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Hardware in the Loop Simulation of Vehicle Stability Control using Regenerative Braking and Electro Hydraulic Brake for Hybrid Electric Vehicle

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Abstract: In this paper, hardware in the loop simulation(HILS) for a hybrid electric vehicle(HEV) braking performance is performed to investigate the vehicle stability control algorithm in the varying road surface condition. The vehicle stability control algorithm consists of the optimal braking torque distribution between the regenerative braking and the electro hydraulic braking. In addition to the optimal braking torque distribution, a sliding mode type wheel slip control algorithm is proposed to maintain the target slip ratio. The HILS system is composed of 4 wheel calipers and the electro hydraulic brake(EHB) module, and dynamic model of the HEV powertrain constructed by MATLAB Simulink is used as a software part. It is found from the HILS results that vehicle stability control algorithm using the regenerative braking, EHB and slip ratio control is able to provide the improved braking performance such as shorter braking distance, smaller error of the sideslip angle and yaw rate.

1. INTRODUCTION

When a car encounters unexpected road condition such as split-μ road, the tyre slip angles and consequently, the vehicle slip angle may increase rapidly, which causes the car to reach its physical limit of adhesion between the tyres and the road. Since most drivers have few experiences in operating the car under this situation, they might loose controllability of the vehicle eventually. Vehicle stability control system manages the vehicle behaviour to be predictable using the active control of the drive torque or the individual wheel brake so that the driver could re-establish the controls of the vehicle. The vehicle stability control systems known as anti-lock braking system(ABS), traction control system(TCS), electronic stability program(ESP), vehicle dynamic control(VDC), etc. have become very popular and applications of these systems have been expanded. For the vehicle stability control system application, many control schemes have been suggested. The wheel slip control using the linear characteristics between the slip ratio λ and the road friction coefficient μ (Kin *et al*., 2003) and maximum slip ratio estimation(Wakamatsu *et al*., 1997) have been typically applied in the ABS or TCS control to ensure the vehicle behaviour in longitudinal direction. The vehicle stability control algorithm such as the offset yaw moment generation using the brake force control of the each wheel, the wheel slip control based on the estimated friction coefficient between the tyre and the road(Bang *et al*., 2001) and the torque split control to generate drive torque difference between the left and right wheels(Liu *et al*., 2002) have been investigated.

In hybrid electric vehicles(HEVs), the motor can be used as a generator to recuperate the kinetic or potential energy during the braking. The recuperated energy which is stored in the energy storage device such as battery or ultra capacitor is used to propel the vehicle, which provides the improvement of the fuel economy. Moreover, the regenerative braking using the motor can be used to improve the vehicle stability since the response time of the motor torque generation is very fast compared with the existing hydraulic friction braking, and motor torque control can be carried out accurately, even in the nonlinear region of the tyre(Sakai *et al*., 2001). Studies on the braking performance for the HEVs by considering the regenerative braking have been investigated vigorously since the Toyota HEV Prius and 4WD HEV RX400h have been introduced. It is reported that RX400h is able to provide the ABS and VDC functionality using the regenerative braking and the independent hydraulic brake force distribution to each wheel(Soga *et al*., 2005). Recently, anti lock-up regenerative braking algorithm which increases the fuel economy up to 19% for FUDS and integrated regenerative braking algorithm equipped with ABS(Gao *et al*., 2001) have been proposed. However, in these studies, only hydraulic braking was used without regenerative braking when the vehicle stability control was applied.

In this paper, a vehicle stability control algorithm using the regenerative braking and electro hydraulic brake is investigated by hardware in the loop simulation. The vehicle stability control algorithm with optimal torque distribution between the regenerative braking and EHB torque from the previous work(Kim *et al*., 2007) is used with the slip ratio control. For the HILS, 4 wheel callipers, digital signal processor, host computer, valve driver, pressure sensor and the EHB module are used as the hardware part meanwhile HEV dynamic model and the proposed control algorithm are used as the software part. In the HILS, performance of the vehicle stability control algorithm is validated for various road conditions such as dry, rainy, snowy and icy road.

