한국수소 및 신에너지학회 논문집(2002.12), 제13권 제4호
Trans. of the Korea Hydrogen and New Energy Society (2002.12), Vol. 13, No. 4, pp. 287~296

연료전지 하이브리드 자동차의 연료 경제성 및 Life cycle 비용 분석

정귀성*, 오병수**
*전남대학교 대학원, **전남대학교 기계공학과

Fuel economy and Life Cycle Cost Analysis of Fuel Cell Hybrid Vehicle

Kwi Seong Jeong*, Byeong Soo Oh**
**Grad. School of Chonnam National University,*
***Department of Mechanical Engineering, Chonnam National University,*
300 Youngbong-Dong, Pukgu, Kwangju 500-757, Korea

ABSTRACT

현재 자동차의 문제점을 해결할 수 있는 가장 확실한 엔진은 수소를 이용한 연료전지라고 판단된다. 연료전지는 화학적 에너지를 전기적 에너지로 직접 변환하는 장치이다. 순수한 연료전지 차량과 연료전지 하이브리드 차량을 비교 분석하였다. 연료전지 하이브리드 차량에서 고려하여야할 점은 효율, 연료경제성, 출력 특성 등이 있다. FUDS 싸이클 시뮬레이션 비교를 하면 하이브리드화가 순수 연료전지 차량 보다 효율이 높다. 이는 회생 제동 에너지를 이용할 수 있으며 battery를 이용하여 연료전지를 효율적인 영역에서 작동하게 할 수 있기 때문이다. Life cycle 비용은 연료전지의 크기, 연료전지의 가격, 수소의 가격 등에 지배적인 영향을 받는다. 연료전지의 가격이 고가이면 하이브리드화가 유리하나, 연료전지의 가격이 400$/kW 이하가 되면 순수한 연료전지 자동차가 비용면에서 유리하다.

주요기술용어 : Fuel cell hybrid vehicle(연료전지 하이브리드 자동차), Life cycle cost, Fuel economy(연료경제성), Battery(전지)

1. Introduction

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

Fuel cells are devices that change chemical energy directly into electrical energy without combustion. Using fuel cell as automotive engine, there is not Carnot limitation and the efficiency will increase about two times than that of internal combustion. Because fuel cells have no moving part, fuel cells are very quiet and reliable.

Hydrogen, methanol, natural gas, gasoline can be fuels of fuel cells, but the last form of fuels must be hydrogen to be used in fuel cells especially in the PEMFC(Polymer Electrolyte Membrane Fuel Cell). Because such fuels except hydrogen have carbon, it is impossible to avoid exhaust gas of carbon dioxide. When hydrogen is used as fuel of fuel cells, the exhaust is pure water only and there is no need of fuel processor.

Pure fuel cell vehicle and fuel cell hybrid vehicle that is combined fuel cell and battery as energy sources are being studied. Considerations of efficiency, fuel economy, characteristics of power output in hybridization of fuel cell vehicle are necessary.

Hybridization of fuel cell enables to reduce the size of fuel cell by using battery when power demand is high such as higher load or acceleration and to operate fuel cell system more efficiently. It enables to reduce initial cost of vehicle manufacturing because the cost of expensive fuel cell can be reduced. When the power demand is low, fuel cell provides required power. The use of battery allows fast start-up of fuel cell and allows capture of regeneration energy. The disadvantages of hybridization are complexity of vehicle system, weight increase, complexity of control system and extra battery cost.

Vehicle, fuel cells, battery and motor model and control strategy are setup and computer simulation is developed to examine overall vehicle design. Vehicle cost and life cycle cost of fuel cell hybrid vehicle are analyzed by using the result of simulation.

2. Configuration of fuel cell hybrid vehicle

Fig. 1 shows the configuration of fuel cell hybrid vehicle consisted of fuel cell system, assistant power battery, driving system including motor and control system. Fuel cell system consists of fuel supply system, air supply system, humidification system to operate more efficiently and thermal management system to control operation temperature and to use heat of fuel cell.

