

HEV Diffusion Forecast by Key Device Analysis

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Abstract

Recently, the automotive industry has encountered a significant technical turning point. This was brought on by the shift from the internal combustion engine vehicle (ICEV) to the hybrid electric vehicle (HEV) and electric vehicle (EV). At this time, in order to maintain its competitive advantage, an automotive manufacturer has to adjust product development speed to match the diffusion speed of new products.

In a prior paper [5], on a case study of consumer electronics, the author established a new method to estimate the diffusion speed of new products by making use of key device analysis to measure development speed. Key devices are the components or “building blocks” that have a major influence on the quality, performance, and cost of a product. The purpose of this investigation was to apply the key device analysis method to the HEV in its early diffusion stage, to predict diffusion speed, and to identify other issues that will hamper further diffusion.

Keywords: diffusion speed, key device, HEV, market, vehicle performance

1 HEV, mass production, and diffusion

1.1 The behaviour of Japanese consumer towards HEV

In order to determine how the hybrid electric vehicle (HEV) has become popularized in Japan, transition of sales volumes of the HEV was investigated. The results are shown in Figure 1. For this investigation, the new release of Toyota (prior to 2003) and the magazine of The Next Generation Vehicle Promotion Center (2004 and later) were referred to [1]. Since the introduction of the HEV in the market in 1997, the sales volume of HEVs was very low until 2003. When the second generation Prius was released to the market in 2003, consumers’ concerns about fuel economy increased with the sharp increase in oil

prices. Subsequently, the sales volume of HEVs increased as well. The third generation Toyota Prius and the Honda Insight were introduced simultaneously to the market in 2009, and at this time, an eco-friendly car subsidiary payment policy was implemented in Japan, which made the volume of the annual sales of HEVs increase significantly.

As a result, full HEVs (serial-parallel system and parallel system) comprised 14% of new car registrations in Japan by 2011. The sales volume gradually increased because of not only social requirements but also consumers’ acceptance of the new model specifications. From this viewpoint, analyzing the detailed specifications of products could determine the factors that influence the purchase of an HEV. Although the sales value increased to 600,000 in 2011, the total number of HEVs comprised only 5% of the total number of Japanese passenger cars, that is, about 40 million vehicles, excluding mini cars.

According to Professor E.M. Rogers's study, if the market penetration rate exceeds 16%, it begins to rise autonomously [2]. Therefore, it cannot be determined if the present HEV will become a replacement for the ICEV in the future. In order to replace the ICEV with the HEV, car manufacturers should identify and improve the problem which hampers the further diffusion of HEV and to ensure that the penetration rate reaches 16%.

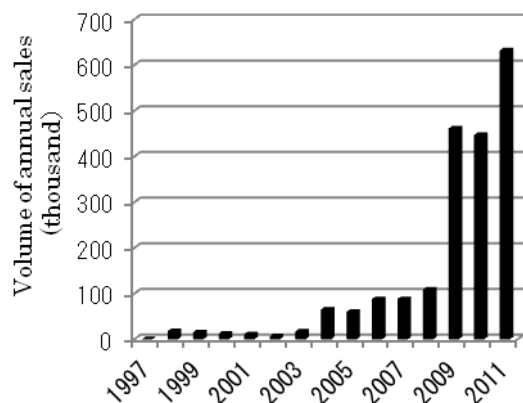


Fig. 1 Increase in the annual HEV sales value in Japan

1.2 Challenge faced by Japanese automobile manufacturers for fuel economy improvement

Figure 2 illustrates the challenges faced by Toyota and Honda—the most common automobile manufacturers of HEVs—to improve the fuel economy of the HEVs.

