

Estimation of Probability Distribution of Li-ion Battery Performance for Electrically-propelled Vehicles

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ABSTRACT

The usage and performance status of Li-ion batteries installed in hybrid electric vehicles were collected by means of fault diagnosis devices. Analysis of the collected data showed the existence of a margin between the Li-ion battery capacities in users' usage conditions and the estimated capacity degradation line that is foreseen during development to show the most rapid degradation. The distribution of the actual Li-ion battery performances in the users' usage conditions is composed of the initial performance distribution, the degradation distribution created by different usage patterns, the degradation distribution of Li-ion batteries within an identical set, and the performance calculation errors made by the electric control units. The capacity margin occurred as a result of the estimated performance degradation line foreseen during development being calculated under conditions in which the distributions of the above performance factors were simultaneously positioned at severe extreme values.

A formula, which reflects the actual distributions and the correlations between the distributions, was created to calculate the probability distribution of performance degradations of Li-ion batteries. Usage data and capacity data on 126,742 cars of the 2013 model FIT HYBRID for the Japanese market were used to verify the validity of the formula that was created. The results show that the probability distribution of real capacity at 1.5 years after a vehicle is registered agrees with the probability distribution of estimated capacity after 1.5 years as calculated using the created formula. This verified the validity of the formula. This also successfully quantified the position of the capacity estimated using the estimated capacity degradation line foreseen during development with respect to the estimated probability distribution of performance after a target use period as 9.6σ . As it became possible to calculate the probability distribution of performance after degradation, this enabled optimal cost design of Li-ion batteries, bringing out the maximum vehicle performance of hybrid electric vehicles during the target use period.

1. Introduction

The performance of a Li-ion battery (LIB) means its capacity as well as its input and output power characteristics. A LIB degrades as it is used and as time passes. This has an influence on fuel economy and other such factors in hybrid electric vehicles (HEV) that have a LIB installed. Therefore grasping LIB usage and the extent of performance degradation in the users' usage conditions is crucial for the function design of LIB.

Honda started LIB installation in HEV with the 2012 model of Civic Hybrid for the North America market. Function design of LIB is conducted on the foundation of surveys of the past users' usage conditions and engineering expertise. In order to obtain users' usage conditions and performance statuses of LIBs, all HEVs equipped with

LIBs store the data of their performance status and usage in their on-board electric control units (ECUs), which are measured by on-board sensors and calculated by the ECU. The accumulated data is collected non-periodically at Honda dealers during vehicle inspections and other such occasions by means of the Honda Diagnostic System (HDS)⁽¹⁾. The collected data is sent to Honda servers for analysis and use⁽²⁾. When the collected data was analyzed, it became apparent that there was a margin between the LIB capacities in the users' usage conditions and the estimated capacity degradation line that is foreseen during development to show the most rapid degradation, and between the input and output power characteristic values in the users' usage conditions and the line of input and output power characteristics degradation estimation that is foreseen during development to show the most rapid degradation.

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As an example, Fig. 1 shows the estimated capacity degradation line foreseen during development and the capacity calculated by ECU in 126,742 cars of the 2013 model FIT HYBRID for the Japanese market.

It is apparent from Fig. 1 that comparison shows that there is a margin between the estimated capacity degradation line foreseen during development and the capacities in the users' usage conditions.

