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Journal of Power Sources 105 (2002) 58–65

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Fuel economy and life-cycle cost analysis of a fuel cell hybrid vehicle

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Received 2 July 2001; accepted 28 September 2001

Abstract

The most promising vehicle engine that can overcome the problem of present internal combustion is the hydrogen fuel cell. Fuel cells are devices that change chemical energy directly into electrical energy without combustion. Pure fuel cell vehicles and fuel cell hybrid vehicles (i.e. a combination of fuel cell and battery) as energy sources are studied. Considerations of efficiency, fuel economy, and the characteristics of power output in hybridization of fuel cell vehicle are necessary. In the case of Federal Urban Driving Schedule (FUDS) cycle simulation, hybridization is more efficient than a pure fuel cell vehicle. The reason is that it is possible to capture regenerative braking energy and to operate the fuel cell system within a more efficient range by using battery.

Life-cycle cost is largely affected by the fuel cell size, fuel cell cost, and hydrogen cost. When the cost of fuel cell is high, hybridization is profitable, but when the cost of fuel cell is less than 400 US$/kW, a pure fuel cell vehicle is more profitable.

Keywords: Fuel cell hybrid vehicle; Life-cycle cost; Fuel economy; Battery

1. Introduction

Gasoline and diesel fuels are used in present vehicle engines. These engines are operated by combusted working fluid. The internal combustion engine has been used for more than 100 years for vehicle power. The environmental problem caused by vehicles and the limitation of fossil fuel are demanding new engines with new fuels. The most promising vehicle engine that can overcome the problems of present internal combustion is the hydrogen fuel cell.

Fuel cells are devices that convert chemical energy directly into electrical energy without combustion. Using a fuel cell as an automotive engine, there is no Carnot limitation and the efficiency increases to about twice that of an internal combustion. Because fuel cells have no moving parts, fuel cells are very quiet and reliable.

Hydrogen, methanol, natural gas and gasoline can be used as fuels in fuel cells, but the best option is hydrogen in a polymer electrolyte membrane fuel cell (PEMFC). Because such fuels, except hydrogen, contain carbon, it is impossible to avoid exhaust gas of carbon dioxide. When hydrogen is used, the exhaust is pure water only and there is no need for a fuel processor.

Pure fuel cell vehicles and fuel cell hybrid vehicles that consist of a fuel cell and battery are being studied. Considerations of efficiency, fuel economy and characteristics of power output in hybridization of fuel cell vehicles are necessary. Hybridization of a fuel cell enables the size of fuel cell to be reduced by using a battery, when power demand is high, such with higher loads or acceleration, and allows the fuel cell system to be operated more efficiently. In addition, the initial cost of vehicle manufacturing is less because the cost of the expensive fuel cell can be reduced. When the power demand is low, the fuel cell provides the required power. The use of a battery allows fast start-up of the fuel cell and allows capture of regeneration energy. The disadvantages of hybridization are complexity of the vehicle system, weight increase, complexity of the control system, and extra battery cost.

In this study, the vehicle, fuel cells, battery and motor model and the control strategy are established and computer simulation is developed to the examine overall vehicle design. The vehicle cost and the life-cycle cost of the fuel cell hybrid vehicle are analyzed by using the results of the simulation.

2. Configuration of fuel cell hybrid vehicle

Fig. 1 shows the configuration of the fuel cell hybrid vehicle which consists of a fuel cell system, an assistant

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0378-7753/02/$ – see front matter
PII: S0378-7753(01)00965-X

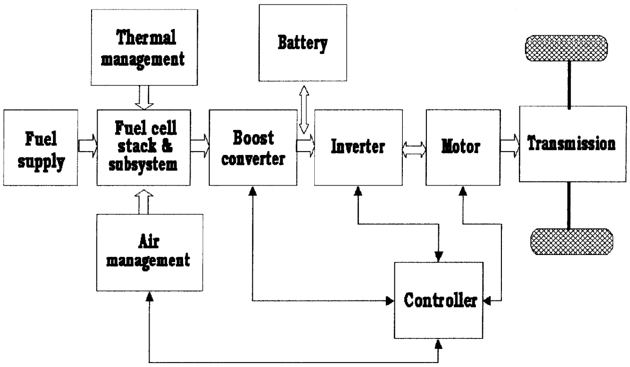

Fig. 1. Fuel cell hybrid vehicle system.

power battery, and a driving system which includes a motor and a control system. The fuel cell system comprises a fuel supply system, an air supply system, a humidification system to operate the fuel cell more efficiently, and a thermal management system to control the operation temperature and to use the heat of the fuel cell.

