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Development of Cycle Life Test Profiles of Lithium-ion Batteries for Plug-in Hybrid Electric Vehicles

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Abstract

Although life of lithium-ion batteries for electrically propelled road vehicles must be improved to promote the diffusion of the vehicles, currently there is no testing standard for those batteries. Therefore in this study, formulation method of cycle life test profile of lithium-ion batteries for plug-in hybrid electric vehicles was studied. As a result, following prospects looked brighter; Simplified "L" profile realize equivalent battery load with that of actual vehicle driving by conforming (1) peak, (2) energy, (3) rest-time rate and (4) joule heat of cycle life test profile to that of complicated charge-discharge wave on actual vehicle.

Keywords: cycle life, lithium battery, PHEV (plug in hybrid electric vehicle), simulation, standardization

1 Introduction

To promote high-performance batteries for use in “next-generation vehicles” such as plug-in hybrid electric vehicles (PHEVs), hybrid electric vehicles (HEVs), battery electric vehicles (BEVs) and fuel cell vehicles (FCVs), it is important to increase research-and-development efficiency for these batteries by establishing a standardized test procedure on battery performance and safety. However, there are only two such technical standards currently existing, one for BEV lead-acid batteries and BEV nickel-metal hydride (NiMH) batteries and the other for HEV NiMH batteries; both Japan Electric Vehicle Association Standards (JEVS). There is no standard for lithium-ion (Li-ion) batteries considered the most prospective successor to the NiMH batteries.

Since fiscal 2007, therefore, JARI has engaged itself in the development of a test method on Li-ion battery cycle life, taking into account actual Li-ion battery usage conditions [1]. With the above background, this paper reports formulation methodology for a Cycle Life Test Profile (CLTP) and the CLTP developed by JARI for PHEV Li-ion batteries.

2 Development Procedures for CLTPs

The CLTP of JARI was developed according to the following procedures. First, the existing battery test methods such as JEVS and the U.S. “FreedomCAR Battery Test Manual for Plug-in Hybrid Electric Vehicles” were researched to find out what are the characteristics of CLTPs and to outline a desirable CLTPs to be developed. Next, parameters influential on battery life were extracted, and a CLTP simplification method from vehicle-driving charge-discharge data (VCDD) considering extracted parameters was devised. The simplification method was examined from the standpoint of battery temperature rise. Then CLTPs for PHEV were formulated by applying the simplification method to the VCDD acquired from simulations and vehicle tests.

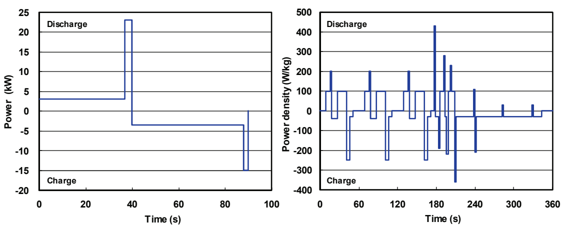
3 Setting of a CLTP Target

3.1 Investigation of the existing CLTPs

To help develop from VCDD a simplification method for CLTP, the characteristics of CLTP were investigated from the stipulations of the JEVS, the U.S. "FreedomCAR Battery Test Manual for Plug-in Hybrid Electric Vehicles", the VDA's proposed test method on HEV Li-ion battery systems, and the U.S. Electric Power Research Institute (EPRI)'s Sprinter PHEV battery test project.

As a result it was found that basically two versions of test profiles exist. As shown in Figure 1(a) and (b), there are two kinds of profiles, one is a highly simplified profile made up of one unit of profile repeating itself, and the other is a more complex profile consisting of several different profile units. In addition, as shown in Table 1, existing CLTPs were found to have the following characteristics.