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2. VEHICLE MODELLING

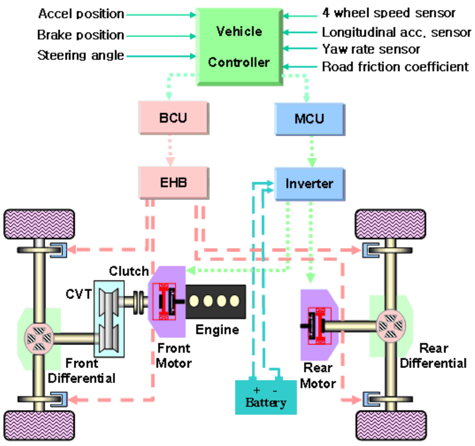


Fig. 1. 4WD HEV powertrain structure

Figure 1 shows the 4WD HEV used in this study. The 4WD HEV is driven by the engine, front and rear motor. The front axle is driven by the engine and the front motor while the rear axle is driven by the separate rear motor. A continuously variable transmission(CVT) is used as a transmission.

2.1 Actual vehicle model

The vehicle is modelled as a four-wheel model by considering the traction and brake force. Governing equations of the longitudinal, lateral, yaw, and roll motion for the actual vehicle model are expressed as follows

$$m\dot{V} = \sum F_x = F_{xfr} + F_{xfl} + F_{xrr} + F_{xrl} \tag{1}$$

$$\begin{aligned} mV(\dot{\beta}+\gamma) - m_s h_s \ddot{\phi} &= \sum F_y \\ &= F_{yfr} + F_{yfl} + F_{yrr} + F_{yrl} + F_{yf\phi} + F_{yr\phi} \end{aligned} \tag{2}$$

$$\begin{aligned} I_z\dot{\gamma} - I_{xz}\ddot{\phi} = \sum M_z &= (F_{xfr}+F_{xfl})\cdot L_f - (F_{xrr}+F_{xrl})L_r \\ &- (L_f F_{yf\phi} - L_r F_{yr\phi})\phi + M_{yaw} \end{aligned} \tag{3}$$

$$I_\phi \ddot{\phi} - I_{xz}\dot{\gamma} - m_s h_s(\dot{\beta}+\gamma) = \sum M_x = (C_\phi - m_s h_s g)\phi + D_\phi \dot{\phi} \tag{4}$$

$$M_{yaw} = -\frac{w}{2}(F_{xfr} - F_{xfl} + F_{xrr} - F_{xrl}) \tag{5}$$

where F is the force, I is the moment of inertia, L is the wheel base, M is the moment, M_{yaw} is the direct yaw moment that is generated from the longitudinal force at each wheel, V is the vehicle velocity, β is the sideslip angle, γ is the yaw rate, ϕ is the roll angle, m is the vehicle mass, m_s is the sprung mass, h_s is the height of roll centre from the CG(centre of gravity), C_ϕ is the roll stiffness, D_ϕ is the roll damping coefficient, $F_{yf\phi}$ is the lateral force by roll effect at front wheel, $F_{yr\phi}$ is the lateral force by roll effect at rear wheel, subscript x means the longitudinal direction, y means the lateral direction, z means the vertical direction, fr means the front right wheel , fl means the front left wheel, rr means the rear right wheel and rl means the rear left wheel.

2.2 Driver model

A driver model is used to trace the desired path for the closed-loop simulation. The steering driver model manipulates the steering angle to compensate the error between the estimated position and the desired position. The estimated position x^* and y^* can be calculated from the following equations

$$x^* = x + (V_x\cos\psi - V_y\sin\psi)\cdot\frac{L_{look}}{V} \tag{6}$$

$$y^* = y + (V_x\sin\psi + V_y\cos\psi)\cdot\frac{L_{look}}{V} \tag{7}$$

$$e = \sqrt{(x_d - x^*)^2 + (y_d - y^*)^2} \tag{8}$$

$$\delta = PID(s)\cdot e \tag{9}$$

where x^* is the estimated longitudinal displacement, y^* is the estimated lateral displacement, x_d is the desired longitudinal displacement, y_d is the desired lateral displacement, δ is the steering angle, ψ is the vehicle heading angle, e is the error of the displacement between the estimated position and the desired position, L_{look} is the look ahead distance, $PID(s)$ is the PID control gain.

