Operation Algorithm for a Parallel Hybrid Electric Vehicle with a Relatively Small Electric Motor

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In this paper, operation algorithms for a parallel HEV equipped with a relatively small motor are investigated. For the HEV, the power assist and the equivalent fuel algorithms are proposed. In the power assist algorithm, an electric motor is used to assist the engine which provides the primary power source. In the equivalent fuel algorithm, the electric energy stored in the battery is considered to be an equivalent fuel, and an equivalent brake specific fuel consumption for the electric energy is proposed. From the equivalent fuel algorithm, distribution of the engine power and the motor power is determined to minimize the fuel consumption for a given battery state of charge (SOC) and a required vehicle power. It is found from the simulation results that the fuel economy and the final battery SOC depend on the motor discharge energy and it is the best way to charge the battery only by the regenerative braking, not by the engine to improve the overall fuel efficiency of the HEV with the relatively small motor.

Key Words : HEV, Fuel Economy, Power Assist Algorithm, Equivalent Fuel Algorithm

1. Introduction

Growing environmental and economic concerns have led to recent effort to produce more fuel efficient and lower emission 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. Hydrogen driven cars are limited because of non-existent infrastructure. EVs are a niche solution because of short range. FCVs are very promising in the long term because it will take some years to get to large production volumes. In short to mid term, HEVs offer the best promise. With minimum extra cost they show improve-

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ments in fuel consumption and emission (Mueller et. al., 2000).

A HEV has two or more sources of on-board power. A power control strategy is needed to control the flow of power while taking into account reserves of energy in storage devices. There are two distinct extremes in the spectrum of control strategy (Anderson et. al., 1995). One is a system that uses a "thermostat" algorithm to command the engine. In this mode, the battery must accommodate to all the transient power requirements. The other extreme commands the engine to follow the actual wheel power whenever possible, which is similar to a conventional automobile. Using this strategy, the engine must operate over its entire range of power levels. For HEVs, fuel consumption and emissions depend on the way that the electrical energy stored in the batteries is substituted to the chemical energy of fuel. Therefore, HEV control strategy can be constructed according to the depth of discharge of the batteries from the viewpoint of the battery energy management. But other parameters such as engine temperature are also taken into account to define the best strategy (Trigui et. al., 2003). For most of the engines and the batteries under consideration, neither of these strategies would be the optimum strategy. The optimum strategy is highly dependent on the characteristics of the powertrain components and the planned use of the vehicle.

In this paper, operation algorithms for a single shaft parallel HEV are evaluated for the minimum fuel consumption. Power assist and equivalent fuel algorithms are proposed and dynamic models of the HEV powertrain are derived to evaluate the algorithms. Using the HEV simulator, performance of the HEV is investigated by considering the regenerative braking.

2. HEV Operation Algorithm

Figure 1 shows a schematic diagram of the parallel HEV used in this study. Engine is connected 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 torques 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 adopts 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 Fig. 1 should be "electric-assisted". In this study, two control strategies are proposed and evaluated for the HEV in Fig. 1.

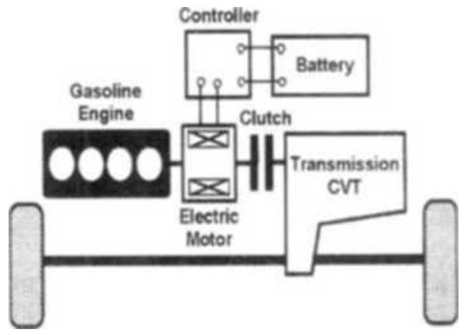


Fig. 1 Schematic diagram of parallel HEV

2.1 Power assist algorithm

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 from decelerations.

In the power assist algorithm used in this study, the drive mode is divided into initial engine cranking, idle and creep, acceleration, normal, deceleration, engine off and engine cranking mode. The power assist of the electric motor is adapted in acceleration mode when the HEV requires high power. In the normal mode where the vehicle runs in a slight acceleration or deceleration, the engine propels the vehicle since the required power is not large. When the vehicle runs in a slight deceleration, the regenerative braking is performed to recuperate the battery state of charge (SOC).

