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Evaluation of Fuel Economy for a Parallel Hybrid Electric Vehicle

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In this work, the fuel economy of a parallel hybrid electric vehicle is investigated. A vehicle control algorithm which yields operating points where operational cost of HEV is minimal is suggested. The operational cost of HEV is decided considering both the cost of fossil fuel consumed by an engine and the cost of electricity consumed by an electric motor. A procedure for obtaining the operating points of minimal fuel consumption is introduced. Simulations are carried out for 3 variations of HEV and the results are compared to the fuel economy of a conventional vehicle in order to investigate the effect of hybridization. Simulation results show that HEV with the vehicle control algorithm suggested in this work has a fuel economy 45% better than the conventional vehicle if braking energy is recuperated fully by regeneration and idling of the engine is eliminated. The vehicle modification is also investigated to obtain the target fuel economy set in PNGV program.

Key Words : HEV (Hybrid Electric Vehicle), Fuel Economy, Control Algorithm, SOC (State of Charge), Operational Cost, Regeneration

1. Introduction

A hybrid electric vehicle (HEV) is classified into 3 major types, series type, parallel type and split type (A. F. Burke, 1992). Since the hybrid powertrain of a parallel HEV can be designed compactly enough to be packaged into a small-size front wheel drive vehicle, and it can also be developed with relatively small cost due to easiness of adopting the engine and transmission used in the conventional vehicle, the parallel HEV is preferred by the engineers who are interested in the commercial development of HEV. This is manifested by the fact that two commercial HEVs developed so far in the world, Toyoda's Prius and Honda's Insight, are adopting the parallel type hybrid powertrain.

In this study, fuel economy is evaluated by simulations for a 2 shaft type parallel hybrid system adopting CVT (continuously variable transmission). Not much research has been performed on the fuel economy of the parallel type HEV (F. G. Willis and R. R. Radke, 1985) until early 1990's because parallel type HEVs were considered not easy to realize even a decade ago. The most difficult part of developing parallel HEVs was complexity of their control system. With rapid development of electronic control unit technology in recent years, the advent of commercial HEVs became possible in late 1990's eventually. Accordingly, studies on the fuel economy of parallel HEVs are also increasing recently (M. R. Cuddy, 1997 ; U. Zoelch, 1997 ;

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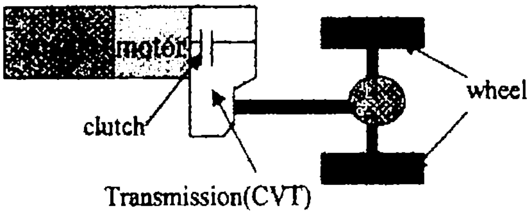
C. H. Kim, 1999).

When evaluating the fuel economy of a HEV, the vehicle control algorithm should be defined and applied to the vehicle operation. In this work, a vehicle control algorithm for the HEV is proposed, which is designed to give minimal fuel consumption at any instance of vehicle driving. For the evaluation of fuel economy of HEV, a simulation program is developed based on the dynamic model of the HEV powertrain. Using the simulation program, the fuel economy of the parallel HEV is investigated for various vehicle specifications.

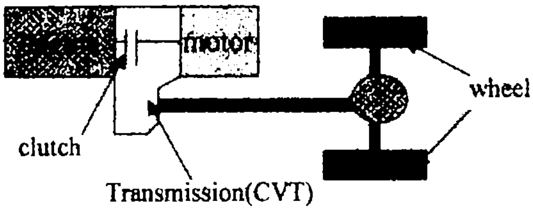
2. Hybrid System Configuration and Operation

Figure 1 shows schematic diagrams of parallel hybrid systems : (a) for single shaft type and (b) for 2 shaft type. An engine and an electric motor are directly connected in the single shaft type HEV, whereas they are separated by the clutch located inside of transmission in the 2 shaft type HEV, so that the engine and the electric motor can deliver their power to the wheels independently. More versatile driving modes are possible in the 2 shaft type HEV than in the single shaft type HEV.

In this work, a 2 shaft type HEV of which the specification is summarized in Table 1, is chosen for the study of fuel economy of HEV. A subcompact passenger car with gross vehicle weight of 1400 kg is assumed for HEV. The engine with maximum power of 70 kw and the electric motor with maximum power of 30 kw are chosen for the HEV powertrain. The transmission type is assumed as CVT, by which it is possible to have the engine or the electric motor operate at the desired speed regardless of vehicle speed.



