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Analysis of Adverse Effects on Vehicle Performance Due to Hybrid Vehicle Battery Deterioration

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Abstract

This paper presents the results of analysis into the adverse effects on vehicle performance caused by the deterioration in capacity and increase in resistance of lithium-ion batteries installed in hybrid electric vehicles (HEVs). Detailed evaluations were conducted based on simulations to determine the adverse effects on HEV performance. It was concluded that the battery resistance at which the CO_2 emissions rate and the Fuel Consumption reaches 120% of the level of a new vehicle is approximately 350% of the initial battery resistance value.

Keywords: environment, HEV (hybrid electric vehicle), internal resistance, lithium battery, vehicle performance

1 Introduction

In recent years, the electrification of the automobile has been vigorously promoted from the standpoint of addressing environmental and energy problems. This paper summarizes the results of research into the permissible deterioration of the battery, which is considered the heart of an electrically powered automobile.

Battery power deterioration naturally has an adverse effect on the power and environmental performance of the vehicle. However, the specifics and extent of this effect on vehicle performance differ greatly depending on the type of vehicle system. For example, the effects on vehicle performance are completely different if batteries with the same power deterioration characteristics are installed in a battery electric vehicle (BEV) or a hybrid electric vehicle (HEV). Consequently, it is important to determine the permissible battery deterioration for each type of vehicle system separately, based on the characteristics of the effects.

Consequently, this study examines the effects of battery deterioration on vehicle performance using an HEV equipped with a lithium-ion battery as the test vehicle. First, the study analyzed in detail the effect on vehicle performance as the battery deteriorated. Here, the research studied deterioration in battery capacity as well as deterioration in internal resistance. Subsequently, this battery deterioration data was utilized to determine the permissible deterioration of the HEV lithium-ion battery, with a particular focus on the effect on CO_2 emissions and fuel consumption.

2 Details of Simulation

2.1 Outline of Test HEV and Simulation

Table 1 shows the specifications of the vehicle, which is a passenger vehicle installed with a series-parallel hybrid system. The simulation model reproduces the power split device, which links the motor, engine, and generator, as well as phenomena such as engine cranking (Fig. 1) [1], [2], [3].

Table 1: Vehicle Specifications

	Parameter	Value
Vehicle	Curb Weight	1,310 kg
Engine	Max Power	73 kW@5,200 rpm
Motor	Max Power	60 kW
Generator	Max Power	30 kW
Battery	Voltage/ Weight	345 V/ 22.4 kg
	Number of Cells	92
	Capacity	6.5 Ah

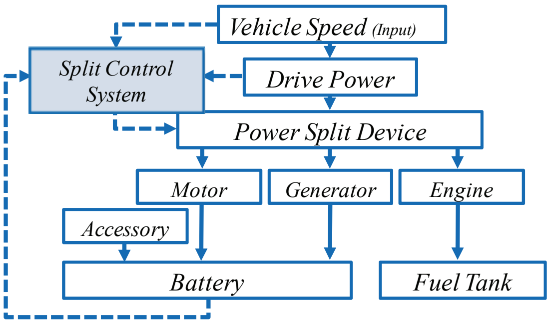


Figure 1: HEV Simulation Model

2.2 Engine ON Conditions

Table 2 shows the conditions under which the engine is switched on. The following three elements are used as the triggers: 1) required drive power, 2) vehicle speed, and 3) the state of charge (SOC) of the battery. These three elements are further divided into controls for high and low SOCs, and values were set independently for these two categories. When the vehicle is started, the engine is operated following the operating curve.

Table 2: Engine on Conditions

Control (SOC)	
Low (Under 32.5%)	High (Above 32.5%)
● Drive Power : 10 kW or Over ■ Vehicle Speed : 25 km/h or Over ◆ SOC : Under 30%	● Drive Power :15 kW or Over ■ Vehicle Speed : 55 km/h or Over ◆ (Engine OFF) SOC : Above 35%

2.3 Test Battery

Figure 2 shows the SOC dependency of the open-circuit voltage and the internal resistance of the test lithium-ion battery. In this study, the upper limit of the terminal voltage is 4.3 V and the lower limit is 2.5 V for both the new and the deteriorated batteries. In addition, a maximum discharge rate of 20C and a maximum charge rate of 10C were also set as limitations.

This paper defines capacity retention (*Cs* [%]) as the capacity of a new battery compared to the capacity of the battery after deterioration. Internal resistance increase (*Rs* [%]) is defined in the same way. The criteria for battery SOC are the capacity when the battery is new and the capacity of the battery after deterioration. Furthermore, battery capacity deterioration is assumed to have no effect on the SOC dependency of the open-circuit voltage.

