International Journal of Automotive Technology, Vol. 13, No. 7, pp. 1067−1075 (2012)
DOI 10.1007/s12239−012−0109−1
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pISSN 1229−9138/ eISSN 1976−3832

DEVELOPMENT OF A FAIL-SAFE CONTROL STRATEGY BASED ON EVALUATION SCENARIOS FOR AN FCEV ELECTRONIC BRAKE SYSTEM

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(Received 11 July 2011; Revised 31 July 2012; Accepted 7 August 2012)

ABSTRACT−This study presents a few fail-safe control strategies based on reliability evaluation scenarios for the electronic brake systems of green cars in several critical cases. CarSim and MATLAB Simulink were used to develop the FCEV model with regenerative braking involving EWBs and EMBs. The proposed reliability evaluation scenarios were simulated, and a few fail-safe control algorithms were verified using the proposed reliability evaluation scenarios with the developed FCEV simulation model. The reliability evaluation scenarios were developed using a combination of driving modes and FMEA results for these electronic brake systems.

KEY WORDS: Fuel cell electric vehicle (FCEV), Electronic brake system, Regenerative sbraking, Electronic wedge brake (EWB), Electronic mechanical brake (EMB), Reliability evaluation scenario, Fail-Safe control strategy, FMEA (Failure Mode and Effect Analysis)

NOMENCLATURE

m_w : mass of an EWB wedge [kg]
x_w, y_w : positions of an EWB wedge [m]
F_M : force actuating to wedge of EWB [N]
F_B : braking force in EWB [N]
F_N : normal (clamping) force in EWB [N]
F_R : reaction force on inclined wedge in EWB [N]
α : angle of inclined wedge in EWB [deg]
β : angle of actuator motor force in EWB [deg]
T_L : loading torque in EWB motor [Nm]
η : efficiency of a screw in EWB [-]
L : pitch of an EWB screw [-]
L_M : reluctance of EWB motor [A-turn/Wb]
R_M : resistance of EWB motor [Ohm]
i_M : current of EWB motor [A]
K_e : EWB motor torque constant [Vs/rad]
ω_M : angular speed of EWB motor [rad/s]
u_M : control voltage of EWB motor [V]
$J_{M,emb}$: moment of inertia of EMB system [kg m^2]
$\omega_{M,emb}$: angular speed of EMB motor [rad/s]
$T_{M,emb}$: motor torque in EMB motor [Nm]
$T_{L,emb}$: loading torque in EMB motor [Nm]
$T_{F,emb}$: torque due to EMB screw friction [Nm]
$K_{t,emb}$: EMB motor characteristic constant [Nm/A]
$i_{M,emb}$: current of EMB motor [A]
η_{emb} : efficiency of a screw in EMB [-]
L_{emb} : pitch of an EMB screw [-]
$F_{N,emb}$: normal (clamping) force of EMB [N]
$K_{Cal,emb}$: stiffness of EMB caliper [N/m]
$y_{p,emb}$: nominal displacement of an EMB pad [m]
$L_{M,emb}$: reluctance of EMB motor [A-turn/Wb]
$R_{M,emb}$: resistance of EMB motor [Ohm]
$i_{M,emb}$: current of EMB motor [A]
$M_{e,emb}$: EMB motor torque constant [Vs/rad]
$u_{M,emb}$: control voltage of EMB motor [V]

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1. INTRODUCTION

Limited resources and environmental problems have led to increasing interest in eco-friendly vehicles, such as the HEV, FCEV, and the pure EV (Sung *et al*., 2010; Kizaki *et al*., 2009). A core technology in eco-friendly vehicles is regenerative braking, which generates electric energy and saves the energy in a battery. Regenerative braking enhances the energy efficiency of eco-friendly cars and has thus been adapted for electric motors and batteries (Ahn *et al*., 2009). Brake-by-wire systems such as the EWB and the EMB could potentially serve as replacements for current hydraulic brake systems (Kim *et al*., 2010; Malila and

Mallikarjun, 2009; Fox *et al*., 2007; Ho *et al*., 2006).

Passenger safety directly depends on the reliability of a vehicle's brake system (Lee *et al*., 2010; Haggas *et al*., 2007). Between 1998 and 2010, Toyota issued a Prius model recall due to unreliable acceleration pedals and braking systems. This further proves the importance of reliable systems within a vehicle.

This study developed a few fail-safe control strategies based on reliability evaluation scenarios for electronic brake systems in green vehicles. CarSim and MATLAB Simulink were used to develop an FCEV model in which regenerative braking—EWB and EMB actuators and controllers—were applied.

The electronic brake system reliability evaluation scenarios were developed using various driving modes in correlation with current brake test standards and the FMEA results.