(a) single shaft parallel type



(b) 2 shaft parallel type

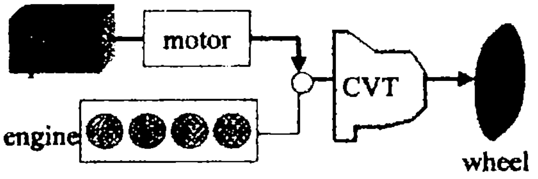
Fig. 1 Schematic diagram of parallel hybrid powertrain

Figure 2 shows the power flows of a 2 shaft type parallel hybrid system at each driving mode. Bold arrows are used to show the power flow in the figure. Five driving modes are possible for the given system, which are ZEV (zero emission vehicle) mode, engine mode, hybrid mode and regeneration mode. The hybrid mode is divided into a motor driving hybrid mode and a motor generating hybrid mode.

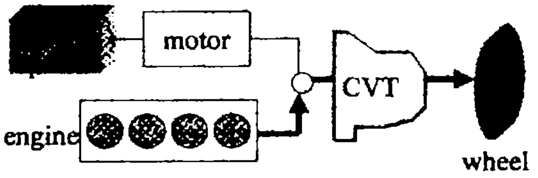
The ZEV mode is the one in which only electric motor is used for driving and this mode is usually selected when the speed of HEV is low. Idling of engine is eliminated at the ZEV mode, which means that the engine is completely stopped even for the short duration when the vehicle is standstill. In the engine mode, the vehicle uses engine power only as in a conventional vehicle. This mode can be used when the speed of vehicle is in

Table 1 Vehicle specifications

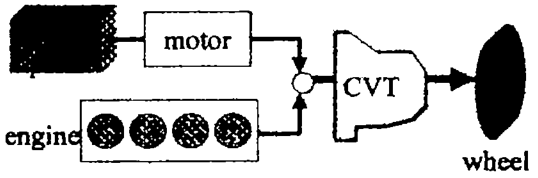
	Item	Value	Units
Vehicle	mass	1400	kg
	tire radius	0.278	m
	proj. area	1.83	m^2
	drag coef.	0.32	–
	rolling resistance	0.1484	$m/kg\text{-}sec^2$
Engine	displacement	1498	cc
	max. power	70(94)	kw(ps)
Motor	max. power	30(42)	kw(ps)
	max. torque	125	Nm
Transmission	type	CVT	
	ratio range	0.45–2.45	–
	final gear ratio	5.763	–
Battery pack	voltage	288	volt
	capacity	2	kwh



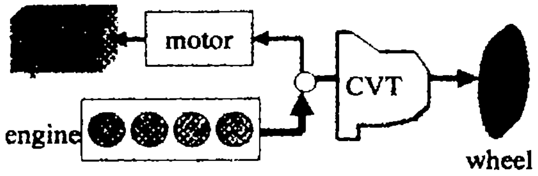
(a) ZEV mode



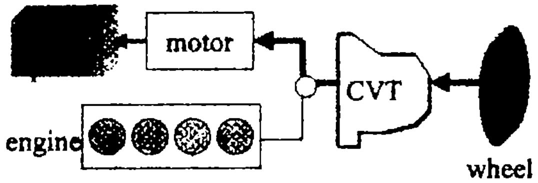
(b) Engine mode



(c) Hybrid mode (motor driving)



(d) Hybrid mode (motor generation)



(e) Braking (regeneration) mode

Fig. 2 Power flow diagram of 2 shaft type parallel HEV

medium range or when battery power is not available because of low SOC (state of charge).

In the motor driving hybrid mode, both the engine and the electric motor deliver power to the vehicle. This mode is required normally when the power demand of the vehicle is very high, such that the electric motor should assist engine power to obtain the required power of the vehicle. In the motor generating hybrid mode, the engine operates at the power level which is bigger than the power required in the vehicle, so that the spared power of the engine is used for operating the electric motor as a generator to produce the electric energy. The electric energy produced is stored in the battery pack.