2.3 Desired vehicle model

The error e which is obtained from the equation (8) is transformed to the steering angle δ by considering the control gain PID as in the equation (9). From the steering angle δ, the desired yaw rate γ_d and the sideslip angle β_d considering by the roll effect can be obtained as follows

$$\gamma_d = \frac{1}{1+A' V^2}\cdot\frac{V}{L}\cdot\delta \tag{10}$$

$$\beta_d = \frac{1 - \dfrac{m}{2L}\cdot\dfrac{L_f}{L_r C_r}V^2}{1 + A' V^2}\cdot\frac{L_r}{L}\cdot\delta \tag{11}$$

$$A' = \frac{m}{2L^2}\cdot\frac{L_r C_r - L_f C_f}{C_f\cdot C_r} + \frac{m_s h_s}{L(C_\phi - m_s g h_s)}\left[\frac{\partial\alpha_r}{\partial\phi} - \frac{\partial\alpha_f}{\partial\phi}\right] \tag{12}$$

where A' is the steering stability factor, C_f is the front tyre cornering stiffness, C_r is the rear tyre cornering stiffness, $\frac{\partial\alpha_f}{\partial\phi}$ is the front roll steer coefficient, $\frac{\partial\alpha_r}{\partial\phi}$ is the rear roll steer coefficient.

3. VEHICLE STABILITY CONTROL

For the vehicle stability control, a fuzzy control algorithm is used to obtain the target direct yaw moment. The inputs of the fuzzy controller are the errors of the vehicle side slip angle and yaw rate. The error is defined as the difference between the desired value from the desired vehicle model and the actual value from the actual vehicle model. Using these inputs, the fuzzy controller generates the direct yaw moment that is required to compensate the errors.

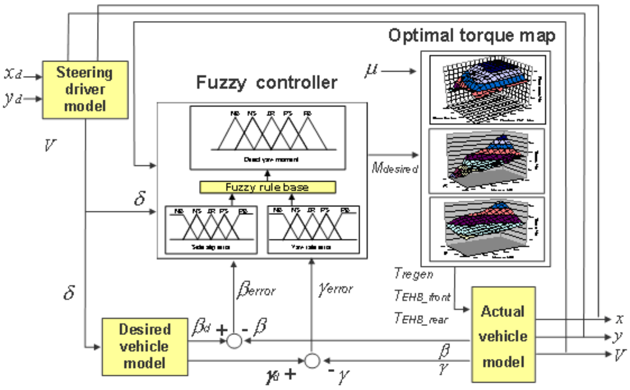


Fig. 2. Block diagram of vehicle stability control algorithm

In Fig. 2, a block diagram for the vehicle stability control used in this study is shown. The driver model manipulates the steering angle δ to follow the desired vehicle trajectory. For the steering angle, the vehicle manoeuvres by the actual vehicle model and the actual sideslip angle β and yaw rate γ are measured from the actual vehicle model. The actual sideslip angle β and yaw rate γ are compared with the desired sideslip angle β_d and yaw rate γ_d. The errors β_{error} and γ_{error} are used as the inputs of the fuzzy controller. The fuzzy controller calculates the desired yaw moment $M_{desired}$ to compensate the errors.

Now, we need to determine the front and rear braking torque to generate the desired yaw moment $M_{desired}$. The front and rear braking torque can be supplied by the regenerative braking and the EHB.

Generally, the HEV supply the regenerative braking together with the hydraulic friction braking in the braking mode because the only regenerative braking is not large enough to cover the demanded braking force. Therefore, it is required for the vehicle stability control algorithm for the HEV to distribute the regenerative braking and EHB effectively. In order to distribute the regenerative braking torque and EHB torque, an optimal torque distribution using genetic optimization was used from the previous work(Kim *et al.*, 2007).

In this study, in addition to the fuzzy control and optimal torque distribution, a wheel slip control is used to improve the vehicle stability under various road conditions such as split-μ road, friction coefficient changing road and so on.

When the vehicle conditions such as the braking force and road friction coefficient are changed rapidly, the vehicle behaviour is deteriorated by the increased wheel slip ratio. Therefore, the wheel slip ratio is required to maintain the peak value at the given road condition. The wheel slip ratio(λ) is defined as the difference between vehicle velocity(V) and wheel speed(ω_w), normalized to vehicle velocity as follows

$$\lambda = \frac{R_t\omega_w - V}{R_t\omega_w} \quad (acceleration)$$
$$\lambda = \frac{V - R_t\omega_w}{V} \quad (deceleration) \tag{13}$$

where λ is the wheel slip ratio, R_t is the tyre radius, ω_w is the wheel speed.

