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EFFICIENCY MEASUREMENT AND ENERGY ANALYSIS FOR A HEV BENCH TESTER AND DEVELOPMENT OF PERFORMANCE SIMULATOR

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ABSTRACT−This paper presents the efficiency measurement and energy analysis for a parallel HEV. Using the HEV test rig, the efficiency of each powertrain component is measured for a given driving cycle including the regenerative braking system. Accompanied by the efficiency measurements, a detailed energy analysis is performed. Based on the efficiency measurement and energy analysis, a HEV performance simulator is developed. Using the simulator, the HEV performance is evaluated for a mild hybrid system. It is expected that the HEV simulator developed can be used to obtain further optimization potentials.

KEY WORDS : HEV (hybrid electric vehicle), Efficiency, Energy

1. INTRODUCTION

Growing environmental and economic concerns have led to recent effort to produce more fuel efficient and lower emissions vehicles. General technical measures towards increased fuel economy and emission reduction such as lowering weight, reducing air drag and rolling drag coefficients are essential in conventional as well as alternate drivetrains. As alternate drivetrains, electric vehicle (EV), H_2/CNG-driven engines, hybrid electric vehicle (HEV) and fuel cell vehicle (FCV) are being examined to meet the legal restrictions on the fuel economy and the emission. In a comparison of alternate drivetrains, they show advantages and disadvantages at different criteria. In short to mid term, HEVs offer the best promise. With minimum extra cost they show improvements in fuel consumption and emissions (Mueller, 2000).

In design of hybrid electric vehicle, the role of simulator is essential. The simulator can be used to investigate the effect of design parameters and control algorithms on the vehicle performance. However, the simulation results are useful only when dynamic model of every powertrain component is accurate. Therefore, in developing the dynamic models, the system characteristics should be modeled as detail as possible.

This paper presents the efficiency measurements and energy analysis of a parallel HEV. A HEV bench tester is developed to investigate energy flow of the power transmission components such as electric motor, battery, and brake. In addition, regenerative braking energy is measured to evaluate various energy management algorithms. Based on the test results and dynamic models of the HEV powertrain, a HEV performance simulator is developed. Using the simulator, the HEV performance is evaluated for a mild hybrid system.

2. PARALLEL HEV SYSTEM

Figure 1 shows a schematic diagram of the parallel HEV used in this study. Internal combustion engine is connected

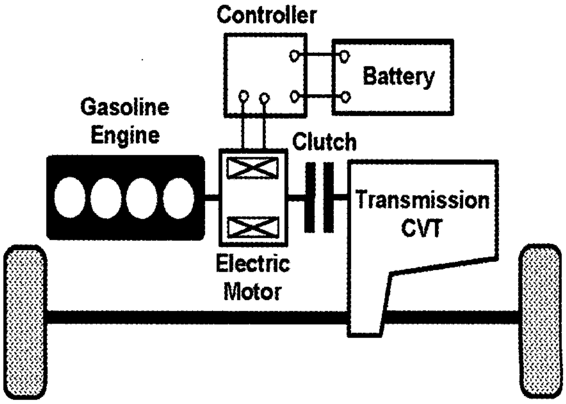

Figure 1. Schematic diagram of the parallel HEV.

**Corresponding author.* e-mail: hskim@me.skku.ac.kr with a motor by a single shaft. Although the rotational speed of the motor is equal to the engine speed, the engine and the motor torque remain independent. One clutch is used between the motor and the transmission. As a transmission, a metal belt CVT is used to maintain the engine operation on the minimum fuel consumption region independent of the vehicle speed. The HEV used in this study employs a front-wheel drive. 10 kW electric motor and Ni-MH batteries are mounted. Since the electric motor size is relatively small, the basic control strategy of the HEV in Figure 1 should be "electric-assisted".

3. HEV BENCH TESTER CONSTRUCTION

3.1. Bench Tester

A HEV bench tester is designed and realized to investigate the energy flow between the HEV power transmission components. In Figure 2, the HEV bench tester developed is shown. The bench tester consist of the IC engine, BLDC motor, power supply, clutch, CVT, flywheel, brake, dynamometer and control systems.

