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Regenerative Braking Algorithm for a HEV with CVT Ratio Control During Deceleration

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ABSTRACT

A regenerative braking algorithm is proposed to make maximum use of regenerative brake for improvement of fuel consumption. In the regenerative braking algorithm, the regenerative torque is determined by considering the motor capacity, battery SOC and vehicle velocity. The regenerative braking force is calculated from the brake control unit by comparing the demanded brake force(torque) and the motor torque available. The wheel pressure that is reduced by the amount of the regenerative braking force is supplied form the hydraulic brake module. In addition, CVT speed ratio control algorithm is suggested during the braking. The optimal operation line is obtained to operate the motor in the most efficient region. It is found from the simulation that the regenerative braking algorithm including the CVT ratio control provides improved fuel economy as much as 4 percent for federal urban driving schedule.

INTRODUCTION

The demand for more environmentally friendly and fuel efficient vehicle has been increased in response to growing concerns on the clean environment and saving energy. In this context, the hybrid electric vehicle(HEV) has emerged as a viable solution to meet those requirements in short to midterm. In the HEV, braking energy that would normally be wasted as heat can be recuperated through the application of regenerative braking. In the regenerative braking, the energy recuperation takes place by storing the kinetic or potential energy in the energy storage device. The energy stored in the energy storage device is used to propel the vehicle. Regenerative braking is an effective approach to improve the vehicle efficiency, especially for the vehicles in heavy stop and go traffic. For example, the braking energy ratio to the total traction energy reaches 48.3 percent for FUDS(federal urban driving schedule) and 53 percent for Japan 10-15 driving mode. Mechanical, hydro-mechanical, or electro-magnetic means such as flywheels, pressure reservoirs linked with hydro-mechanical machines can be used as the energy storage device to accomplish the regenerative braking[1]. However, for the passenger car applications, generator-battery or generator-ultra capacitor regenerative braking technology is considered to be the most promising option [2].

Generally, the regenerative braking system works together with the conventional friction brake for the following reasons : (1) the regenerative braking torque is not large enough to cover the required braking torque, (2) the regenerative braking can not be used for many reasons such as high state of charge(SOC) or high temperature of the battery to increase the battery life. In these cases, the conventional friction braking system works to supply the required braking torque. Therefore, in order to apply the regenerative braking, a control algorithm on how to distribute the braking torque into the regenerative torque and the mechanical friction torque is required with respect to the battery SOC, motor speed, etc. It is also important to provide a brake feeling that is similar to that of the conventional brake during the regenerative braking. It is required for the brake system of a hybrid passenger car to make maximum use of regenerative brake for further reduction of emissions, improvement of fuel consumption and also to ensure higher vehicle stability equivalent to that of ordinary passenger cars.

As for regenerative braking, few investigations have been reported. A regenerative braking algorithm was proposed for the EV from the viewpoint of stability by considering proportioning the braking force to the front and the rear wheel[1]. As for the regenerative braking of the EV, Wyczalk[3] suggested a mathematical formulation of the regenerative braking energy by considering the charging and discharging efficiencies and showed that a significant improvement in the regenerative braking could be achieved by adopting a continuously variable transmission (CVT). Panagiotidis et. al.[4] suggested a regenerative braking model for a parallel HEV using ADVISOR. This model computes the wheel pressure, based on a look-up table yielding the distribution of braking forces between the front and rear wheel and the generator. A regenerative braking algorithm and a hydraulic module have been proposed for parallel HEV equipped with CVT[5]. In this algorithm, the regenerative braking torque is calculated by considering the battery SOC, vehicle velocity, motor capacity and CVT speed ratio.

