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論 文
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Relative Cost Modeling for Main Component Systems of Parallel Hybrid Electric Vehicle

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Abstract - There is a growing interest in hybrid electric vehicles due to environmental concerns. Recent efforts are directed toward developing an improved main component systems for the hybrid electric vehicle applications. Soon after the introduction of electric starter for internal combustion engine early this century, despite being energy efficient and nonpolluting, electric vehicle lost the battle completly to internal combustion engine due to its limited range and inferior performance. Hybrid Electric vehicles offer the most promising solutions to reduce the emission of vehicles.
This paper describes a method for cost reduction estimation of parallel hybrid electric vehicle. We used a cost reduction structure that consisted of five major subsystems (three-type battery and two-type motor) for parallel hybrid electric vehicle. Especially, we estimated the potential for cost reductions in parallel hybrid electric vehicle as a function of time using the learning curve. Also, we estimated the potentials of cost by depreciation.

Key Words : Hybrid Electric Vehicle(HEV), Cost Modeling, Cost Structure, Learning Curve Analysis, Depreciation Analysis

1. Introduction

Industrial users frequently make economic decisions about the purchase of systems for new installations, and about system repair, or replacement of existing systems that have failed in service. It is becoming increasing important to consider the economic impact of system cost on the business when making such decisions. In many situations, decision is based upon the lowest initial cost. The tools of economic analysis can help users make more intelligent decisions regarding system purchase and replacement[1].

On the other hand, the Internal Combustion Engine (ICE) automobile at the present is a major source of urban pollution. Besides air pollution, the other main objection regarding ICE automobiles is its extremly low efficiency use of fossil fuel. Hence, the problem associated with ICE automobiles are three fold, environmental, economical, as well as political[2,3]. These concerns have forced governments all over the world to consider alternative vehicle concepts. The concept of electric vehicle (EV) was conceived in the middle of previous century. EVs offer the most promising solutions to reduce the emission. In 1998, the California Air Resources Board established rules that mandate 10[%] of all vehicles sold in California in 2003 must be Zero Emission Vehicles (ZEV's) In response to technological needs for EV's, the development of power electronics technology will take an accelerated pace in future years[4-5]. The revival of EV's is becoming more and more definite. This opinion is not only found in technical literature[6-8], but also in business magazines[9].

EVs constitute the only commonly known group of automobiles that qualify as ZEV. These vehicles use an electric motors for propulsion, and batteries as electrical energy storage devices[10-15]. Hybrid Electric Vehicles (HEV) offer the most promising solutions to reduce the problem of limited range and inferior performance of EV. Based on our previous work, namely, application examples for cost estimation modelling[16-18], the purpose of this paper is to review the main component systems of Parallel HEV(P-HEV) and to estimate various relative cost of main component systems in P-HEV's.

In Section 2, the concept of P-HEV is described. Cost modelling in battery, motor and control system, engine and transmission, body frame, and other related systems are described in Section 3, respectively. Also, In Section 4, today's cost estimation results are described. The results of potential cost reduction estimation using various estimation criteria in P-HEV's is briefed in Section 5.

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Concretely speaking, we made costs estimates based on today's technology and projected how the costs might be reduced due to increased production cost savings (i.e., learning curve effects) or increased competition, and we estimated the potentials of cost by depreciation. Also, today's costs and projections at 1 ~ 10 years were calculated, as discussed later[19-24].

The cost reduction guidelines presented in this paper are general in nature, and may be applied to any type or size system through small transformation. Although not included in the economic analysis, users should also be aware that premium characteristics systems generally run more accurate than standard systems, leading to longer system life.

2. Outline of parallel hybrid electric vehicle

Recently in the world, many projects are developing P-HEV because environment on earth are recognized as the most important problem. Namely, the P-HEV offers one of the most promising solutions for improving air quality while reducing the reliance on fossil fuels to power vehicles. The use of P-HEVs remains limited, however, because their driving performance has been too poor and cost has been too high. In order for an P-HEV to be accepted in society, the P-HEV design should take advantage of attributes which could only be incorporated into P-HEVs, such as lower maintenance, and quieter and easier driving.