2. SIMULATION MODEL

2.1. 100 kW FCEV Simulation Model

The FCEV simulation model containing the EWB and the EMB shown in Figure 1 comprises a 100 kW traction motor model, a converter model, a fuel cell stack model, a battery model, a vehicle dynamics model, an electronic brake system model, a driver model, and controller models for each component. The FCEV simulation model was developed with MATLAB/Simulink and CarSim (Jeon *et al*., 2010).

Figure 2 shows how the information is exchanged between the FCEV model and the EWB/EMB model.

Figure 3 shows the flow chart of the regenerative braking control algorithm of the target FCEV model.

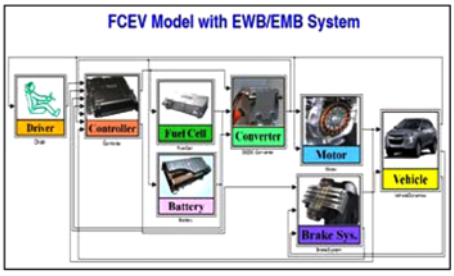

Figure 1. 100 kW FCEV simulation model.

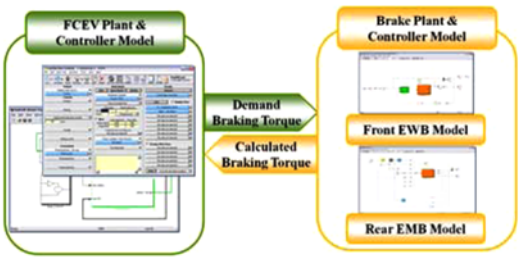

Figure 2. Data flow between FCEV and EWB/EMB.

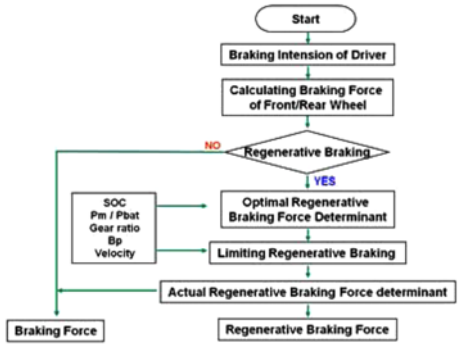

Figure 3. Regenerative braking control algorithm.

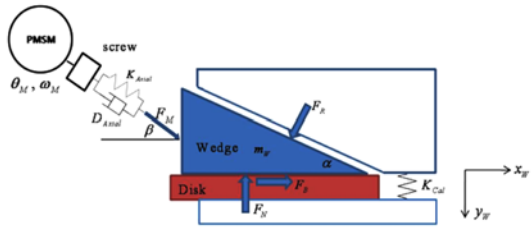

Figure 4. Schematic diagram of the EWB system.

2.2. EWB Simulation Model of Front Wheels

Figure 4 shows a schematic diagram of the EWB system, and the governing equations of the EWB system are represented by equations (1) to (7) (Park *et al*., 2011).

$$m_w\ddot{x}_w = F_M\cos\beta + F_B - F_R\sin\alpha \tag{1}$$

$$m_w\ddot{y}_w = F_M\sin\beta - F_N + F_R\cos\alpha \tag{2}$$

$$F_M = -K_{axial}\left(\frac{x_w}{\cos\beta} - \frac{L}{2\pi}\theta_M\right) - D_{axial}\left(\frac{\dot{x}_w}{\cos\beta} - \frac{L}{2\pi}\omega_M\right) \tag{3}$$

$$F_B = \mu F_N \tag{4}$$

$$F_N = K_{Cal}y_w \tag{5}$$

$$y_w = \tan\alpha \cdot x_w \tag{6}$$

$$2\pi\eta T_L = LF_M \tag{7}$$

$$L_M\dot{i}_M = -R_M i_M - K_e\omega_M + u_M \tag{8}$$

$$T_M = K_e\omega_M \tag{9}$$

Equations (8) and (9) are the electronic actuating motor's governing equations, and indicate the relationships between the current, input voltage, motor speed and motor torque.

The EWB plant model was implemented with MATLAB/Simulink, as shown in Figure 5, using Equations (1) to (9).

The EWB controller was designed using a sliding mode control law (Slotine and Li, 1991) and implemented with

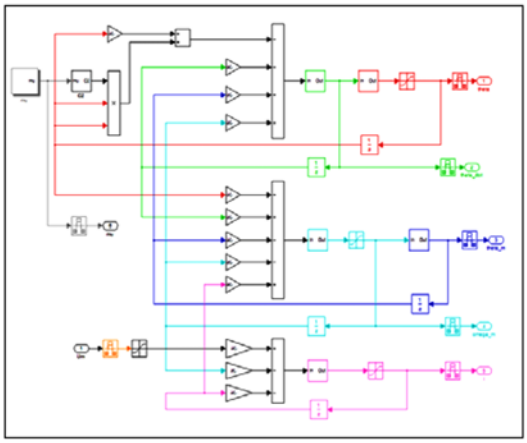

Figure 5. Plant model of the EWB.