Meanwhile the regenerative braking offers improved fuel economy for the HEVs, continuously variable transmission(CVT) has been adopted in many HEVs to obtain minimum fuel consumption in normal driving mode. It is well known that the CVT provides optimal engine operation for the minimum fuel consumption independent of the vehicle velocity. In normal driving, the CVT ratio is controlled to maintain the engine operation on the optimal operation line for the given driving mode. During the braking, the same control strategy can be applied. However, in the braking, ensuring the lowest gear ratio is more important rather than the optimal engine operation since the engine throttle opening is closed.

In this paper, a regenerative braking control algorithm including the CVT speed ratio control is proposed for a parallel HEV. First, regenerative braking algorithm is developed by considering the ideal brake force distribution, battery SOC and vehicle velocity. In addition, a CVT speed ratio control algorithm is proposed to obtain the maximum efficiency of the regenerative braking. Performance of the regenerative braking algorithm is evaluated by the simulation and time response of the vehicle speed, motor torque, motor speed, CVT speed ratio, battery SOC and fuel economy are investigated.

DEVELOPMENT OF REGENERATIVE BRAKING HYDRAULIC MODULE

In Fig. 1, the parallel HEV is shown with regenerative braking system. The engine is connected to a 12kW motor with a single shaft. The power from the engine and motor is transmitted to a transmission via clutch. As a transmission, a metal belt continuously variable transmission(CVT) is used to maintain the engine operation on the minimum fuel consumption region independent of the vehicle speed. In the HEV in Fig. 1, the braking of the drive wheel, i.e, the front wheel is performed by using both a regenerative brake and a hydraulic brake meanwhile the rear wheel braking is carried out only by a hydraulic brake.

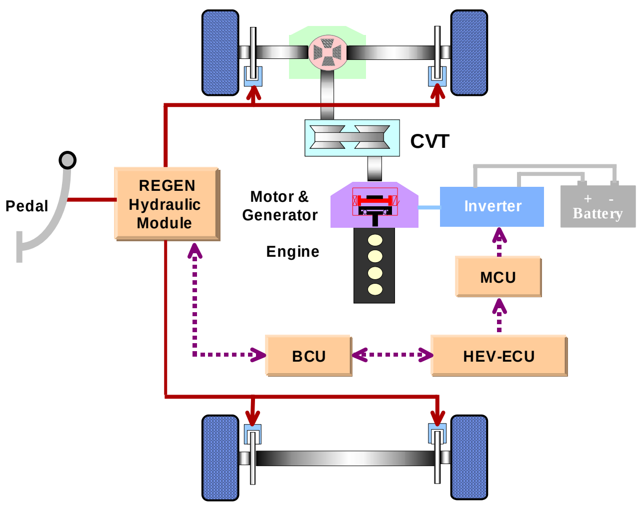


Fig.1 Schematic diagram of parallel HEV

In the hydraulic brake, a hydraulic pressure is supplied to a wheel cylinder so as to generate a brake force in response to a braking operation by a driver. Whereas, in the regenerative brake, a brake force is generated by a regeneration action obtained based on a reverse electromotive force generated in a traction motor which drives the drive wheels. The regenerative brake generates electric energy which is to be charged to a battery based on the reverse electromotive force generated by inertial rotation of the traction motor.