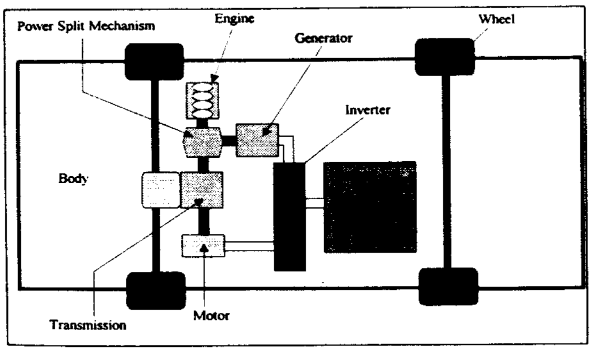

Fig. 1 Main system composition of the P-HEV

The main system composition of the P-HEV is shown Fig. 1. As main components of the P-HEV, a battery is installed within the bottom of the body, and a motor and control system, an engine and transmission, an automatic speed change gear and a compressor for an air-conditioner are installed within a bonnet. The features of the main components of the P-HEVs are described below.

3. Cost modeling

Economic evaluation is a useful tool to determine the relative merit of system proposals with different characteristics. The results of the evaluation help the user to choose the alternative that is most profitable for the business.

We used cost reduction structure that consisted of five major subsystem in case of P-HEVs[16-18].

1)battery
2)motor and control system
3)engine and transmission
4)body frame
5)other related system

Also, to alleviate the problem of price variation with time, we choose to express the various cost not in dollars or other official monetary units, but in an arbitary unit which is the cost of one ampere-hour of nickel-metal hydride(Ni-MH) battery.

These cost reduction structure are dealt with seperately as follows:

3.1 Battery

In this study, the nickel-metal hydride(Ni-MH) batteries are selected for criteria of P-HEV application. Because the specific energy and specific power of electrochemical batteries are generally significantly lower than those of gasoline, a large number of batteries are required to assure a desired level of power performance. However, mounting a large number of batteries on the vehicle suffers from several disadvantages ; the reduction of interier and luggage spaces, the decrease in vehicle preformances. Thus, the development of battery technology has been accelerated, in which a set of criteria including the specific energy, specific power, energy efficiency, charging rate, cycle life, operating environment, cost, safety and recycling must be considered.

In this paper, the economic data are as follows;

- Relative cost of nickel-metal hydride(Ni-MH) battery : 65[pu]
- Relative cost of lithum-ion(Li-ion) battery : 75[pu]
- Relative cost of polymer battery : 95[pu]

The cost of the battery is based on the energy capacity of battery.

$$C_B = E_B \cdot U_B \tag{1}$$

where C_B = total cost of battery [pu]
E_B = energy capacity of battery [Ah]
U_B = unit cost of battery per Ah[pu/Ah].

3.2 Motor and control system

In the past decades, DC variable-speed drive systems were commonly used for industrial drive and EV applications. Especially, the main component systems of P-HEV drivetrain are its electric motor and engine. Motors generally used for driving the P-HEV are brush DC motor, and AC induction motor and Permanent Magnet Synchronous Motor(=PMSM) etc. The brush DC motor has a large electromagnetic wave noise due to its composition of brushes and a commutator, the necessity of maintenance of brush due to its structure depending on mechanical contacting, and the limits to speed. For these drawbacks, the brush DC motor has disadvantage in reducing the size and weight of the P-HEV driving system.

Also, the AC induction motor and the PMSM have no mechanically contacted parts, and therefore more suitable for the P-HEV driving system than the brush DC motor. In this paper, the author applied the PMSM and BLDC motor into the P-HEV driving system.

The cost of the motor is proportional to the electric power requirement of the motor, P_M[W].

$$C_M = P_M \cdot U_M + C_{CS} \tag{2}$$

where C_M = total cost of motor [pu]
P_M = electric power requirement of motor[W]
U_M = unit cost of motor [pu/W].
C_{CS} = cost of control system [pu].

The motor power is estimated from

$$P_M = P_L \,/\, (\,\eta_T \,/\, 100) \tag{3}$$

where P_L = load [VA]
η_T = motor efficiency [%].

Generally, the motor's efficiency is about 90[%], assuming a middle motor.

3.3 Engine and transmission

The cost of the engine and transmission are calculated by the eq. (4).

$$C_{ET} = C_{EN} + C_{TM} \tag{4}$$

where C_{ET} = total cost of engine and transmission[pu]
C_{EN} = subtotal cost of engine [pu]
C_{TM} = subtotal cost of transmission [pu].