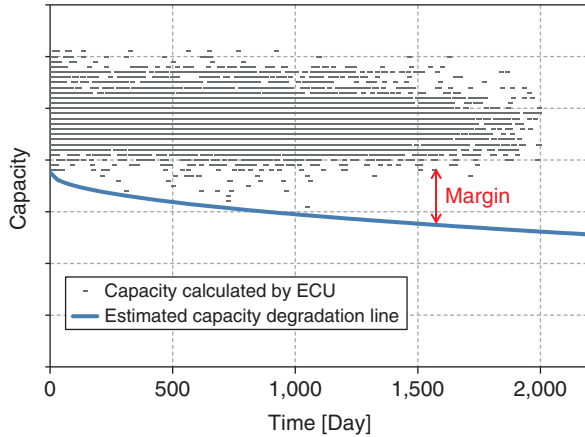


Fig. 1 LIB capacity of FIT HYBRID calculated by ECU

2. Current Issues

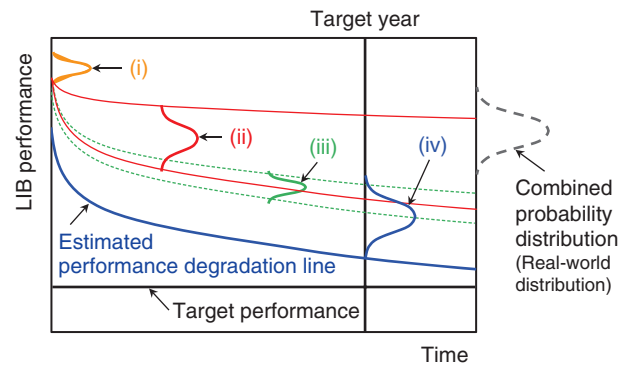
In order to analyze the causes of the margin noted in the previous chapter, the factors in LIB performance after degradation were broken down into the following four component factors of performance: (i) initial performance distribution, (ii) degradation distribution created by different usage patterns, (iii) degradation distribution of LIB within an identical set, and (iv) distribution created by ECU calculation errors.

The (i) initial performance distribution is due to variations between individual batteries, found in component materials that occur during the LIB manufacturing process and that affect initial LIB performance. The (ii) degradation distribution created by different usage patterns is defined as the distribution in the extent of degradation in LIB performance caused by HEV use by various different users under various different driving conditions and environmental conditions. The main factor in occurrence of the degradation distribution created by different usage patterns is the differing rates of LIB degradation that are due to the differences in current load on the LIB during driving and differences in the ambient temperatures of the LIB. The (iii) degradation distribution of LIB within an identical set is defined as the distribution in the extent of degradation in LIB performance that occurs when LIBs that initially have identical performance are used under identical usage conditions and identical environmental conditions.

The cause of degradation distribution of LIB within an identical set is the variation in LIB component materials that occurs during the manufacturing process and influences the rate of degradation. The (iv) distribution created by ECU's calculation errors is the error that occurs when the ECU calculates LIB performance, and it includes sensor error and control error. Use of these four distribution factors makes it possible to break down LIB performance after degradation into its component factors without omission or repetition.

As shown in Fig. 2, the estimated performance degradation line foreseen during development is defined by conditions under which every distribution factor simultaneously shows severe extreme values. On the other hand, once the probability distribution of LIB performance after a target use period, which is made up of these distribution factors, as estimated during development, had been calculated, nothing had been done to confirm where the estimated performance degradation line foreseen during development would be positioned on the estimated probability distribution.

Generally, the factors that accelerate LIB performance degradation are said to be the LIB temperature, charge and discharge current values, and the usable state of charge (SOC) or voltage width⁽²⁾. Examination of the (ii) degradation distribution created by different usage patterns, such as the performance degradation line foreseen during development for the LIB installed on the FIT HYBRID, shows that they have been calculated for conditions in which the most severe corner-case values that could be foreseen occur simultaneously for each of these degradation accelerating factors (Table 1).



	Distribution factor	Value for estimation
(i)	Initial performance distribution	Lower specification limit
(ii)	Degradation distribution created by different usage patterns	Most severe usage profile
(iii)	Degradation distribution of LIB within an identical set	-3σ of distribution
(iv)	Distribution created by ECU's calculation errors	-3σ of distribution

Fig. 2 Factors of LIB performance degradation

Table 1 Usage factors in performance degradation for FIT HYBRID LIB

Usage factors in performance degradation		Test condition of durability test based performance estimation line
Drive	LIB temperature	Highest operational limit
	Charge and discharge pattern	Follows hardest pattern among all drive patterns
	Charge and discharge time	Longest time among real-world data
Park	LIB temperature	Highest temperature profile among major cities
	Voltage or SOC	Highest operational limit

However, analysis of LIB usage began to make it clear that the main degradation factors showed a margin between the most severe usage conditions foreseen during development and the actual usage conditions experienced by users (Figs. 3, 4, and 5).