The voltage of the fuel cell is usually lower than that of the vehicle. Increase of the fuel cell voltage can be made possible by increasing the stack number, but a dc to dc converter or a dc to ac inverter is more general. The direct vehicle wheel-drive system consists of a motor and a speed reducing transmission. A controller regulates the fuel cell operation conditions, such as temperature, pressure, humidification, battery state-of charge (SoC), charge-discharge current, boost converter and hybrid power output.

2.1. Vehicle model

The forces of vehicle driving are rolling resistance, air drag, accelerating force and climbing force. The force needed in vehicle driving is the sum of these forces and the power needed in vehicle driving can be written as

$$P_{\mathrm{d}} = (ma + C_{\mathrm{R}}mg + mg\sin\theta + \tfrac{1}{2}\rho_{\mathrm{a}}C_{\mathrm{D}}A_{\mathrm{F}}v^2)v \qquad (1)$$

where P_{d} is the power needed by vehicle, m the total mass of vehicle, a the acceleration of vehicle, C_{R} the coefficient of rolling resistance, g the gravity constant, θ the angle of gradient, ρ_{a} the density of air, C_{D} the drag coefficient, A_{F} the formal area of vehicle.

On vehicle driving, there are power losses in many vehicle components. The required power of the fuel cell and battery includes these component losses as well as the auxiliary power for cooling, air supply, fuel supply, head lights etc. The main losses in a fuel cell hybrid vehicle are largely motor and controller losses, transmission losses, breaking losses, and dc–dc boost converter losses. The vehicle parameters [1–3] used in this study are shown in Table 1.

Table 1
Vehicle parameters

Glide mass (kg)	600
Drag coefficient	0.2
Frontal area (m^2)	2.0
Vehicle wheel base (m)	2.755
Cargo/passenger weight (kg)	136

Hydrogen, methanol and gasoline can be used as fuels in fuel cells. Gasoline and methanol can be supplied by the present infrastructure for vehicles. With hydrogen, however, a fuel reformer is needed to produce hydrogen from gasoline or methanol. A fuel reformer increase both the complexity and the cost of the vehicle. Start-up to normal operation takes between a few minutes and 30 minutes. According to many studies, because of the need for a fuel processor, the estimated cost of fuel cell vehicle using gasoline or methanol is much higher than that of a vehicle fueled by hydrogen.

When hydrogen is used as a fuel, a fuel processor is not necessary, the exhaust gas is pure water, start-up time and response to load change are fast, and efficiency is increased. on the other hand, a much higher cost for infrastructure is needed.

Methods of hydrogen storage on the vehicle are liquid hydrogen, compressed hydrogen, metal hydride, and hydrogen absorbed in carbon nanotubes. The energy density of liquid hydrogen is high. To store hydrogen in a liquid state, it is necessary to maintain it at −253 °C at ambient pressure. Thus, a highly insulated liquid hydrogen tank is needed. A quarter of the chemical energy of hydrogen itself is consumed in the liquefaction process. Metal hydride is safest, but it is very heavy and much time is consumed to store hydrogen. Carbon nonotube are at the developmental stage. In the case of compressed hydrogen, the stored energy density is low and energy is consumed in compression. Table 2 shows the compressed hydrogen storage characteristics used in this study [2].

2.2. Fuel cell model

Fuel cells are devices that convert chemical energy directly into electrical energy. In general, the characteristics of a fuel cell are represented by current–potential curves. The characteristics of a fuel cell differ according to the operating conditions. A fuel cell system consists of a fuel supply system, an air supply system, a water management system, and a fuel cooling system. Part of the fuel cell power output is used to drive auxiliary systems. The polarization curve model uses the current–potential curve including auxiliary driving power.