The voltage of fuel cell is commonly lower than that of vehicle. To increase fuel cell voltage, it can be possible by increasing stack number, but DC to DC converter or DC to AC inverter is more general. Direct vehicle

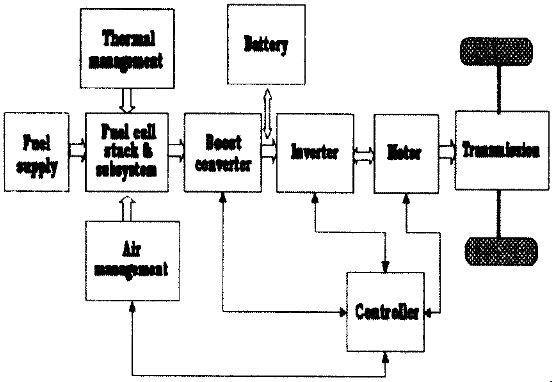

Fig. 1. Fuel cell hybrid vehicle system.

wheel drive system consists of motor and speed reducing transmission. Controller controls fuel cell operation condition such as temperature, pressure, humidification, battery state of charge, 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

$$P_d = (ma + C_R mg + mg \cdot \sin\theta + 1/2\rho_a C_D A_F \nu^2)\nu \qquad (1)$$

At real vehicle driving, there are power losses of many vehicle components. The required power of fuel cells and battery includes these component losses and auxiliary driving power such as cooling, air supply, fuel supply, head light and so on. The main losses of fuel cell hybrid vehicle are largely motor and controller loss, transmission loss, breaking loss and DC-DC boost converter loss. Table 1 shows vehicle parameter for this study$^{1\sim3)}$.

Table 1. Vehicle parameter

Glide mass	600kg
Drag coefficient	0.2
Frontal area	2.0㎡
Vehicle wheel base	2.755m
Cargo/passenger weight	136kg

Hydrogen, methanol and gasoline can be fuels of fuel cells. Gasoline can be supplied by current infrastructure for vehicle. Because methanol is liquid at environmental condition, the utilization of current infrastructure can be highly used. But because the last form of the fuels must be hydrogen to be used in the fuel cells especially in PEMFC, fuel reformer is needed to make hydrogen from gasoline or methanol. Fuel reformer increases vehicle complexity and the cost of the vehicle. It takes time between few minutes and thirty minutes from start to normal operation state. According to many studies, because of the fuel processor the estimated cost of fuel cell vehicle using gasoline or methanol as fuel is much higher than that of hydrogen fueled fuel cell vehicle.

When hydrogen is used as fuel of fuel cells, fuel processor is not necessary, exhaust gas is pure water, start-up time and response for load change are fast and efficiency is increased. But much higher cost for infrastructure is needed.

The methods of hydrogen storage for vehicle are liquid hydrogen, compressed hydrogen, metal hydride and hydrogen absorbed carbon nano-tube. Energy density of liquid hydrogen is high. But to store hydrogen as liquid state, it is necessary to maintain 253℃ at ambient pressure. So high insulation of liquid hydrogen tank is needed. A quarter of chemical energy of hydrogen itself is used to liquefy hydrogen. Metal hydride is safest. But it is very heavy and much time is consumed to store hydrogen. Carbon nano-tube is just developing, which might be used as hydrogen stroage. In the case of compressed hydrogen, stored energy density is low and energy is consumed to compress. Table 2 shows

Table 2. Compressed hydrogen tank(5000psig)

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

compressed hydrogen storage characteristics used in this paper[2].

2.2 Fuel cell model

Fuel cells are devices that change chemical energy directly into electrical energy. In general, the characteristics of fuel cell are represented by current-potential curve. The characteristics of fuel cell are different according to operating condition. Fuel cell system consists of fuel supply system, air supply system, water management system and cooling system. Part of fuel cell power output is used to drive auxiliary system. Polarization curve model uses current-potential curve including auxiliary driving power.