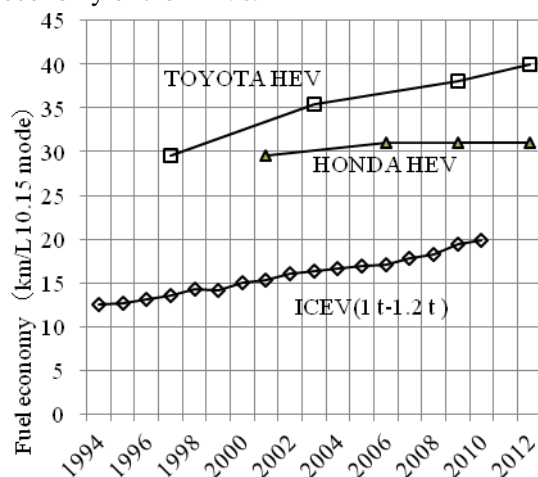


Fig. 2 Progress in the fuel economy improvement of motor vehicles in the Japan market

In order to compare fuel economy, the average value of the fuel economy in ICEVs in Japan is

also shown [3]. One can see that the fuel economy was affected by vehicle weight. For the purpose of this comparison, the weight of the passenger car was set at 1000-1200 kg.

When it appeared on the market in 1997, the first generation HEV of Toyota, the Prius, achieved an impressive fuel economy of about twice that of an ICEV. After that, each time a new HEV model was placed on the market, its fuel economy improved and it was always twice as efficient as an ICEV. The HEV of Honda, the Civic Hybrid, placed on the market in 2001, also realized two times better fuel economy than the ICEVs. As a result, HEV sales increased gradually; however, it could not yet be said that full-scale diffusion has commenced.

1.3 Challenge faced by automobile manufacturers for the diffusion of HEVs in Japan

Figure 3 shows how the performance and the price of the Toyota Prius have improved. In Figure 3, the value of Toyota ICEVs of the same weight is shown with their system power output and their price. The system power output is the composite maximum power output produced when a motor and an engine operate simultaneously in an HEV. The system output of an HEV was not indicated in the specifications of the motor vehicle, but it was shown in the manufacturer's catalogue. In 1997, compared to ICEV (Corona 1.8 L), the output of the Prius was lower than 50 kW and it cost more than 500,000 yen.

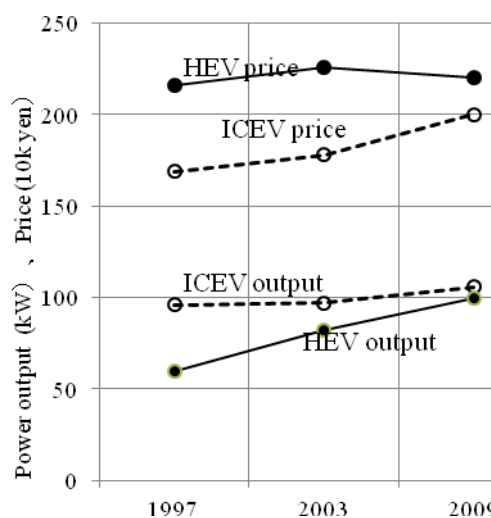


Fig. 3 Challenge of performance and price of the Toyota Prius

Although the HEV's power output was almost equal that of the ICEV (Corolla Spacio 1.8 L) by 2003, the price was still higher 500,000 yen. In 2009, although there was still almost a 200,000 yen difference in the price, the power output differed by only a few kW. Today, the Prius has become the most fuel-economic car and is comparable in performance and price to an ICEV. As a result, consumers accepted HEVs as possible replacements for ICEVs, and their sales share increased to 17% of passenger cars in Japan. However, the penetration ratio for households will be only 5% or less, and the HEV manufacturers are only two companies, namely, Toyota and Honda. Therefore, in order to enter full-scale diffusion, it is expected that some remaining issues be solved.