The power–efficiency curve is used in modeling fuel cell systems. The power–efficiency model does not consider the characteristics of current–potential and the auxiliary system in detail, but uses the relationship between fuel cell power

Table 2
Compressed hydrogen tank (5000 psig)

Specific energy (HHV) (Wh/kg)	2630, 6.7% H_2
Energy density (HHV) (Wh/l)	780, 20 kg H_2 (m^3)
Fuel tank mass (kg)	50
Stored hydrogen mass (kg)	3.35

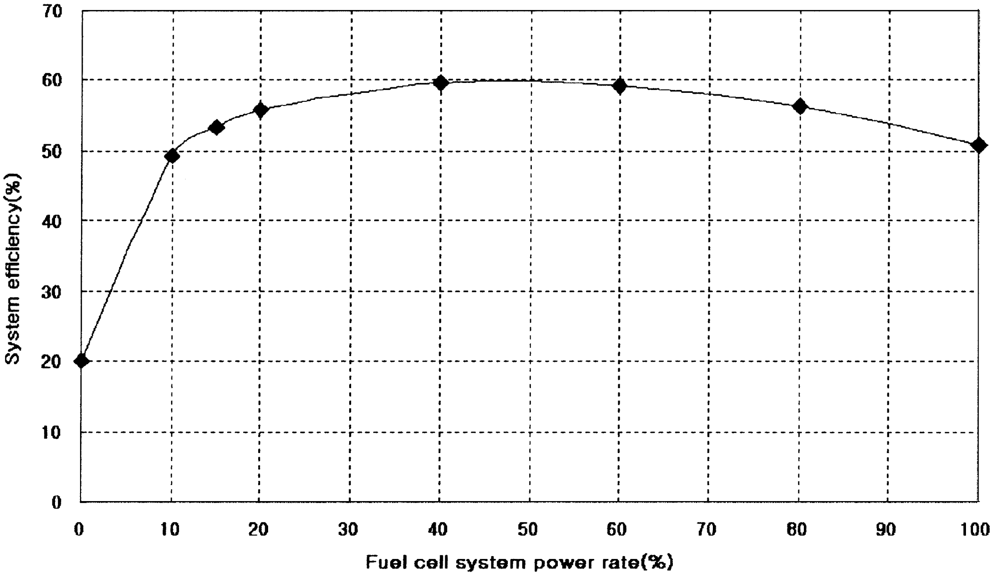

Fig. 2. Fuel cell system power rate versus efficiency.

Table 3
Fuel cell system

Fuel cell system energy efficiency at peak (%)	60
Power density (W/l)	250
Specific power (W/kg)	250
Durability (h)	3000

and efficiency. The relation between fuel cell system power and efficiency has been the subject of many studies. At low load, the fuel cell system efficiency is very low because of the operation of the air compressor or blower to supply air, and operation of the cooling system and the humidifying system. The fuel system efficiency is high at medium load. At high load, the efficiency is again low because fuel cell efficiency decreases as the fuel cell current increases. The power–efficiency model is shown in Fig. 2. This study uses this power–efficiency model [2,4]. The present technology of fuel cells is summarized in Table 3.

2.3. Battery model

The role of the battery in a fuel cell hybrid vehicle can be summarized as follows:

1. energy source of vehicle electrical devices;
2. regenerative braking energy storage;
3. electrical energy storage that is generated from the fuel cell at low load;
4. fuel cell power assist at higher load;
5. main energy supplier when fuel cell system operates at low load.

Various types of battery are under development. The factors in selecting a battery for vehicles are specific power, specific energy, life-cycle and cost. Table 4 shows the characteristics of various types of battery. This paper uses an advanced lead-acid battery for the vehicle simulation model. Details of this battery [3,5,6] are given in Table 5.

Peukert expressed the relation between the rate of battery discharge and capacity as follows:

$$I^n \times t = \text{constant} \qquad (2)$$

where I is the current, t the time, and n the constant.

This equation can be rewritten as

$$C_i = \text{Coeff} \times I^{\text{exp}} \qquad (3)$$

where C is the battery residual capacity, $\text{exp} = 1 - n$, Coeff the constant coefficient.

This study used a Hawker Genesis lead-acid battery for which the Coeff is 16.28 and exp is -0.225 [7].

