32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19 - 22, 2019

Analysis of Degradation Mechanisms of Electric Vehicle Batteries Using Driving Data

Nobuo Kihira[1], Takuya Nayuki, Tomohiko Ikeya

[1]Central Research Institute of Electric Power Industry (CRIEPI), 2-6-1 Nagasaka Yokosuka-shi Kanagawa-ken 240-0196, Japan, kihira@criepi.denken.or.jp

Summary

To develop a new method for estimating the degradation level of EV battery, we constructed a device that collects data on vehicle states, and analysed the EV driving test data collected by that. The apparent discharge capacity (Q_{355V}) and apparent resistance at SOC 100% (R_{SOC100}) were calculated using the collected data to create a 2D map for estimating the capacity of EV battery. A correlation was confirmed between Q_{355V} and R_{SOC100}. However, since the solid electrolyte interphase growth which is one of the degradation factors for lithium ion batteries is affected by the temperature, it is necessary to correct the correlation between Q_{355V} and R_{SOC100} by the temperature.

Keywords: battery ageing, battery SoH, diagnosis, internal resistance, lithium battery

1 Introduction

Wider adoption of electric vehicles (EVs) is expected to decrease CO_2 emissions from the transportation sector. CO_2 emissions can be reduced further by charging EVs using low-carbon power sources such as renewable energy and nuclear power, and by running EVs with high efficiency.

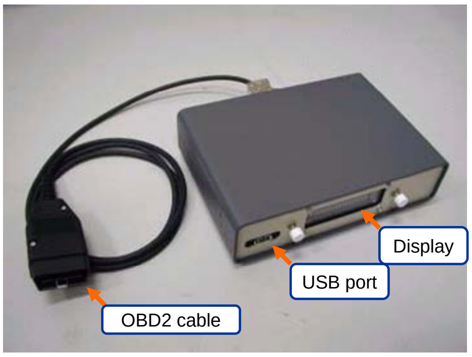
A problem with EVs that must be addressed is degradation of onboard batteries. As the batteries degrade, the battery capacity decreases and the battery internal resistance increases, which leads to a decrease in the discharge capacity and driving range per charge. This degradation cannot be suppressed, and it is difficult for drivers to understand the level of degradation. To operate EVs more efficiently, it is important to monitor the degradation state of the battery quantitatively, so that the EV user can predict the travelable distance for daily driving and the battery maintenance time.

We have built an onboard auxiliary device that can monitor the battery voltage, current, and temperature as well as driving speed using a controller area network (CAN). To develop a method for estimating the degradation level of the battery easily, we have been collecting data about EV driving in a city and analysing the degradation factor of the battery.

2 EV Driving Test

2.1 Onboard Auxiliary Device

We constructed an onboard auxiliary device to monitor vehicle information from the CAN interface via the diagnostic connector (Figure 1). The vehicle information collected by the device was state of charge (SOC), cruising range, battery current, battery voltage, driving speed, cumulative mileage, and battery temperature. The vehicle information data were stored in the USB memory as time series data at 1 s intervals via the device USB interface.



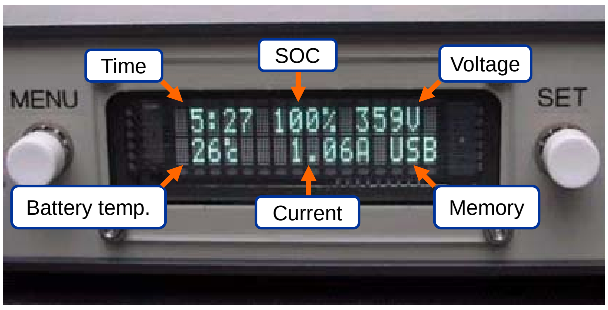


Figure 1: Photographs of the onboard auxiliary device.

2.2 Driving Test Procedure

Six Nissan LEAFs, which have a 24 kWh/360 V battery system and a driving range of 228 km per charge in JC08 mode, were used in a driving test.

The procedure for the driving test was as follows.

Step 1. LEAF was fully charged in normal charge mode (AC 200 V).

Step 2. LEAF was driven while monitoring the battery voltage, current, and speed until the panel meter indicated that recharging was needed.

Step 3. LEAF was recharged in normal charge mode, and the charging capacity was recorded.