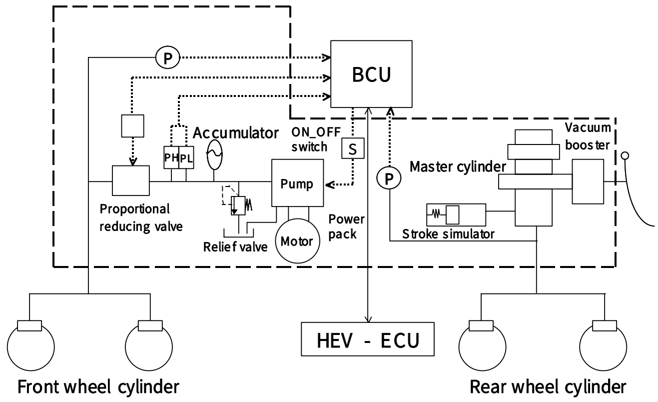


Fig.2 Schematic diagram of regenerative braking hydraulic module

Figure 2 shows a schematic diagram of the regenerative braking hydraulic module developed in this study. When a driver pushes a brake pedal, pedal force is transmitted to master cylinder through a vacuum booster. In the hydraulic module in Fig. 2, the conventional master cylinder and vacuum booster are used. The master cylinder pressure generated by the brake pedal is supplied to the rear wheel cylinder. In the front wheel, the regenerative braking is performed corresponding to the required braking force which is calculated from a brake control unit(BCU). If the regenerative braking force is not large enough to meet the required force, the hydraulic brake works simultaneously to supply the insufficient braking force. Therefore, the front wheel pressure which is reduced by the amount of the regenerative braking force is supplied by proportional reducing valve. The required front wheel pressure is calculated at BCU. The regenerative hydraulic module consists of powerpack, accumulator, relief valve and proportional valve. The powerpack motor is operated only when the accumulator pressure drops below the lower limit, which saves the system power.

When the regenerative braking is applied, the hydraulic oil supply from the master cylinder to the front wheel actuator is cut off, and the reduced hydraulic pressure is supplied from the powerpack instead. This may cause unfamiliar pedal feeling to the driver. Therefore, a stroke simulator is used to consume the oil flow that is blocked at the master cylinder, which provides the driver a similar brake pedal feeling. The BCU calculates the regenerative braking force using the signals of the battery state of charge(SOC), CVT ratio, vehicle velocity and wheel cylinder pressure. Since the vacuum booster in Fig. 2 is operated by the engine back pressure, the engine should be running at all times except idle stop.

REGENERATIVE BRAKING CONTROL

In order to provide an appropriate regenerative braking for the given driving conditions, a control algorithm is required to determine the magnitude of the regenerative torque with respect to the battery SOC, motor speed and etc. corresponding to the driver's demand. The regenerative torque applied to the front wheel T_R is represented as[5]

$$T_R = \frac{i \cdot N \cdot T_{REG}}{\eta} W_1 W_2 , \tag{1}$$

where i is the CVT speed ratio, N is the final reduction gear ratio, T_{REG} is the regenerative torque by the motor, which is determined from the motor characteristic curve for a given speed. η is the generation efficiency, W_1, W_2 are the weight factors. Weight factors W_1 and W_2 are expressed as

$$W_1 = W_1(SOC)$$

$$W_2 = W_2(Velocity). \tag{2}$$

In Fig. 3(a), the weight factor for the battery SOC is shown. In this study, a weight factor 1 is used in charging the battery for SOC=0~80% to increase the SOC level. For SOC=80~90%, the weight factor decreases linearly. This protects the battery from overcharging that may affect the battery life. In addition, the magnitude of the REGEN torque varies depending on the vehicle velocity(Fig. 3(b)). Below V_1, no REGEN torque is generated. From V_1 to V_2, the REGEN torque increases in proportion to the vehicle velocity. In this study, no REGEN torque is applied below $V_{1,}$ in other words, at low speed for the following reasons : (1) the regeneration energy is not large and (2) the comfort could be deteriorated. For a velocity above V2, the maximum motor torque available is applied to obtain as much regeneration energy as possible.