It can also be seen from Figs. 3 and 4 that LIB temperature and charge and discharge current both show a margin between the upper limit values and lower limit values of LIB usage in the zone of accelerated performance

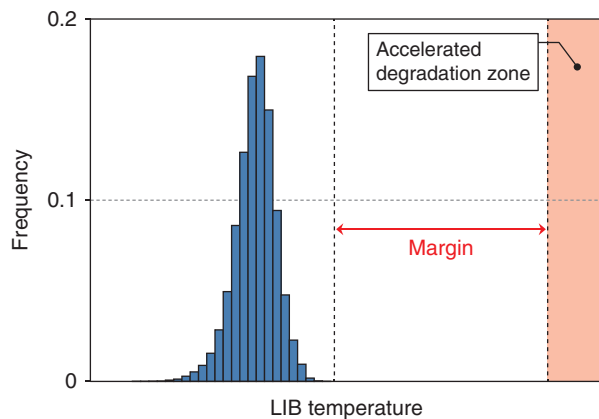


Fig. 3 LIB temperature during operation

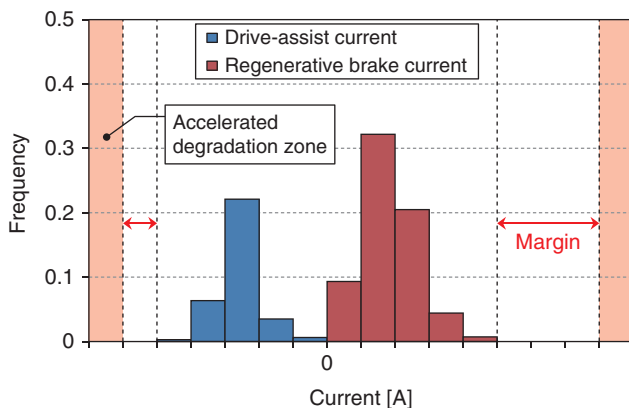


Fig. 4 Current during operation

degradation and the users' usage conditions. Similarly, Fig. 5 shows that there is a margin between the SOC envisioned as undergoing the most severe degradation and the upper limit value for SOC in the users' usage conditions.

As these findings suggest, LIB function design was carried out for conditions that can be expected to cause the most severe degradation among the conditions foreseen because of the desire to provide satisfactory LIB target performance at a high reliability level during the target use period.

On the other hand, HEV design is carried out on the assumption that fuel economy and other such factors of vehicle performance will be maintained during the target use period. Since it is equipped with a LIB that degrades over time, the HEV is designed according to the criteria of LIB performance values after the target use period. If we take the hypothetical case of a LIB that is under-valued for performance after target use, then this would mean that the vehicle performance during the target use period is under-configured.

In order to extract the maximum HEV performance during the target use period, it is necessary to accurately estimate the LIB performance after the target use period, and to design the vehicle performance according to those accurate performance values. For that purpose, it is necessary to accurately estimate the changes in LIB performance distribution according to how they occur in the actual users' usage conditions and to design LIB performance following target use with adequate reliability. In order to design LIB performance and reliability quantitatively, it is necessary to calculate LIB performance after degradation in the users' usage conditions as a probability distribution.

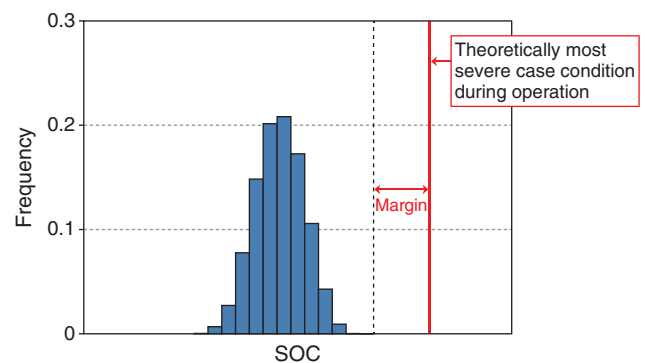


Fig. 5 SOC during park

3. Development Aims

For the purpose of extracting the maximum HEV performance during the target use period, the probability distribution of LIB performance degradation in the users' usage conditions needs to be calculated. The distribution created by ECU calculation errors has an influence on

the values calculated for LIB performance when installed in a vehicle, but it does not have any influence on LIB performance itself. Therefore it was excluded from the examination in this paper, and the following three points were taken as the main aims.

