta}\dot{\phi} = l_f(T_{y1} + T_{y2}) - l_r(T_{y3} + T_{y4}) \\ - t_f(T_{x1} - T_{x2}) - t_r(T_{x3} - T_{x4}) - \sum M_{si} \tag{6}$$

where, x is longitudinal distance, y is lateral distance, z is vertical distance, ψ is yaw angle, θ is pitch angle, ϕ is roll angle, M is total mass of vehicle, M_s is sprung mass, $\sum F_x$ and $\sum F_y$ are resultant forces in each direction, $\sum F_{si}$ is sum of suspension force acting on each wheel, *e* is the distance from the roll center to the sprung mass center, *t* is the y-direction distance from mass center to wheel center, t_s is the y-direction distance from center of vehicle mass to suspension, *l* is the x-direction distance from mass center to wheel center, *b* is the distance from road to roll center, and K_r is roll stabilize stiffness. And the subscript *f* and *r* represent front and rear respectively.

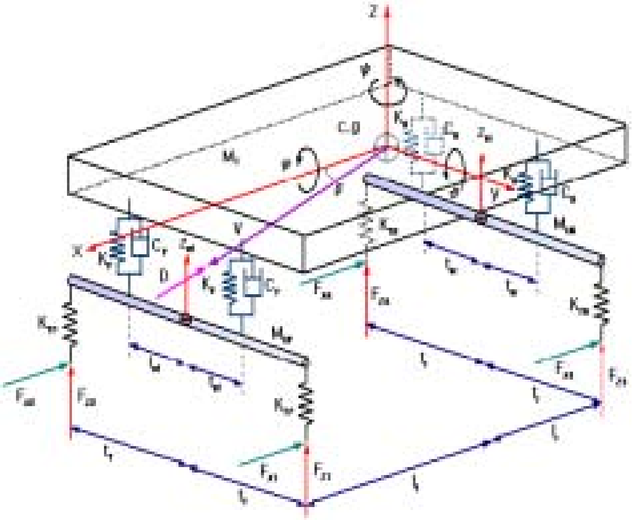

Fig 2. Configuration of vehicle dynamics model

3.1.2 Dynamic equations of unsprung mass

The translational and rotational motions of unsprung mass are described by (7)~(10).

$$M_{uf}\ddot{z}_{uf} = -K_t(z_{uf} - z_{rl} + t_f\phi_{uf}) \\ -K_t(z_{uf} - z_{r2} - t_f\phi_{uf}) + F_{s1} + F_{s2} \tag{7}$$

$$M_{ur}\ddot{z}_{ur} = -2K_t(z_{ur} - z_{r3} + t_r\phi_{ur}) \\ -2K_t(z_{ur} - z_{r4} - t_f\phi_{ur}) + F_{s3} + F_{s4} \tag{8}$$

$$I_{xuf}\ddot{\phi}_{uf} = t_{sf}(F_{s1} - F_{s2} - F_{t1} + F_{t2}) - K_{rf}(\phi_{uf} - \phi) \tag{9}$$

$$I_{xur}\ddot{\phi}_{ur} = t_{sr}(F_{s3} - F_{s4} - F_{t3} + F_{t4}) - K_{rr}(\phi_{ur} - \phi) \tag{10}$$

Where, M_{uf} and M_{ur} are mass of front and rear shaft, I_u is inertia of front and rear shaft, and K_t is stiffness of tire.

3.2 Wheel and Tire Dynamics Model

Wheel dynamics model can be drawn like Fig. 3. When braking torque is applied at a wheel, braking forces are generated at the interface between the tire and the road surface. As the force at the wheel increases, slippage occurs between the tire and the road surface. With further increase in brake torque, this slippage between the tire and road surface increases until locking-up and skidding of the wheel occurs.

The dynamic equations on the wheel is represented by (11)

$$I_{\omega_i}\dot{\omega}_i = T_{si} - T_{bi} - R\cdot F_{xi} - rr_i \quad (i = 1,2,3,4) \tag{11}$$

Where, F_x is braking force on the wheels, T_s is engine torque, T_b is braking torque, rr is rolling friction, and I_ω is rotational inertia of each wheel. The tire is one of the most important factors to increase the non-linearity of vehicle dynamics. The forces obtained from the tire model are used to determine the vehicle's longitudinal and lateral motion, as well as yaw rate. And these forces are affected by vehicle dynamics, characteristics of tire, and road conditions. The braking force and slip curve, which are used as a tire model of test vehicle in HILS, is presented in Fig. 4.