In Steps 2 and 3, vehicle information was collected by the onboard auxiliary device.

During the driving tests, accessories, such as air conditioning and heating, were operated appropriately to maintain the driver's safety and a comfortable environment.

Figure 2 (a)–(d) show examples of EV driving data for the changes in battery voltage, current, battery temperature, and vehicle speed collected by the onboard auxiliary device when driving on the highway for about 2 h and the city area for about 1 h (total of 3 h). The data provided the following results.

(1) The current changed greatly with acceleration and deceleration (for example, from +120 to −120 A at the end of discharge).

(2) Regenerative charging (current value in the negative region) occurred during deceleration.

(3) Battery temperature increased (23 to 30 °C) as the battery voltage decreased (390 to 275 V).

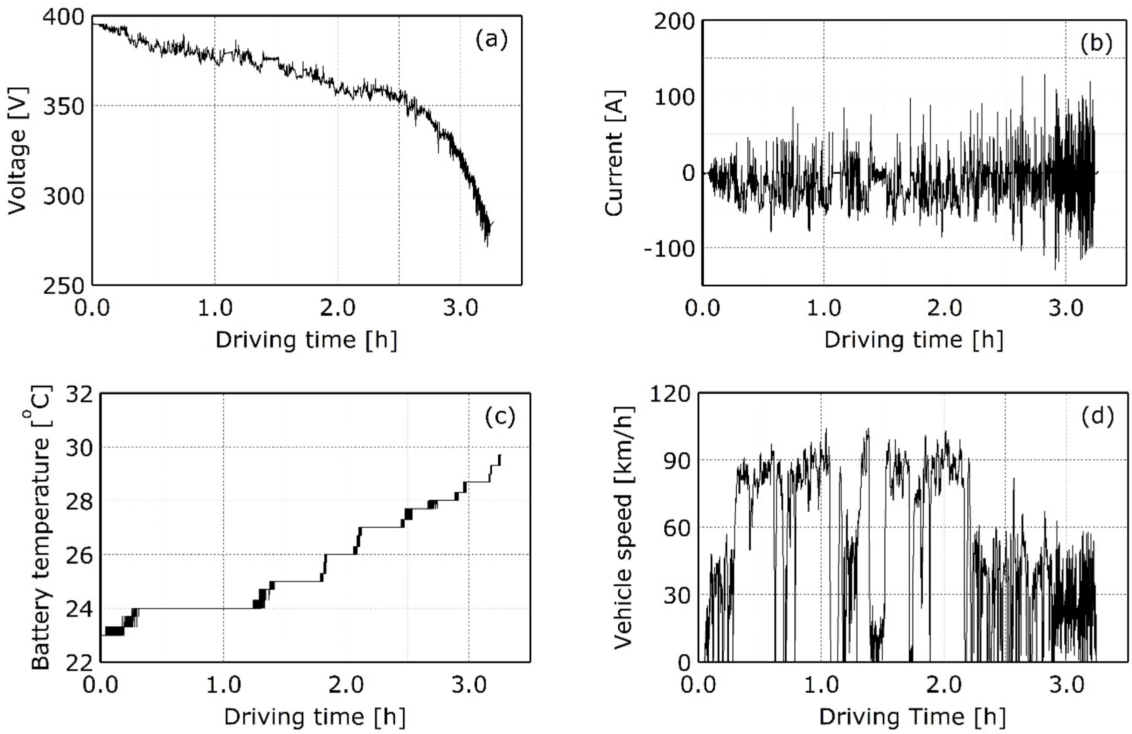


Figure 2: Examples of EV driving data collected by the onboard auxiliary device.
(a) Battery voltage, (b) current, (c) battery temperature, (d) vehicle speed.

3 Results and Discussion

3.1 Simulation of Discharge Voltage Curve of EV Battery with Pseudo Constant Current

The discharge capacity was calculated by integrating the battery current values measured at 1 s intervals, assuming that all regenerative currents were charged and considering regenerative charging. Figure 3 shows a plot of the battery voltage against the discharge capacity (Ah) calculated by this method. Generally, a discharge voltage curve with a constant current is used to evaluate the discharge characteristics and discharge capacity of a battery. However, because the voltage and current fluctuation is large due to acceleration and deceleration, the discharge characteristics of the battery are difficult to determine and are unsuitable for judging the capacity reduction in Figure 3. Therefore, the apparent internal resistance value (R_{app}) was calculated from the correlation between the battery voltage and the current value in each discharge state. The dependence of the voltage on the current value was corrected by R_{app} to simulate the discharge voltage curve with a pseudo constant current (0 A).