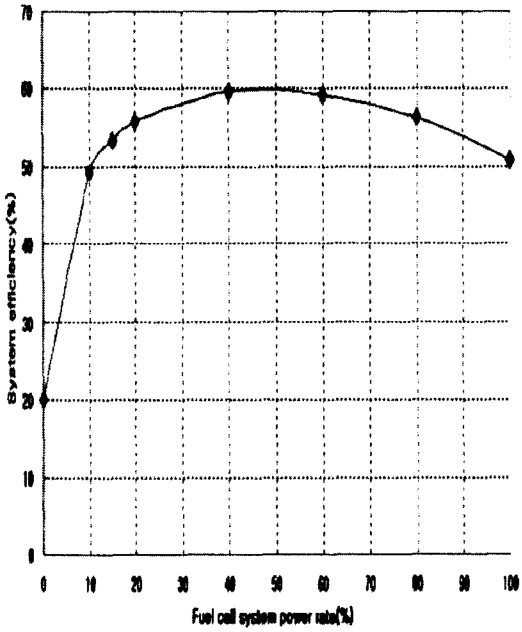

Fig. 2. Fuel cell system power rate vs. efficiency.

Power-efficiency curve is used in modeling fuel cell system. Power-efficiency model not considers the characteristics of current-potential and auxiliary system in detail, but uses relation between fuel cell power and efficiency as fuel cell model. The relation between fuel cell system power and efficiency has been studied and written in many papers by experiment and theory. At lower load, fuel cell system efficiency is very low because of operation of air compressor or blower to supply air, and operation of cooling system and humidifying system. Fuel system efficiency is high at medium load. At high load, fuel cell system efficiency is lower because fuel cell efficiency decreases as fuel cell current increases. Fig. 2 shows the power-efficiency model. This paper used this power-efficiency model[2,4]. Table 3 summarizes current technology of fuel cell.

2.3 Battery model

Battery can emit electrical from stored chemical energy and can store chemical energy by converting electrical energy

Table 3. Fuel cell system

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

Table 4. Rechargeable battery option

Technology	Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Power density (W/L)	Initial cost ($/kW)	Cycle life
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				

reversely. The role of battery in 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 fuel cell at lower load.
4) Fuel cell power assist at higher load.
5) Main energy supplier when fuel cell system operates at lower load.

Various types of battery are developing. The consideration factors to select battery for vehicle are specific power, specific energy, cycle life and cost. Table 4 shows characteristics of various types of battery. This paper uses advanced lead-acid battery for vehicle simulation model. Table 5 summarizes this battery[3,5,6].

Peukert expressed the relation between battery discharge rate and capacity as follow,

$$I^n \times t = const \tag{2}$$

where I : current, t : time, n : constant. This equation can be rewritten as follow,

$$C_i = Coeff \times I^{\exp} \tag{3}$$

where C_i: battery residual capacity, exp= 1-n, *Coeff* : constant coefficient.

This paper used Hawker genesis lead acid batterys empirically derived data. *Coeff* is 16.28 and exp is 0.225[7].

When fuel cell hybrid vehicle drives on the road, the current of battery charge-discharge is changed. If we know the current of unit time, we can calculate the variation of battery *SOC*(State Of Charge).

Table 5. Parameters of advanced lead-acid battery

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

$$\begin{aligned}\triangle SOC &= -\frac{\triangle C_i}{C_i} = -\frac{I_i . \triangle t}{3600 C_i} \\ &= -\frac{I_i . \triangle t}{3600 \cdot Coeff \cdot I^{\exp}}\end{aligned} \tag{4}$$

At certain time t, *SOC* is as follow.

$$SOC = SOC_{inial} + \int_0^t \triangle SOC dt \tag{5}$$

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

2.4 Hybrid control methods

The methods of fuel cell hybrid control are on the basis of battery SOC. Vehicle simulation mode is FUDS. When required vehicle power is lower than 20% of fuel cell maximum power, battery supplies all the driving power of the vehicle and fuel cell shuts off. When required vehicle power is greater than fuel cell maximum power, battery supplies surplus power.

Battery is charged at the range between 20% and 80% of fuel cell maximum power. When SOC is below 0.4 battery is charged and above 0.8 battery charging is stopped.