3.4 Body frame

The body frame of the vehicle consists of various components. In this study, we assumed the cost of a body frame is constant like conventional use. Therefore, the cost of body frame is about 217.1[pu]. These costs are based on discussions with conventional users. Support components were not included in the cost estimate.

3.5 Other related system

Other related system of vehicle consists of conventional system like air-conditioner, steering system, braking system, lighting system, power transfer system, wheel system, et al, and technical system for the P-HEV like battery capacity meter, battery level meter, diagonosis system for electric circuits, et al. Therefore, we assumed the cost of the other related system shown in eq. (5). Especially, it assumes that the cost of a conventional system is constant.

$$C_R = C_C + C_T \tag{5}$$

where C_R = total cost of other related system [pu]
C_C = subtotal cost of conventional system [pu]
C_T = subtotal cost of technical system for P-HEV [pu].

The cost of the conventional system, C_C, is estimated from

$$C_C = C_{C1} + C_{C2} + C_{C3} + C_{C4} + C_{C5} + C_{C6} \tag{6}$$

where C_{C1} = cost of air-conditioner [pu]
C_{C2} = cost of steering system [pu]
C_{C3} = cost of braking system [pu]
C_{C4} = cost of lighting system [pu]
C_{C5} = cost of power transfer system [pu]
C_{C6} = cost of wheel system [pu].

Also, the cost of the technical system, C_T, is estimated from

$$C_T = C_{T1} + C_{T2} + C_{T3} \tag{7}$$

where C_{T1} = cost of battery capacity meter [pu]
C_{T2} = cost of battery level meter [pu]
C_{T3} = cost of various diagonosis system [pu].

4. Today's cost estimation results

The estimated cost using the basic cost assumptions described above is given in Table 1. Labor costs for assembly are not included. The results are referred to as "Today's costs", no credit is taken for future price reductions due to the benefits of mass production, technology improvements, or competitions. Fig. 2 has been plotted from the values given in Table 1.

Table 1 Cost estimation of P-HEV

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ni-MH	PM Synchronous Motor	65	130	520	217.1	367.9	1300
Li-ion		75	130	520	217.1	367.9	1310
Polymer		95	130	520	217.1	367.9	1325
Ni-MH	AC Induction Motor	65	108	520	217.1	367.9	1278
Li-ion		75	108	520	217.1	367.9	1288
Polymer		95	108	520	217.1	367.9	1308

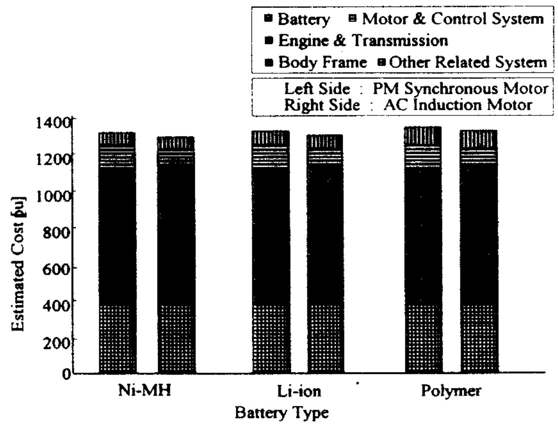

Fig. 2 Cost estimation results for P-HEV in case of various battery and motor

5. Potential cost reduction estimation

We estimated the potential for cost reduction in P-HEV as a function of time. The assumptions and results are summarized in this section.

5.1 Learning curve analysis

We assumed that the system cost is reduced by 10[%] for each doubling in total P-HEVs produced (referred to as a 90[%] learning curve).

Consequently, this leads to the following generalized relationship[25].

$$C_p = C_1 \cdot p^{n'} \qquad (8)$$

where C_p = cost of total P-HEV produced
p = total P-HEV produced
C_1 = cost of the first P-HEV
n' = ln 0.9 / ln 2.

therefore, $C_p = C_1 \cdot p^{-0.152}$ (9)

In order to determine the learning curve savings, we assumed a production schedule shown in Table 2. The learning curve analysis was applied to the battery, motor and engine as discussed below.