The regeneration mode or braking mode occurs when the vehicle is to be decelerated. In this mode, the electric motor acts as a generator to absorb the kinetic energy, i.e, braking energy of the vehicle. The electric energy obtained is stored in the battery pack. Clearly, regeneration of braking energy is one of the important factors for better fuel economy of HEV compared to the conventional vehicle, in which braking energy is simply wasted in heat generation. Since the regeneration results in braking effect on the vehicle, the brake force exerted by the hydraulic brake unit should be adjusted during regeneration.

3. Control Algorithm of Hybrid System

Since HEV aims mainly at fuel economy improvement, the control algorithm for HEV should be also decided in the aspect of fuel economy. The most popular control algorithm for a parallel HEV is the load levelling algorithm, with which an engine operates at the most efficient operating point at all times and the electric motor takes the role of levelling the deviation between engine power and vehicle load. In this work, a vehicle control algorithm which yields the operating points where the operational cost of the hybrid system is minimal is derived.

In HEV, an engine consumes fossil fuel and an electric motor consumes electric energy stored in the battery pack. Fossil fuel and electric energy are two different forms of the fuel for HEV. Therefore, both fossil fuel and electric energy consumed should be taken into consideration when the operational cost of HEV is evaluated. The operational cost of HEV at any instant can be derived considering the cost of fossil fuel consumed by the engine and the cost of electricity consumed by the electric motor during a unit interval of time. By introducing a unit price of fossil fuel denoted by λ_f and a unit price of electric power denoted by λ_e, the operational cost of HEV for a unit time can be expressed as

$$\Phi=\lambda_f Q_f+\lambda_e P_b \tag{1}$$

where Φ is the operational cost of HEV, Q_f is the quantity of fuel consumption of the engine for a unit time, and P_b is the battery power.

In the above equation, the battery power can take a positive or a negative value. It is assumed that the battery power is positive for discharging and negative for charging. The discharging condition corresponds to the condition in which the electric motor exerts power and the charging condition corresponds to the condition in which the electric motor acts as a generator.

The fuel consumption of an engine for any instantaneous moment of driving condition can be expressed by

$$Q_f=S_f(\omega_e,\ \tau_e)P_e \tag{2}$$

where S_f is the specific fuel consumption of an engine, P_e is the engine power, ω_e and τ_e are the engine speed and the engine torque, respectively.

The electric motor in a parallel hybrid system can operate as a traction device as well as a generating device. In case that the electric motor acts as a traction device, the battery power is obtained as the motor power divided by the motor efficiency and the discharging efficiency of a battery. In the opposite case, it can be obtained as the motor power multiplied by the motor efficiency and the charging efficiency of a battery.

$$\begin{aligned} P_b&=\frac{P_m}{\eta_m(\omega_m,\ \tau_m)\,\eta_{b,dc}} && \text{for } P_m\geq 0\\ &=\eta_m(\omega_m,\ \tau_m)\,\eta_{b,c}P_m && \text{for } P_m\leq 0 \end{aligned} \tag{3}$$

where P_m is the motor power, η_m is the motor efficiency, $\eta_{b,c}$ is the charging efficiency of a battery, $\eta_{b,dc}$ is the discharging efficiency of a battery, ω_m is the motor speed and τ_m is the motor torque, respectively.

In a parallel hybrid system, the electric energy is generated and stored in the battery pack by engine operated generation or by regeneration of braking energy. In the evaluation of the unit price of electric power in the hybrid system, we assume the portion of regeneration is relatively small compared to engine operated generation. In this case, we can express the unit price of electricity, λ_e in terms of the cost of fossil fuel consumed in generating the electricity. Since the engine operated generation can occur at various operating points, the average values, denoted by the subscript avg, are used for the evaluation of λ_e. It can be written as

$$\lambda_e=\frac{\lambda_f S_{f,avg}}{\eta_{m,avg}\,\eta_{b,c}} \tag{4}$$

Now, combining Eqs. (1) ~ (4), the operational cost of HEV can be obtained as

$$\Phi=\lambda_f S_{f,avg}\left[\frac{S_f(\omega_e,\ \tau_e)}{S_{f,avg}}P_e+\eta_{esys}(\omega_m,\ \tau_m)P_m\right] \tag{5}$$

where η_{esys} is the combined efficiency of the electric system and can be expressed by

$$\begin{aligned} \eta_{esys}&=\frac{1}{\eta_{m,avg}\,\eta_m(\omega_m,\ \tau_m)\,\eta_{b,c}\,\eta_{b,dc}} && \text{for } P_m\geq 0\\ &=\frac{\eta_m(\omega_m,\ \tau_m)}{\eta_{m,avg}} && \text{for } P_m<0 \end{aligned} \tag{6}$$