The required vehicle power is calculated corresponding to the drive pedal opening. For a given

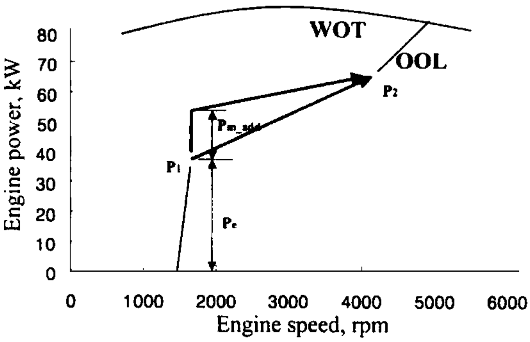


Fig. 2 Control strategy for power assist algorithm

vehicle power, the motor assist power is determined by considering the battery SOC. The rest of the required power is delivered by the engine. The control strategy of the power assist algorithm can be explained as follows. In Fig. 2, 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

$$P_{m\_add} = P_{\max} \times fac_{motor} \quad (1)$$

$$fac_{motor} = fac_{velocity} \times fac_{AP} \quad (2)$$

where $P_{\max}$ is the motor maximum power, fac_{motor} is the weight factor of the motor, $fac_{velocity}$ is the weight factor which depends on the velocity, fac_{AP} is the weight factor which depends on the drive pedal opening, Ap.

In the braking mode, the regenerative braking is carried out.

2.2 Equivalent fuel algorithm

The equivalent fuel algorithm assumes that the electric power flowing to/from the motor can be represented as an equivalent fuel (Kim et. al., 1999). In Fig. 3, power flow of the HEV is shown for charge and discharge. From Fig. 3, the required power P_{req} is represented as

$$P_{req} = P_e - P_m \text{ at charge} \quad (3)$$

$$P_{req} = P_e + P_m \text{ at discharge,} \quad (4)$$

where P_e is the engine power, P_m is the motor

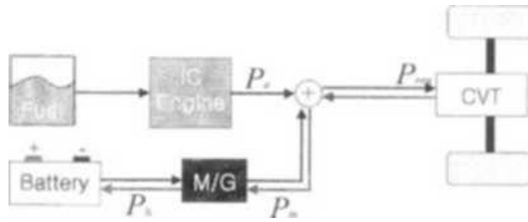


Fig. 3 Power flow of HEV

power. The fuel consumption of the engine, F_e is

$$F_e = bsfc \times P_e \quad (5)$$

where *bsfc* is the brake specific fuel consumption. Assuming that the battery is charged by the engine, the equivalent fuel flowing to the battery through the motor can be represented as

$$F_{mc} = \eta_{mc}\eta_{bc} \times bsfc \times P_m \quad (6)$$

where F_{mc} is the equivalent fuel of the motor, η_{mc} and η_{bc} are the charge efficiency of the motor and the battery, respectively.

From Eqs. (3), (5) and (6), the net fuel consumption at charge, F_c is obtained as

$$F_c = F_e - F_{mc} = bsfc \times P_e - \eta_{mc}\eta_{bc} \times bsfc \times P_m \quad (7)$$

At discharge, the equivalent fuel flowing from the motor is represented as

$$F_{md} \times \eta_{md} \times \eta_{bd} = ebsfc \times P_m \quad (8)$$

where F_{md} is the equivalent fuel of the motor at discharge, η_{md} and η_{bd} are the motor and the battery efficiency, respectively. *ebsfc* is the motor equivalent brake specific fuel consumption.

Since the electric energy discharged by the motor is the energy stored by the engine, the *ebsfc* of the motor at discharge can be assumed as

$$ebsfc = bsfc_{at\_charge} \times \eta_{m\_charge} \times \eta_{b\_charge} \quad (9)$$

where $bsfc_{at\_charge}$ is the engine *bsfc* at the moment of charge, η_{m_charge} and η_{b_charge} are the motor and the battery efficiency at the moment of charge.