Most control strategies define their performance goal as maintaining the slip ratio near a value of 0.2 throughout the braking trajectory.

In this study, a sliding mode control is used to maintain the wheel slip to a known and desired level for different road condition. For the sliding mode controller design, the wheel slip ratio error is defined as

$$e_\lambda = \lambda_{opt} - \lambda \tag{14}$$

where e_λ is the error of wheel slip ratio, λ_{opt} is the optimal wheel slip ratio. A sliding surface index is designed using the wheel slip ratio error e_λ and derivative of e_λ,

$$\sigma = m_\lambda e_\lambda + \dot{e}_\lambda \tag{15}$$

where σ is the sliding surface index, m_λ is the sliding surface slope. A sliding mode control gain is obtained from the following equation according to the sign of the sliding surface

$$u_\lambda = \begin{cases} 1 & : \ \mathrm{sign}(\sigma) > 0 \\ u_{\text{low bound}} & : \ \mathrm{sign}(\sigma) < 0 \end{cases} \tag{16}$$

where u_λ is the sliding control gain, $u_{lowbound}$ is the low bound control gain which is selected as “0.2” in this study. Using the control gain, the front and rear wheel torque are obtained as follows

$$T_{w\_ij} = (T_{regen} + T_{EHB\_ij}) \times u_{\lambda\_ij} \tag{17}$$

where i means the front or rear wheel, j means the left or right wheel, T_{regen} equals zero for $i = front$, u_{λ_ij} means the sliding control gain for each wheel.

For the given $M_{desired}$ and the road condition μ, the optimal regenerative braking torque of the rear wheel and the EHB torque of the front and rear wheel are obtained from the optimal torque map and the wheel slip controller calculates the wheel torque to provide the desired slip ratio for the given road condition.

4. HARDWARE IN THE LOOP SIMULATION

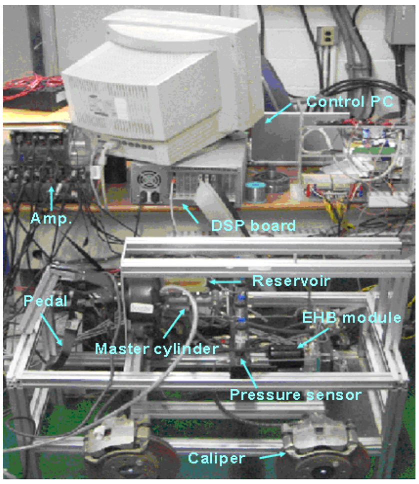


Fig. 3. Configuration of HILS system

In Fig. 3, HILS system constructed in this study is shown. The HEV HILS system consists of hardware part, software part and input/output(I/O) part. The hardware part is composed of 4 wheel callipers, digital signal processor(DSP: DS1103 controller), host computer, valve driver, pressure sensor and the EHB module. The DSP board which has a 400MHz main processor, 2Mbyte local SRAM, 32Mbyte global DRAM is used to realize real time simulation.

For a software part, the HEV dynamic model is constructed by MATLAB Simulink as shown in Fig. 4. Each component of the HEV powertrain and vehicle dynamics are modelled based on their dynamic characteristics.