As noticed in Eq. (5), the value of operational cost Φ varies depending on the operating points of the engine and the electric motor, and there is an operating point which gives a minimum value of function Φ. The operating point at which Φ has a minimum value is the optimal operating point and can be found by comparing the value of Φ at every operating point which satisfies the following conditions.

$$\begin{aligned} &P_{req}=P_e+P_m\\ &\omega_m=\omega_e,\ \text{for } \omega_e\neq 0 \end{aligned} \tag{7}$$

Equation (7) is the constraints for obtaining the optimal operating points of a hybrid system, of which meaning is that the required power of a vehicle denoted by P_{req} is a sum of the engine power and the electric motor power, and the speed of the engine and the electric motor should be the same except in the ZEV mode.

Figure 3 shows the procedure for obtaining optimal operating points in detail. In obtaining the optimal operating points, the specific fuel consumption map of an engine and the motor efficiency map are required. In this work, Fig. 4 and Fig. 5 are used for the specific fuel consumption of the engine and the motor efficiency, respectively. Also, charging and discharging efficiencies of the battery are required in evaluating the operational cost and they are assumed to be

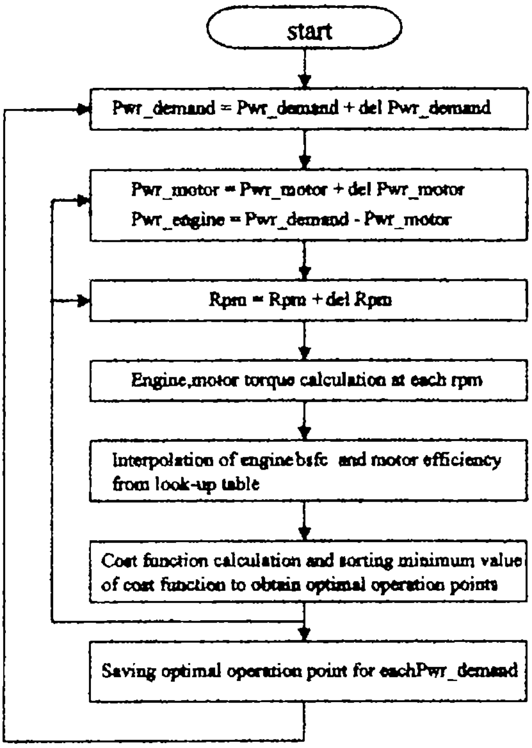


Fig. 3 Procedure for obtaining optimal operation points

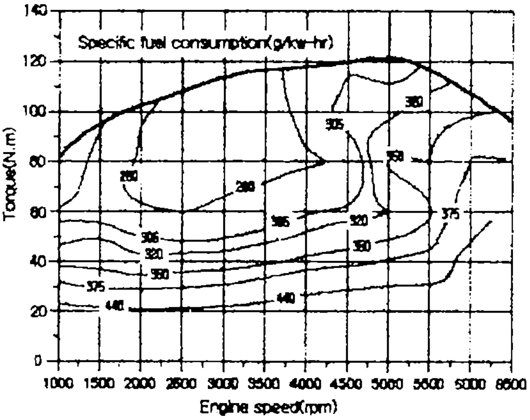


Fig. 4 Specific fuel consumption map of engine

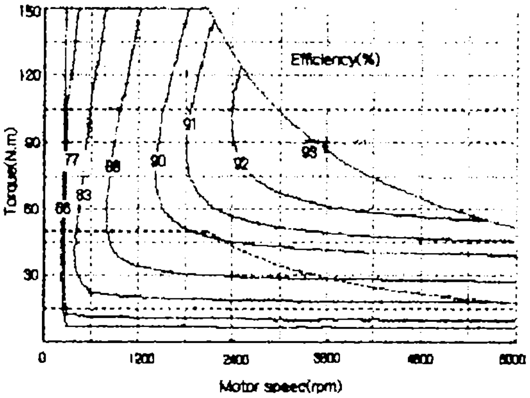


Fig. 5 Efficiency map of electric motor

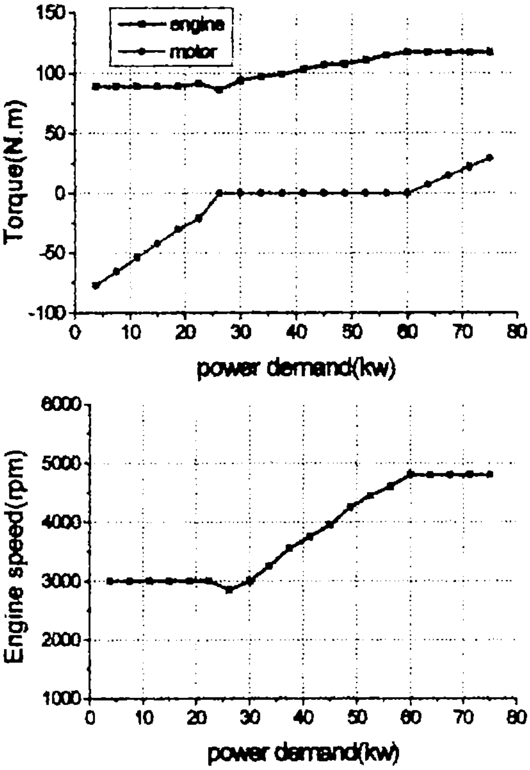


Fig. 6 Operating points for minimal fuel consumption

constant values as 0.75 and 0.95, respectively.