Table 4
Rechargeable battery option

Technology	Specific energy (Wh/kg)	Energy density (Wh/l)	Specific power (W/kg)	Power density (W/l)	Initial cost (US$/kW)	Life-cycle
Advanced lead-acid	35	71	412	955	180	500–1000
Nickel–metal hydride	80	200	220	600	450	1000
Lithium–polymer	155	220	315	445	400	1000
Sodium–nickel chloride	90	150	100	200		
Nickel–cadmium	50	150				

Table 5
Parameters of advanced lead-acid battery

Number of cell per module	6
Voltage per module (V)	12
Capacity (*C*/20) (Ah)	12
Mass of single module (kg)	4.785

When a fuel cell hybrid vehicle drives on the road, the battery charge-discharge current changes. If the current at unit time, is known, the variation in battery SoC, can be determined, i.e.

$$\Delta \mathrm{SoC} = -\frac{\Delta C_i}{C_i} = -\frac{I_i \Delta t}{3600 C_i} = -\frac{I_i \Delta t}{3600 \times \mathrm{Coeff} \times I^{\mathrm{exp}}} \tag{4}$$

At time t, the SoC is

$$\mathrm{SoC} = \mathrm{SoC}_{\mathrm{inial}} + \int \Delta \mathrm{SoC}\, \mathrm{d}t \tag{5}$$

The efficiency of charge-discharge is associated with the loss due to the battery internal resistance, and actual measured data are used.

2.4. Hybrid control methods

Methods of fuel cell hybrid control are based on battery SoC. The vehicle simulation mode is Federal Urban Driving Schedule (FUDS). When the required vehicle power is lower than 20% of the fuel cell maximum power, the battery supplies all the driving power of the vehicle and the fuel cell shuts off. When the required vehicle power is greater than the fuel cell maximum power, the battery supplies surplus power.

The battery is charged between 20 and 80% of the fuel cell maximum power. When the SoC is below 0.4, the battery is charged above 0.8, battery charging is stopped.

The efficiency of the motor and the motor controller is affected by speed and torque. The efficiency is assumed to be 0.78 in this paper. When regenerative energy is recovered at deceleration and brake operation, the efficiency is assumed to be 0.5.

3. Simulation results

For a fuel cell system of 30 kW and a battery power of 45 kW, the vehicle power requirement, battery power and fuel cell power output are shown for a FUDS cycle in Fig. 3. The fuel cell operates only when the required vehicle power is 6–30 kW. The battery operates only when the required vehicle power is lower than 6 kW. Both the fuel cell and the battery operate when the required vehicle power is more than 30 kW. When the vehicle is decelerating and braking, regenerative energy is recovered and stored.

The fuel economy of a fuel cell hybrid vehicle changes with operation condition, control method, etc.The hybridization ratio defined as

$$\text{hybrid ratio} = \frac{\text{maximum vehicle power} - \text{maximum fuel cell power}}{\text{maximum vehicle power}} \tag{6}$$

The simulation results for the fuel of economy of fuel cell hybrid vehicles are shown Fig. 4. As battery power increases to 25 kW, fuel economy is increased. This is possible because regenerative braking energy can be recovered and stored in the battery. At low loads, it is possible that the fuel cell operates more efficiently by operation the battery when

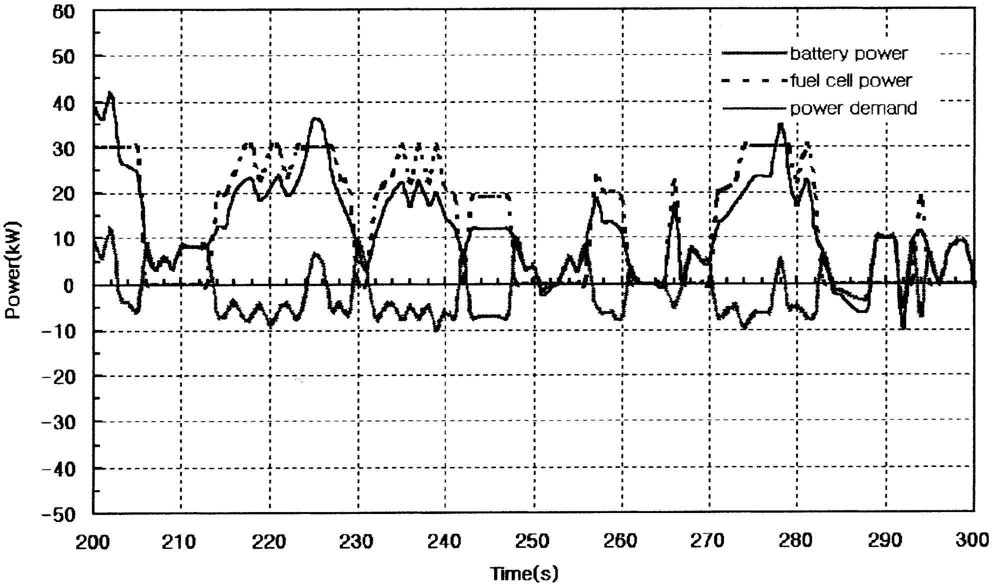

Fig. 3. Power demand, battery power and fuel cell power as a function of time for FUDS cycle.