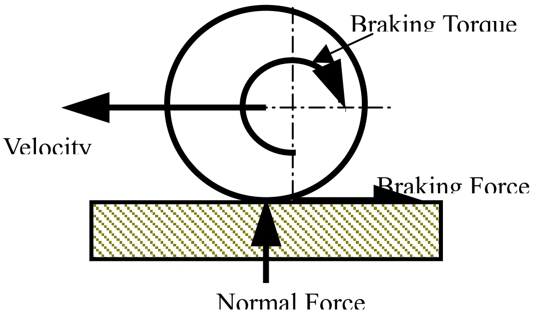

Fig. 3. Braking Force at a wheel

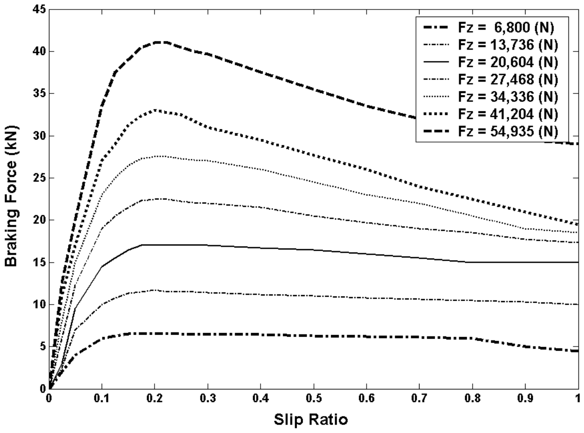

Fig 4. Braking force - slip curve between tire and road

4. In-Vehicle Test

After tested on HILS in laboratory, the ABS controller was equipped in a bus. The in-vehicle test, the vehicle's braking performance test with the ABS controller in it and with the data acquisition system and test driver in it, was done at test section on the Korea Automotive Technology Institute (KATECH) in Korea.

4.1 Data Acquisition System for in-vehicle tests

The test section has ABS test road of 200 m long in addition to asphalt road. The ABS test road is composed of a lot of basalt sheets. With sprinkled with water, the adhesion coefficient of this road can be as lower as 0.35.

In order to measure behavioral of the test vehicle, when ABS controller is operated, various senses were equipped in the test vehicle. Fig. 5 shows schematic diagram of this data acquisition system in the test vehicle. *Steering wheel sensor* monitors the angle and angular velocity of steering wheel and steering torque command. The *gyro-platform system*, put on the center of test vehicle, can monitor translational (longitudinal, lateral, vertical) acceleration and rotational (yaw, roll, pitch) angle of the vehicle. And the *speedometer*, fixed on the side of the vehicle, is an optic sensor for monitoring longitudinal and lateral velocity of the bus. The *brake pedal trigger sensor* is used to check the driver's braking action and inform the starting time of vehicle's stopping.

4.2 Procedure of In-vehicle Test

The in-vehicle test was done at different road conditions. -High adhesion coefficient road, and low adhesion coefficient road and split μ road condition. In each test, the test procedures are as follows. Initially, the vehicle was traveling at a pre-selected fixed speed; then it was commanded to begin to stop with driver's putting the brake pedal. The transmission gear was in neutral point before braking. All the experiments were recorded by the data acquisition system.

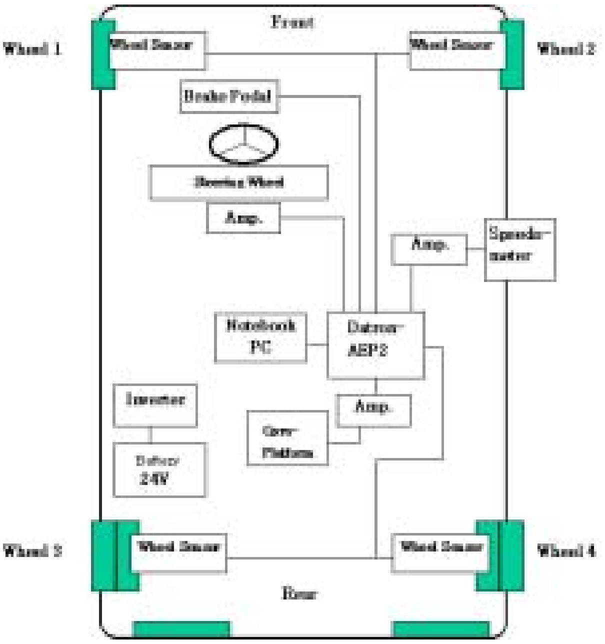

Fig 5. Data Acquisition System for ABS equipped Vehicle

5. Experimental Results

The ABS ECU was turned from the constructed HILS, and it was equipped in a real bus and tested in a test road. Followings are the results of these two experiments.

5.1 Test Results in Laboratory using HILS System

To check the performance of developed ECU and control algorithm, laboratory test was performed with the help of constructed HILS. The initial velocity of braking is 75 km/h. As for the road condition, we simulated two cases, i.e., wet and slippery road ($\mu = 0.3$), and split road ($\mu_{\text{left}} = 0.8$, $\mu_{\text{right}} = 0.3$).