With the procedure shown in Fig. 3, the optimal operating points are obtained. The torque distribution of the engine and electric motor, and the speed of engine at the optimal operating points for each required power are shown in Fig. 6. In the low power region, it is seen that the engine and the electric motor experience a load levelling, that is, the engine operates with the speed of around 3000 rpm where the specific fuel consumption of the engine is the lowest, and the electric motor acts as a generator. In the medium power region, the motor torque is zero and the engine takes all the required power of the vehicle, which implies that the vehicle should be in the engine mode. In the high power region, the electric motor assists the engine in delivering the required power, which corresponds to the motor driving hybrid mode.

4. Simulation Procedure

Simulations are performed according to the procedure shown in Fig. 7. For a driving cycle chosen, the power demand of the vehicle at any instant can be obtained by the following equation.

$$P_{req}=V_{veh}\cdot\left(R_a+R_r+(M_{veh}+\Delta M)\cdot\frac{dV_{veh}}{dt}\right) \quad (8)$$

where M_{veh} is the vehicle mass, V_{veh} is the vehicle velocity, R_a is the air resistance, R_r is the rolling resistance. ΔM is the equivalent mass of the rotational parts and can be expressed as

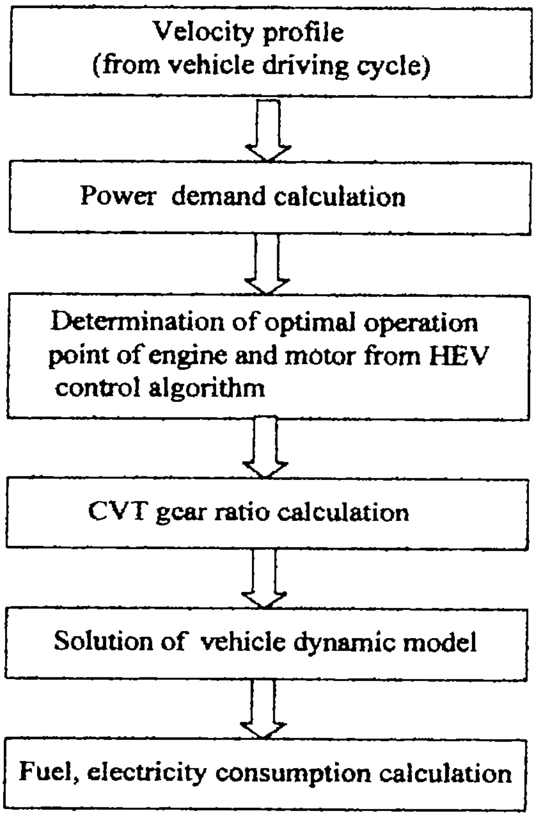


Fig. 7 Simulation procedure

$$\Delta M=\frac{i_f^2 i^2 I_e+I_{axle}}{r_{tire}^2} \quad (9)$$

where i is the CVT speed ratio, i_f is the final gear ratio, I_e is the rotational moment of inertia for the engine, I_{axle} is the rotational moment of inertia for axle and r_{tire} represents dynamic radius of tire.