Figure 4 shows the voltage plotted against the current for data in the range of ±0.5 Ah in the discharge capacity cross section every 10 Ah from 10 to 30 Ah. The data were extracted on the discharge side only (excluding regenerative charging) and on condition that the current value increased from the point 1 s previously. A linear relationship was obtained for all discharge capacities. The slope of the straight line was determined as R_{app} in the discharge capacity cross section. Using the average value of R_{app}, a pseudo discharge voltage curve at 0 A constant current discharge was simulated (Figure 5). Compared with the measured curve, the voltage fluctuation was small in the simulated curve.

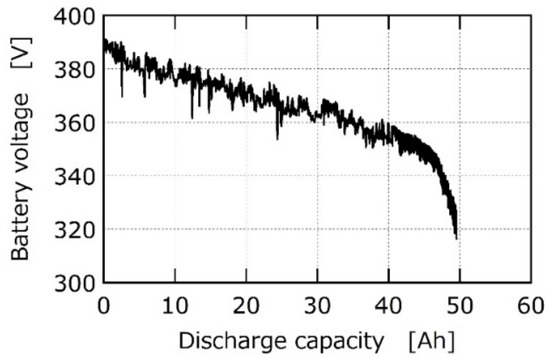


Figure 3: Plot of battery voltage against discharge capacity

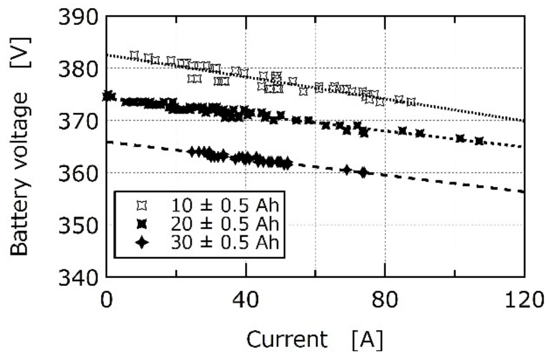


Figure 4: I-V characteristics at each discharge capacity cross section

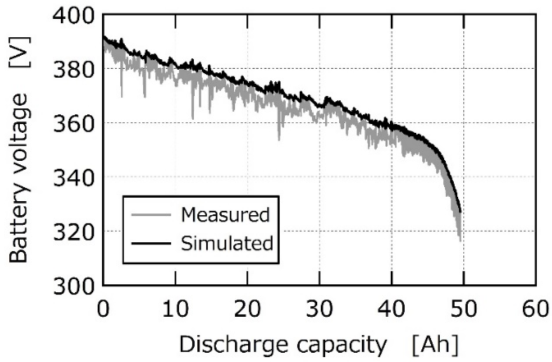


Figure 5: Pseudo constant current discharge curve simulated by voltage correction

3.2 Representative Value for Degradation of Battery Internal Resistance

Because the progress of the degradation reaction in lithium ion batteries depends on the usage conditions and environment, the internal state of battery is not necessarily the same even if the capacity reduction is similar. The average value of R_{app} in each cross section of the discharge capacity can represent the battery internal resistance in each driving test. However, because the driving conditions at each discharge capacity vary with each driving test, R_{app} cannot be used as a representative value for degradation.

The change in R_{app} against the discharge capacity every 1 Ah is shown in Figure 6. As the discharge progressed, R_{app} decreased gradually at a steady rate. This correlation between R_{app} and the discharge capacity indicated the characteristics of the onboard battery. Figure 6 also shows the time-dependent change of R_{app} at each discharge capacity in a driving test conducted at the same battery temperature. The slope of the correlation remained similar, but the *y* intercept (R_{app} at SOC 100%) increased. Therefore, we used R_{app} at SOC 100% (R_{SOC100}) as a representative value for the degradation of the internal resistance of the EV battery.

R_{SOC100} calculated from the data from each driving test was plotted against the cumulative mileage (Figure 7 (a)) and the square root of days elapsed (Figure 7 (b)). There was no correlation between R_{SOC100} and the cumulative mileage, whereas R_{SOC100} increased with the square root of days elapsed. Thus, days elapsed mainly affected the increase in R_{SOC100} due to the degradation of the battery.