For the bench tester, 4-cylinder DOHC engine with 1.5 *l* volume stroke is used. The fuel injection and ignition timing are controlled by an electronic control unit (ECU). The throttle valve opening (TVO) is controlled by throttle controller using a stepping motor. A 10 kW BLDC motor is connected directly to the IC engine. Motor system consist of the electric motor, motor control unit (MCU) and DC/DC converter. Electric power to drive the motor is supplied by the 144 V, 6.5 Ah power supply instead of the battery in the bench tester. The battery system consist of DC power supply and safe discharge unit (SDU). To measure the engine and motor torque, torque sensor is installed between the motor and the clutch, because it is difficult to measure the motor and engine torque respectively. A magnetic clutch is used between the torque sensor and the CVT. The CVT rig is developed, which is modified using an electronic-controlled CVT. The modification of the CVT is required to perform the CVT ratio control on the bench without signals at the actual running state of the vehicle. In the CVT rig, the CVT speed ratio control is performed at proportional pressure control valve. To simulate the inertia of the HEV, the flywheel is designed. Road load is applied from the load simulator. The load simulator consist of the gear pump and pressure relief valve. The braking is performed by the hydraulic brake and regenerative brake. The hydraulic brake caliper pressure is controlled by proportional pressure control valve. In regenerative braking, 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. The electric energy generated by the regenerative brake varies in response to a regenerative braking force.

3.2. Operation and Control

Figure 3 shows a schematic diagram of the HEV bench tester operation system. From the bench tester, the following parameters are measured : a summation of the engine and motor torque, drive torque, load torque, TVO, engine and motor speed, flywheel speed, input/output

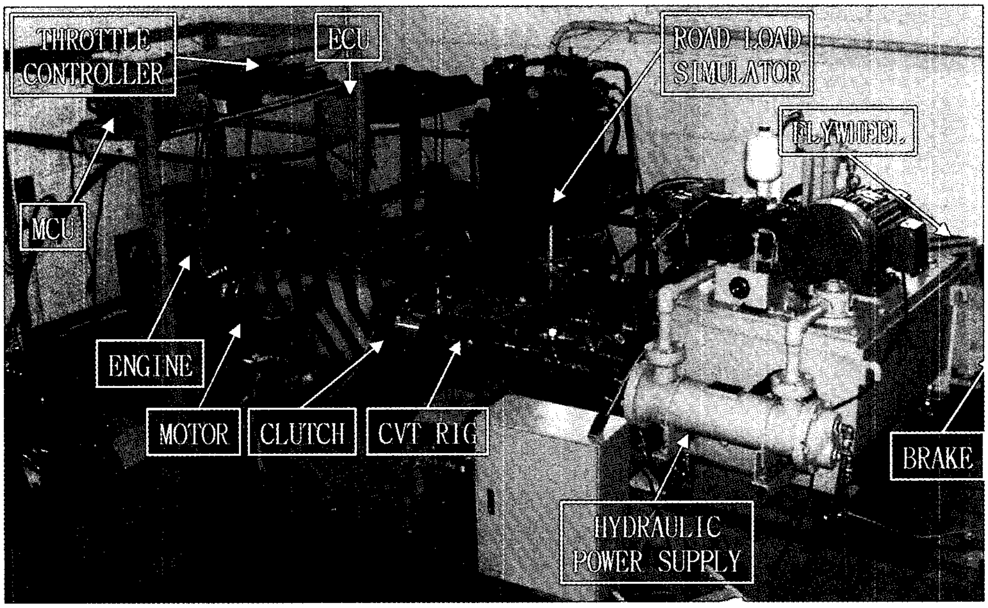

Figure 2. HEV bench tester.