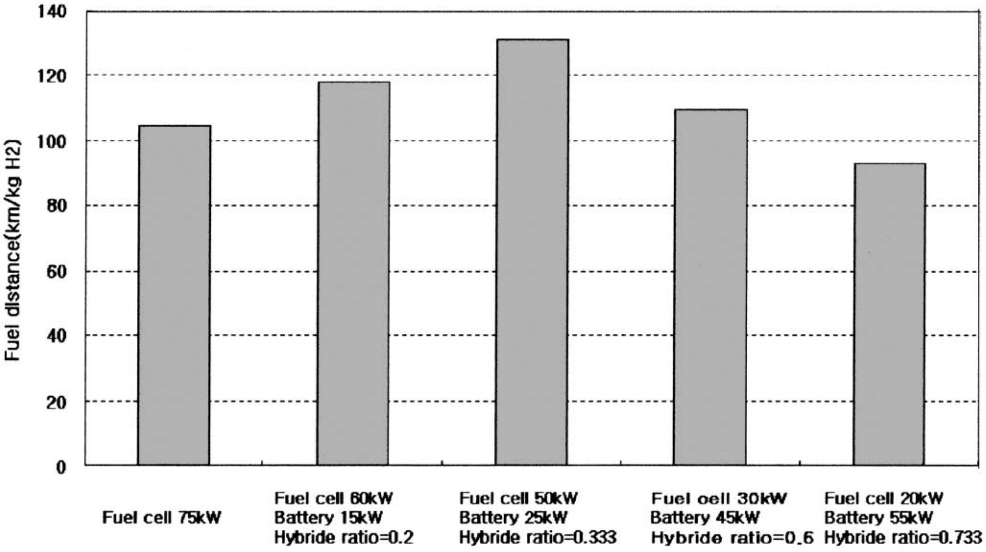

Fig. 4. Comparison of fuel economy for fuel cell and fuel cell hybrid vehicles.

the fuel cell efficiency is low. The reasons that fuel economy is lower when the hybridization ratio is 0.2 rather than 0.33 are (i) sometimes the fuel cell cannot be operated efficiently because the battery is so small and (ii) the battery charge-discharge efficiency is low because the battery current is large. When the hybridization ratio is more than 0.33, the fuel economy is decreased. The reason for this is that the time of charge-discharge and the current from the battery are increased because the battery is the main vehicle power source. When the battery power is 55 kW and the fuel cell power is 20 kW, the efficiency is lower than that for a pure fuel cell vehicle.

4. Vehicle and life-cycle costs

The life-cycle cost is the sum of the initial vehicle cost and the maintenance cost. The initial vehicle cost is affected by the fuel cell cost and battery cost. Because the fuel cell cost is presently more than 1200 US$/kW, hybridization of the fuel cell vehicle can reduce initial vehicle cost.

The maintenance cost is affected greatly by the hydrogen fuel cost. If fuel economy is increased by hybridization of the fuel cell vehicle, the life-cycle cost is decreased. Because the initial vehicle cost is settled at the time of manufacturing, development of fuel cell technology and performance cannot affect life-cycle cost. Because the hydrogen fuel cost can be decreased by increase of demand and development of manufacturing technology, how ever, the life-cycle cost can be decreased.

4.1. Fuel cell cost

The PEM fuel cell cost is 1000–2000 US$/kW at present. Table 6 summarizes the material cost for a fuel cell stack today. The fuel cell cost will be decreased through reduction of platinum loading, improvement of stack performance, and mass production. It is forecast that the fuel cell cost will be decreased to 200 US$/kW in 1 or 2 years. The fuel cell cost must be lower than 50 US$/GJ in order to compete with internal combustion engines [8].