The equivalent fuel algorithm is focused on determining the optimal power distribution of the engine and the motor to achieve the minimum fuel consumption for various levels of the vehicle power and the battery SOC. Now, we need to obtain *ebsfc* of the motor at every moment. In the previous study (Kim et. al., 1999), *ebsfc* was calculated as an average of the stored energy which is charged by the engine. This, however, requires predetermined information on the amount of charge and efficiencies of the motor and battery at every moment for unknown driving cycles, which seems to be almost impossible. In order to handle this problem, a weight function of SOC, which is inversely proportional to the SOC was introduced in obtaining the minimum operational cost of the HEV (Choi et. al., 2002). In this study, it is assumed that the efficiencies of the battery and motor are constant at the moment of charge, and the battery charge is carried out in the low *bsfc* region of the engine on the OOL. This assumption is reasonable since nobody wants to operate the engine on the high *bsfc* region when charging the battery from the viewpoint of global efficiency of the HEV. In addition, if the battery SOC does not change much and remains within a certain bound, the charge and discharge efficiencies can be assumed to be constant. In Fig. 4, the operation region at charge is shown, which is selected between the power P_{upper} and P_{lower} on the OOL. The engine *bsfc* at charge is determined as an average of the *bsfcs* in the selected operation region.

From Eqs. (4), (5) and (8), the net fuel consumption at discharge can be obtained.

$$F_d = F_e + F_{md} = bsfc \times P_e + \frac{ebsfc}{\eta_{md}\eta_{bd}} \times P_m \quad (10)$$

From the assumption that the efficiencies of the motor and battery at charge are equal to those at discharge, the equivalent fuel consumption can

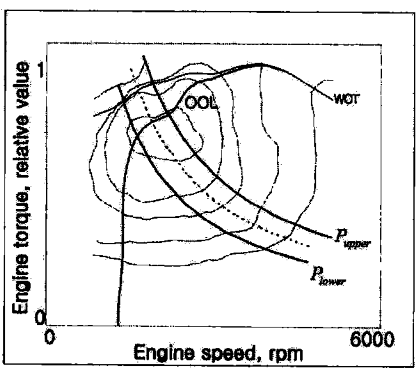


Fig. 4 Engine map

be represented as

$$EFC = \alpha \times bsfc + \eta_m\eta_b(1+\alpha)\, bsfc \quad \text{at charge} \quad (11)$$

$$EFC = \alpha \times bsfc + \frac{(1-\alpha)}{\eta_m\eta_b}\, ebsfc \quad \text{at discharge} \quad (12)$$

where EFC is the equivalent fuel consumption, α is the ratio of the motor power to the required vehicle power, which is defined as

$$\alpha = \frac{P_e}{P_{req}} \quad (13)$$

For a non plug-in type HEV, the battery SOC should be maintained above some level after running a given driving cycle. The battery SOC depends on the amount of motor discharge energy, engine charge energy, and the regenerative braking energy. In order to maintain the battery SOC, the motor discharge needs to be controlled. This can be achieved by introducing a weight function to the EFC as

$$EFC = \alpha \times bsfc + \frac{(1-\alpha)}{\eta_m\eta_b}\, ebsfc \times \gamma(SOC) \quad \text{at discharge} \quad (14)$$

where $\gamma(SOC)$ is the weight function for the battery SOC, which is defined

$$\gamma(SOC) = 1 - (SOC - SOC_{initial}) \quad (15)$$

By introducing the weight function, $\gamma(SOC)$, the amount of motor discharge can be controlled. For instance, when the battery SOC becomes low, EFC at discharge becomes large, which limits the application of the motor since it is inefficient to use the motor when the *ebsfc* is high. On the contrary, when the battery SOC becomes high, EFC becomes small, which promotes the application of the motor. Similar motor operation can be achieved by introducing an exponential form of *ebsfc* which is a function of the battery SOC (Cho et. al., 2001).