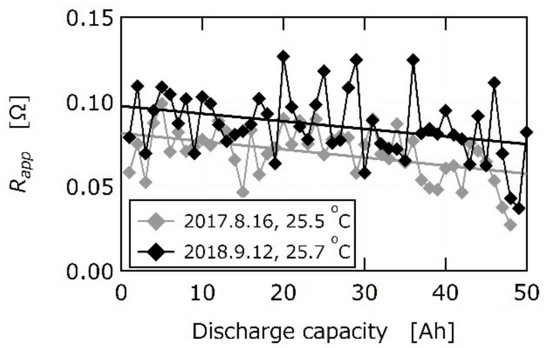


Figure 6: Plot of R_{app} against the discharge capacity (every 1 Ah)

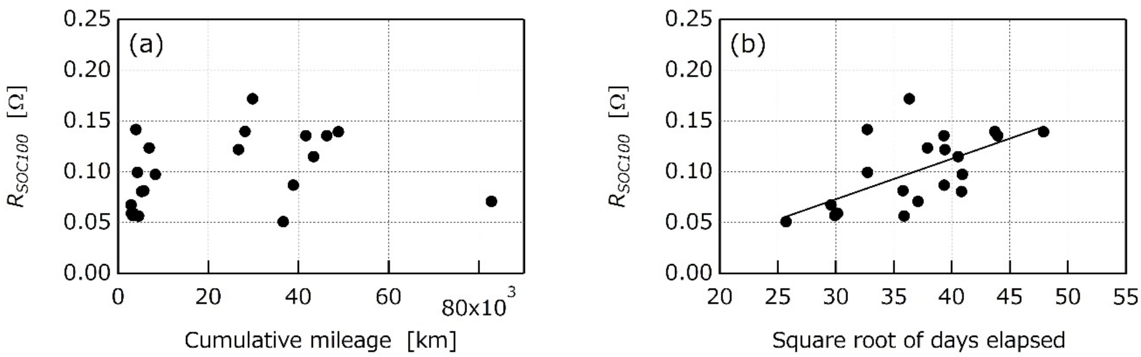


Figure 7: Plots of R_{SOC100} against the cumulative mileage (a), and the square root of days elapsed (b)

3.3 Estimation of Dischargeable Capacity from Battery Internal Resistance

Using the discharge voltage curve with a pseudo constant current, the apparent discharge capacity (Q_{355V}) when the temporary discharge limit was set to 355 V was calculated (Figure 8). For each driving test, Q_{355V} was calculated with the simulated pseudo constant current discharge curve.

Figure 9 shows R_{SOC100} plotted against Q_{355V}. As Q_{355V} decreased, R_{SOC100} increased. Although there was a correlation between Q_{355V} and R_{SOC100}, there were variations in the regression line. The average battery temperature during the driving test was about 10 °C for the points that were above the regression line and about 40 °C for the points that were below the regression line. At low temperatures, the resistance increased as the ion diffusion rate in the battery decreased, and at high temperatures, the resistance decreased as the ion diffusion rate in the battery increased.

Therefore, the plot in Figure 9 was divided into three regions according to the average battery temperature during the driving test (Figure 10). Regression analysis of the plots in each temperature region revealed that the slope of the regression line decreased as the average battery temperature increased. This result suggests that the effect of battery temperature cannot be ignored when evaluating R_{SOC100}.

Based on these results, it should be possible to estimate the battery capacity by using the correlation between R_{SOC100} and Q_{355V}; however, further analysis considering the effect of battery temperature is necessary. Therefore, we will continue to collect EV driving data to develop a method of estimating the degradation level of the onboard battery by clarifying the relationships among discharge capacity, internal resistance, and battery temperature.