1.4 The remaining issues for further diffusion of HEVs

In order for HEVs to replace ICEVs completely, the issues that are still hampering this replacement, should be identified and addressed. Geoffrey A. Moore posed the Chasm theory about the diffusion of high-tech products in his works [4] to identify these issues. This theory states that in order for high-tech products to become popularized in the early majority (users who consider the price and quality as the most important matters) as well as the early adopters (users who consider a vision as the most important matter), the products have to satisfy customers universal criteria. Therefore, the products have to satisfy consumers' universal selection criteria. The criteria that have to be met to satisfy all consumers' needs are therefore "quality," "performance," and "price." If his theory is applied to the diffusion of HEVs, the HEVs should be compared to the ICEVs in terms of performance and price. Here, the quality level should be assumed to be the same. Therefore, in this study, the performance and the price of the HEV were compared to that of the ICEV. The performance and price are affected not only by the difference in mechanical structure, but also by the difference between the design concept of an automobile manufacturer, the design, the purpose of use, the production system, the branding strategy, the distribution system, etc. In order to evaluate as much as possible, this study was limited to domestic HEVs and ICEVs of the same manufacturer, looking at the same type of car, and the same engine displacement. The subcompact, the compact car, and the minivan were chosen as

examples of HEVs and ICEVs and ten models of each were evaluated.

Firstly, the vehicles were analyzed on performance. Because an HEV has more parts compared to an ICEV, the weight difference between HEVs and ICEVs is considered to be because of the HEV's parts. Figure 4 shows the vehicles' weight differences as a scatter chart.

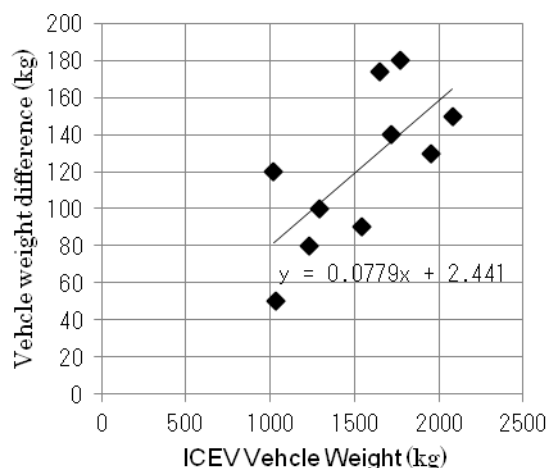


Fig. 4 Vehicle weight difference between an HEV and an ICEV

According to this figure, the HEV's parts weight increases proportionally to vehicle weight, and is about 100 kg for a subcompact car and about 150 kg for a passenger car. There is no clear difference between the weight of the hybrids with parallel systems and those with series-parallel systems. According to the approximation, it is clear that there was about an 8% increase in vehicle weight in the ICEV. In addition, although not shown here, regarding the overseas manufacturers' HEVs, the results of the weight differences was the same as between the Japanese manufacturers' HEVs and ICEVs.

In order to determine which performance grade the HEV achieved, the relationship between vehicle weight, power output and fuel economy was calculated. The results are shown in Figure 5. The running resistance of a car consists of rolling resistance, hill climbing resistance, air resistance, and acceleration resistance. Among these, the resistance that relates to vehicle weight are rolling resistance, hill climbing resistance, and acceleration resistance, and these all work together in direct proportion to vehicle weight. Therefore, when weight and power output increase at the same time, by the same ratio, travelling performance of a vehicle would not change. Referring to Figure 5, since the vehicle weight of an HEV is 8% higher than that of an

ICEV, if an output ratio also increases by 8%, the travelling performance of the vehicle would not change. The broken line on the figure indicates this. According to Figure 5, an HEV weighing over 1500 kg has a power output ratio of higher than 110%, but an HEV weighing less than 1500 kg has a power output ratio of lower than 100%. Running capability of the current small HEVs is considered inferior compared to that of the ICEVs.