Since today's body frame is fairly mature technology and its capability is not expected to improve greatly in the future, these costs was not applied to a learning curve reduction model. It is assumed that the cost of the battery, motor and engine, and other related system could be reduced by technology development, mass production and competition. the greater energy capability of battery is the larger cost

Table 2. Assumed production schedules and learning curve factor

End of Year	P-HEV per Year	Total P-HEVs Built	Learning Curve Factor
[illegible]	12,000	12,000	0.900
[illegible]	30,000	42,000	0.198
[illegible]	50,000	92,000	0.176
[illegible]	75,000	167,000	0.161
[illegible]	100,000	267,000	0.150
[illegible]	150,000	417,000	0.140
[illegible]	220,000	637,000	0.131
[illegible]	300,000	937,000	0.124
[illegible]	400,000	1,337,000	0.117
[illegible]	560,000	1,897,000	0.111

reduction of battery. Therefore, it assumed that technologies of battery can be improved like Table 3. Also, it assumed that technologies of other related system can be improved to give 2[%] by year 1, 5[%] by year 2, 8[%] by year 3, 12[%] by year 4, 16[%] by year 5, 20[%] by year 6. 25[%] by year 7, 30[%] by year 8, 35[%] by year 9 and 40[%] by year 10. Lastly, we assumed that the costs of motor and engine could be reduced by 90[%] for the first commercial system. We assumed that this can be achieved for the smaller systems with P-HEV as the market and technology develop. For years 2~10, the learning curve factors from Table 2 are applied to the year one cost. Fig. 3 shows the cost of a motor and engine of P-HEV as a function of time relative to today's cost.

Table 3 Cost-saving of technology improvement of battery

[illegible]	[illegible]	[illegible]	[illegible]
1	5	5	4
2	10	11	8
3	17	18	13
4	22	24	18
5	28	32	24
6	35	41	32
7	44	50	39
8	53	60	47
9	62	71	55
10	72	82	64

Fig. 3 Relative cost vs. time for a motor and engine of P-HEV

5.2 Estimation of cost by depreciation

A dollar available today is worth more than the same dollar available tomorrow, or next year, or ten years from now. If a cost of 100[$]/year for the next ten years is discounted at 2[%], it will have a present value of 898.2[$] as seen below(table 4):

The cost for the first year is 100[$]. This amount is multiplied by the discount factor of 0.980 to yield a present value of 98.0[$].

The discount factor is calculated by eq. (10):

$$\text{Discount Factor} = 1 / (1 + (D / 100))^n \qquad (10)$$

where D = discount rate in [%]
n = number of years.

The discount factor is calculated for the remaining years in the above example, and the discounted values are totaled to obtain a net present value of 898.2[$] for the sequence of cost during the ten years.

In case of considering cost depreciation in this study, the total cost of system were more reduced by depreciation. We assumed that discount rate of cost is 2[%].

Table 4 Cost estimation by depreciation

[illegible]	[illegible] [$]	[illegible] Factor	[illegible] Value [$]
1	100	0.980	98.0
2	100	0.961	96.1
3	100	0.942	94.2
4	100	0.924	92.4
5	100	0.906	90.6
6	100	0.888	88.8
7	100	0.871	87.1
8	100	0.853	85.3
9	100	0.837	83.7
10	100	0.820	82.0
Net Present Value = $ 898.2			

5.3 Summary of cost reduction

Table 5 summarized the estimation method using the basic assumption described above.

Also, Fig. 4 shows the cost comparisons of three-type battery graphically. In case of Ni-MH battery and PM synchronous motor, the estimated cost, without and with cost by depreciation, is given in Table 6. Fig. 5 shows the cost comparisons of two-type motor with cost by depreciation graphically and Fig. 6 have been plotted from the values given in Table 6. For our assumptions, the overall cost is reduced by 51.6[%] by year 3, 46[%] by year 5 and 32.9[%] by year 10. There are a significant reduction in the driving motor and inverter between 3 and 10 due to technical improvements in the design.