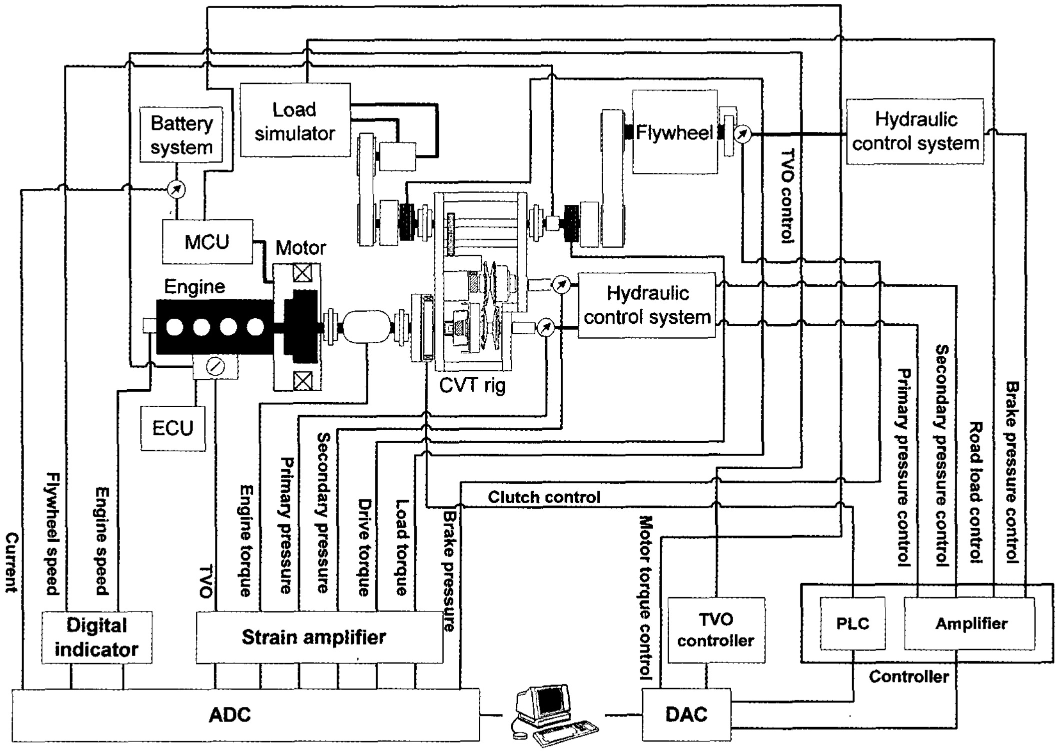

Figure 3. Schematic diagram of HEV bench tester operation system.

current between motor system and battery system, primary and secondary pressure of the CVT and hydraulic brake control pressure. From the measured signals, the TVO, motor torque, primary pressure, secondary pressure, brake pressure and the road load control signals are supplied by the operation program. In addition, the clutch slip control is performed by the programmable logic controller (PLC).

3.3. HEV Operation Algorithm

To operate the HEV bench tester, a power assist algorithm is used. The power assist algorithm is basically equal to the electric-assisted control strategy. In the power assist algorithm, the motor is used to assist the engine in the acceleration mode or hill climbing while the engine is used as a primary power source. The electric motor and batteries are also available to capture regenerative braking energy in the deceleration mode. In the power assist algorithm used in the bench test, the drive mode is defined as: acceleration, normal and deceleration. The power assist of the electric motor is adapted in the acceleration mode when the HEV requires high power. In the normal mode where the vehicle runs in a slight acceleration, the engine propels the vehicle since the required power is not large. When the vehicle runs in a deceleration mode, the regenerative braking is performed.

The required vehicle power is calculated corresponding to the drive pedal opening. For the given vehicle power, the motor assist power is determined, in priority, by considering the battery SOC, vehicle velocity and drive pedal opening. The remaining power is delivered by the engine. In Figure 4, the concept of the power assist algorithm is shown. The control target is to move the engine operation point from P_1 to P_2 by the power assist of the electric motor. The motor generates the power P_{m_add} to assist the engine while the engine operation is carried out on the optimal operation line (OOL) by the CVT ratio control. The motor assist power P_{m_add} is determined by considering the weight factor as

$$P_{m\_add} = P_{max} \times fac(motor) \tag{1}$$

$$fac(motor) = fac_1(velocity) \times fac_2(Ap) \times fac_3(SOC), \tag{2}$$

where P_{max} is the motor maximum power, fac is the weight factor of the motor, fac_1 is the weight factor which depends on the velocity, fac_2 is the weight factor which depends on the drive pedal opening, fac_3 is the weight factor which depends on the battery SOC (Choi, 2003).