- (1) To accurately grasp the three factors of distribution that make up LIB performance: (i) initial performance distribution, (ii) degradation distribution created by different usage patterns, and (iii) degradation distribution of LIB within an identical set.
- (2) To accurately grasp the correlations among the above factors (i), (ii), and (iii) of distribution (to include non-linear correlations).
- (3) To create a method for convolution of distributions that incorporates (1) and (2), and to calculate LIB performance after degradation in the users' usage conditions as a probability distribution.

4. Creation of a Method for Calculation of the Probability Distribution of Performance after Degradation

4.1. Method for Grasping Correlations Between Distribution Values and Distribution

Table 2 summarizes the methods used to achieve the aim given in the previous chapter by grasping the distribution values that make up LIB performance as well as the correlation between the distributions.

The (i) initial performance distribution can be grasped from the data provided by LIB manufacturers on LIB performance values during the production process. When the number of samples and the period of initial performance distribution data are inadequate, it is also possible to use the initial performance distribution estimated from the process

Table 2 Methods to find distributions or correlations

Distribution or correlation		Method to find
Distribution	(i) Initial performance	Production history or production process
	(ii) Usage degradation	Models -Vehicle performance -LIB degradation
	(iii) Degradation within identical set	Durability tests
Correlation	(i) and (ii)	Models -Vehicle performance -LIB degradation
	(ii) and (iii)	Durability tests under various usage conditions
	(iii) and (i)	Durability tests of LIB with various initial performance levels

control values (for example, design target centers, upper and lower specification limits, and production capacity index) for the production process.

The (ii) degradation distribution created by different usage patterns, and the correlation between (i) and (ii), are derived using the vehicle model and LIB degradation estimation model (Fig. 6). The vehicle model will take LIB initial performance and time series speed, outside air temperature, and amount of solar radiation as its input, and will output the LIB applied voltage changes for the corresponding vehicle. The LIB degradation estimation model calculates the LIB voltage, current, and temperature in time series corresponding to those applied voltage changes, and based on the changes in those calculated values, it outputs the amount of LIB degradation.