Table 5 Summary of assumptions for P-HEV components

[illegible]	[illegible]
Battery	see Table 3
Motor & Control System	Learning Curve Analysis
Engine & Transmission	Learning Curve Analysis
Body Frame	Technology Constant
Other Related System	Technology Improvements ; 2, 5, 8, 12, 16, 20, 25, 30, 35, 40[%] by year 1~10 respectively

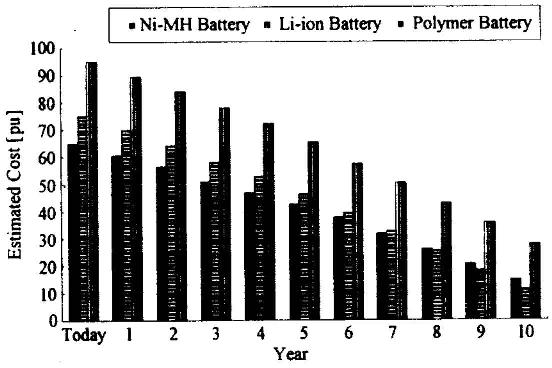

Fig. 4 Cost comparisons of three-type battery with cost by depreciation

Table 6 Estimated cost for P-HEV in case of Ni-MH battery and PM synchronous motor, without and with cost by depreciation

	Year	Without Cost by Depreciation	With Cost by Depreciation
Estimated Cost [pu]	Today	1300.00	1300.00
	Year 1	1224.39	1199.91
	Year 2	740.81	711.91
	Year 3	712.22	670.91
	Year 4	685.8	633.69
	Year 5	660.69	598.58
	Year 6	635.57	564.39
	Year 7	606.13	527.92
	Year 8	577.98	493.02
	Year 9	549.19	459.67
	Year 10	521.04	427.25

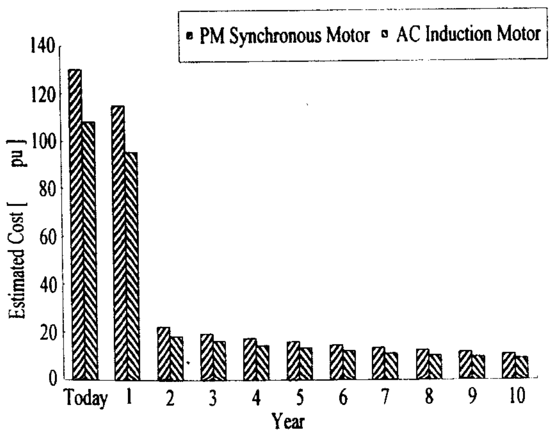

Fig. 5 Cost comparisons of two-type motor with cost by depreciation

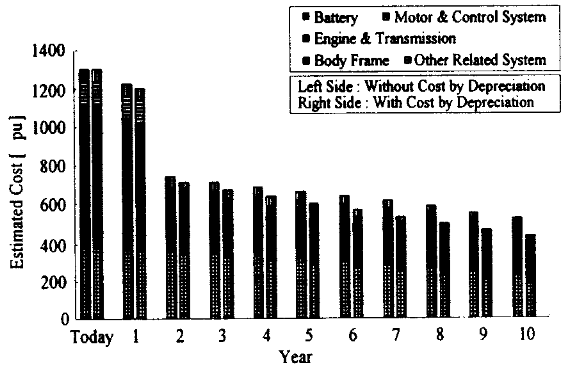

Fig. 6 Estimated cost for P-HEV in case of Ni-MH battery and PM synchronous motor without and with cost by depreciation

6. Conclusion

This paper has received the main component systems (five parts ; battery, motor and control system, engine and transmission, body frame and other related system) of P-HEV and evaluated various relative cost of the main components systems by proposed criteria. Today's P-HEV system is dominated by the cost of engine and transmission, with a second major cost component being the other related system. Technology improvements and cost reductions caused by mass productions and competition are expected over the next ten years. We project that a reduction to one-quarter of today's cost could be possible with aggressive market and technology development. The cost model of this paper was applied to an actual P-HEV to demonstrate its benefits. Clearly the detailed cost model of P-HEV is more complicated than in our cost model examples. Also, cost reduction methods have been applied to common system decisions faced in industry. Investment guidelines justify the purchase of optimum systems for new installations. The guidelines are general in nature, and may be applied to any type or size system. The economic tools are also applicable for commercial applications.