4.2. Initial cost of fuel cell vehicle

The assumed price of the fuel cell vehicle component is given in Table 7. The vehicle is calculated based on these data. Fig. 5 shows the initial cost of fuel cell hybrid vehicle. If the fuel cell cost is high, hybridization can reduce the initial cost of the vehicle. If the fuel cell cost is lower than 50 US$/kW, how ever, hybridization will increase the initial

Table 6
Material costs for a present-day fuel cell stack

	Material mass (kg/kW)	Material cost (US$/kW)
Membrane	0.025	120
Electrode	0.082	31.16
Catalyst	0.016	243.2
Bipolar plate	3.3	825
End plate	0.12	0.24
Plastic frame	0.105	0.105
Total	3.684	1219.705

Table 7
Initial cost of fuel cell vehicle components

Car body (US$)	10000
Battery (US$/kWh)	50
Motor and controller (US$)	5000
Fuel, air supply and water management (US$)	4000

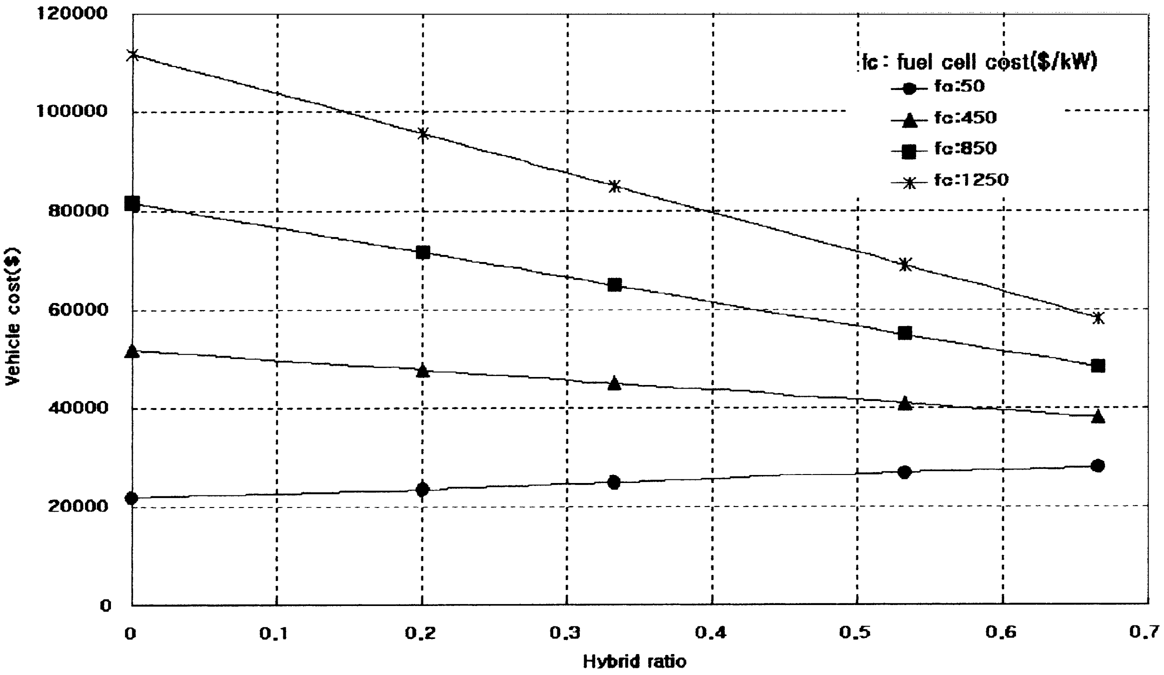

Fig. 5. Fuel cell vehicle cost as a function of hybridization ratio.

cost of the vehicle because battery cost increases and the vehicle control system is complex.

4.3. Hydrogen fuel cost

Hydrogen production methods are natural gas steam reforming, electrolysis of water, and by product of the chemical industry. An infrastructure for supplying hydrogen for vehicles is not in place. To use hydrogen as a fuel in fuel cell vehicles, an infrastructure for production and supply must be established. The cost of hydrogen is very high. If many fuel cell vehicles are produced, however, the hydrogen cost will be decreased through the mass production of hydrogen. If hydrogen fueled vehicles become more than