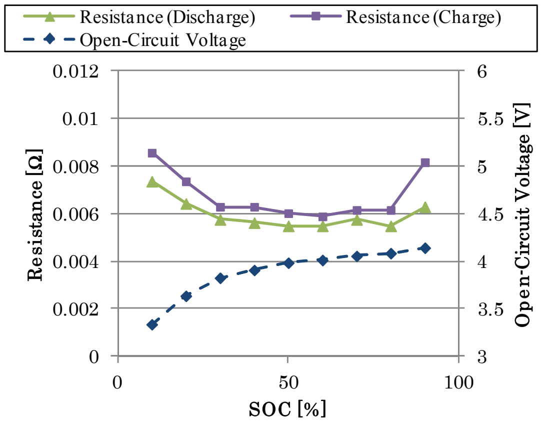


Figure 2: Characteristics of Internal Resistance and Open-circuit Voltage of the Lithium-ion Battery (Single Cell)

2.4 SOC Correction and Hot/Cold Start Correction for HEV

An evaluation of the fuel economy of an HEV must be performed under conditions where there is no difference in SOC before and after the vehicle is driven. Therefore, the fuel economy when ΔSOC=0 is estimated based on the results of a fuel consumption simulation with various initial SOC levels. The evaluation then uses this data as the corrected fuel economy.

Furthermore, this research performed a test cycle under both cold and warm start conditions. The fuel economy value was then calculated based on the following proportions: cold start = 25% and hot start = 75%. This made it possible to obtain results that considered the effect of warming up on fuel economy.

3 Effects of Deterioration in Capacity and Internal Resistance on Vehicle Performance

This section analyzes and evaluates the effects of lithium-ion battery capacity and internal resistance deterioration on vehicle performance, and describes the results of the tests. To make it easier to identify the effects on vehicle performance, the study first assumed that each of the following types of battery deterioration advanced independently.

3.1 Effects of Battery Capacity Deterioration

Table 3 and Fig. 3 show the simulation results for the effect of decreases in battery capacity on vehicle performance. These results confirmed that fuel economy (i.e., km driven per liter of fuel) worsened slightly when the capacity retention was 40%. This is because the SOC is more susceptible to fluctuation when the battery capacity decreases (Fig. 4), which increases the frequency at which a SOC of 35% is reached. Since the signal to switch the engine off is transmitted when the SOC reaches 35%, the number of times that the engine is turned ON and OFF also increases. This also leads to an increase in engine cranking, which involves large current flows, and causes an increase in internal resistance loss. However, the results also show that battery capacity deterioration has a very minor effect on vehicle performance.

Table 3: Relationship between Capacity Retention (*Cs*) and Fuel Economy

Cs [%]	Warm up conditions	Initial SOC [%]	Final SOC [%]	⊿SOC [%]	Fuel Economy [km/l]	Corrected fuel Economy [km/l]
100	HOT	35.00	35.78	-0.78	32.76	32.24
		32.50	35.79	-3.29	30.69	
		30.00	35.79	-5.79	28.76	
	COLD	35.00	35.79	-0.79	28.38	
		32.50	35.79	-3.29	26.68	
		30.00	35.22	-6.22	24.87	
80	HOT	35.00	36.63	-1.63	32.17	32.04
		32.50	36.61	-4.11	30.59	
		30.00	36.63	-6.63	29.10	
	COLD	35.00	36.64	-1.64	27.92	
		32.50	36.63	-4.13	26.59	
		30.00	36.63	-6.63	25.46	
60	HOT	35.00	37.11	-2.11	32.08	32.02
		32.50	37.11	-4.61	30.81	
		30.00	37.11	-7.11	29.53	
	COLD	35.00	37.15	-2.15	27.77	
		32.50	37.15	-4.65	26.74	
		30.00	37.11	-7.11	25.84	
40	HOT	35.00	37.97	-2.97	31.79	31.67
		32.50	38.13	-5.63	30.76	
		30.00	38.07	-8.07	30.07	
	COLD	35.00	38.14	-3.14	27.54	
		32.50	37.97	-5.47	26.95	
		30.00	38.07	-8.07	26.19	