Once the power demand of a vehicle is decided at each point of a given driving cycle, the speed and torque of the engine and the electric motor are determined by the operating points shown in Fig. 6. After determining the operation speed of the engine or electric motor, the speed ratio of CVT can be obtained by the relationship between the vehicle speed and the rotational speed of the engine or electric motor. It can be given by

$$i=\frac{2\pi r_{tire}\omega_e}{60 i_f V_{veh}} \quad (10)$$

The engine torque, the motor torque and the CVT speed ratio determined by the above procedure constitute the inputs to the hybrid system, which are the target values of the system at steady state. With these inputs, the actual values of vehicle velocity, engine and motor torque and CVT ratio are obtained by solving the following equations simultaneously.

$$\begin{aligned}(M_{veh}+\Delta M)\frac{dV_{veh}}{dt}&=\frac{\eta_t i_f i}{r_{tire}}(\tau_e+\tau_m)\\&\quad-2V_{veh}\frac{I_e i_f^2 i}{r_{tire}^2}\frac{di}{dt}-R_a-R_r\end{aligned} \quad (11)$$

$$\frac{d\tau_e}{dt}=\frac{1}{t_{eng}}(\tau_{e,target}-\tau_e) \quad (12)$$

$$\frac{di}{dt}=\frac{1}{t_{cvt}}(i_{target}-i) \quad (13)$$

where η_t is the transmission efficiency including the drive line, t_{eng} is the time constant of engine torque response and t_{cvt} is the time constant of CVT speed ratio response.

In the above equations, Eq. (11) denotes the vehicle dynamic model when subjected to the engine and motor power input. The first term on the right side of Eq. (11) is the traction force originated from the engine torque and motor torque. The second term arises from the change in rotational inertia of a vehicle resulted from continuous shifting of CVT. This term occurs only in the vehicle adopting CVT and it occurs as a shifting shock when a gear shift is made in the vehicle adopting the conventional step transmission. The third and fourth terms represent air resistance and rolling resistance of a vehicle, respectively. Equations (12) and (13) denote the dynamic model of the engine and the CVT speed ratio response respectively, both of which are assumed as the first order systems (T. C. Kim and H. S. Kim, 1998). In the simulation, the motor torque response is assumed to be instantaneous.

Solving the above dynamic equations simultaneously, the dynamic state variables such as the torques of engine and motor, the speed of engine and motor and the speed ratio of CVT are obtained. Then, the fuel consumption of the HEV can be calculated using the specific fuel consumption map of the engine, and the electric energy consumed can be calculated using the motor efficiency map.

5. Simulation Results

In hybrid vehicle simulations, a rule based algorithm is combined with the minimal fuel consumption algorithm proposed in the previous section. The rule based algorithm adopted is the one that the ZEV mode is implemented when the vehicle velocity is less than approximately 30 km/h and the engine mode is implemented when the vehicle velocity is in the range of approximately 30 km/h to 55 km/h. Consequently, the operating points obtained in the previous section is applied when the vehicle speed is over approximately 55 km/h. When a transition velocity of the ZEV mode is chosen, the transition velocity of the engine mode to the hybrid mode is determined so that the final value of SOC is restored to the initial value within small deviation. By introducing the rule based algorithm, it is expected that ZEV mode is assured at low vehicle speeds and the power density of discharge is moderate, otherwise the life cycle of the battery pack falls quickly. Also it is expected that the final SOC is maintained almost the same as the initial value. The rule based algorithm offers these properties, which are necessary in operating HEV and evaluating the fuel economy of HEV but are not included in the minimal fuel consumption algorithm.