- Wave profile: Rectangular
- Scales: Power output, power ratio, power density, discharge rate
- No. of input-output steps: 1 ~ 18 steps
- Minimum duration: 2, 5, 8 seconds
- Test time: 60, 90, 180, 300, 360 seconds



(a) PHEV (FreedomCAR) (b) HEV (JEVS D716)

Figure 1: Examples of existing CLTPs

3.2 Development Target of CLTP

Based on the research results of existing CLTP, the development target of CLTP was set as follows:

- Battery load should be equal to the VCDD of transient driving cycle in order to enable the prediction of deterioration advance during vehicle driving.
- To improve national receptivity when a CLTP is to be proposed to the ISO, the desirable CLTP should be universal and not preferential to a certain nation(s) or region(s). Specifically, the CLTP needs to be formulated using all the VCDD of subject vehicles driven according to the emission and fuel economy certification test cycles of Japan, the U.S. and Europe (i.e., JC08, UDDS and NEDC).
- The test procedure shall be as simple as possible to enable the use of widely available charge-discharge testing machines and facilitate the analysis of deterioration factors. Specifically, the minimum duration of CLTP should be 2 seconds and its wave profile be rectangular with the smallest possible number of input-output steps.

4 Devising of a Simplification Method

4.1 Extraction of Relevant Parameters

In the testing of the battery's charge-discharge cycle life, the following 6 types of parameters are considered influential on battery life:

a) I_{max}	: Max. current	A
	or	
P_{max}	: Max. power	W
b) Q_{tot}	: Charge-discharge electricity	Ah
	or	
E_{tot}	: Charge-discharge energy	Wh
c) R_{SOC}	: SOC range of charge-discharge	%
d) t_{rest}	: Rest time ratio	%
e) H_{gen}	: Amount of heat generation	J
f) T_{rise}	: Battery temperature rise	⊿C

Table 1: Comparison of existing CLTPs

Target vehicle		BEV		HEV		PHEV (CD mode)		PHEV (CS mode)	
Test procedure		JEVS D708 (1)	JEVS D708 (2)	JEVS D716	VDA	FreedomCAR	EPRI	FreedomCAR	EPRI
Definition unit		Discharge rate	Proportion of the maximum power	Power density	Discharge rate	Power	Power	Power	Power
Wave profile		Rectangular	Rectangular	Rectangular	Rectangular	Rectangular	Rectangular	Rectangular	Rectangular
Number of power steps	Discharge	2	4	7	4	7	18	2	18
	Charge	1	3	7	5	4	10	2	10
Minimum duration (s)		5	8	2	5	2	2	2	2
Test time (s)		60	360	360	300	360	180	90	180

When a CLTP of a certain duration is assumed, the above parameters a), b), c) and d) relate to the structural change and relaxation of electrode active materials, while the parameters a), d), e) and f) relate to the heat generation and radiation of the battery.

Viewing from the perspective of driving a vehicle, battery burden is expressed in terms of electric power instead of current. Since voltage varies according to battery types, current may differ even though power is equal between two batteries. Consequently current values are expressed in terms of power values. Explanations of the selected parameters are as follows:

a) The greater the maximum power P_{max} is, the faster the deterioration is advanced [2].

b) The charge-discharge energy E_{tot} can be represented by Equation (1) below.

$$E_{tot} = \int |P(t)| dt \qquad (1)$$

c) The range of the state of charge (SOC) R_{soc} during charging can be made a constant if the upper and lower limits of SOC is fixed in a cycle life test.

d) The rest time ratio t_{rest} can be represented by Equation (2) below.

$$t_{rest} = \sum \Delta t(I = 0) / t_{cycle} \qquad (2)$$

Where t_{cycle} means the time required for one cycle.

e) The amount of heat generation H_{gen} is the time integral of internal resistance R and current I square. Assuming that both internal resistance R and voltage V are constant throughout the charge-discharge process, H_{gen} can be represented by Equation (3) where current I is replaced by power P.

f) A battery temperature rise is determined by the balance between heat generation H_{gen} and heat radiation H_{rad}. As shown by Equation (3) above, heat generation H_{gen} is a value intrinsic to the battery and CLTP. However, since heat radiation H_{rad} is variable by the ambient conditions of the battery, H_{rad} is excluded from among the parameters.

$$H_{gen} = \int R[I(t)]^2 dt = a \int [P(t)]^2 dt \quad (3)$$

Where a means the coefficient related to heat generation amount.