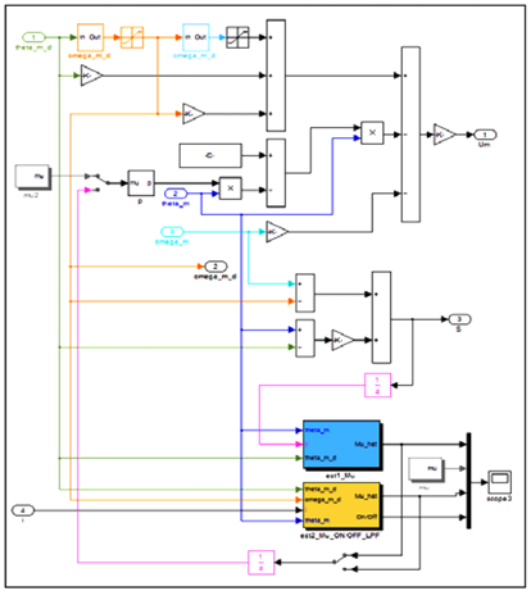

Figure 6. Controller model of the EWB.

MATLAB/Simulink, as shown in Figure 6.

The error function is defined as the difference between a demanded motor angle and an actual motor angle in equation (10). The sliding surface and the sliding condition for the EWB control system to reduce the error function are defined by Equations (11) and (12). S represents the sliding surface, λ is the weighting factor and K_s is the sliding mode controller gain.

$$\varepsilon = \theta_M - \theta_{Md} \tag{10}$$

$$s = \dot{\varepsilon} + \lambda\varepsilon \tag{11}$$

$$\dot{s} = \ddot{\varepsilon} + \lambda\dot{\varepsilon} = -K_s s \tag{12}$$

2.3. EMB Simulation Model of the Rear Wheels

Figure 7 shows a schematic diagram of an EMB using a

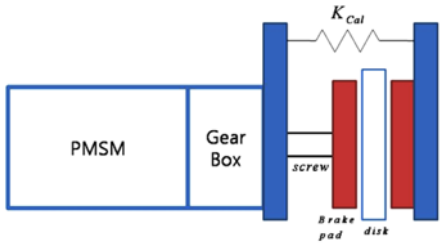

Figure 7. Schematic diagram of the EMB system.

PMSM motor. The EMB model's governing equations are given in equations (13) to (17) (Park *et al.*, 2011).

$$J_{M,emb}\dot{\omega}_{M,emb} = T_{M,emb} - T_{L,emb} - T_{F,emb} \tag{13}$$

$$T_{M,emb} = K_{t,emb} i_{M,emb} \tag{14}$$

$$T_{M,emb} = (L_{emb}/2\pi\eta_{emb}) F_{N,emb} \tag{15}$$

$$F_{N,emb} = K_{Cal,emb} y_{p,emb} \tag{16}$$

$$L_{emb}\dot{i}_{M,emb} = -R_{M,emb} i_{M,emb} - K_{e,emb}\omega_{M,emb} + u_{M,emb} \tag{17}$$

The EMB plant model was implemented with MATLAB/Simulink, as shown in Figure 8, using equations (13) to (17).

The control algorithm for the EMB was designed using a sliding mode control law in conjunction with equations (10) to (12) and implemented with MATLAB/Simulink, as shown in Figure 9.

2.4. Verification of the Simulation Model using Brake Tests

Brake field tests were performed to verify the FCEV with

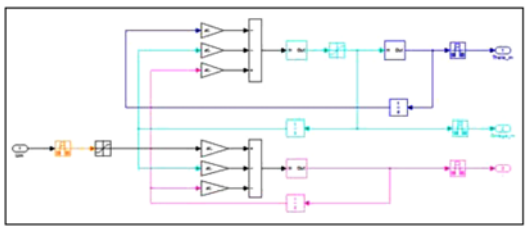

Figure 8. Plant model of the EMB.

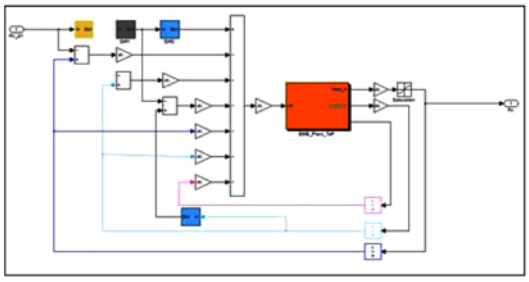

Figure 9. Controller model of the EMB.