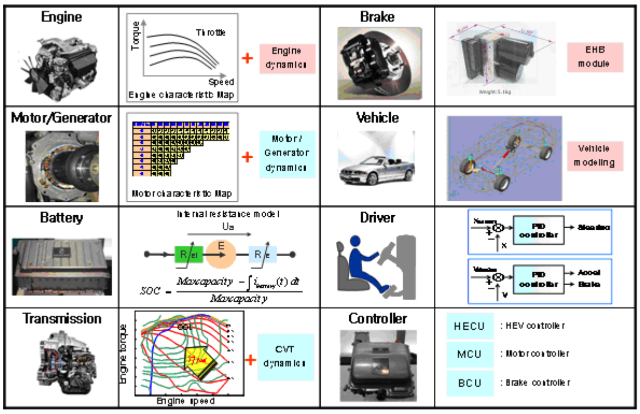


Fig. 4. Dynamic model of HEV powertrain component

In Fig. 5, block diagram of the HILS procedure is shown. When the driver model manipulates the steering angle to follow the desired vehicle trajectory, the fuzzy controller generates the desired yaw moment based on the driver's steering angle input, vehicle velocity, yaw rate error and sideslip angle error. For the given desired yaw moment $M_{desired}$ and road condition μ, the optimal regenerative braking torque of the rear wheel T_{regen}, the front and rear EHB torque are obtained from the optimal torque map and the wheel torque at each wheel is determined by the slip controller designed in this study. Since the required wheel braking torque is implemented by the hydraulic actuator pressure, the calculated wheel torque at each wheel is transformed to the required actuator pressure and is supplied at the EHB module, which controls the actuator pressure by the pulse width modulation(PWM) duty signal from the valve driver. Four (4) pressure sensors are used to measure the actuator pressure at each wheel. The measured pressure is transformed to the braking torque and is transmitted to the HEV simulator to calculate the vehicle parameters such as vehicle velocity, displacement, sideslip angle, yaw rate, etc.

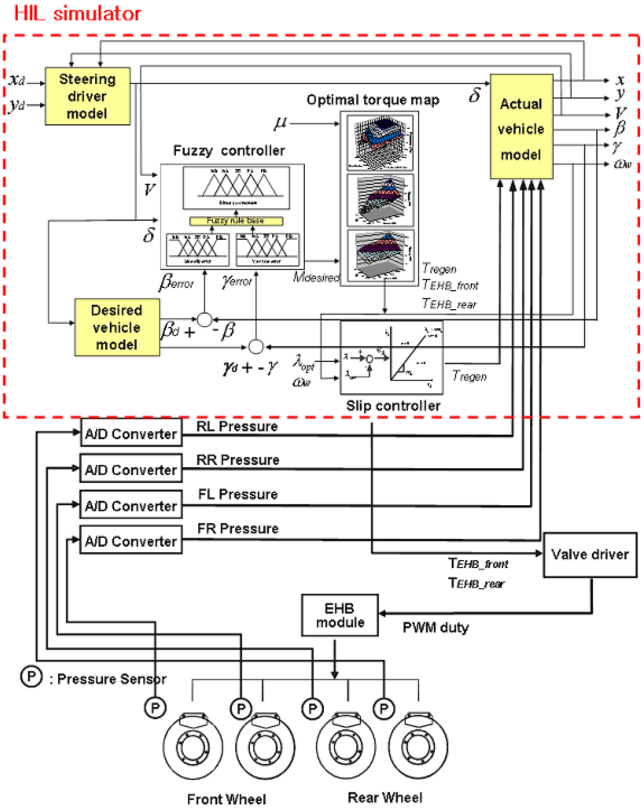
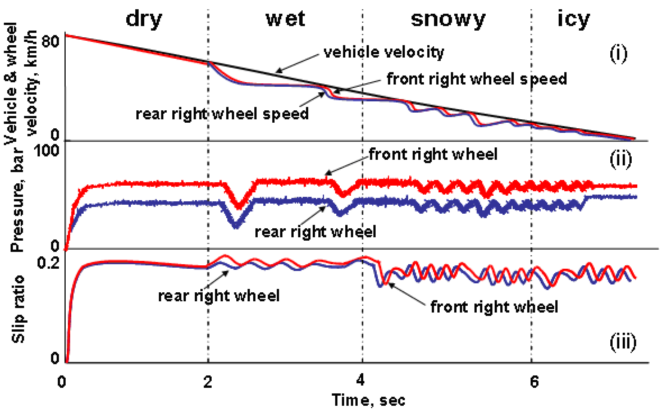