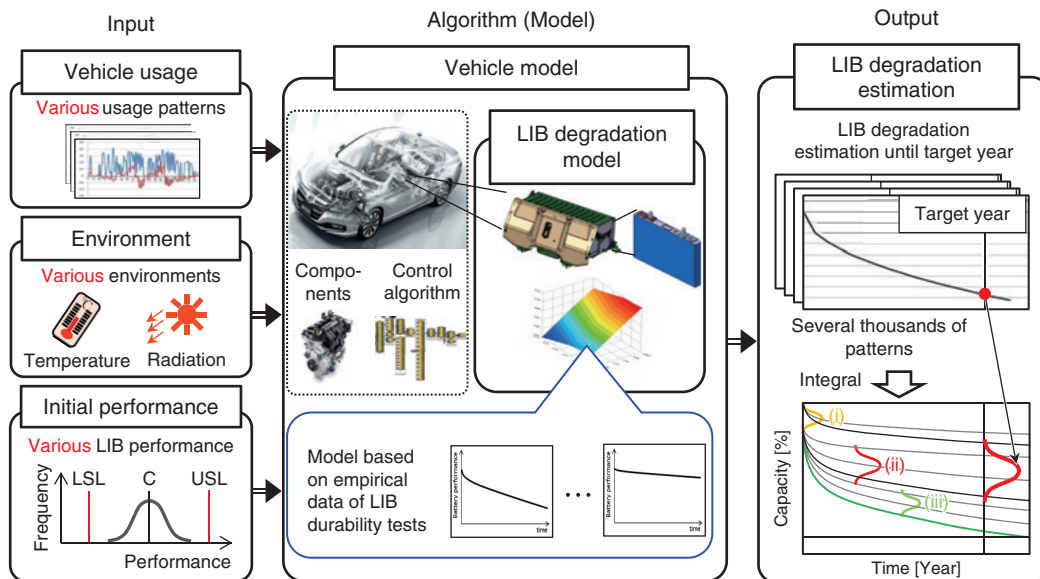


Fig. 6 Models for estimating performance degradation

As to the degradation distribution created by different usage patterns, this occurs as a result of vehicle usage under a variety of different conditions. Given constraints on resources, however, patterns of voltage changes in an enormous number of vehicles cannot readily be applied to an actual LIB to determine the distribution of degradation. Therefore models are used to calculate this distribution. In order to determine the degradation distribution created by different usage patterns in the case of a certain initial performance, a variety of different usage conditions are input to the model, with the initial performance held constant. This yields a variety of LIB degradation changes corresponding to the usage. Taking the frequency of occurrence into consideration, the numbers of iterations are added together from the data obtained, which is in the range of several thousands of items, and this makes it possible to grasp the degradation distribution created by different usage patterns. As to a grasp of the correlation between (i) and (ii), a variety of different usage conditions are similarly input into the model, but the initial performance is varied when this is done. Doing this makes it possible to grasp the influence on the degradation behavior when the initial performance is varied, or in other words the correlation between (i) and (ii).

The (iii) degradation distribution of an LIB within an identical set, as well as the correlation between (ii) and (iii) and the correlation between (iii) and (i), can be grasped by means of durability testing of multiple LIBs. As shown in Fig. 7, durability tests that keep the initial performance fixed and vary the usage, as well as durability tests that keep the usage fixed and vary the initial performance, are both implemented. This makes it possible to grasp the correlation with the distribution values. The causal factor for occurrence of degradation distribution of LIB within an identical set is the distribution of the LIB process factors that have not emerged in the initial performance. This means that in either test, the initial performance is made generally identical for multiple cells, and those trial objects should be randomly selected from the process line.

4.2. Creation of a Method for Convolution of Distribution Factors

A method for convolution of the distribution factors (i), (ii), and (iii) was created on the basis of the correlations that were grasped.

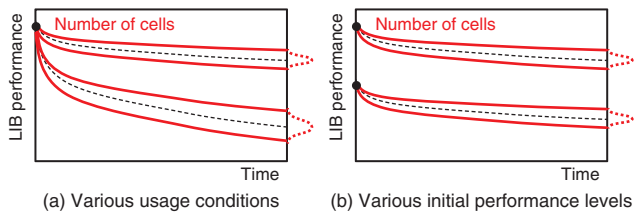


Fig. 7 LIB durability tests to obtain degradation distribution within identical set

Regarding the correlation of (i) and (ii), the results of simulation performed using models have shown that this is not a simple linear correlation, but rather a conditional probability distribution. This means that if the initial performance differs, then the probability distribution of performance degradation, created by different usage patterns obtained from applying multiple differing power changes to the LIB, will differ. This is because even if the same power changes are applied to the LIB, if the initial performance is different, then there will be differences in the LIB usable SOC range, the applied current, the resulting LIB temperature, and other such quantities.

With regard to the correlations between (ii) and (iii), and between (iii) and (i), it was also found from durability tests that here, too, the correlation is not linear, but is a conditional probability distribution. This means that even if durability tests are conducted from the same initial performance, if the usage differs, then the probability distribution of performance after degradation distribution will differ. Also, even if the usage is the same, if the initial performance differs, then the probability distribution of performance after degradation distribution will differ.

Consequently, vehicle usage is divided into environmental conditions and driving conditions, and put as follows.

Initial performance: Per_{ini}

Environmental conditions (time series data set for air temperature and amount of solar radiation): Env

Driving conditions (time series data set for vehicle speed, etc.): $User$

Performance after degradation: Per

The conditional probability density function for performance, after degradation when a certain initial performance, environmental conditions, and driving conditions are given, including (iii) degradation distribution of LIB within an identical set, can be defined as follows.

$$g(Per|Per_{ini}, Env, User) \quad (1)$$

This means that when certain initial performance, environmental conditions, and driving conditions are assigned, the probability distribution of the corresponding performance after degradation distribution will be unique. For the probability density function $f(Per)$ of performance after degradation, which is what is ultimately desired here, it will suffice to use the approach of convolution, applying the probability density function formed from initial performance, environmental conditions, and driving conditions to this formula and convoluting it over the whole range. This can be expressed as follows.

$$f(Per) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(Per|Per_{ini}, Env, User) h(Per_{ini}) u(Env, User) dPer_{ini} dEnv dUser \quad (2)$$

Here $h(Per_{ini})$ is the probability density function of initial performance and $u(Env, User)$ is the simultaneous

density function for environmental conditions and driving conditions. Generally, there is no correlation between LIB initial performance and environmental conditions or driving conditions. However, since environmental conditions and driving conditions can be considered to have a correlation, a simultaneous density function is used for the expression.