Using Eqs. (11), (14), the optimal distribution of the engine and the motor power can be determined, which minimizes the equivalent fuel consumption for various levels of the battery SOCs. Fig. 5 shows the optimal distribution of the motor and the engine power with respect to the demanded vehicle power for battery SOC 40~60%. As shown in Fig. 5, for the vehicle power under 10 kW, it is better to use only the engine for the all

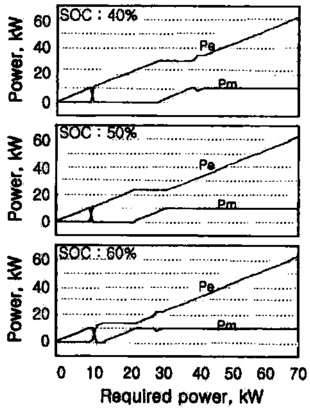


Fig. 5 Power distribution for equivalent fuel algorithm

battery SOC levels from the viewpoint of fuel economy. As the battery SOC increases, the portion of motor power increases since the equivalent fuel consumption becomes smaller from Eq. (14) and Eq. (15). In actual driving, the distribution of the engine and the motor power is carried out according to the drive pedal opening and look-up table based on Fig. 5.

3. HEV Simulator

Analyzing and comparing the operation algorithms and performance of the HEV requires a powertrain simulation model. Modeling of HEV powertrain is performed using MATLAB SIMULINK. In simulink model each part of the powertrain is separately modeled and can easily be connected with other parts.

Engine : Since the engine and the motor is connected, state equation of the engine is expressed as

$$(J_e+J_m)\frac{d\omega_e}{dt}=T_e+T_m-T_{loss}-T_{net} \quad (16)$$

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

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

$$U_a=E-i_aR_i \text{ at discharge} \quad (17)$$

$$U_a=E+i_aR_i \text{ at charge} \quad (18)$$

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

$$Q_u(i_a, t, \tau)=Q_r(\tau, i_a)-\int_0^t i_a(t)\,dt \quad (19)$$

where Q_u is the temporary usable capacity which is a function of the current i_a, temperature t, and time τ. Q_r is the accumulator's capacity. The integral term in Eq. (19) is the usable charge, which has been drawn from the accumulator.

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 or equivalent fuel algorithm and the maximum motor torque available at the present motor speed. Using the motor torque and the 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.

CVT : 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

$$i_d=\frac{R_t\omega_d}{N_dV} \quad (20)$$

where ω_d is the desired engine speed which can be obtained as a point where the OOL and the throttle valve opening curve cross each other (Kim et. al., 2000).

4. 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.

Table 1 Vehicle data

Engine	Stroke volume	1600 cc
	Maximum torque	140 Nm
Motor (BLDC)	Peak power	10 kW
	Rated speed	2000 rpm
	Continuous power	5 kW
	Maximum torque	50 Nm
Battery (Ni-MH)	Total power	12 kW
CVT	CTT gear ratio range	0.455~2.47
	Final veduction gear ratio	5.763
Vehicle	Vehicle mass	1375 kg
	Tire radius	0.279 m

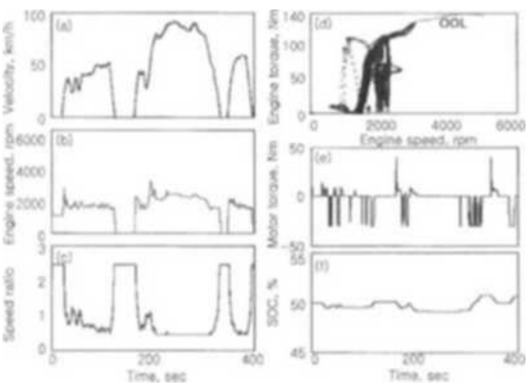


Fig. 6 Simulation results for power assist algorithm

In Fig. 6, simulation results are shown for 0~400 seconds of FUDS cycle by the power assist algorithm. The vehicle velocity (a) follows closely the driving mode. The engine speed (b) is controlled by the CVT ratio control (c). Since the idle-stop strategy is adopted for the HEV, the engine speed remains zero during the vehicle stop. As shown on the engine operation trajectory (d), most of the engine operation is performed near the OOL. The motor torque (e) 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 (f) decreases from the initial SOC, 50% while 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 factor of the motor discharge was selected to maintain the battery SOC.