The test results about wet and split road condition are presented below. Fig 6 and Fig 7 Show the laboratory test result for low adhesion coefficient road. Fig 6 shows vehicle and wheel speeds and Fig 7 shows braking pressures in each chamber of wheel.

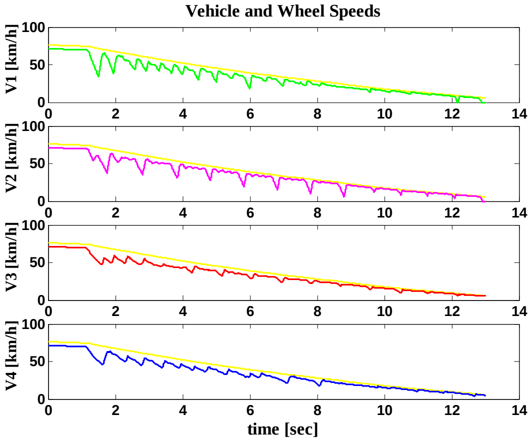

Fig. 6. HILS test result under low μ (μ=0.3)

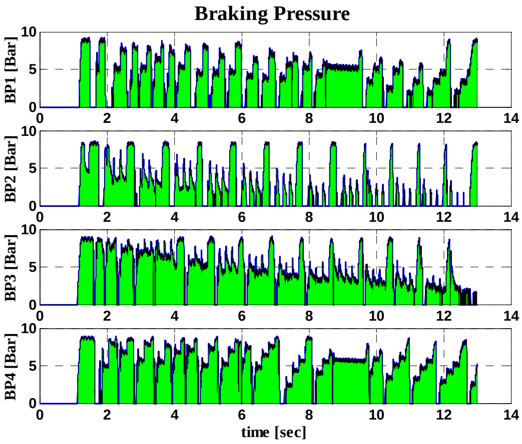

Fig.7. HILS test result under low μ (μ=0.3)

Fig 8 and Fig 9 Show the laboratory test result for split road condition. Fig 8 shows vehicle and wheel speeds and Fig 9 shows braking pressures in each chamber of wheels. In split μ road

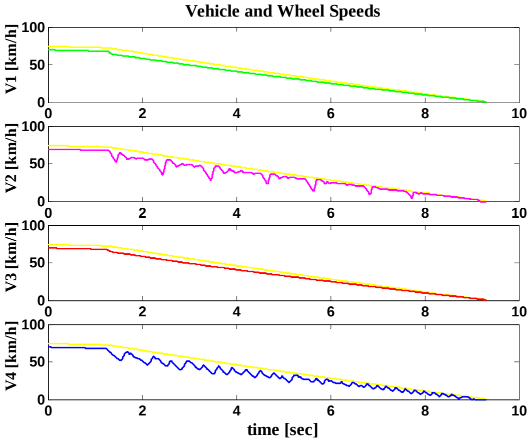

Fig. 8. HILS test result under split μ (μ_{left} = 0.8, μ_{right} =0.3)

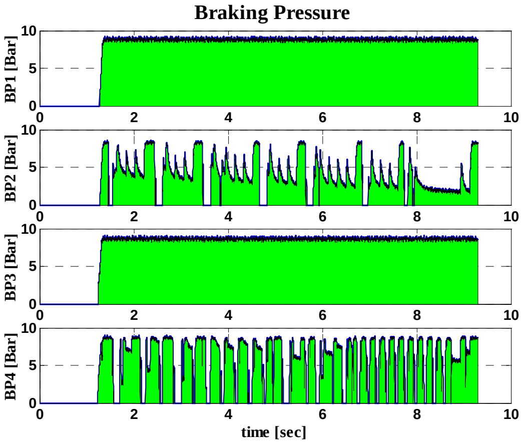

Fig. 9. HILS test result under split μ (μ_{left} = 0.8, μ_{right} =0.3)

5.2 Test Results of In-Vehicle Tests

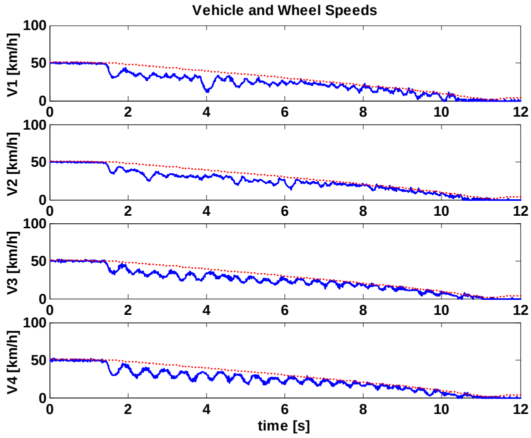

Fig. 10. Test result under low μ (μ ≈ 0.3)