Fig. 5. Block diagram of HILS system

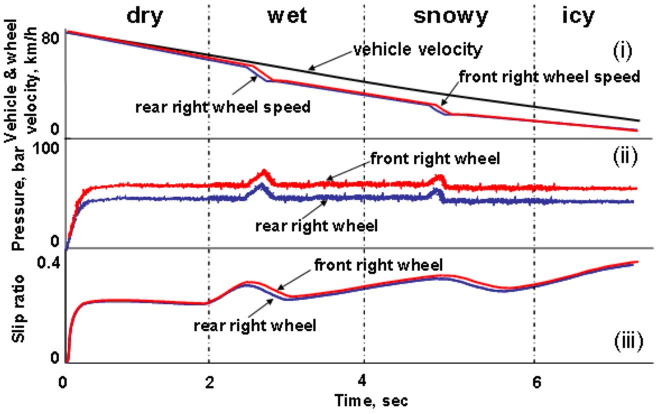
5. HILS RESULTS AND DISCUSSION

HIL simulations are performed to evaluate the vehicle stability control algorithm when the braking is carried out on the road with varying friction coefficient. In the HILS, the driver pushes the brake pedal with 0.3g deceleration demand and the vehicle passes the dry, wet, snowy and icy road in turn as shown in Fig. 6. In the HILS, the vehicle performance for the following three cases are evaluated: 1) the optimal regenerative braking plus the EHB braking using the slip control(REGEN+EHB+SLIP control), 2) the optimal regenerative braking plus the EHB braking(REGEN+EHB control), and 3) conventional braking(NO control).

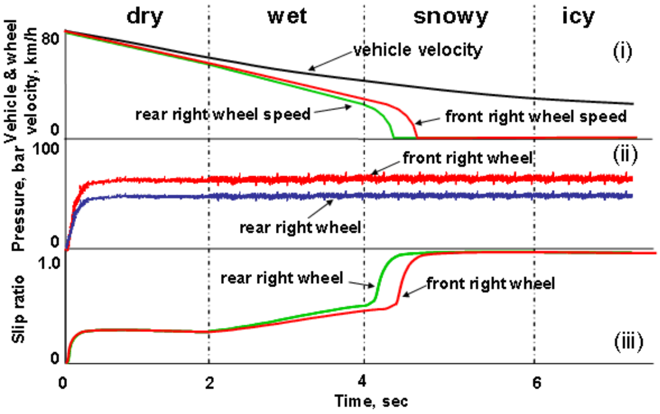
In Fig. 6, the HILS results are compared. In Fig. 6, the vehicle velocity, wheel speed and slip ratio of the right wheel and actuator pressures of the front and rear right wheel are shown.



(a) REGEN+EHB+SLIP control



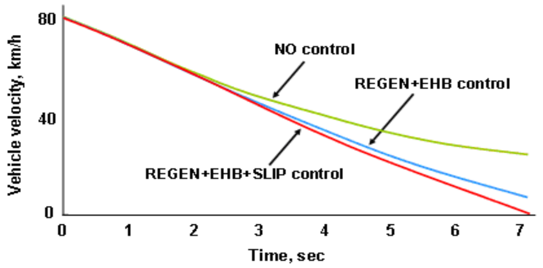
(b) REGEN+EHB control



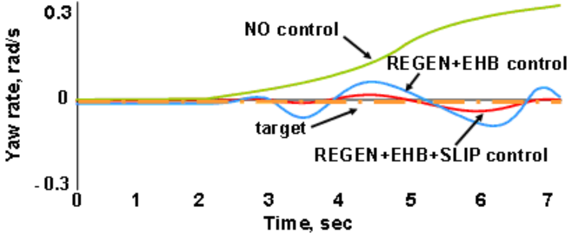
(c) NO control

Fig. 6. HILS results for braking performance on the varying road condition

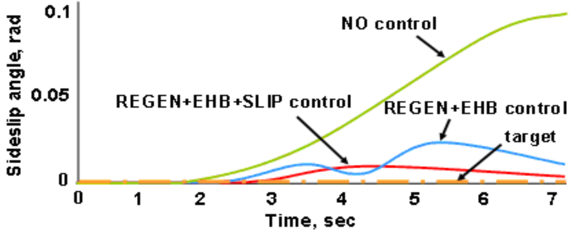
It is seen from Fig. 6a that the wheel speed by REGEN+EHB+SLIP control follows the target vehicle velocity closely showing some errors. It is noted that when the velocity error occurs, this causes a slip ratio error and a pressure modulation of the actuator is carried out to maintain the target slip ratio. It is found that the wheel slip ratio remains around the target 0.2 by the control algorithm designed in this study. It is also noted that the actuator pressure of the rear right wheel is controlled much lower than that of the front wheel since the regenerative braking is carried out simultaneously at the rear side. For REGEN+EHB control, once the wheel speed error occurs due to the vehicle rotational motion(Fig. 6b), it causes the increased slip ratio and the error can not be reduced since there is no slip ratio control. The actuator pressure shows pressure modulation to generate the direct yaw moment by the vehicle stability control algorithm, which reduces the sideslip angle and yaw rate errors. As the wheel speed error increases, the slip ratio error also increases. For NO control, the wheel speed error increases continuously as the vehicle passes the wet road. The actuator pressure is maintained around 70 bar at the front wheel and 35 bar at the rear wheel to stop the vehicle. However, the wheel speed decreases rapidly resulting in the increasing slip ratio and lock-up occurs in the snowy zone when the slip ratio reaches the maximum value.