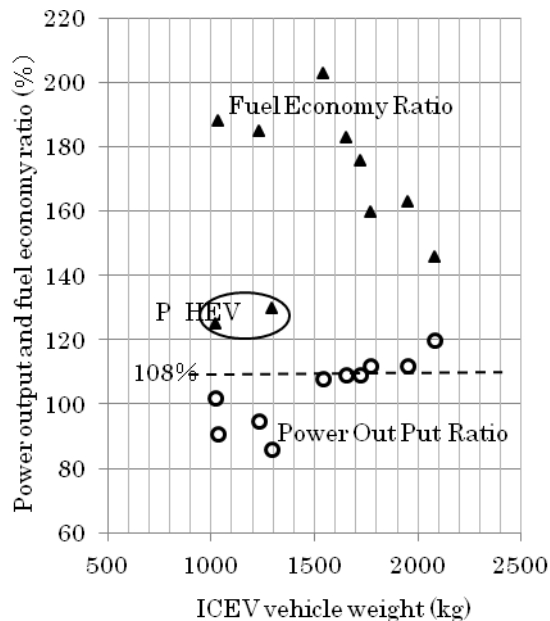


Fig. 5 Power output and fuel economy ratio of an HEV and an ICEV

Following this, the price criteria were analyzed. When purchasing a car nowadays, most consumers will choose a car based on the comparison of price versus engine performance. If the price and performance of the HEV becomes the same as that of the ICEV, the HEV will become popularized. These differences between the HEV and the ICEV are shown in Figure 6. For comparison, the price difference and output difference between a popular ICEV and a high grade are indicated by a broken line in Figure 6. In this figure, almost all HEVs lie below the straight line of the ICEV. Price difference and output difference have not balanced out yet. Especially the power output difference of a lightweight HEV is negative. Since a hybrid system is integrated in an HEV and therefore increases its weight, the power output of this type of vehicle must increase. This problem is an important issue that must be solved to ensure further diffusion of HEVs.

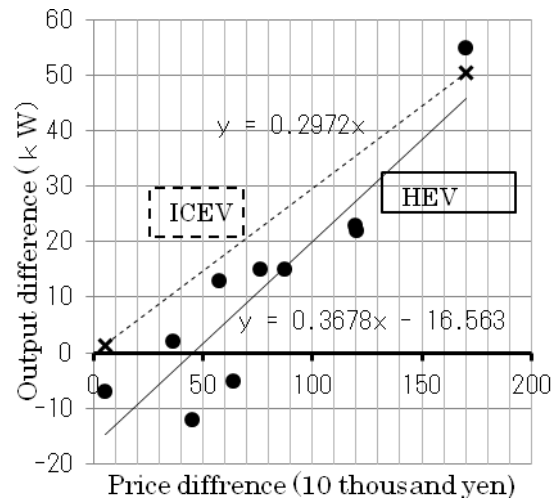


Fig.6 Price and output difference of an HEV and an ICEV

2 Further popularization of HEVs

2.1 Analysis of the key devices of HEVs

Determining the time it will take to solve the problems described above is very important in development strategy planning. This time period should be proportional to the popularization speed of the HEV. In order to estimate the HEV's diffusion speed, a new method of estimating the diffusion speed by analyzing the key devices was employed [5]. Figure 7 shows the evidence of the new method and shows the relationship between the development speed of key devices and the diffusion rate of products.

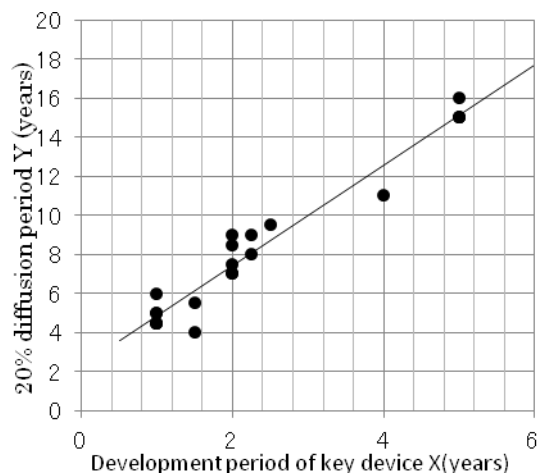


Fig. 7 Scatter chart of the development period of key devices X and 20% diffusion period Y