Evident from the above, to extract from VCDD and simplify a CLTP for PHEV batteries, it is important to equalize with VCDD the time average values of the 4 parameters (i.e., max. power P_{max}, charge-discharge energy E_{tot}, rest time ratio t_{rest}, and heat generation H_{gen}).

4.2 CLTP Simplification Method

In light of the conclusion of the preceding section and the development target established in section 3.2, CLTP simplification methodology is examined as follows:

4.2.1 Calculation of Average Values of the Certification Driving Cycles of Japan, the U.S. and Europe

To formulate a CLTP capable of representing the total 42 trips contained in the JC08, UDDS and NEDC with only one trip, the average time of "Trip+Idle" and "Trip" in the three test cycles was calculated respectively. As shown in Table 2, the average length of "Trip+Idle" turned out to be 89.4 seconds and of "Trip" to be 67.7 seconds when the three test cycles are added together. As shown in Figure 2, the former average time is equivalent to the test time per CLTP cycle, and the latter is equivalent to the time between vehicle start and vehicle stop (i.e., from discharge start to charge end). The average vehicle speed is 29.89 km/h.

Table 2: Average of three driving cycles

Item	Unit	JC08	UDDS	NEDC	Integrated
Test time	(s)	1204	1371	1180	3755
Driving distance	(km)	8.172	11.989	11.013	31.175
Number of trips	(piece)	11	18	13	42
Average of (trip + idle) time*1	(s)	109.5	76.2	90.8	89.4
Average trip time*2	(s)	77.0	61.7	68.2	67.7
Average speed	(km/h)	24.43	31.48	33.60	29.89

Average of (trip+idle) time*1 = Test time / Number of trips
Average trip time*2 = Summation of each trip time / Number of trips

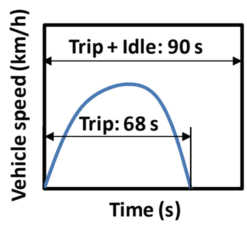


Figure 2: Image of average driving cycle

4.2.2 VCDD Sorting and Compression

The following procedures (1) and (2) are taken to obtain compressed data on the basis of which the target CLTP will be formulated, and an example of formulation is shown in Figure 3.

(1) The VCDDs of JC08, UDDS and NEDC are stringed together into a total 3,755-second data, and the combined data are rearranged from large to small values irrespective of driving pattern.
(2) Thus the total 3,755-second data are compressed into a 90-second data.

4.2.3 Simplification

The target CLTP are formulated by applying the following rules to the compressed data:

(1) The wave profile shall be rectangular, and the minimum duration be at least 2 seconds. Power density shall be the scale item to be applied for the time being.
(2) There shall be two steps (high power P_H and low power P_L) on each of the charge and discharge counts. Two-second VCDD per test cycle (6-second VCDD considering 3 test cycles) shall be extracted, and the average value divided by time is adopted as the maximum power P_{max}.
(3) By adjusting the time ratio of high and low steps (ratio of t_H to t_L) and the value of low power P_L, the values of charge-discharge energy E_{tot} and heat generation H_{gen} shall be made as much identical as possible to the compressed data without changing the rest time ratio t_{rest} (Figure 4). In the CS mode, the ratio of charge to discharge shall be equalized with the battery's energy efficiency (in this study, discharged electric energy / charged electric energy = 0.95) in order to maintain the SOC constant.
(4) To match the time from discharge start to charge end with the time from vehicle's starting/acceleration to deceleration/stopping (68 seconds in this study), the data on the charge side shall be moved forward. To match with discharge data, the compressed data shall be rearranged from inversed L to non-inversed L (Figure 5).