The regenerative braking force at the wheel is obtained

$$F_{REGEN} = \frac{T_R}{R_t} \tag{3}$$

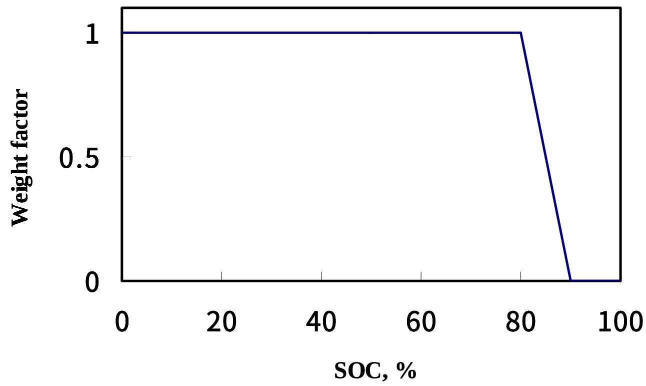
where R_t is the tire radius. If F_{REGEN} is larger than the required front wheel braking force F_{bf}, the front wheel is braked only by the regenerative brake. Otherwise, the hydraulic brake works together with the regenerative brake. The hydraulic braking force required at the front wheel is obtained

$$F_{f\,HYD} = F_{bf} - F_{REGEN} \tag{4}$$

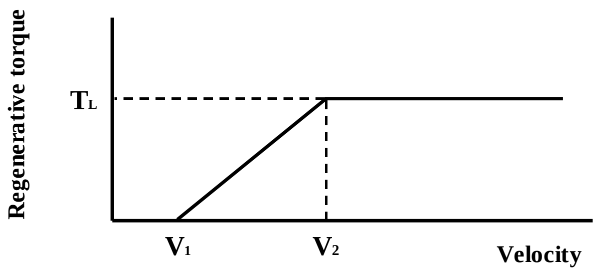
The front wheel cylinder pressure equivalent to F_{fHYD} is expressed as [4]

$$P_f = \frac{R_t F_{fHYD}}{2ra\mu_b} \tag{5}$$

where R_t is the brake effective radius, a is the wheel cylinder area, μ_b is the brake friction coefficient.



(a) Weight factor for battery SOC



(b) Regenerative torque vs. velocity

Fig. 3 Weight factors for regenerative braking

In Fig. 4, the regenerative braking algorithm is shown. For the driver's pedal input, the rear wheel cylinder pressure, in others words, the rear braking force F_{br} is obtained from the pressure sensor. The required front braking force F_{bf} is determined from the ideal braking force distribution for the given F_{br}. In the mean time, BCU calculates the regenerative force F_{REGEN} for the input signals of the battery SOC, vehicle velocity and CVT ratio by considering the weight factors, W_1 and W_2 and the generation efficiency η . If the demanded front braking force is less than F_{REGEN}, only the regenerative brake is applied and the magnitude of the regenerative braking force is limited not to exceed the demanded braking force. In case that the demanded front braking force F_{bf} is larger than F_{REGEN}, the hydraulic brake works together with the regenerative brake. The front wheel pressure P_f is applied from the regenerative hydraulic module.