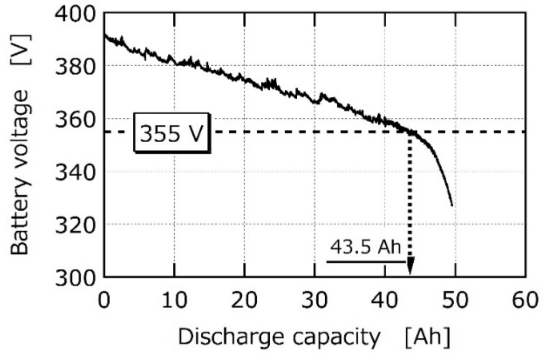


Figure 8: Diagram of the calculation method of Q_{355V}

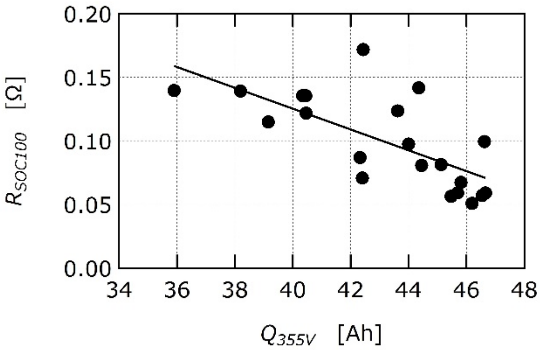


Figure 9: Plot of R_{SOC100} against Q_{355V}

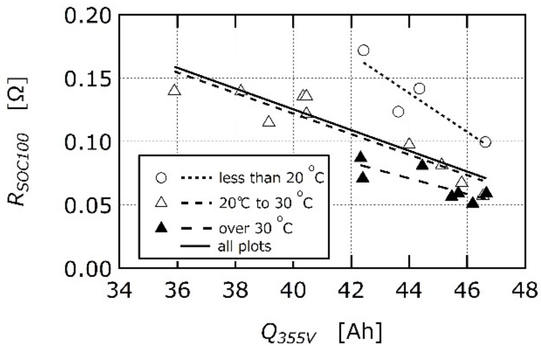


Figure 10: Plot of R_{SOC100} against Q_{355V} divided into three regions according to the average battery temperature during driving test.

3.4 Degradation Mechanisms of EV Batteries

For lithium ion batteries, it is proposed that the capacity reduction due to battery degradation is proportional to the square root of time elapsed [1], [2]. This is an empirical rule based on a model that the solid electrolyte interphase (SEI) layer grown on the negative electrode active material surface is proportional to the square root of the time elapsed. Lithium ions on the surface of the negative electrode active material react with the electrolyte to form SEI. Since lithium ions are consumed on the surface of the negative electrode active material by the growth of SEI, the chargeable / dischargeable capacity of the battery decreases in proportion to the square root of the time elapsed [1]. In addition, internal resistance of the battery and SEI thickness also increase with the increase in time elapsed and temperature [3]. Therefore, SEI formed on the surface of the negative electrode active material is considered to be one of the degradation factors of EV batteries.

4 Conclusions

Driving tests were carried out periodically using six EVs and driving data were collected. The data were compiled and analysed, and the results were as follows.

- Using the onboard auxiliary device, battery voltage, current, temperature, and vehicle speed, were measured during driving, and the apparent internal resistance was calculated from the driving data.
- The discharge voltage curve at a pseudo constant current was simulated by correcting the battery voltage with the apparent resistance (R_{app}), and the discharge capacity at the threshold value of 355 V (Q_{355V}) was calculated.
- R_{app} at SOC 100% (R_{SOC100}) was calculated from the correlation between discharge capacity and R_{app}. There was no correlation between R_{SOC100} and cumulative mileage, but there was a correlation between R_{SOC100} and the square root of days elapsed. This result suggests that the days elapsed mainly affected the increase of R_{SOC100} due to battery degradation.
- A correlation was found between Q_{355V} and R_{SOC100}. However, the battery temperature also affected R_{SOC100}. To develop a simple capacity diagnostic method for EV batteries, further analysis considering the effect of battery temperature is necessary.
- The solid electrolyte interphase formed on the surface of the negative electrode active material is considered to be one of the degradation factors of EV batteries.

References

[1] H. Yoshida, N. Imamura, T. Inoue and K. Komada, *Electrochemistry*, 71, 1018 (2003).

[2] M. Broussely, S. Herreyre, P. Biensan, P. Kasztejna, K. Nechev and R. J. Staniewicz, *J. Power Sources,* 97-98, 13 (2001).

[3] T. Yoshida, M. Takahashi, S. Morikawa, C. Ihara, H. Katsukawa, T. Shiratsuchi, and J. Yamaki, *J. Electrochem. Soc.*, 153 (3), A576 (2006)