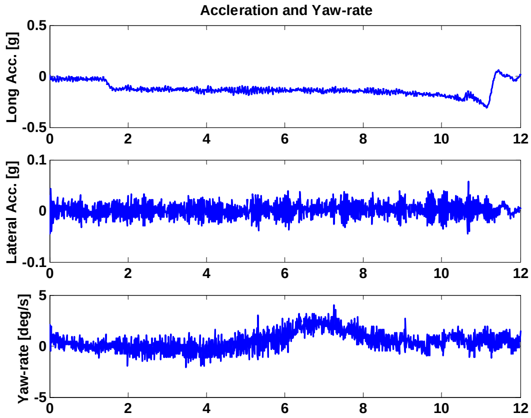

Fig.11. Test result under low μ (μ ≈ 0.3)

After HILS test in the laboratory, the parameter-turned ECU was equipped in a bus. And the bus was driven and stopped in a ABS test road, where wet basalt was put. It is known as the adhesion coefficient of this road is about 0.3.

Fig 10 and Fig 11 shows bus braking test results on this road. In this experiment, the bus was initially driven to the speed of 50 km/h and stopped immediately by the drive's putting the pedal. Fig 10 shows the measured vehicle speed and each wheel speed. Fig 11 shows the longitudinal and lateral decelerations and yaw rate of the vehicle.

Fig 12 and Fig 13 shows bus braking test results on the split road. In this experiment, the bus was initially driven to the speed of 50 km/h and stopped immediately by the drive's putting the pedal with left wheels on the wet basalt road and right wheels on the wet asphalt road.

Fig 12 shows the measured vehicle speed and each wheel speed. Fig 13 shows the longitudinal and lateral decelerations and yaw rate of the vehicle.

From these two experiments, the dynamic behavior of each wheel on the slippery road seems the same both on HILS and on test road.

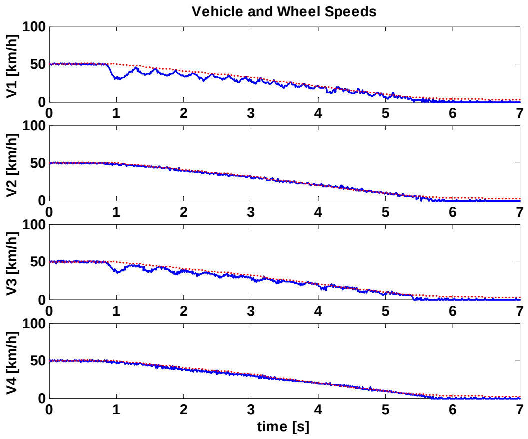

Fig.12. Test result under split μ ($\mu_{left} \approx 0.8$, $\mu_{right} \approx 0.3$)

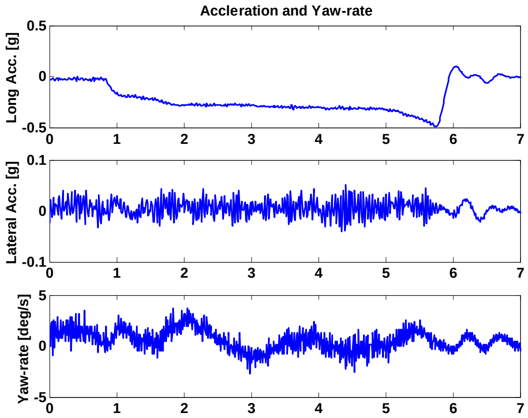

Fig. 13. Test result under split μ ($\mu_{left} \approx 0.8$, $\mu_{right} \approx 0.3$)

6. Conclusion

Antilock Brake System is essential equipment for vehicle, which improves driver’s safety and maneuverability. In order to develop new ABS ECU suitable for pneumatic brake system of a bus, a Hardware In-the-Loop Simulation (HILS) System was developed. In this HILS, the pneumatic brake system of a bus and antilock brake component were used as hardware. For the computer simulation, the 14-Degree of Freedom (DOF) bus dynamic model was constructed using the Matlab/Simulink software package. Additional commercial package, the ControlDesk was used to monitor the dynamic simulation results and physical signal values. This paper will focus on the procedure and results of evaluating the ECU in the HILS simulation. Two representative cases, wet basalt road and split-μ road, were used to simulate real road conditions.

At each simulated road, the vehicle was driven and stopped under the help of the developed ECU. In each simulation, the dynamical behavior of the vehicle was monitored. After enough tests in the laboratory using HILS, the parameter-tuned ECU was equipped in a real bus, which was driven and stopped in the real test field in Korea. And finally, the experiment results of ABS equipped vehicle's dynamic behavior both in HILS test and in test fields were compared.

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