This research has been conducted in the fields of consumer electronics apparatus, home electricity apparatus, and ICEVs. The development period of the key devices for these fields was set as X , and the 20% diffusion period of the products was set as Y . A strong correlation was noticed between X and Y . The following equation explains this correlation:

$$Y=2.5X+2.5 \quad (1)$$

Therefore, in another industrial field, this method could also be applied to investigate key devices.

The key devices identified for HEVs include the engine, motor, battery, power control unit (PCU), and electronic control unit (ECU). The details of the development processes of these key devices have been summarized in numerous technical reports by Toyota and Honda, and the key points of the results are summarized in Table 1. The technical releases were described in the papers of the Toyota Technical Review (1997-2010), the HONDA R&D Technical Review (1999-2009), and the EVS Conference (2006-2009). Mr Abe published an analysis of the first generation Prius

[6], and Mr Fukuo published an analysis of the Insight [7]. Also Mr Yaguchi published a paper on the analysis of the third generation Prius [8]. Table 1 shows the details of the points of improvement for each generation, improvement value, development period, development method, and users' relationship with the supplier of each key device. The most important factor in improving many aspects was increasing power output. Therefore, in this table, only the power output was indicated. A main factor contributing to the quality of the motor and the battery was power density (kW/kg). Regarding the PCU, progress has been made in increasing power output and promoting miniaturization. Regarding the ECU, the development of stable computer systems and precise software were the important contributing factors. There are more ECUs in the HEV than in the ICEV. These include the motor control ECU, battery charge-and-discharge management ECU, DC/DC converter ECU that charges a storage battery, and electric air conditioner ECU.

Table 1 Analysis of the key devices of the HEV

	The main improvement factor (The former generation is set at 100%)				Development period (years)	Development style of key devices
	Improvement	Developer	1st to 2nd gen.	2nd to 3rd gen.		
Engine	Power output	Toyota	132%	128%	3	Independent
		Honda	100%			
Motor	Power density	Toyota	166%	133%	6	Independent
		Honda	117%		8	Independent
Battery	Power density	Toyota	325%	123%	6	Cooperation
		Honda	138%			
PCU	Capacity	Toyota	88%	63%	5	Independent
		Honda	52%			
ECU	Stability	—	—	—	3	Cooperation

2.2 Estimation of the diffusion speed of HEVs using the development speed of its key devices

When planning a new product development project, it is very important to determine the finalization date of the project. Therefore, in our study, it becomes necessary to estimate the diffusion speed of the HEV. To do so, we employed the diffusion speed estimation method for new products to analyze the key devices [5]. The key devices of the HEV include the engine, motor, battery, PCU, and other electronic control units. The details of key device development

were summarized based on a large amount of technical information on HEVs obtained from Toyota and Honda. We found that for both these manufacturers, the development period of the motor, battery, and PCU is much longer than that of other components; thus, these development periods are key factors affecting the design schedule of a new HEV model. The development period of the motor and battery was six to eight years. The purpose of developing a new motor and new battery was to increase the power output without adding weight to the vehicle. A longer time was required to test new material and a new structure.

Based on the above discussion, an average of seven years is considered the development period for the key devices of the HEV. This figure was applied to the results of a prior study to estimate the diffusion rate of the HEV and its price [5]. Equation (1) determines the period until the penetration rate for households reaches 20% (i.e., a 20% diffusion rate) and substitutes seven years for the key device development period X . Therefore,

$$X=7.$$

As a result, Y is 20 years. We expect that within 20 years of introduction, the penetration rate for households will reach 20%. Equation (2) calculates the number of times product development needs to be repeated until the penetration rate for households reaches 20%, and equation (3) determines the real price decreasing rate, Z , per one cycle of product development. The annual GDP (gross domestic product) growth is set at 0.8%.