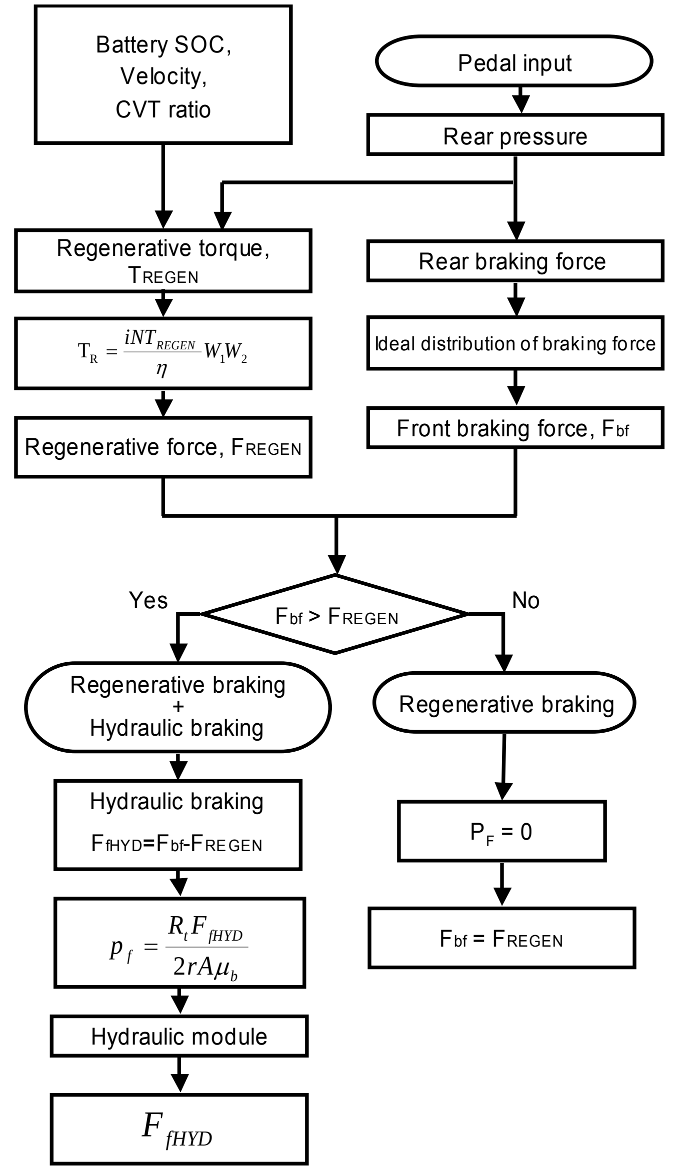


Fig. 4 Flow chart for regenerative braking

CVT SPEED RATIO CONTROL

In regenerative braking, the kinetic energy is transmitted to the battery through the CVT and motor. The regenerative torque at the wheel T_{wheel} is represented

$$T_{wheel} = \eta_{CVT} \cdot \eta_{gen} \cdot \eta_f \cdot T_m \times i \times N_f \quad (6)$$

where η_{CVT} is the CVT efficiency, η_{gen} generator efficiency, η_f final reduction gear efficiency, and N_f is the final reduction gear ratio. It is seen from Eq. (6) that in order to make the maximum use of recuperation energy, the regenerative braking should be performed following the most efficient process. In Eq. (6), the CVT efficiency η_{CVT} depends on the input torque and CVT speed ratio[7]. In this study, it is assumed that η_{CVT} and final reduction gear efficiency η_f is constant.

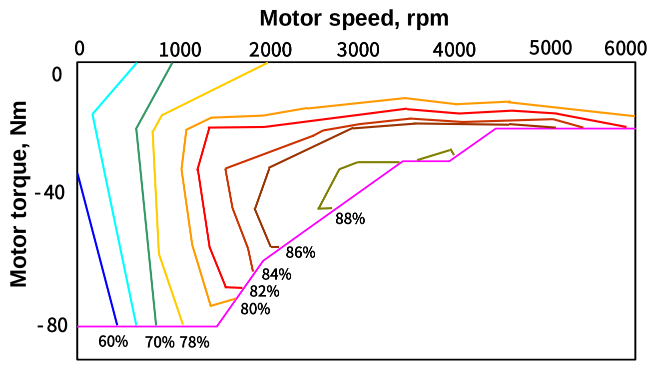


Fig. 5 Motor efficiency map

In Fig. 5, the motor efficiency map is shown. It is noted from Fig. 5 that the motor efficiency varies from 60 percent to 88 percent. Therefore, if the CVT ratio is controlled to operate the motor on the most efficient region during the braking, maximum use of the braking energy can be achieved, which results in the improved fuel economy. In this study, the optimal operation line(OOL) is proposed for the most efficient motor operation during the braking. The OOL can be determined as follows: for a given regenerative braking power, there exists a point where the motor efficiency is the highest. The OOL is obtained by connecting the high efficiency points.