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

3. Simulation result

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

The fuel economy of fuel cell hybrid

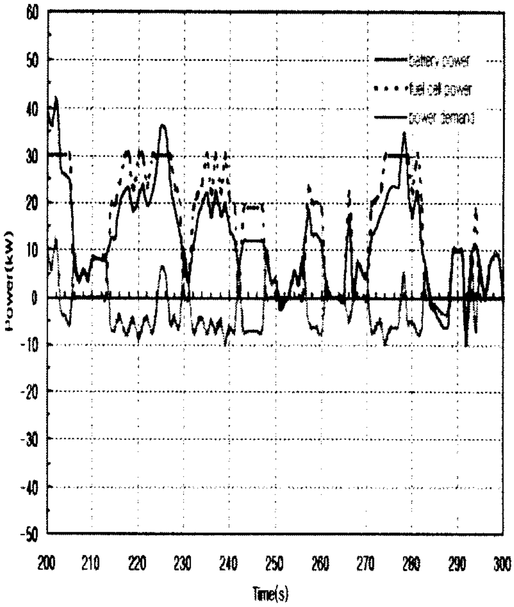

Fig. 3. Power demand, battery power and fuel cell power as a function of time for FUDS cycle.

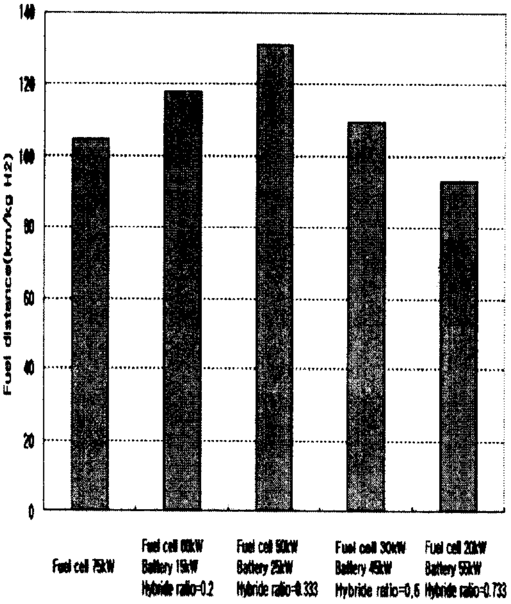

Fig. 4. Comparison of fuel economy for fuel cell and fuel cell hybrid vehicles.

vehicle changes by operation condition, control method and so on.

Hybridization ratio defined as

$$Hybridratio = \frac{P_{vehicle} - P_{fuel\ cell}}{P_{vehicle}}$$

$P_{vehicle}$: maximum vehicle power
$P_{fuel\ cell}$: maximum fuel clell power

Fig. 4 shows simulation result of fuel economy for fuel cell hybrid vehicles. As battery power increases to 25kW, fuel economy is increased. This is possible because regenerative braking energy can be recovered and stored to battery. At lower load, it is possible that fuel cell operates more efficiently by operating battery when fuel cell efficiency is low. The reasons that fuel economy is lower when hybridization ratio is 0.2 than 0.33 are i) sometimes fuel cell cant be operated efficiently because battery is so small, ii) battery charge-discharge efficiency is low because battery current is large. When hybridization ratio is more than 0.33, fuel economy is decreased. The reason of this is that the times of charge-discharge and the current of battery are increased because battery is main vehicle power source. When battery power is 55kW and fuel cell power is 20kW, the efficiency is lower than pure fuel cell vehicle.

Table 6. Material cost for a fuel cell stack today

Car body	$10,000
Battery	50$/kWh
Motor & controller	$5000
Fuel, air supply & water management	$4000

4. Vehicle costs and life cycle cost

Life cycle cost is sum of initial vehicle cost and maintenance cost. Initial vehicle cost is affected by fuel cell cost and battery cost. Because fuel cell cost is more than 1200$/kW today, hybridization of fuel cell vehicle can reduce initial vehicle cost.

Maintenance cost is greatly affected by hydrogen fuel cost. If fuel economy is increased by hybridization of fuel cell vehicle, life cycle cost is decreased. Because initial vehicle cost is settled at the time of manufacturing, development of fuel cell technology and performance cant affect life cycle cost. But because hydrogen fuel cost can be decreased by increase of demand and development of manufacturing technology, life cycle cost can be decreased.