Figure 8 is the simulation result of HEV for ECE (Economic Commission for Europe) driving cycle (Bosch, 1993). It is seen in the simulation result that the actual vehicle velocity follows

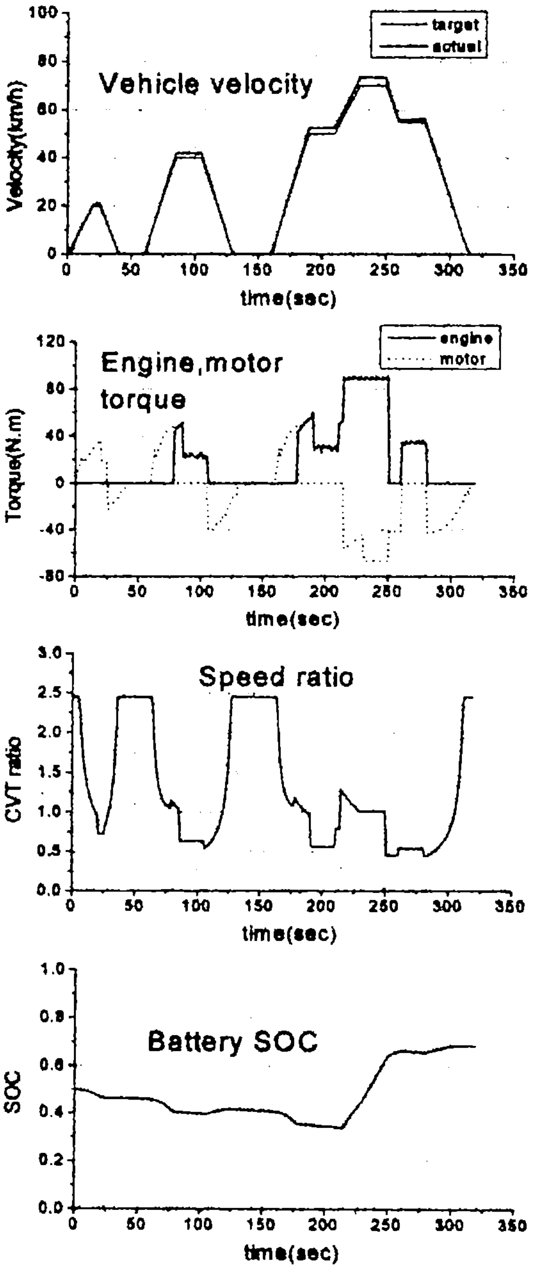


Fig. 8 Simulation results for ECE driving cycle

the target value closely, implying that the simulation procedure is correct. It is observed that the motor torque is negative in the period of deceleration, meaning regeneration of braking energy. Also, the electric motor acts as a generator when load levelling is carried out, which happens in the velocity range above the engine mode. The response of CVT speed ratio shows smooth changes during the total driving cycle. This phenomenon can be explained by the fact that the engine mode implemented in the vehicle control algorithm takes a role of smoothing engine torque change in the mode transition. It is seen that the SOC decreases during the motor driving condition and increases during the motor generating condition and regeneration.

In order to check improvement of fuel economy by hybridization, simulations are carried out for a conventional vehicle and 3 variations of HEV. Figure 9 shows the fuel economy obtained by the simulation. HEV A is the case that only power assist of the electric motor is applied. HEV B is the case that the regeneration of the braking energy is fully utilized in addition to the power assist of the electric motor. HEV C is the case that engine idling is eliminated in HEV B. In simulations, vehicle specifications and the performance of an engine and an electric motor are assumed identical in each case. LA-4 driving cycle is used for investigating the fuel economy and the final SOC is maintained the same as the initial SOC so that the pure consumption of fossil fuel is accounted for the travelled distance of HEV. This condition can be met by changing the transition velocities of the ZEV mode to the engine mode and the engine mode to the hybrid mode with trial and error method.