(a) vehicle velocity



(b) yaw rate



(c) sideslip angle

Fig. 7. HILS results for vehicle motion

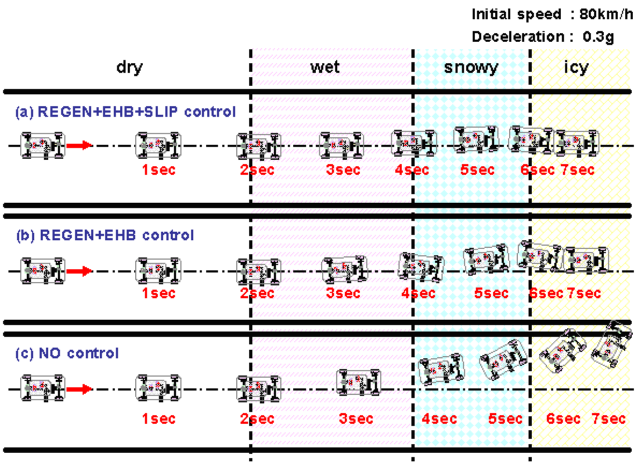


Fig. 8. HILS results for vehicle trajectory

In Fig. 7, vehicle motions by the HILS are compared. The vehicle motion by REGEN+EHB+SLIP control shows the complete stop at t =7.3 sec.(Fig. 7a). However, the vehicle by REGEN+EHB control, and by NO control still maintains the velocity at t=7.3 sec. showing v=15 km/h and v=35 km/h, respectively. From Fig. 7, it is noted that the vehicle stability control algorithm proposed in this study is also able to improve the vehicle braking performance on the varying road condition. As shown in Fig. 7b and Fig. 7c, the yaw rate and sideslip angle by REGEN+EHB+SLIP control converse to zero following the target values even if small errors are observed when the vehicle passes through the wet, snowy and icy road. For REGEN+EHB control, the yaw rate and sideslip angle also converge to the target showing the increased errors. However, those by NO control increase continuously from the moment when the vehicle enters the wet road. This means that the vehicle becomes unstable and encounters the spin.

In Fig. 8, the vehicle trajectories are compared for 3 control algorithms. It is seen from Fig. 8 that the vehicle behaviour by REGEN+EHB+SLIP control shows a stable braking performance keeping the straight line in spite of the varying road condition. For REGEN+EHB control, the vehicle shows a slight rotational motion on the snowy road but recovers the straight movement by the optimal regenerative braking control with the EHB function. For NO control, the vehicle begins to rotate from the wet road and experiences a spin on the snowy and icy road.

6. CONCLUSIONS

In this paper, hardware in the loop simulation(HILS) for a hybrid electric vehicle(HEV) braking performance is performed to investigate the vehicle stability control algorithm in the varying road surface condition. The vehicle stability control algorithm consists of the optimal braking torque distribution between the regenerative braking and the electro hydraulic braking. In addition to the optimal braking torque distribution, a sliding mode type wheel slip control algorithm is proposed to maintain the target slip ratio. The HILS system is composed of 4 wheel callipers, digital signal processor, host computer, valve driver, pressure sensor and the EHB module, and dynamic model of the HEV powertrain constructed by MATLAB Simulink is used as a software part. It is found from the HILS results that vehicle stability control algorithm using the regenerative braking, EHB and slip ratio control is able to provide the improved braking performance for the varying road surface condition such as shorter braking distance, smaller error of the sideslip angle and yaw rate.

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