The conditional probability density function in Eq. (1) is created from the simulation results with a model and a test of degradation distribution of LIB within an identical set. The probability density function for initial performance on the right side of Eq. (2) was established on the basis of data provided by LIB manufacturers. The simultaneous density function for environmental conditions and driving conditions was established from vehicle data collected in actual environments. However, it is permissible to use an estimated probability density function when development is still underway and fully reliable data is not available. It will be necessary to formulate an appropriate probability density function in accordance with the purpose.

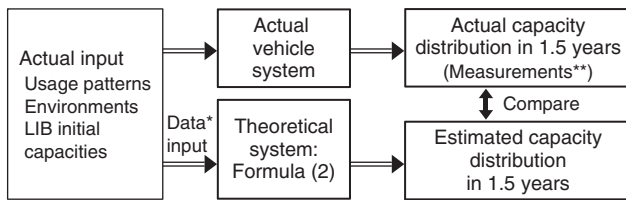
5. Equation Validity and Estimated Calculation

5.1. Verification of the Validity of Equation for Probability Distribution of Performance after Degradation

In order to verify the validity of Eq. (2) for the probability distribution of performance after degradation of a LIB in the users' usage conditions, a comparison was made of the probability distribution of real capacity of a LIB installed in an actual vehicle, and the probability distribution of estimated capacity calculated from data on actual LIB usage. The flow of comparison between the two is shown in Fig. 8.

When the probability distribution of estimated capacity becomes close to the probability distribution of real capacity, this means that the performance distribution is being correctly calculated and the validity of the equation can be demonstrated. As in a previous chapter, the validity of the equation was verified using data from the 2013 model FIT HYBRID for the Japanese market.

A vehicle model of the FIT HYBRID as described above was created for use in behavior analysis was used.



* Input data acquired through HDS or by LIB manufacturer

** Measurements acquired through HDS

Fig. 8 Analysis flow of comparison between actual and estimated capacity distributions

A model created for the LIB installed in the FIT HYBRID was used as the model for LIB degradation. Driving patterns, environmental conditions, and actual power data were collected by means of HDS, and the data on LIB initial capacity was obtained from the manufacturers of the installed LIB. The HDS's actual power data is for capacity calculated by the on-board ECU, so it includes estimation errors. In order to align the conditions of comparison, the distribution for capacity estimation errors obtained in previous testing was assigned for the probability distribution of estimated capacity.

Figure 9 shows a comparison of the probability distribution of real capacity and the probability distribution of estimated capacity at a point 1.5 years after vehicle registration.

The histogram in blue shows the probability distribution of real capacity, and the probability distribution marked in red shows the probability distribution of estimated capacity. It is apparent that the median values, the distribution