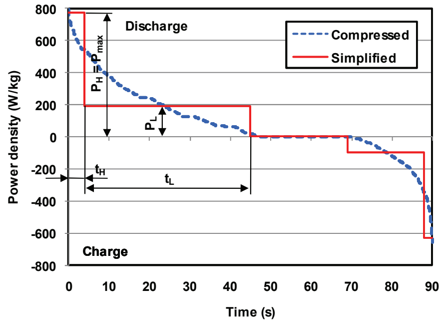


Figure 4: Simplification of compressed data

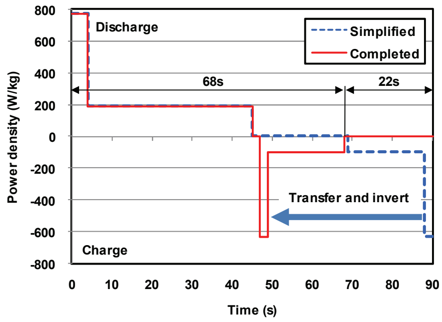


Figure 5: Transfer and invert of charge side data

4.3 Demonstration of the Simplification Method

4.3.1 Demonstration Test Method

To examine the CLTP simplification method from the standpoint of thermal load on the battery, a

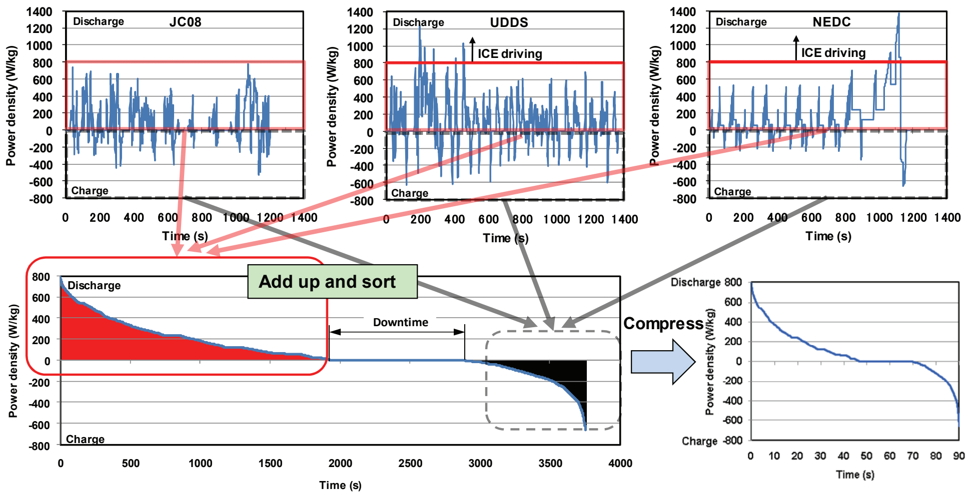


Figure 3: Sorting and compression of VCDD

single-cell test was conducted using 5 types of wave profiles (i.e., the original VCDD in UDDS for an HEV, compressed profile, and three simplified profiles with different peak pulse widths). Then, their effects on battery temperature rise were investigated.

To obtain a clear battery temperature variation, the power density was increased 1.5 times and the laminated lithium polymer cell was insulated with urethane foams. The ambient temperature was set at 25 ± 2 ºC, and the power generation as well as current and voltage of the CLTP were measured with the thermocouples attached to the cell surfaces. The five types of wave profiles used in the test are summarized in Table 3 and Figures 6 and 7.

Table 3: Five types of wave profiles for verification of simplification method

Name of profile	Feature	Time (s)
Original VCDD	Charge–discharge profile of an actual HEV (1/10 second step)	1371
Compressed profile	Eighteenth part of original VCDD, and sorted	76
Simplified profile – 1	Pulse width of peak is 1 second (Charge–discharge energy is equal to compressed profile)	76
Simplified profile – 2	Pulse width of peak is 2 second (Charge–discharge energy is equal to compressed profile)	76
Simplified profile – 3	Pulse width of peak is 3 second (Charge–discharge energy is equal to compressed profile)	76