4.1 Fuel cell cost

PEM fuel cell cost is 1000- 2000$/kW at the present time. Table 6 summarizes material

Table 7. Initial cost of fuel cell vehicle component

	Material mass (kg/kW)	Material cost ($/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

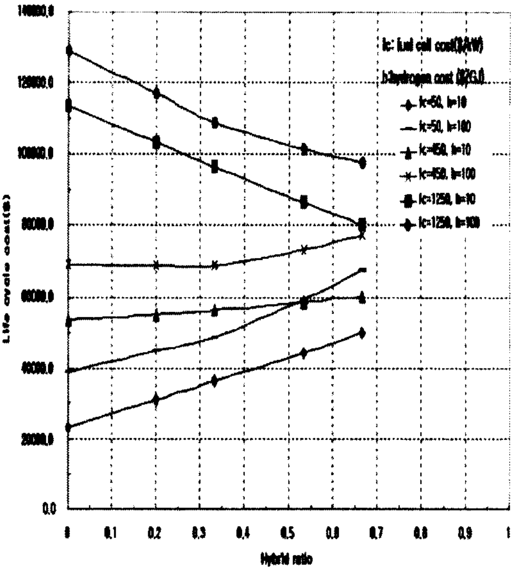

Fig. 5. Fuel cell vehicle cost as a function of hybridization ratio.

cost for a fuel cell stack today. Fuel cell cost will be decreased on account of reduction of platinum loading, improvement of stack performance and mass production. It is forecasted that fuel cell cost will be decreased to 200$/kW in 1 or 2 years. Fuel cell cost must be lower than 50$/GJ in order to compete with internal combustion engine[8].

4.2 Initial cost of fuel cell vehicle

Table 7 summarizes assumed price of fuel cell vehicle constituent. Initial cost of fuel cell vehicle is calculated based on this table. Fig. 5 shows initial cost of fuel cell hybrid vehicle. If fuel cell cost is high, hybridization can reduce FCHV initial cost. If fuel cell cost is lower than 50$/kW on the other hand, hybridization will increase FCHV initial cost because battery cost increases and vehicle control system is complex.

4.3 Hydrogen fuel cost

Hydrogen production methods are natural gas steam reforming, electrolysis of water and byproduct of chemical industry. Infrastructure of supplying hydrogen for vehicle is not constructed in the present day. Production of hydrogen is not so much. To use hydrogen as fuel of fuel cell vehicle, the infrastructure of production and supply must be settled. Hydrogen fuel cost is very expensive today. But if many fuel cell vehicles are provided, hydrogen cost will be decreased by mass production of hydrogen. If hydrogen fueled FCVs are more than 50000, estimated hydrogen cost is to be 20-30$/GJ in California[9,10].

4.4 Life cycle cost

Life cycle cost includes vehicle cost, used hydrogen fuel cost and battery cost. There are

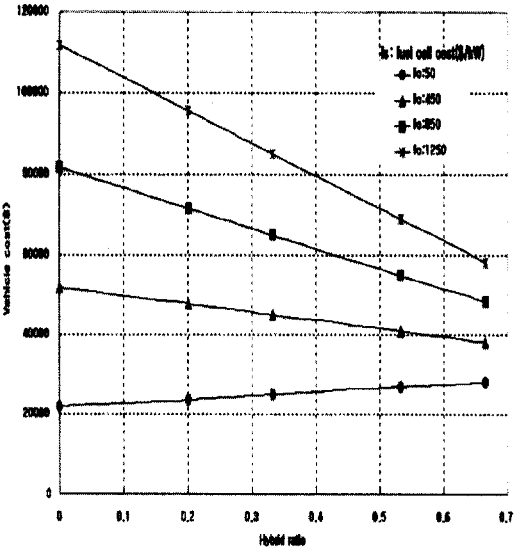

Fig. 6. Life cycle cost of fuel cell hybrid vehicle.