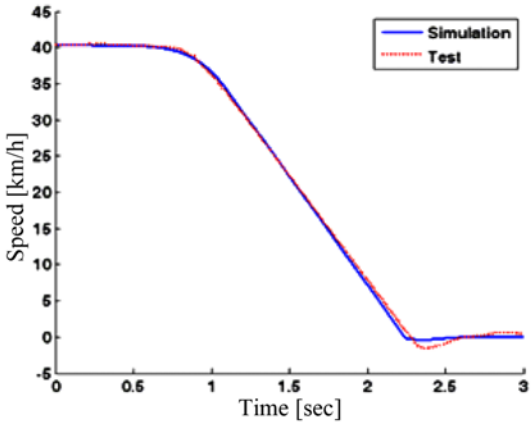

Figure 10. Comparison of vehicle speed.

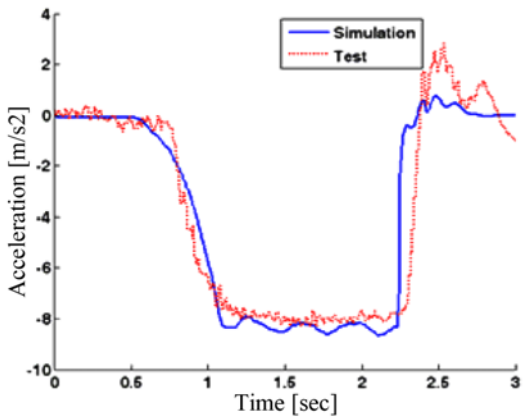

Figure 11. Comparison of vehicle deceleration.

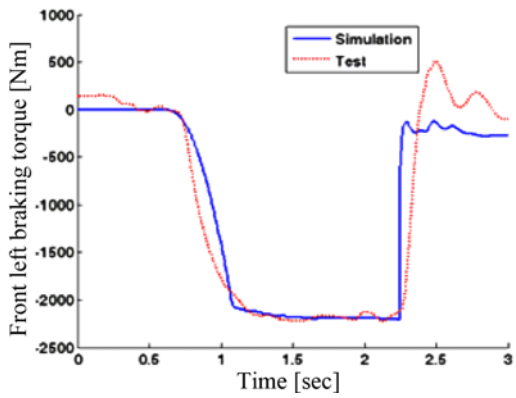

Figure 12. Comparison of front brake torque.

the EWB/EMB models under the following conditions: full braking on dry asphalt at an initial speed of 40 kph using a real targeted FCEV at the proving grounds.

Figures 10 to 13 show vehicle speed, deceleration, front brake torque, and rear brake torque data comparisons

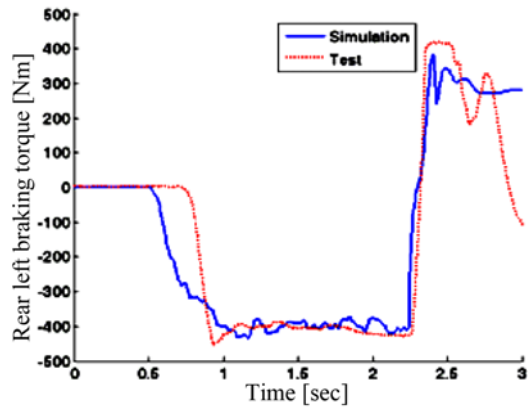

Figure 13. Comparison of rear brake torque

between the experimental and simulation results. The comparisons indicate that the simulation model is sufficiently accurate for predicting the FCEV's braking performance.

3. FMEA FOR FCEV WITH EWB/EMB

FMEA for the FCEV containing the EWB and the EMB was conducted to predict field failures and to develop the

Table 1. Critical failure modes in FMEA results.

System	Part name	Failure mode	Failure effects
Traction motor	Stator coil	Wire harness Open/Short	Motor malfunction
Inverter & Converter	Power supply	Wire harness Open/Short	Power cannot be supplied
	IGBT Circuit	IGBT chip is destroyed	Motor malfunction
	PWM generator	Chip destroyed, Open/Short	Motor driver malfunction
EWB/ EMB	Actuating motor	Wire harness Open/Short	Actuator malfunction
	Position Sensor	Destroyed, Wire harness Open/Short	Actuator control malfunction
	Speed Sensor	Destroyed, Wire harness Open/Short	Actuator control malfunction
	Current Sensor	Destroyed, Wire harness Open/Short	Motor control malfunction
	Controller	Circuit broken Open/Short	Control malfunction
	CAN	Error	Controller malfunction
Brake pedal simulator	Position Sensor	Destroyed, Wire harness Open/Short	Missing driver's decelerating will

Table 2. Driving condition scenarios.

No	Driving mode	Vehicle speed	Braking	Code
1	Braking in high μ	40 kph, 80 kph	Full	A1, A2
			0.3 g	A3, A4
2	Braking in low μ	40 kph, 80 kph	Full	B1, B2
			0.3 g	B3, B4
3	μ Jump1 Braking (High → Low)	40 kph, 80 kph	Full	C1, C2
			0.3 g	C3, C4
…	…	…	…	…
			…	…

fault tolerant algorithm that will prevent the failures.