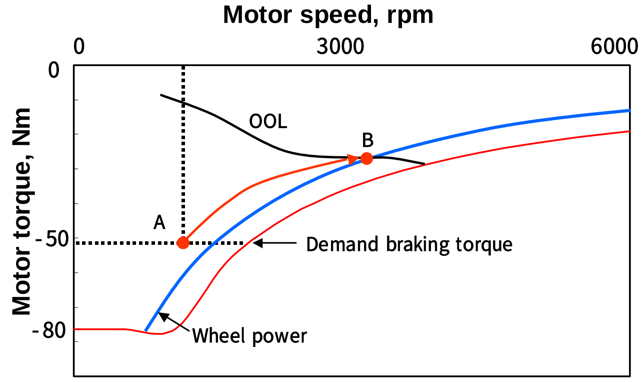


Fig. 6 Optimal operating line in regenerative braking

In Fig. 7, a flow chart of the CVT ratio control during the braking is shown. When the driver works the brake pedal, the BCU calculates the wheel power and determines the desired motor speed $\omega_m)_d$ from the optimal operating point. Then, the desired CVT ratio i_d is obtained by the following equation

$$i_d = \frac{\omega_m)_d \cdot R_t}{V \cdot N_f} \quad (7)$$

For example, when the demanded regenerative torque is obtained as –50 Nm at the motor speed 1500rpm(point A) from the BCU, the motor operating point is moved by the CVT ratio control from A to B where the OOL crosses with the given iso-power curve at the wheel.

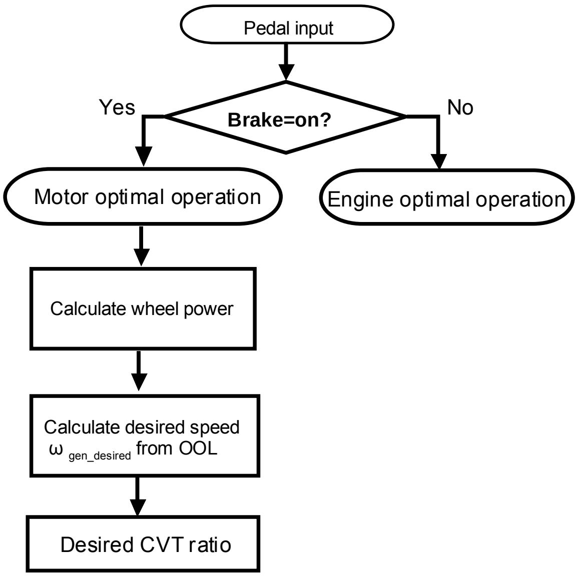


Fig. 7 Flow chart of CVT ratio control

SIMULATION RESULTS AND DISCUSSION

Performance of the regenerative braking algorithm developed in this study is evaluated by the simulation. In the simulation, dynamic models of the HEV powertrain are developed. In the modeling, dynamic models of the I.C engine, motor, battery, CVT, tire and other vehicle parts are obtained by modular approach using MATLAB simulink. In Fig. 8, the MATLAB model of HEV powertrain is shown[5].

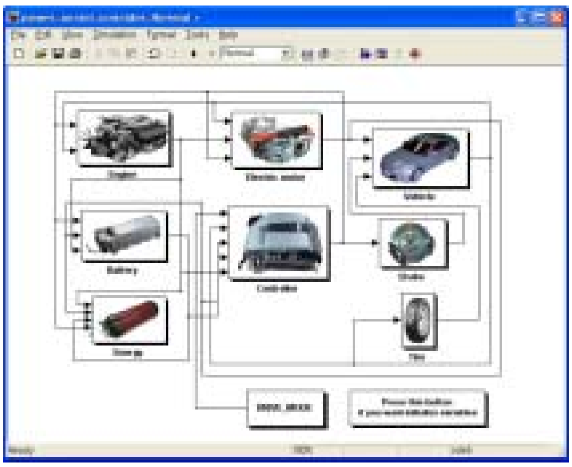


Fig. 8 MATLAB model of HEV powertrain

Table. 1 Vehicle data

Engine	Stroke volume Maximum torque	1600cc 140Nm
Motor	10kW Motor torque at base rpm	50Nm
Vehicle	CVT gear ratio range Final reduction gear ratio Vehicle mass Front project area Drag coefficient Tire radius	0.455 ~ 2.47 5.763 1380 kg 1.964 m^2 0.346 0.279 m