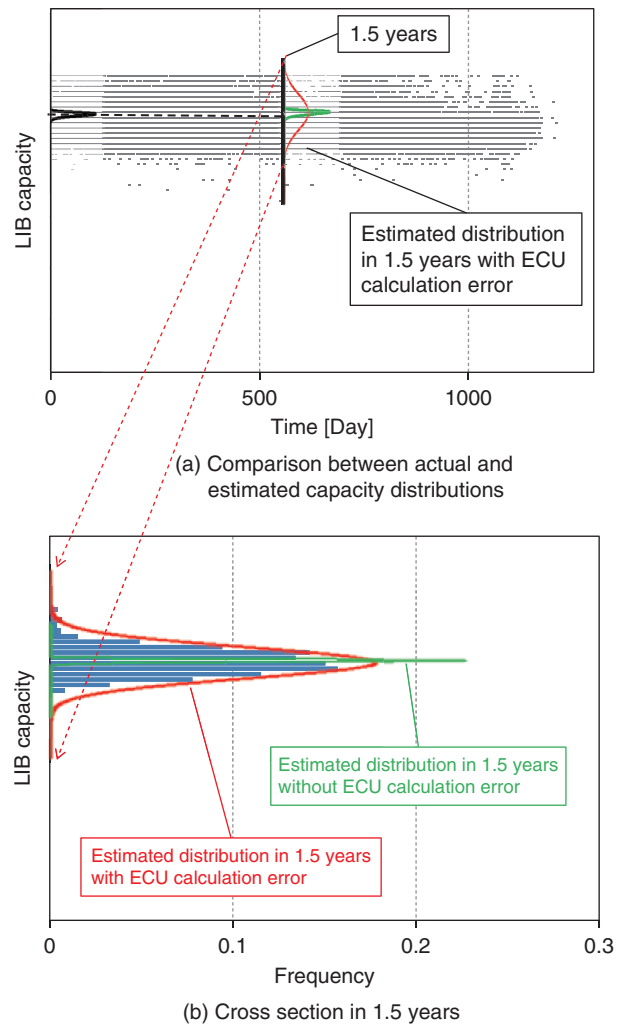


Fig. 9 Comparison between actual and estimated capacity distributions of LIB for FIT HYBRID

widths, and the distribution profiles for the probability distribution of real capacity and the probability distribution of estimated capacity generally coincide. This can be taken as demonstration that the probability distribution of performance after degradation is correctly calculated using the created equation.

5.2. Probability Distribution Estimation of LIB Performance after Target Use Period

Next, the probability distribution of LIB performance after a target use period is calculated. By comparing the probability distribution of performance after degradation with the estimated performance degradation line foreseen during development, the position of the estimated line in the users' usage conditions was quantified. Figure 10 shows the flow of comparison between these two.

In calculating the estimated performance degradation line foreseen during development and the probability distribution of performance after degradation in the users' usage conditions, the same models as those described in previous sections were used, vehicle models and LIB degradation models alike. The estimated line was calculated so that the (i) initial performance distribution, the (ii) degradation distribution created by different usage patterns, and the (iii) degradation distribution of LIB within an identical set would simultaneously show severe values, as described in chapter 2. On the other hand, in calculating a degradation distribution reflecting the actual environment, a continuing target period of use was assumed for the patterns of driving conditions and environmental conditions envisioning the actual environment that are for the purpose of calculating the (ii) degradation distribution created by different usage patterns, and the distribution obtained from the LIB manufacturers was used as the LIB data for (i) initial performance and for (iii) degradation distribution of LIB within an identical set.

Figure 11 shows the estimated probability distribution of LIB performance, after the target use period and the estimated performance degradation line foreseen during development to show the most rapid degradation both

plotted against capacity and input and output power characteristics.

The new creation of Eq. (2) and the distribution of input data made it possible to calculate LIB performance after the target use period as a probability distribution. With regard to the estimated probability distribution of LIB performance after the target use period, estimation performance using the estimated degradation line foreseen during development as indicating the most rapid degradation was quantified at 9.6σ for capacity and at 9.1σ for input and output power characteristics.

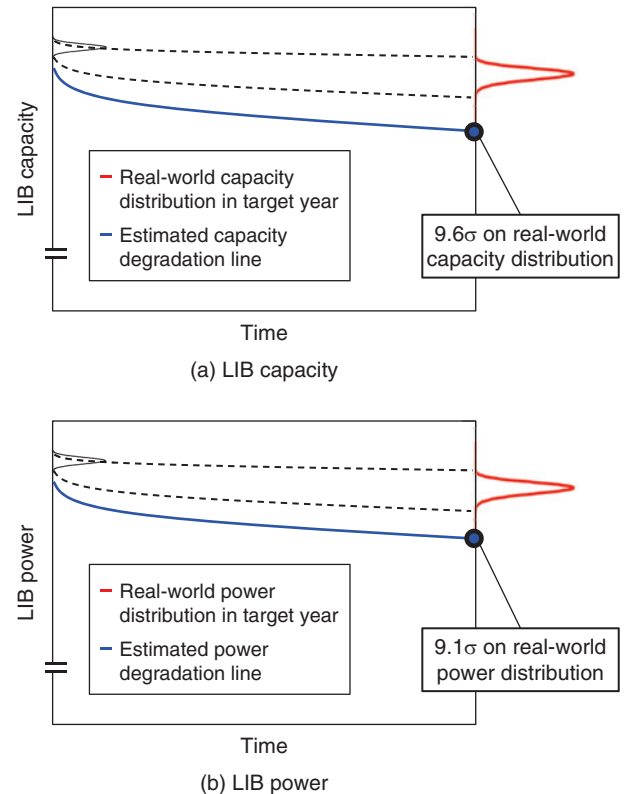


Fig. 11 Comparison between real-world performance distribution and estimated performance degradation line in target year