The critical failure modes and their effects in each system are summarized in Table 1.

4. DEVELOPMENT OF RELIABILITY EVALUATION SCENARIOS

Reliability evaluation scenarios were developed using the matrix of two sub-scenarios. One sub-scenario concerned the driving conditions based on the braking test regulations given in Table 2. The second sub-scenario concerned the failure modes based on the FMEA results given in Table 3.

The reliability evaluation scenarios were a combination of driving conditions and failure situations. Each code was named after each condition and situation. For example, the scenario code was "A2-E1" when the driving condition comprised full braking in high μ with an initial speed of 80 kph and when the current sensor in EMB failed.

Table 3. Failure mode scenarios.

No	Failure system	Failure mode	Code
1	Normal	-	00
2	Brake pedal simulator	A signal wire open	B1
3		Two signal wires open	B2
4	Traction motor & Inverter	1 phase open	M1
5		All phases open	M2
6	EWB/EMB System	Current sensor malfunction	W1/E1
7		Speed Sensor malfunction	W2/E2
8		Position Sensor malfunction	W3/E3
9		Actuator malfunction	W4/E4
10		Controller of EWB/EMB malfunction	W5/E5
11		Jammed wedge	W6/ -
12	CAN comm.. between controllers	CAN comm. malfunction btw. BCU and VCU	T1
13		CAN com. malfunction btw. BCU and wheel ECU	T2

Table 4. Reliability evaluation scenarios.

No	Driving condition	Failures mode	Code
1	A1 (High μ, 40 kph, Full Braking)	00 (Normal)	A1-00
2		B1 (1 of BPSs fail)	A1-B1
3		B2 (all BPSs fail)	A1-B2
4		M1 (1 phase of T/motor fail)	A1-M1
5		M2 (all phase of T/motor fail)	A1-M2
6		E1 (EMB current sensor fail)	A1-E1
7		E2 (EMB speed sensor fail)	A1-E2
…		…	…
…	A2 (High μ, 80 kph, Full Braking)	00 (Normal)	A2-00
…		B1 (1 of BPSs fail)	A2-B1
…		…	…
…	…	…	…

5. FAIL-SAFE CONTROL STRATEGIES AND SIMULATION RESULTS

5.1. Fail-safe Control Strategy for Brake Pedal Simulator Failure

The brake pedal simulator transmits the driver's braking command to the BCU (Brake Control Unit). Thus, a safe

Table 5. Fail-safe control strategy for brake pedal simulator failure.

	Mode 1	Mode 2	Mode 3	Mode 4
BPS Sensor #1 status	Normal	Normal	Failure or abnormal	Failure or abnormal
BPS Sensor #2 status	Normal	Failure or abnormal	Normal	Failure or abnormal
Fail-safe control strategy	Use average value of 2 sensor output	Use BPS sensor #1	Use BPS sensor #2	Case 1) if V = 0 → Warning & BPS 100% (locking)
				Case 2) if V>0, APS=0 → Warning & BPS 50%
				Case 3) if V>0, APS>0 → Warning & BPS 30%

and redundant structure, such as a dual sensor/wiring system, is necessary in the brake pedal simulator. Furthermore, a fail-safe control strategy for various failure modes is also quite necessary.

The proposed fail-safe control strategy for the brake pedal simulator is summarized in Table 5. There are four modes depending on the status of two sensors. If one of the two sensors is broken down or is transmitting an abnormal (noisy or offset) signal, normal sensor output can be used after applying fault detection, such as a state observer method (Blanke *et al*., 2003).

In the worst case, "mode 4", when two sensors have failed, the fail-safe control strategy is classified into 3 cases according to the vehicle state (driving or parking). In the parking case (Case 1), a warning signal is shown to the driver, and the brake position stroke (BPS) signal will be set to 100% (locking mode). In the driving cases (Case 2 or 3), a mild-strong (50%) or mild (30%) braking signal will be sent to the BCU to safely decrease the speed of the vehicle.

Figure 14 shows the vehicle speed and brake torque of the front left and rear left in the case of a normal state, failure state and fail-safe controlled state (Mode 4, Case 2) for the reliability evaluation scenario "A1-B2".