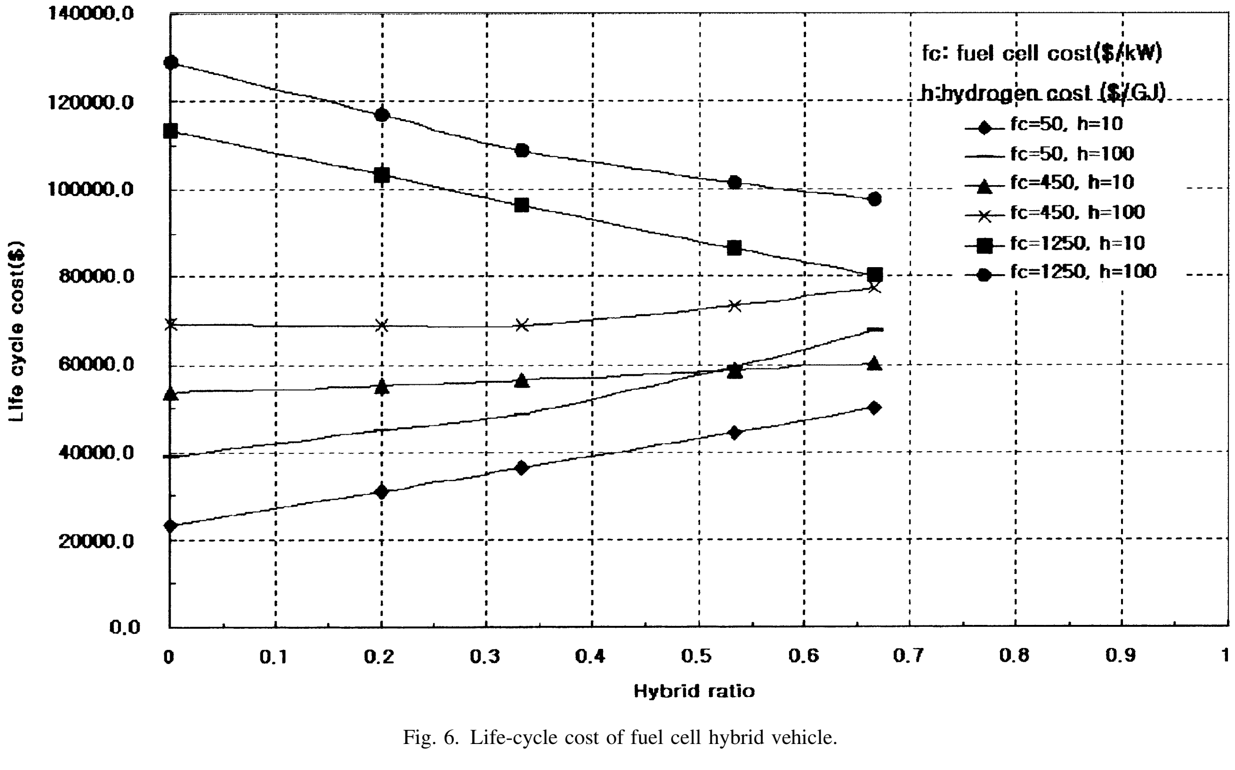

Fig. 6. Life-cycle cost of fuel cell hybrid vehicle.