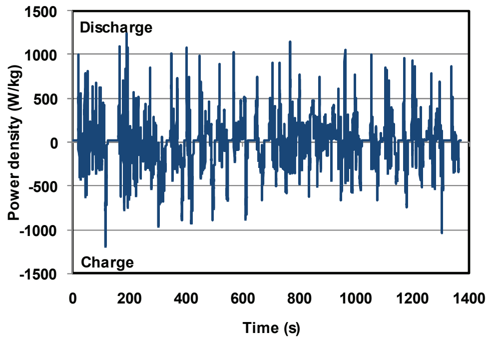


Figure 6: Original VCDD of a representative HEV

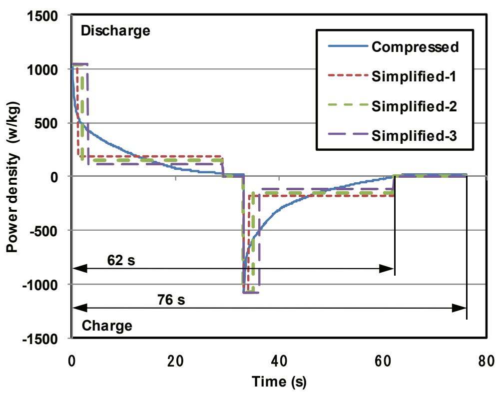


Figure 7: Compressed and simplified CLTPs

4.3.2 Results of the Demonstration Test

Figure 8 shows the measurement results of battery temperature rise after repeating the original VCDD 10 times, the compression profile and simplified profiles each 180 times. While temperature rise behaviors are equivalent among the original, compression and simplified profile-1, the temperature rose notably higher as the peak width widened in the case of simplified profile-2 and -3. Concerning the same data, Figure 9 reports the effect on battery temperature rise of joule heat generation calculated from the measured values of electric current. Evidently, battery temperature rise is dependent more or less totally on the amount of joule heat.

The above results suggest that it is possible to formulate an effective CLTP by equalizing with VCDD the time average values of four parameters--the maximum power P_{max}, charge-discharge energy E_{tot}, rest time ratio t_{rest}, and heat generation H_{gen}.

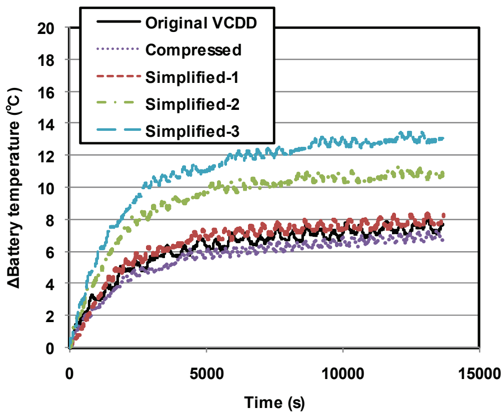


Figure 8: Comparison of battery temperature raise

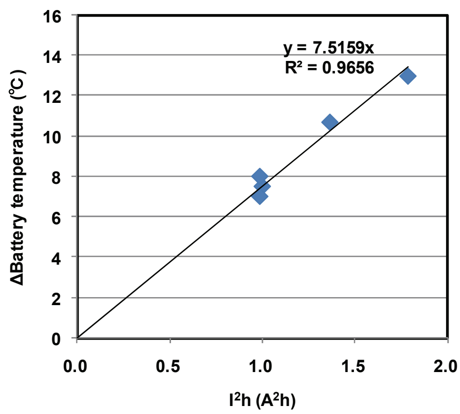


Figure 9: Relationship between square of current and battery temperature raise

5 Formulation of CLTPs for PHEV

5.1 Acquisition of VCDD

A CLTP was formulated, assuming PHEV belonging to a most representative passenger car class in the Japanese market. VCDD were acquired by the following method for the respective driving cycles of JC08, UDDS and NEDC.

5.1.1 Charge depleting (CD) mode

Assuming a PHEV with a 1,250 kg mass, VCDD were calculated through simulation technique. The specifications of the PHEV are listed in Table 4. For the specifications of the main battery, the development target values of the Li-EAD Project [3] were applied. For vehicle control, a blend type was adopted whereby motor drive was switched to engine drive when the power density of the battery pack reached 800 W/kg or higher.