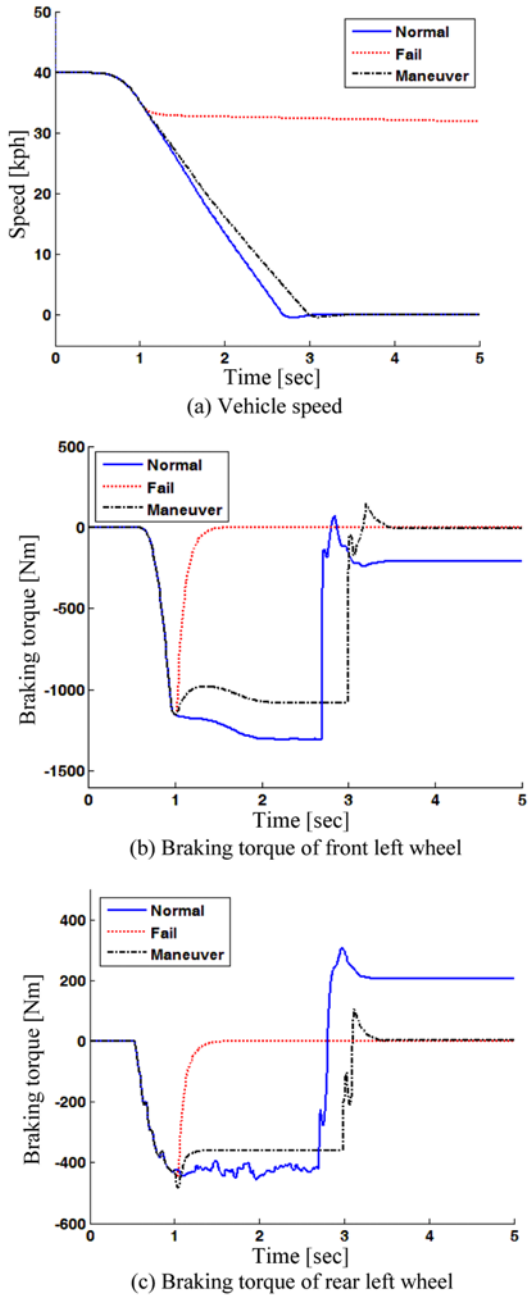

Figure 14. Simulation results for brake pedal simulator.

5.2. Fail-safe Control Strategy for Failure of One Rear EMB

A dangerous situation for a driver would involve the failure of one of the two rear EMBs while the vehicle is in operation.

During the "A2-E1" scenario, the current sensor of the rear left EMB was broken at 1 second after full braking on dry asphalt (high μ) at 80 kph.

The braking torque decreased in the rear left wheel because the EMB current sensor was broken at 1 second. The difference of the braking torque between the rear left wheel and the rear right wheel forced the vehicle to turn. This scenario would be very dangerous in a real traffic situation. The fail-safe control strategy potentially leads to the avoidance of dangerous situations, as shown in Figure 15.

The braking torque of the normal side was controlled to match the braking torque of the failed EMB, and the braking torques in the front wheels were increased to compensate for the total brake torque of the vehicle.

The simulation results of the three cases are presented in Figure 16 to Figure 20.

Figure 16 shows the vehicle speed for the three cases. The vehicle speed decreased during failure because the braking torque decreased in the failed wheel.

Figure 17 shows the braking torques of the rear left wheel for the failure mode and the normal mode. The braking torque decreased because the broken current sensor caused an EMB controller malfunction.

Figure 18 shows the braking torques of the rear right wheel. The fail-safe control strategy controlled the brake

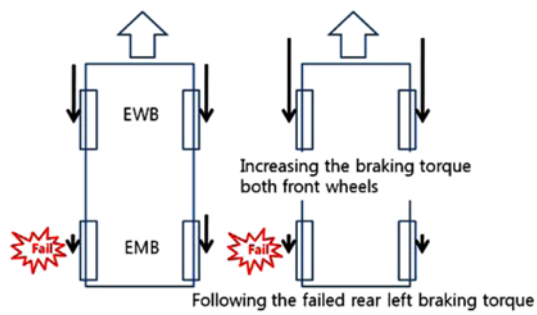

Figure 15. Fail-safe control strategy for one EMB failure.

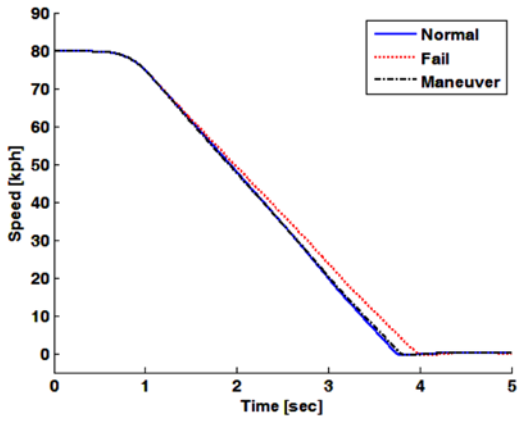

Figure 16. Vehicle speeds.