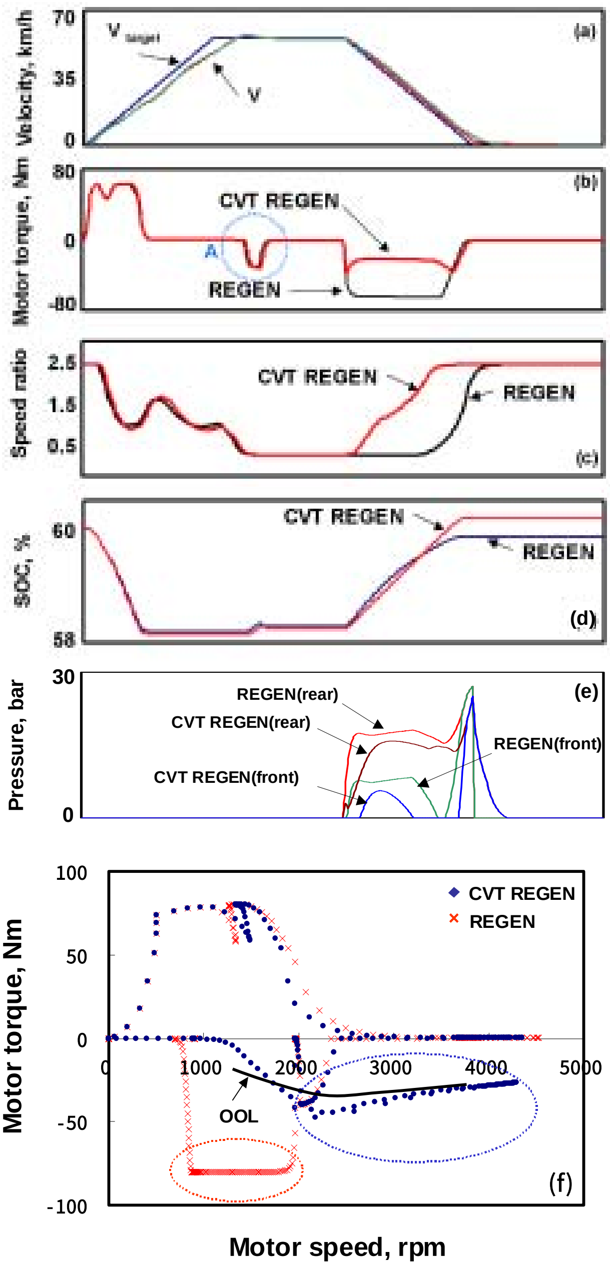


Fig. 9 Simulation results

In Fig. 9, simulation results are shown. The vehicle data used in the simulation are listed in Table 1. The actual vehicle velocity(a) follows the target velocity closely. The motor torque(b) shows a positive value when the motor is used to drive the vehicle and shows a negative value when it is used as a generator. The negative torque in circle A is due to the HEV operation strategy, not by the braking. The HEV operation strategy is designed to carry out the regenerative braking when the vehicle begins to enter the coasting mode. During the braking, the motor torque by the CVT regenerative ratio(CVT REGEN) control shows smaller value than that of the regenerative only(REGEN) control according to the CVT ratio control algorithm. It is seen from Fig. 9c that the CVT ratio by the CVT REGEN control is downshifted much earlier than the REGEN control. This CVT ratio response makes the motor run on relatively high efficiency region, i.e. on the OOL, as shown in Fig. 9f. The battery SOC(d) decreases when the motor is used to propel the vehicle and increases when the motor is used as a generator. The final battery SOC by the CVT REGEN control is higher than that of the REGEN control, which implies that more electric energy is stored by the CVT REGEN control resulting in the improved fuel economy. It is seen from Fig. 9e that wheel pressure by the CVT REGEN control shows smaller value than those by the REGEN control since the motor regenerative torque by the CVT REGEN control is smaller. The front wheel pressure (e) is reduced compared with that of the rear wheel pressure by the amount of the regenerative torque. In Fig. 9f, the motor operation trajectory is shown. It is seen that the motor operation for the CVT REGEN control is performed around the OOL during the braking while the motor for the REGEN control is operated mostly out of the OOL.