5.1.2 Charge sustaining (CS) mode

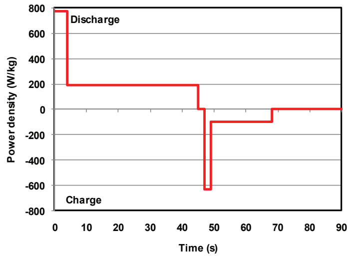
Using a representative strong HEV with a mass of 1,260 kg which is practically identical with the mass of the above PHEV, battery output was measured by a chassis dynamometer test. The values obtained by dividing the measured output value by 30 kg (development target for battery packs) were adopted as VCDD.

Table 4: Specifications of a supposed PHEV

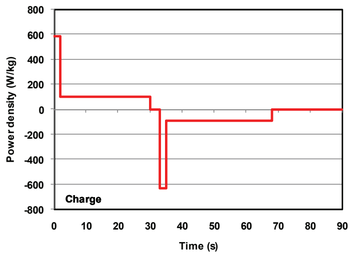
	Parameter	Set value	Remarks
Mass	Vehicle mass (kg)	1250	Japan's representative sedan
	Equivalent rotational part mass（kg）	43.75 (3.5% of vehicle mass)	From TRIAS (light-duty vehicles)
	Passenger mass（kg）	110 (for 2 persons)	From TRIAS (light-duty vehicles)
Road load	Rolling resistance coefficient	0.01	From data base
	Air resistance coefficient $(N/(km/h)^2)$	0.0343	From data base
Powertrain efficiency	Motor efficiency	0.9	Typical efficiency
	Transmission efficiency	0.95	From TRIAS (heavy-duty vehicles)
	Final gear efficiency	0.95	From TRIAS (heavy-duty vehicles)
Battery system	Rated energy (kWh)	3	From project target
	Energy density (Wh/kg)	100	From project target
	Power density (W/kg)	2000	From project target
	Mass (kg)	30	From project target
	Maximum power (kW)	60	From project target
	Discharging efficiency	0.975	From project target
	Charging efficiency	0.975	From project target
	SOC range (%)	90-30	From project target
Other	Braking method	Regenerative braking only	Supposed ideal condition

5.2 Application of the Simplification Method to VCDD

By applying the simplification method to the VCDD acquired as per the preceding section, a CLTP for PHEV was formulated. The formulated CLTP is as shown in Figure 10 and Table 5. The peak output proved to be slightly below 800 W/kg in the CD mode and slightly below 600 W/kg in the CS mode. While the CD mode provided a discharge energy 2.8 times greater than the CS mode, the former's charge energy was 0.7-fold of the latter. This difference is attributable to the fact that the CD mode assumes charging only by regenerative braking but the CS mode assume charging by the engine in addition to regenerative braking.



(a) CD mode



(b) CS mode

Figure 10: Power density CLTPs for PHEV

Table 5: CLTPs for PHEV

PHEV state	Step No.	Step time (s)	Cumulative time (s)	Power density (W/kg)	Power (W)	Energy (Wh)
CD	1	4	4	774.3	23229	25.81
	2	41	45	190.4	5712	65.05
	3	2	47	0.0	0	0.00
	4	2	49	-630.3	-18909	-10.51
	5	19	68	-94.9	-2847	-15.03
	6	22	90	0.0	0	0.00
CS	1	2	2	581.0	17430	9.68
	2	28	30	102.0	3060	23.80
	3	3	33	0.0	0	0.00
	4	2	35	-630.3	-18909	-10.51
	5	33	68	-89.9	-2697	-24.72
	6	22	90	0.0	0	0.00

6 Conclusion

The present study examined CLTP formulation methodology allowing the use of widely available charge-discharge testing machines while reproducing the realworld battery load during vehicle driving. It was confirmed that the use of a simple L-type CLTP does not affect battery temperature rise if the charge-discharge peak value, total energy, rest time ratio and joule heat are equalized with the original VCDD. Accordingly, using this methodology, a CLTP was formulated for PHEV batteries.

Future tasks will be to further improve the original VCDD for CLTP, to review in detail the validity of the simplification method, and to examine the scale. These and other tasks will be addressed in a steady manner.

Acknowledgments

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