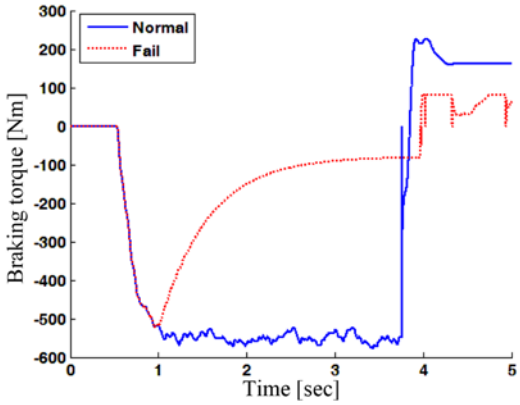

Figure 17. Brake torque in the rear left EMB.

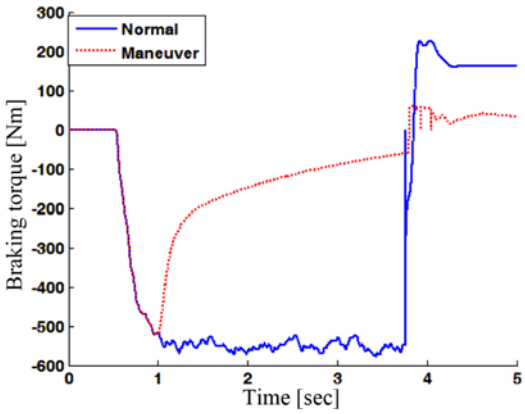

Figure 18. Brake torque in the rear right EMB.

torque of the normal right side EMB to follow that of the failed rear left EMB.

Figure 19 shows the vehicle yaw rate. The fail-safe control strategy reduced the vehicle yaw rate and spinning by one-third compared with that of the failure situation.

Regenerative braking of the driving motor in the front wheels was performed, as shown in Figure 20. The

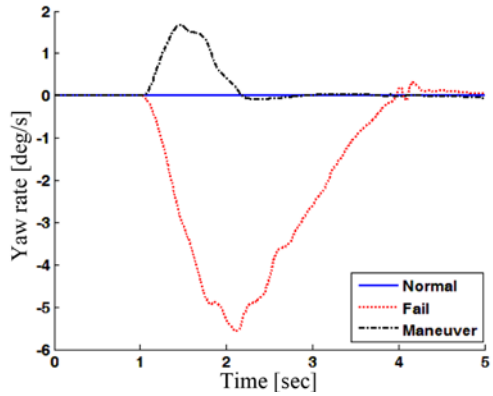

Figure 19. Vehicle yaw rates.

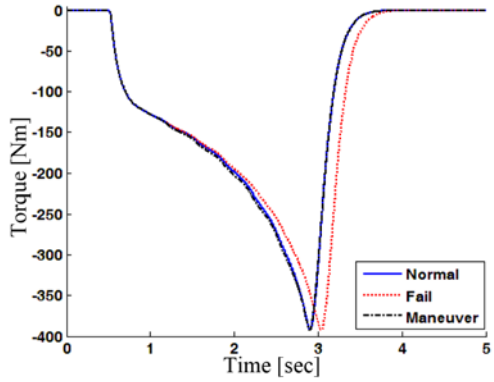

Figure 20. Regenerative braking torque in front wheels.

difference in the regenerative braking torques was due to the differences in the front wheel speeds.

5.3. Fail-safe Control Strategy for Failure of One Front EWB

A driver will be in a dangerous situation when one of the two front EWBs fails and does not properly operate while driving.

In the "A2-W1" scenario, the current sensor of the front left EWB was broken at 1 second after full braking on dry asphalt (high μ) at 80 kph.

The fail-safe control strategy potentially avoids dangerous situations, such as the situation shown in Figure 21. The braking torque of the normal side was controlled to follow the braking torque of the failed EWB, and the braking torques in the rear wheels were increased to a set value to compensate the total brake torque of the vehicle as much as possible without wheel-locking and spinning.

The simulation results of the three cases are presented in Figure 22 to Figure 26.

Figure 22 shows the vehicle speeds for the three cases. The decrease of the vehicle speed during the failure case was caused by the decreased braking torque in the failed wheel. The stopping distance of the controlled case was longer than that of the failure case because the increased

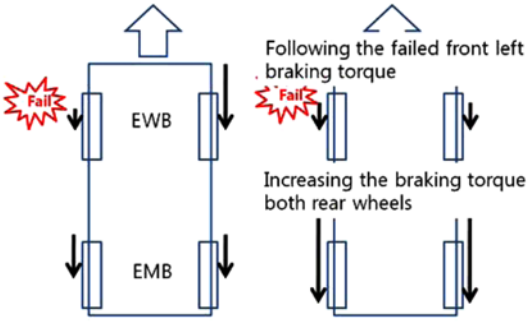

Figure 21. Fail-safe control strategy for one EWB failure.