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References

[1] D. M. Brethaner, et al, "The Impact of Efficiency on the Economics of New Motor Purchase, Motor Repair,

and Motor Replacement", IEEE Trans. on Ind. Appl., Vol. 30, No. 6, pp. 1525-1537, 1994.
[2] "Air pollution-transportation linkage", California Air Resources Board Office of Strategic Planning, 1989.
[3] "2001 : US electric vehicle sales", Elec. Propulsion, Vol. 6, No. 4, pp. 2, 1991.
[4] W. W. Burns, "Power Electronics-Keeping Pace with Society", IEEE Trans. Power Electronics, Vol. PE-1, pp. 1-2, 1986.
[5] M. Nishihara, "Power Electrinics Diversity", Proceedings of the Int. Power Electronics Conference, pp. 21-28, 1990.
[6] C. C. Chan and K. T. Chau, "Electric Vehicle Technology - An Overview of Present Status and Future Trends in Asia and Pacific Areas", Proceedings of the Int. Electric Vehicle Symp., pp. 1, 1992.
[7] M. J. Riezenman, "Electric Vehicles", IEEE Spectrum, Vol.29, No. 11, pp. 18-21, 1992.
[8] C. C. Chan, "An Overview of Electric Vehicle Technology", Proceedings of the IEEE, Vol. 81, pp. 1202-1213, 1993.
[9] D. Woodruff, et al, "Electric Cars", Int. Bus. Week, pp. 36-40, May 30, 1994.
[10]The Electric Vehicle - Technical Report, The Korea Institute of Electrical Engineers, 1992.
[11]C. C. Chan and K. T. Chau, "An Advanced Permanent Magnet Motor Drive System for Battery-Powered Electric Vehicles", IEEE Trans. on Vehicular Tech., Vol. 45, No. 1, 1996.
[12]B. J. Chalmers, et al, "Variable-Frequency Synchronous Motor Drives for Electric Vehicles", IEEE Trans. on Industry Appl., Vol. 32, No. 4, 1996.
[13]F. Anan, et al, "Application of Motor/Drive for the Mini Electric Vehicle", Proceedings of the JIEE National Conference (Industry Application), pp. 343-346, 1996.
[14]I. Miki, et al, "Characteristics of Motor Suitable for Electric Vehicle", Proceedings of the Japanese IEE National Conference (Industry Application), pp. s.54-s.57, 1996.
[15]M. Ehsani, et al, "Propulsion System Design of Electric Vehicles", Proceedings of the International Conference on Industrial Electronics, Control and Instrumentation (IECON'96), pp. 7-13, 1996.
[16]Pill-Soo Kim, et al, "Cost Reduction Estimation of impulse Magnetizer System using the Learning Curve", Proceedings of the International Conference on Power Electronics (ICPE'95), pp. 715-719, 1995.
[17]Pill-Soo Kim and Yong Kim, "A Future Cost Trends of Magnetizer Systems", Proceedings of the International Conference on Industrial Electronics, Control and Instrumentation (IECON'96), pp. 991-996, 1996.
[18]Pill-Soo Kim, Yong Kim and Soo-Hyun Baek, "Relative Cost Comparisons between Capacitor-type and SCR-type Magnetizer System", The Journal of EEIS Vol. 2 ,No. 2, pp.23-29, 1997.
[19]S. M. Schoenung, et al, "Small Technology and Cost Reduction Estimates", IEEE Trans. on Energy Conversion, Vol. 9, No. 2, pp. 231-237, 1994.
[20]Mumford F. J., et al, "A Techno-Economic Study of High Tc Superconducting Power Transformers", Proceeding of the International Conference on Electrical Machines (ICEM'94), pp. 630-635, 1994.
[21]S. Lie and C. Dipietro, "Copper Die-Cast Rotor, Efficiency Improvement and Economic Considerations", IEEE Trans. on Energy Conversion, Vol. 10, No. 3, pp. 419-424, 1995.
[22]M. Poloujadoff and J. C. Mipo, "Some Economical Comparisons between Aluminum and Copper Squirrel Cages", IEEE Trans. on Energy Conversion, Vol. 10, No. 3, pp. 415-418, 1995.
[23]Pill-Soo Kim and Yong Kim, "A Cost Trends Study of Electric Vehicle in Korea, "Proceedings of the 8th Int. Power Electro. & Motion Control Conf.(PEMC'98), Vol. 1, pp. 4.28-4.23, 1998.
[24]Pill-Soo Kim, "Cost Modeling for Cost Reduction Estimation of Electric Vehicle, "Trans. of Korea Society of Automotive Engineers, Vol. 7, No. 2, pp. 288-299, 1999.
[25]J. A. Cunningham, "Using the Learning Curve as a Management Tool", IEEE Spectrum, pp. 45-48, June, 1980.

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