$$n = Y/X \quad (2)$$

$$Z = (1 - 0.008)^n \times 100 \quad (3)$$

$$n = 2.85 \text{ times, } Z = 94.5\%$$

According to this result, after 2.85 product development cycles, the penetration rate for households will become 20%. The penetration rate for households, d , and the real price ratio, p , after t years can be calculated using the following equation, based on the above results:

$$d = 20(t/Y)^2 \quad (4)$$

$$p = (1 - Z/100)^{(t/X)} \times 100 \quad (5)$$

where t represents the years after introduction.

Figure 8 shows the results of the calculation of the change in the penetration rate for households and price change based on the above results. HEVs were placed on the market in 1997; therefore, the actual change in the diffusion rate and price is evident, as indicated in Figure 8. The actual penetration rate for households seemed to have shifted from the calculation results from four years ago. The actual penetration rate for households did not increase until the 11th year since the introduction of HEVs, after which it began increasing drastically. The 12th year after introduction can be seen as the period where a shift took place from the first to the second generation of HEVs. The performance of the first generation HEVs was not acceptable for consumers. However, HEVs have improved by the 12th year.

This result was based on the assumption that the HEV will have a better quality, performance, and price than the ICEV does. As Figure 6 shows, the weak points of the current HEV, compared to the

ICEV, include price and output. By solving these problems, the HEV could eventually reach the point of self-sustained diffusion. Sixteen years have passed since the introduction of the HEV; thus, only one development cycle is remaining until it reaches this point of diffusion.

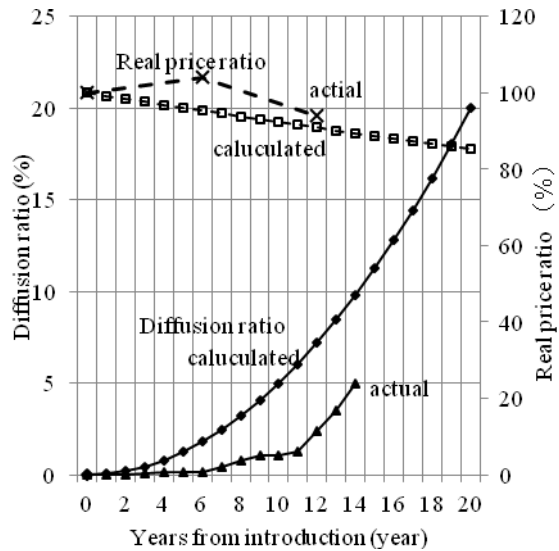


Fig. 8 Forecast of diffusion rate and real price ratio of the HEV

3 Conclusions

(1) Since 1997, the compact HEV has always been twice as fuel efficient as the ICEV. However, the HEV did not compare to the ICEV in terms of power output and price. Therefore, the diffusion of the HEV progressed slowly. Japanese automobile manufacturers have made improvements in the performance and price of the HEV every six years since 1997. As a result, the performance and price of the third generation compact HEV has become comparable to that of the ICEV. Consumers recognized the merits of the HEV, which instigated its rapid diffusion. The HEV has become a realistic replacement for the ICEV.

(2) However, some issues remain to be resolved for the HEV to achieve more popularity. If the HEV is improved, by making its price competitive to that of the ICEV and resolving its power output insufficiency problem, and re-introduced to the market, its diffusion as well as sales could increase substantially.

(3) The key devices in the HEV are the motor and battery. Compared to other components, these require the longest periods for development, that is, an average of seven years, and these key devices

need the close cooperation with the automobile manufacturer and the device makers.

(4) According to our calculation, based on the development period of the key devices, the penetration rate of the HEV will reach 20% within 20 years after introduction. HEVs have already been on the market for 16 years, which means that the penetration rate will reach the 20% mark after one remaining development cycle.

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