From the power assist algorithm, the engine and motor power are delivered to the wheel to drive the vehicle. The driver model controls the drive pedal opening corresponding to the vehicle velocity error by comparing the reference velocity and the actual velocity.

In the braking mode, the regenerative braking is

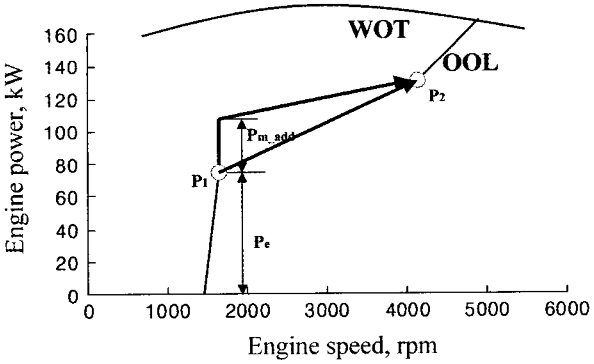

Figure 4. Concept of power assist algorithm.

carried out. In this study, the motor regenerative torque is determined depending on the battery SOC and vehicle velocity.

$$T_{regen\_desired} = min(T_{b\_desired}, T_{regen\_cal}) \tag{3}$$

$$T_{regen\_cal} = fac_4(SOC) \times fac_5(velocity) \times T_{regen\_max}, \tag{4}$$

where $T_{regen\_desired}$ is the regenerative braking torque, $T_{b\_desired}$ is demanded braking torque, T_{regen_cal} is calculated regenerative braking torque, fac_4 is the weight factor which depends on the battery SOC, fac_5 is the weight factor which depends on the velocity, T_{regen_max} is the maximum regenerative braking torque. If the demanded braking torque is less than T_{regen} available at the motor, only the regenerative brake is applied and the magnitude of the regenerative braking torque is limited not to exceed the demanded braking torque. In case that the demanded braking torque is larger than T_{regen}, the hydraulic brake works together with the regenerative brake (Yeo, 2002).

4. EFFICIENCY MEASUREMENT AND ENERGY ANALYSIS

Using the HEV bench tester, efficiency of each powertrain component was measured. In a first step, IC engine was tested on the bench tester and engine map was obtained as shown in Figure 5.

Next, the engine and motor torque were measured. Since the motor runs with the engine on a single shaft, it is not possible to measure the motor torque separately and the summation of the engine and motor torque was measured instead. The engine torque was calculated from the measurement data using a motor torque-voltage map which was constructed by off-line measurement. In Figure 6, test results of the engine and motor torque are shown. Magnitude of the motor torque is determined from the power assist algorithm.

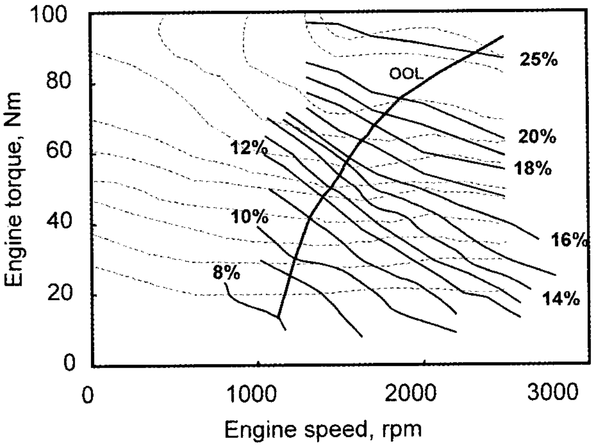

Figure 5. Engine map.