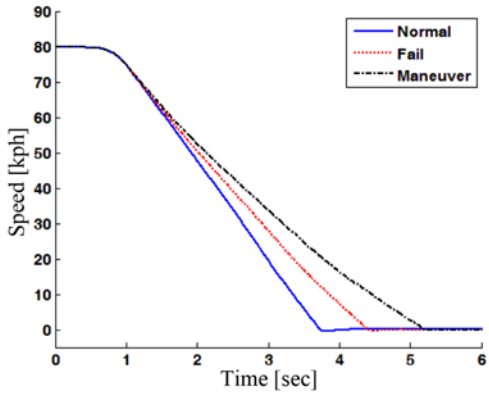

Figure 22. Vehicle speeds at full braking.

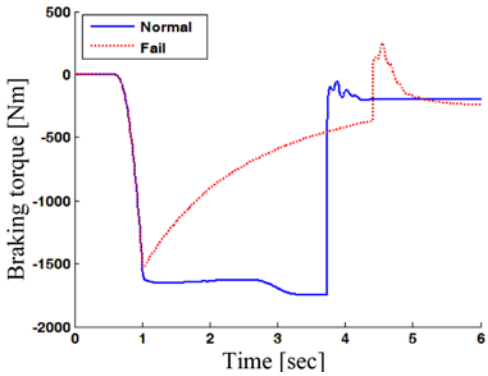

Figure 23. Brake torques in the front left EWB.

(compensated) rear braking torques were not so large and were limited compared with the decreased front braking torques.

Figure 23 shows the braking torques of the front left wheel during the failure mode and the normal mode. The braking torque decreased because the broken current sensor caused the EWB controller to malfunction.

Figure 24 shows the braking torques of the front right wheel. The fail-safe control strategy controlled the brake torque of the normal right side EWB to follow that of the failed front left EWB.

Figure 25 shows the vehicle yaw rate. The fail-safe

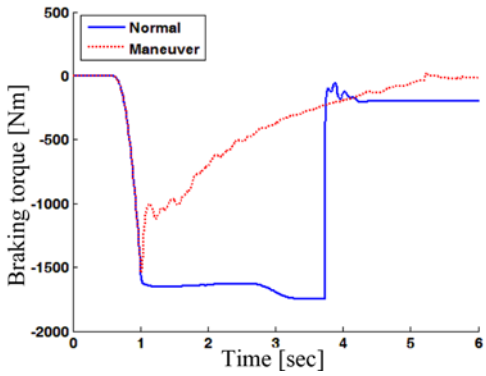

Figure 24. Brake torques in the front right EWB.

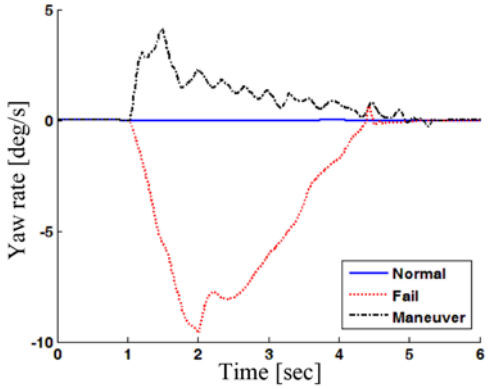

Figure 25. Vehicle yaw rates at full braking.

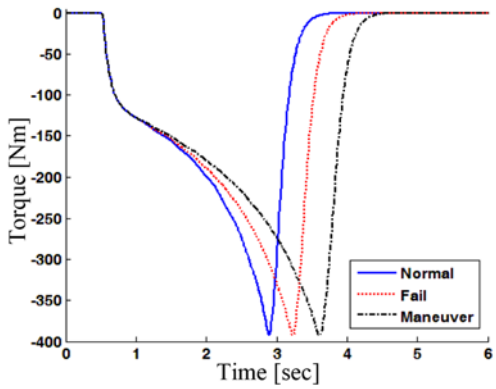

Figure 26. Regenerative braking torque in the front wheel.

control strategy reduced the vehicle yaw rate and spinning by half compared with that of the failure situation.

Regenerative braking of the driving motor in the front wheels was performed, as shown in Figure 26.

6. CONCLUSION

The safety of car drivers directly depends on the reliability of the brake system. In particular, the reliability of the electronic brake system, such as a regenerative braking

system involving EWBs and EMBs, must be verified and validated.

In this paper, an FCEV simulation model with a regenerative braking system—a front EWB and rear EMB system—was developed. Reliability evaluation scenarios were developed using a combination of driving modes and failure modes. With the simulation model and the evaluation scenarios, the effects of electronic brake system failures on vehicle safety were analyzed. Finally, a few fail-safe control strategies were proposed to ensure the safety of FCEVs with an electronic brake system in several critical cases.

ACKNOWLEDGEMENT–This work was supported by the Ministry of Knowledge and Economy of Korea(No. 10033817).

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