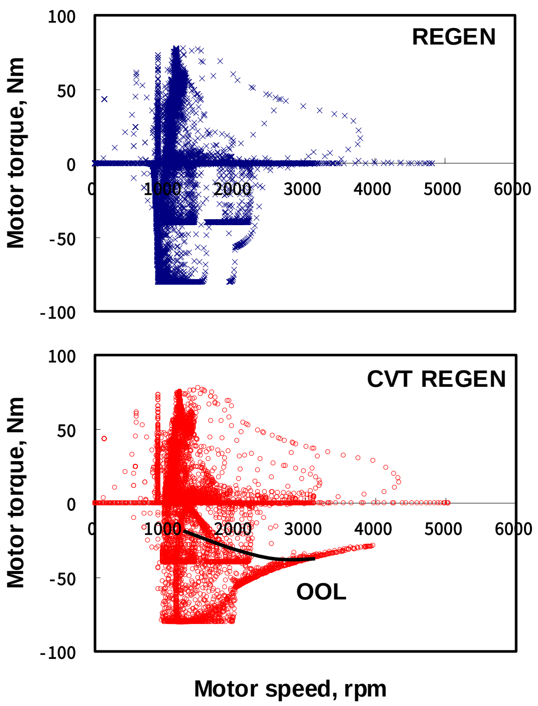


Fig. 10 Motor operation trajectories for FUDS

In Fig. 10, the motor operation trajectories are compared for FUDS. As shown in Fig. 10, the motor operation for the CVT REGEN control is carried out more frequently around the OOL compared with that for the REGEN control, which provides the improved fuel economy.

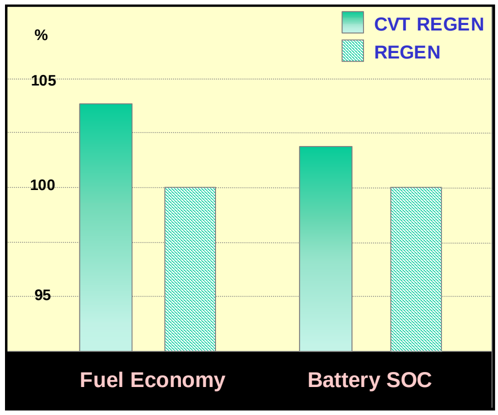


Fig. 11 Comparison of the fuel economy and final battery SOC for FUDS

Figure 11 shows comparison of the fuel economy and final battery SOC for FUDS. It is found that the fuel economy is improved as much as 4 percent by the CVT REGEN control while the final battery SOC shows higher value compared with the REGEN control.

CONCLUSION

A regenerative braking algorithm is proposed to make maximum use of regenerative brake for improvement of fuel consumption. In the regenerative braking algorithm, the regenerative torque is determined by considering the motor capacity, battery SOC and vehicle velocity. The regenerative braking force is calculated from the brake control unit by comparing the demanded brake force(torque) and the motor torque available. The wheel pressure that is reduced by the amount of the regenerative braking force is supplied form the hydraulic brake module. In addition, CVT speed ratio control algorithm is suggested during the braking. The optimal operation line is obtained to operate the motor in the most efficient region. It is found from the simulation that the regenerative braking algorithm including the CVT ratio control provides improved fuel economy as much as 4 percent for federal urban driving schedule.

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