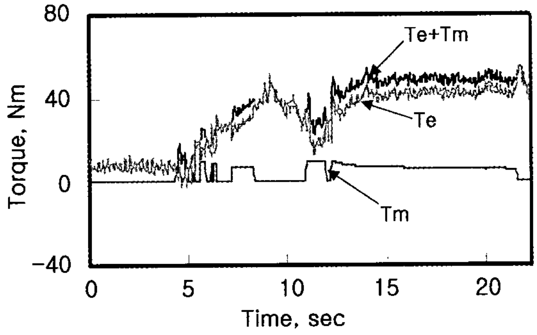

Figure 6. Engine and motor torque.

In Figure 7, bench test results of the HEV are shown. The actual velocity (a) follows the target velocity. Since electro-magnetic clutch used in the test is always engaged during the experiment, the vehicle velocity shows low speed even at the engine idling. Therefore, in the energy analysis, the engine idling energy measured in the experiment was excluded. The engine speed (d) changes by the CVT ratio (e) control corresponding to the throttle valve opening input (b). The engine torque (c) varies according to the TVO (b) and the engine speed (d). The motor torque (f) shows positive value when the motor is used to assist the engine to propel the vehicle and shows negative value during the regenerative braking. When the vehicle restarts from the engine idle stop, the motor is supposed to assist the engine according to the operation strategy. However, in the experiment, the motor does not work since the engine still operates due to the clutch characteristics. The input (g) and output (h) power of the CVT were measured from the torque and speed at each side. The hydraulic power required to maintain the belt clamping force as well as the shift control was obtained from the primary and secondary pressure and pulley speed. From the engine operation trajectory (i), it is found that the engine operation is performed near the optimal

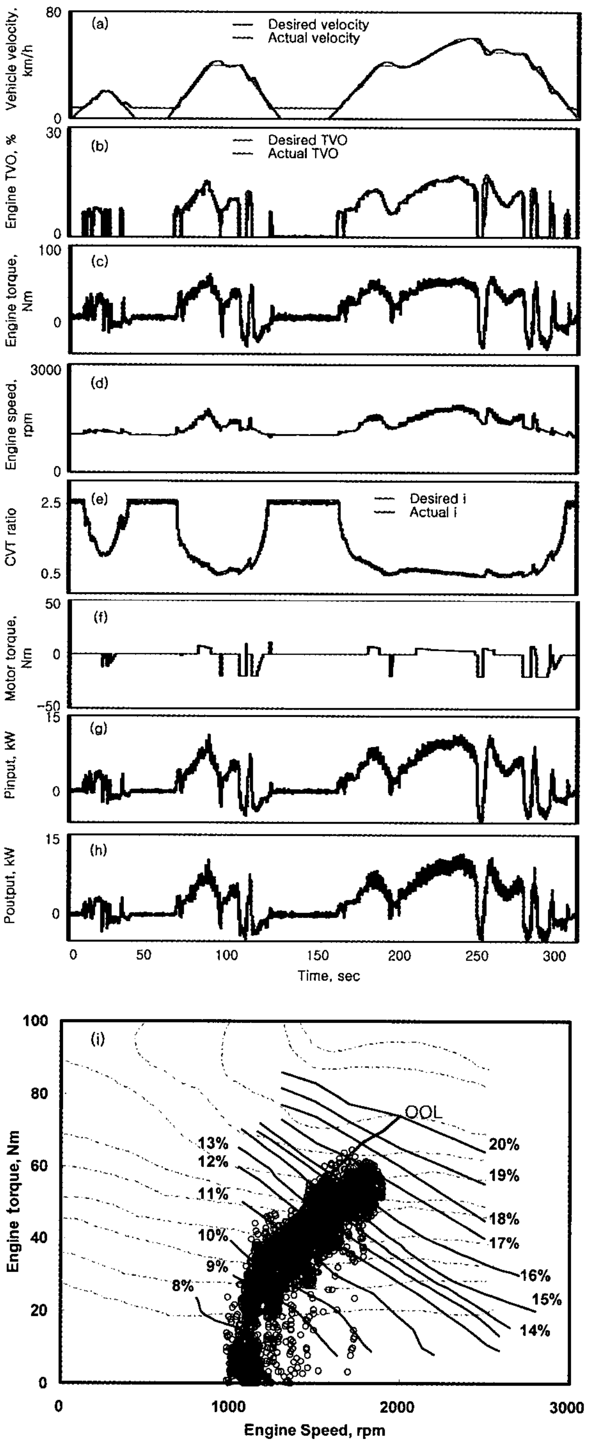

Figure 7. HEV bench test results.

operation line by the CVT ratio control.