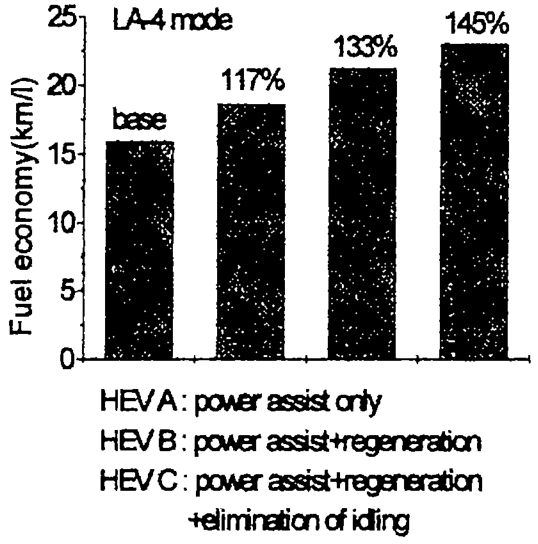


Fig. 9 Comparison of fuel economy

The fuel economy of a conventional vehicle obtained by the simulation is 15.9 km/l which is plausible value for a sub-compact car with CVT. When only power assist of the electric motor is applied, it is shown that fuel economy improvement of 17% compared to that of the conventional vehicle is obtained. This portion of improvement may be contributed by the motor power assist according to HEV control algorithm. HEV with power assist plus regeneration, that is, HEV B shows fuel economy of 21.2 km/l, which is improvement of 33% compared to the conventional vehicle. This improvement by regeneration may not be fully obtainable in a real situation unless the braking system of HEV is modified to fully utilize the braking energy. HEV with regeneration and elimination of idling, HEV C, shows the fuel economy of 23 km/l, which is 45% improved value compared to the conventional vehicle. The elimination of engine idling can be achieved by adopting 2 shaft type hybrid system. But it should be carefully installed in a real case because on-off operation of the engine in driving situation may result in a serious NVH (noise, vibration and harshness) problem.

Even though the hybrid system shows a maximum 45% improvement of fuel economy over conventional vehicle, it is far behind the target value set in PNGV (Partnership for a New Generation of Vehicle) program (T. C. Moore, 1995), 80 miles per gallon, that is approximately 34km/l. To get that goal, further modifications are required such as improvements of the engine efficiency, the motor efficiency etc., and reduction of driving resistance, mainly focused on reducing vehicle weight.

Table 2 shows 2 cases of modifications proposed in this work to obtain the target value of

Table 2 Modification of system parameters and fuel economy

		Original vehicle	Modification A	Modification B
Vehicle weight		1400kg	1050kg	1300kg
Efficiency	Engine	Engine map (Figure 4)	12% improved (overall)	25% improved (overall)
	Motor	Efficiency map (Figure 5)	7% improved (overall)	7% improved (overall)
	Battery (charge/discharge)	0.75/0.95	0.85/0.95	0.85/0.95
	Driveline	0.9	0.95	0.95
Fuel economy		23.0 km/l	33.1 km/l	34.2 km/l

fuel economy. They are simply 2 examples of numerous possible modifications. In both cases, the efficiencies of motor, battery and driveline are assumed to be improved 5~10% commonly, which may not be easy but still possible with current technology.

In modification A, it is assumed that vehicle weight is reduced by 350 kg and the specific fuel consumption of the engine is improved by 12% in overall. This corresponds to the case that the vehicle size is reduced considerably and the efficiency of the current engine is improved moderately. The fuel economy obtained is 33.1 km/l, which is close to the target value. In modification B, the specific fuel consumption is assumed to be improved by 25% in overall and vehicle weight reduction is made by 100 kg. This case corresponds to applying a small sized diesel engine rather than using a current gasoline engine and maintaining the same vehicle size with the moderate effort in weight reduction. The fuel economy obtained in this case is reaching at PNGV target fuel economy.

6. Conclusions

In this study, the fuel economy of a parallel hybrid electric vehicle is evaluated by simulations. The 2 shaft parallel type HEV is chosen for simulation study. A HEV control algorithm is proposed which minimizes the operational cost of HEV. The simulation program for HEV is developed based on the dynamic models of HEV. It is found from the simulation that HEV with the suggested algorithm shows maximum 45% improvement of the fuel economy compared to the conventional vehicle. Fuel economy improvement of 17% is attributed to the motor power assist according to HEV control algorithm and the rest of it results from the regeneration of braking energy and elimination of the engine idling. In addition, further improvements of fuel economy are investigated by changing vehicle specifications. The target fuel economy of PNGV program can be achieved when considerable weight reduction is made or the engine with the higher efficiency such as a diesel engine is applied to HEV.

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