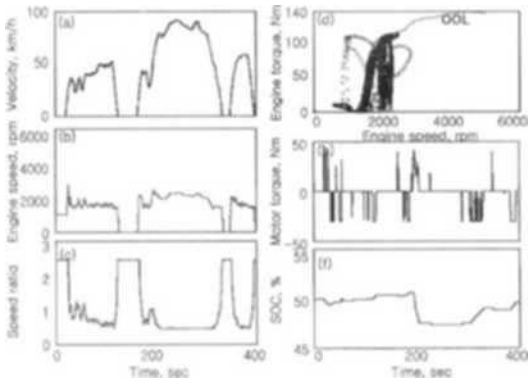
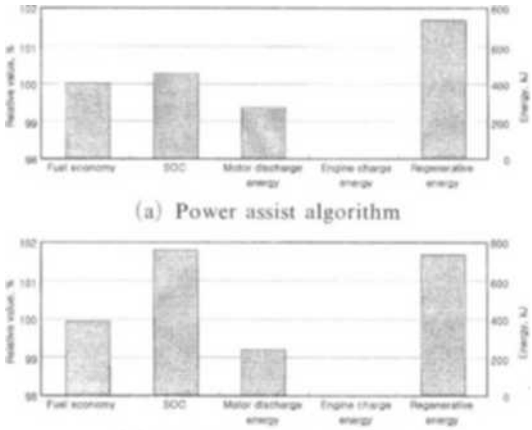


Fig. 7 Simulation results for equivalent fuel algorithm

In Fig. 7, simulation results for the equivalent fuel algorithm are shown. The vehicle velocity (a) follows the drive mode closely. The engine speed (b) and the CVT ratio (c) show almost similar response compared with those of the power assist algorithm. As shown in the engine operation trajectory (d), most of the engine operation is limited below 2500 rpm, while the engine operation by the power assist algorithm reaches more than 3000 rpm. Correspondingly, the motor needs to be discharged to assist the engine. Therefore, it is seen from (e) that the motor is applied more frequently compared with those by the power assist algorithm (Fig. 6(e)). As the frequency of the motor discharge increases, the battery SOC (f) decreases, but the battery SOC level has been recovered after the regenerative braking.

In Fig. 8, the fuel economy, final battery SOC level, motor discharge energy, engine charge energy and regenerative braking energy are compared for the power assist and equivalent fuel algorithm. In this comparison, the fuel economy by the power assist algorithm and the initial SOC value are used for the reference. These simulation results are obtained for FUDS cycle.

It is seen from Fig. 8 that the fuel economy and the final battery SOC level by the power assist algorithm are almost similar with those by the equivalent fuel algorithm within 2% bound since the amount of motor usage is almost same for both algorithms in spite of the different way of



(a) Power assist algorithm

(b) Equivalent fuel algorithm

Fig. 8 Comparison of HEV performance

the motor application. It is also noted that for both algorithms, the battery charge is carried out only by the regenerative braking, not by the engine since the energy recuperation by the regenerative braking is more efficient way to save the fuel consumption compared to the energy storage by the engine. Therefore, it is expected that the best way to increase the fuel economy for the HEV with relatively small motor is to maximize the recuperation energy by the regenerative braking.

5. Conclusion

The power assist and equivalent fuel algorithm are proposed for a parallel HEV equipped with relatively small motor. In the power assist algorithm, the electric motor is used to assist the engine which provides the primary power source. In the equivalent fuel algorithm, the electric energy stored in the battery is considered to be an equivalent fuel. To calculate the equivalent fuel, an equivalent brake specific fuel consumption for the electric energy is proposed, and a weight factor is introduced to maintain the battery SOC level. From the equivalent fuel algorithm, distribution of the engine and the motor power is determined which minimizes the fuel consumption for a given battery SOC and a required vehicle power. In order to evaluate the performance of the operation algorithms suggested, a HEV performance simulator is developed using MATLAB SIMULINK. It is found from the simulation results that the fuel economy and the final battery SOC depend on the motor discharge energy and it is the best way to maximize the recuperation energy by the regenerative braking to increase the fuel economy for the HEV with the relatively small motor.

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