Accompanied by the efficiency measurements, a detailed energy analysis was performed (Höhn, 2002; Kleimaier, 2002) in Figure 8. From the measured input and output power, recuperation power, motor power, braking power, and kinetic energy of the flywheel in transient states, energy flows through the driveline were determined. The engine and motor produce 996.3 kJ, 36.3 kJ of mechanical energy respectively, in propelling the vehicle for the given driving cycle. Energy generated by the engine and motor is transmitted to the CVT. This energy is then reduced by the amount of CVT loss. Finally, output energy of the CVT is used to accelerate the vehicle and overcome the driving resistance. When the vehicle decelerates, kinetic energy of the vehicle generates the motor to charge the battery through the regenerative brake and the rest of the energy is dissipated by the hydraulic brake. From the experiment, the CVT efficiency is measured as η_{CVT} = 82.6%. The regenerative braking power was measured from the regenerative braking torque and motor speed. The battery charging power was measured from the current produced by the regenerative brake and operation voltage. Efficiency of the regenerative braking system can be determined as η_{regen} = 61.1% from the charging energy and recuperation energy.

The efficiency measurement and energy analysis for the HEV test rig are used to improve the dynamic models of the HEV powertrain.

5. HEV PERFORMANCE SIMULATOR

Using the results of efficiency measurement and energy analysis, a HEV performance simulator is developed with MATLAB SIMULINK (Figure 9). In SIMULINK model, each part of the powertrain is separately modeled and can easily be connected with other parts. Modeling procedure of each powertrain element is summarized below (Park, 2004).

5.1. Engine

Since the engine and the motor is connected on a single shaft, state equation of the engine is expressed as

$$(J_e + J_m)\frac{d\omega_e}{dt} = T_e + T_m - T_{loss} - T_{net}, \tag{5}$$

where J_e, J_m are the engine and the motor inertia, respectively, ω_e is the engine speed, T_{loss} is the auxiliary device loss, T_{net} is the CVT input torque.

5.2. Battery

In this study, the input and output current of the battery and the SOC are calculated using the battery internal resistance (Szumanowski, 2000). The internal resistance were obtained from the experiments with respect to the battery SOCs. The battery voltage is represented as