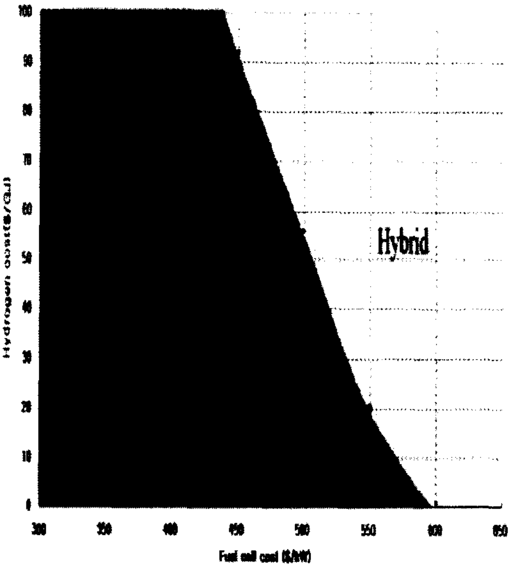

Fig. 7. The base line of fuel cell vehicle hybridization.

some assumptions to calculate life cycle cost. The number of battery charged-discharged is 300 in a year. And battery life is 3.3 years. Vehicle life is ten years. Vehicle drives 15000km in a year. Consumed hydrogen is calculated based on above simulation result.

Fig. 6 shows life cycle cost based on FC cost and hydrogen cost for FCHV. If fuel cell cost is high as 1250$/kW, hybridization can reduce life cycle cost. If fuel cell cost is 50$/kW, hybridization increases life cycle cost because it increases initial vehicle cost.

Hybridization of fuel cell vehicle must to be considered by economical and technical points. Fig. 7 presents a standard of judgment for whether hybridization is necessary or not with variation of fuel cell cost and hydrogen cost, in the point of life cycle cost.

If fuel cell cost is high, hybridization is profitable because initial vehicle cost is decreased. If hydrogen fueled fuel cell vehicles are more than 50000, estimated hydrogen cost is about 30$/GJ by California case. If fuel cell cost is about 550$/kW at the early stage of commercialization, hybridization is economical. If fuel cell cost is lower than 400$/kW, pure fuel cell vehicle is profitable because initial fuel cell cost influences more on life cycle cost than hydrogen cost. If fuel cell vehicles are produced largely, the estimated cost of fuel cell system is about 200- 400$/kW. If this estimate is realized, hybridization of fuel cell vehicle is not necessary in the point of economics.

5. Conclusion

Fuel economy and life cycle cost between pure fuel cell vehicle and fuel cell hybrid vehicle that is combined fuel cell and battery as energy sources are compared.

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

Fuel cell vehicle cost is reduced by hybridization when fuel cell cost is high. Life cycle cost is largely affected by 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 smaller than 400$/kW, pure fuel cell vehicle is more profitable.

Many challenges are remained being solved before 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 performance and cost. Fuel cell can be adopted widely as cleaner and more efficient automotive engine.

Acknowledgement

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

Reference

1) G. Friedlmeier, K. E. Noreikat, F. Panik, Test Experiences with DaimlerChrysler Hydrogen Fueled Fuel Cell Electric Vehicle NECAR4, Proceedings of the 13th World Hydrogen Energy Conference, 2000, P1357-1363
2) Fuel cells for Transportation 98, Contractor's Annual Progress Report
3) Fuel cells for Transportation, FY1999 Progress Report
4) National Renewable Energy Laboratory, Advisor-Advanced vehicle simulator, 1999
5) C. E. Borroni-Bird, Fuel cell commercialization issues for light-duty vehicle applications, Journal of power sources 61, 1996, pp. 33-34
6) W. Luttrell et al, Integration of Fuel Cell Technology into the Virginia Tech 1999, Hybrid Electric Future Car
7) Valerie Johnson, Matthew Keyser, Testing, Analysis, and Validation of a Hawker Genesis Lead Acid Battery Model in ADVISOR.
8) The Fuel Cell Vehicle Analysis of Energy Use, Emission and Cost, Int. J. Hydrogen Energy Vol. 23. No. 5, 1998, pp. 381-385.
9) Joan M. Ogden, Developing an infrastructure for hydrogen vehicles : a Southern California case study, International Journal of Hydrogen Energy 24, 1999, pp. 709- 730.
10) Joan M. Ogden et al, A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicle : implications for vehicle design and infrastructure development. Journal of Power Source 79, 1999, pp 143-168.