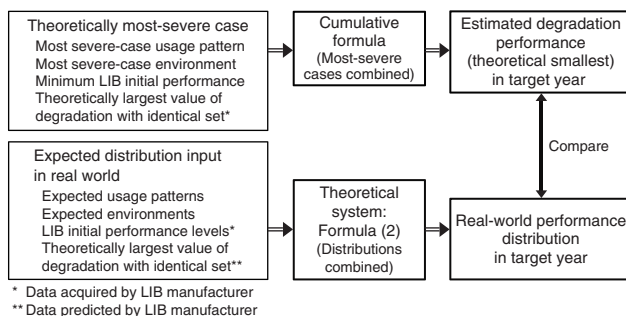


Fig. 10 Analysis flow of comparison between real-world performance distribution and theoretical smallest performance in target year

6. Value

Enabling calculation of LIB performance after the target use period, as a probability distribution, it became possible to design LIB performance and reliability in a quantitative manner. In a hypothetical case of LIB performance designed with excessive reliability in respect to the estimated probability distribution of LIB performance, optimization of the excessive reliability would yield the following two points of value.

The first value would be that, by reducing design performance until it is at an appropriate level of reliability,

LIB cost and LIB weight could be reduced (Fig. 12). When parts costs become more reasonable, it becomes possible to lower the HEV sale price, and that value can return to the user.

The second value would be in increasing the target for LIB performance after target use until it is at an appropriate level of reliability (Fig. 13). Doing this would make it possible to increase the value set for LIB performance in the vehicle that is to have the LIB installed, thereby making it possible to provide an HEV that has a higher performance in terms of fuel economy and other aspects of product appeal.

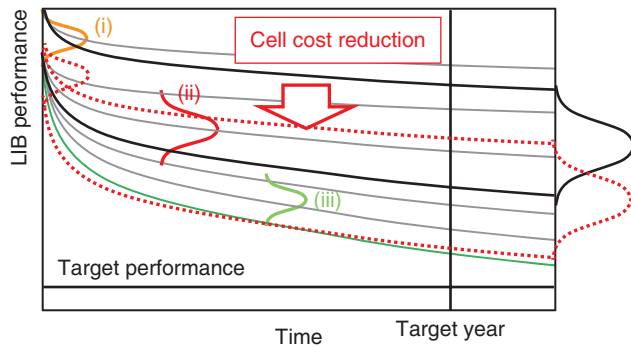


Fig. 12 First value option: Cell cost reduction

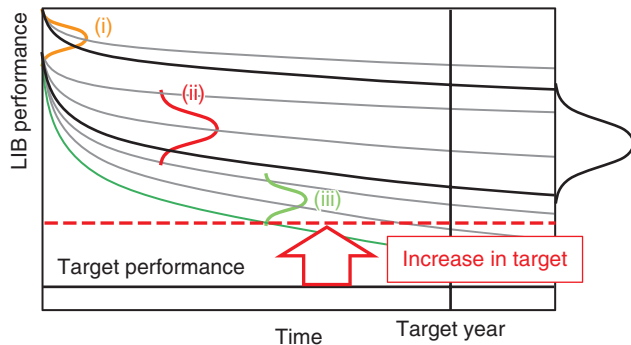


Fig. 13 Second value option: Increase in target

7. Conclusion

LIB usage and performance data for LIBs installed in user HEVs were collected by means of HDS and analyzed, yielding the following results.

- (1) The correlations between the (i) initial performance distribution, (ii) degradation distribution created by different usage patterns, and (iii) degradation distribution of LIB within an identical set were accurately grasped, and a formula was created to calculate the probability distribution of performance after degradation of a Li-ion battery that reflects those correlations.

- (2) Data on 126,742 FIT HYBRID cars was used to verify the validity of the created formula. In regard to the estimated probability distribution of LIB performance after the target use period, an estimation performance using the estimated degradation line, foreseen during development as indicating the most rapid degradation, was quantified at 9.6σ for capacity and at 9.1σ for input and output power characteristics.
- (3) Calculating the probability distribution of LIB performance enabled carrying out an optimal LIB cost and reliability design, as well as bring out the maximum vehicle performance of an HEV during the target use period.

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