$$U_a = E - i_a R_i \text{ at discharge} \tag{6}$$

$$U_a = E + i_a R_i \text{ at charge,} \tag{7}$$

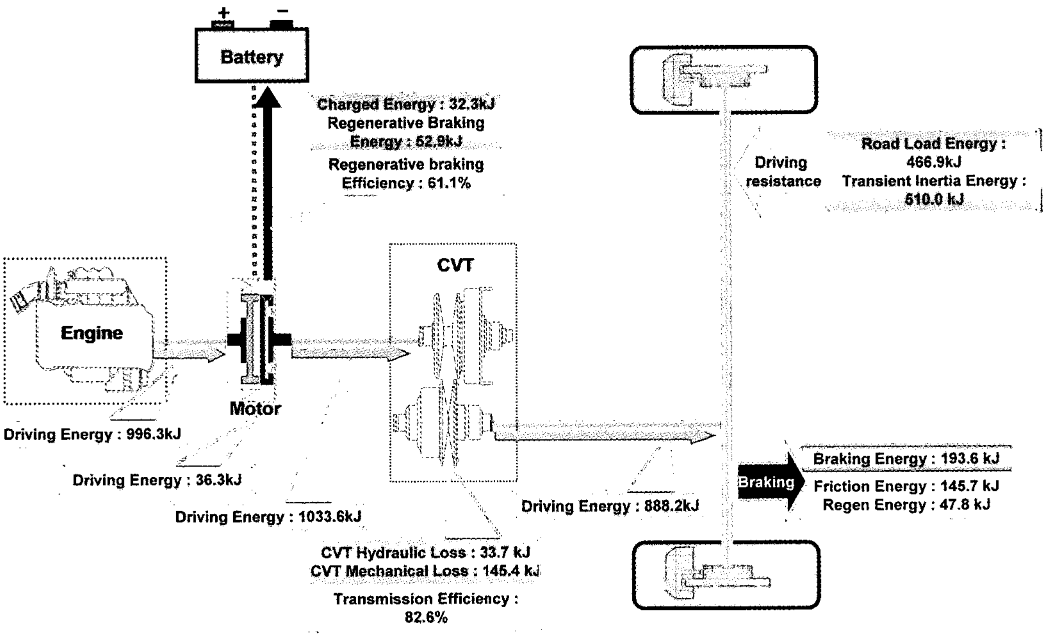

Figure 8. Energy analysis of the HEV bench tester.

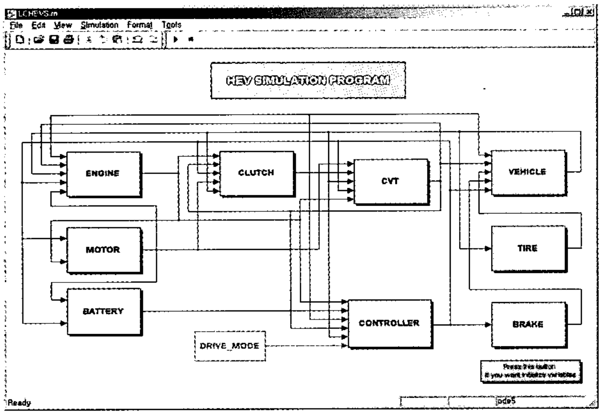

Figure 9. HEV performance simulator.

where U_a is the voltage, E is the electromotive force, i_a is the current, R_i is the internal resistance. The battery SOC is directly related with the battery capacity, which is defined as

$$Q_u(i_a, t, \tau) = Q_\tau(\tau, i_a) - \int_0^t i_a(t)dt, \tag{8}$$

where Q_u is the temporary usable capacity which is a function of the current i_a, temperature t, and time τ. Q_τ is the accumulator's capacity. The integral term in Eq. (8) is the usable charge, which has been drawn from the accumulator.

5.3. Motor

The motor torque is determined as the smaller torque by comparing the target motor torque which is calculated from the power distribution by the power assist algorithm and the maximum motor torque available at the present motor speed. Using the motor torque and speed, the motor efficiency is determined from the efficiency map. Once the required battery power to drive the motor is obtained, the voltage and current of the battery are obtained from the battery model.

5.4. CVT

The CVT shift dynamics plays an integral role in the vehicle response. In addition, the CVT shift dynamics affects the engine performance on the optimal operation line (OOL). For instance, the faster the CVT shift speed becomes, the closer the engine can be operated on the OOL. In this study, the following CVT shift dynamics suggested by Ide (1996) is used

$$\frac{di}{dt} = \beta(i)\omega_p(F_p - F_p^*), \tag{9}$$

where $\beta(i)$ is the constant which is a function of the CVT ratio i, ω_p is the primary pully speed, F_p is the primary thrust and, F_p^* is the primary thrust at a steady state. The CVT ratio needs to be controlled to move the engine operation point on the optimal operation line (OOL) for the best fuel economy. The desired CVT ratio i_d is defined as

$$i_d = \frac{R_t\omega_d}{N_d V}, \tag{10}$$

where ω_d is the desired engine speed which can be

Table 1. Vehicle data.