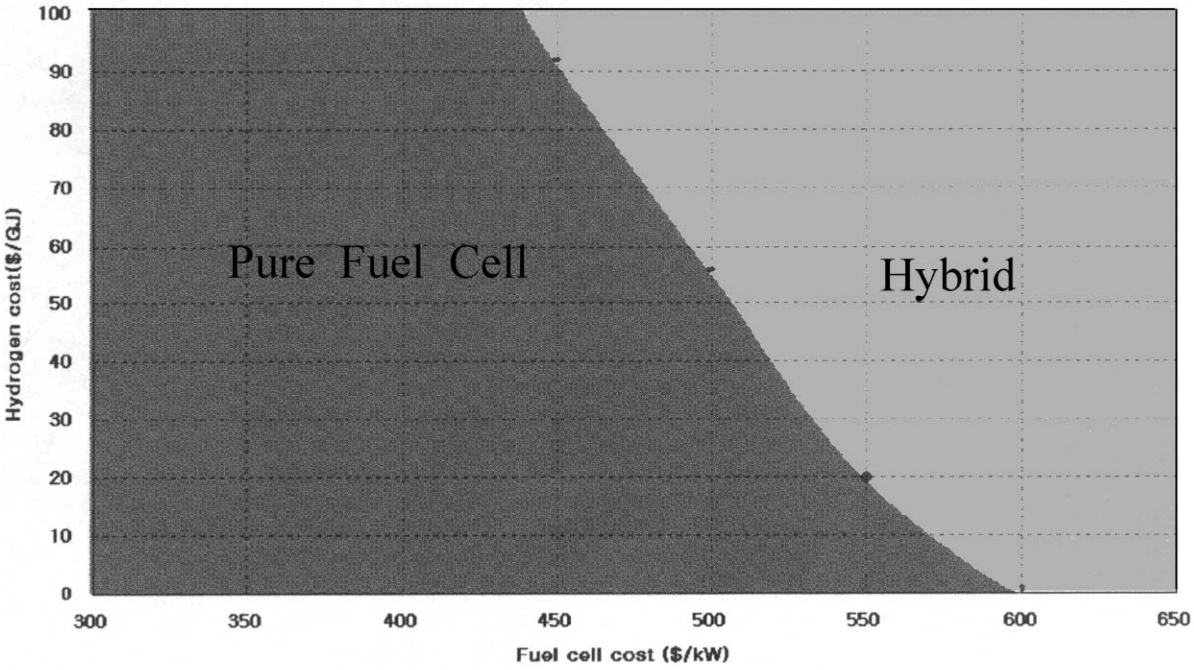

Fig. 7. Base line for fuel cell vehicle hybridization

50,000, the estimated cost of hydrogen is 20–30 US$/GJ in California [9,10].

4.4. Life-cycle cost

Life-cycle cost includes vehicle cost, used hydrogen fuel cost, and the battery cost. Some assumptions must be made in the calculation of life-cycle cost. The number of battery charged-discharged is 300 in a year, and battery life is 3.3 years. Vehicle life is 10 years. The vehicle travels 15,000 km in a year. The hydrogen consumed is calculated based on the above simulation result.

Fig. 6 shows the life-cycle cost based on fuel cell and hydrogen costs. If the fuel cell cost is as high as 1250 US$/kW, hybridization can reduce the life-cycle cost. If the fuel cell cost is 50 US$/kW, then hybridization increases the life-cycle cost because it increases the initial vehicle cost.

Hybridization of a fuel cell vehicle must to be considered in both economical and technical terms. Fig. 7 presents a standard of judgment for whether hybridization is necessary or not with variation in fuel cell cost and hydrogen cost, based on life-cycle costs. If the fuel cell cost is high, hybridization is profitable because the initial vehicle cost is decreased. If there are more than 50,000 hydrogen vehicles, the estimated hydrogen cost is about 30 US$/GJ in California. If the fuel cell cost is about 550 US$/kW, at the early stage of commercialization, hybridization is economical. If the fuel cell cost is lower than 400 US$/kW, a pure fuel cell vehicle is profitable because the initial fuel cell cost has a stronger influence on the life-cycle cost than hydrogen cost. If fuel cell vehicles are produced in large numbers, the estimated cost of the fuel cell system is about 200–400 US$/kW. If this estimate is realized, hybridization of the fuel cell vehicle is not necessary on economic grounds.

5. Conclusions

The fuel economy and life-cycle costs for a pure fuel cell vehicle and a fuel cell hybrid vehicle have been compared.

In the case of FUDS cycle simulation, hybridization is more efficient than a pure fuel cell vehicle. This is because it is possible to capture regenerative braking energy and to operate the fuel cell system within a more efficient range when using a battery. Fuel economy is decreased, however, when battery power is small because of charge-discharge losses. Fuel economy is affected by driving condition, control method, etc.

Fuel cell vehicle cost is reduced by hybridization when the fuel cell cost is high. Life-cycle cost is largely affected by the fuel cell size, fuel cell cost, and hydrogen cost. When the cost of the fuel cell is high, hybridization is profitable, but when the cost of the fuel cell is smaller than 400 US$/kW, a pure fuel cell vehicle is more profitable.

Many challenges have still to be met before a fuel cell power system can achieve the cost, performance and reliability in order to guarantee successful commercialization of fuel cell vehicles. Fuel cell research will provide improvements in both performance and cost. Clearly, fuel cells can be adopted widely as cleaner and more efficient automotive engines.

Acknowledgements

This work was supported by the Brain Korea 21 Project in 2000.

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