Engine	Stroke volume Maximum torque	1500 cc 130 Nm
Motor (BLDC)	Peak power Continuous power Rated speed Maximum torque	10 kW 5 kW 2000 rpm 50 Nm
Battery (Ni-MH)	Total power	12 kW
CVT	CVT gear ratio range Final reduction gear ratio	0.455~2.47 5.763
Vehicle	Vehicle mass Tire radius	1375 kg 0.279 m

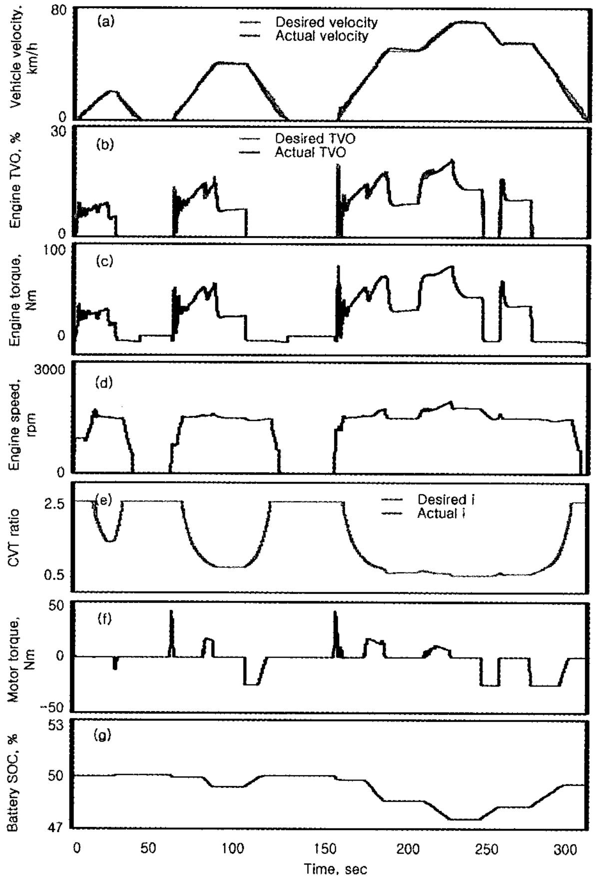

Figure 10. HEV performance simulation results.

obtained as a point where the OOL and the throttle valve opening curve cross each other (Kim, 2000).

6. SIMULATION RESULTS

In the simulation, the initial condition of the battery SOC is assumed to be 50%. In Table 1, vehicle parameters used in the simulation are shown.

In Figure 10, simulation results are shown for ECE-1/3 mode by the power assist algorithm. The vehicle velocity (a) follows closely the driving mode. The engine TVO (b) changes corresponding to the acceleration pedal opening at acceleration and normal mode, and becomes zero at deceleration mode. The engine torque (c) changes corresponding to the TVO. The engine speed (d) is controlled by the CVT ratio control (e). Since the idle-stop strategy is employed for the HEV, the engine speed remains zero when the vehicle stops. The motor torque (f) shows a positive value when the motor is used to propel the vehicle and shows a negative value during the regenerative braking. The battery SOC (g) decreases from the initial SOC when the motor assists the engine in the acceleration mode and increases during the regenerative braking. The battery SOC changes around the initial value, 50% since the weight factors of the motor usage were selected to maintain the battery SOC.

7. CONCLUSION

Efficiency measurement and energy analysis are performed for a parallel HEV bench tester. First, HEV bench tester is developed, which consists of IC engine, CVT, 10 kW BLDC motor, MCU, DC/DC converter, and 144 V, 6.5 Ah power supply system. For the HEV operation, a power assist algorithm is proposed. In the power assist algorithm, the motor assists the engine while the engine is operated on the optimal operation line by the CVT ratio control. Using the HEV bench tester, the efficiency of each powertrain component is obtained from the measured mechanical and electrical power. In addition, regenerative braking efficiency is obtained. Accompanied by the efficiency measurements, a detailed energy analysis is performed. From the measured fuel consumption, recuperation power, motor power, braking power and kinetic energy of the flywheel in transient states, energy flows through the driveline are determined. Based on the efficiency measurement and energy analysis, a HEV performance simulator is developed and performance simulation is carried out. It is expected that the HEV simulator developed can be used to obtain further optimization potentials.

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