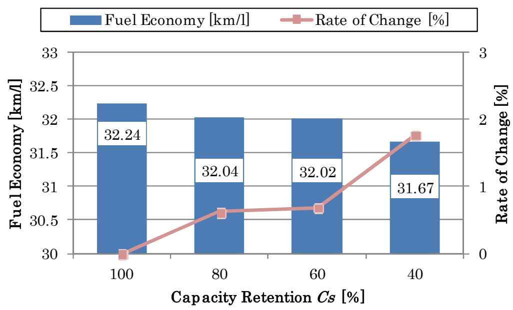


Figure 3: Relationship between Capacity Retention (*Cs*) and Fuel Economy

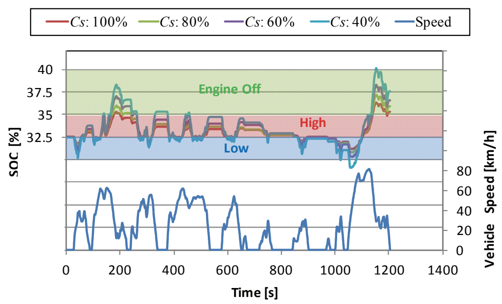


Figure 4: Change in SOC at Different Capacity Retention Values

3.2 Effects of Internal Resistance Increase

Table 4 and Fig. 5 show the simulation results for the effect of increases in internal resistance on vehicle performance. As shown in these results, an increase in internal resistance has a significantly greater effect on fuel economy than a reduction in battery capacity. This section evaluates the following performance values to consider the reason for this result.

Table 4: Relationship between Internal Resistance Increase (*Rs*) and Fuel Economy

Rs [%]	Warm up conditions	Initial SOC [%]	Final SOC [%]	⊿SOC [%]	Fuel Economy [km/l]	Corrected fuel Economy [km/l]
100	HOT	35.00	35.78	-0.78	32.76	32.24
		32.50	35.79	-3.29	30.69	
		30.00	35.79	-5.79	28.76	
	COLD	35.00	35.79	-0.79	28.38	
		32.50	35.79	-3.29	26.68	
		30.00	36.22	-6.22	24.87	
200	HOT	35.00	35.14	-0.14	31.78	30.80
		32.50	35.19	-2.69	29.72	
		30.00	35.60	-5.60	27.48	
	COLD	35.00	35.14	-0.14	27.51	
		32.50	35.20	-2.70	25.92	
		30.00	35.59	-5.59	24.17	
300	HOT	35.00	34.06	0.94	29.42	27.92
		32.50	34.07	-1.57	27.69	
		30.00	34.50	-4.50	26.12	
	COLD	35.00	34.06	0.94	25.90	
		32.50	34.06	-1.56	24.35	
		30.00	34.50	-4.50	23.21	
400	HOT	35.00	32.74	2.26	27.89	25.78
		32.50	32.72	-0.22	26.44	
		30.00	33.22	-3.22	24.86	
	COLD	35.00	32.72	2.28	24.43	
		32.50	32.73	-0.23	23.24	
		30.00	33.18	-3.18	21.51	
500	HOT	35.00	32.83	2.17	25.72	23.99
		32.50	32.83	-0.33	24.69	
		30.00	33.25	-3.25	22.75	
	COLD	35.00	32.84	2.16	23.07	
		32.50	32.83	-0.33	21.80	
		30.00	33.25	-3.25	20.44	

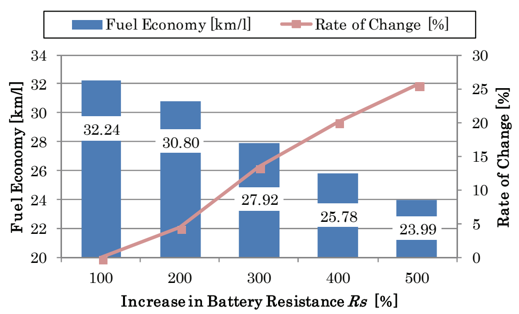


Figure 5: Increase in Battery Resistance and Fuel Economy Performance

■ Charge and discharge efficiency

The discharge efficiency (η_{dis}) and charge efficiency (η_{chg}) are derived via the following equations.

$$\eta_{dis} = \frac{\int (V_0 I_{dis} - I_{dis}^2 R)\, dt}{\int (V_0 I_{dis})\, dt} \times 100 \tag{1}$$

$$\eta_{chg} = \frac{\int (V_{chg} I_{chg} - I_{chg}^2 R)\, dt}{\int (V_{chg} I_{chg})\, dt} \times 100 \tag{2}$$

V_o : Open-circuit voltage [V]
V_{chg} : Terminal voltage during charging [V]
I_{dis} : Discharge current [A]
I_{chg} : Charge current [A]
R : Internal resistance [Ω]

■ Permissible recovery rate

The permissible recovery rate is an index that expresses how much the battery can be charged from the available power (through regenerative braking etc.) from the standpoint of input performance (determined by the upper limit voltage and maximum charge rate). See Equation 3.

Permissible recovery rate [%]

$$= \frac{\text{Amount of power actually charged [kWh]}}{\text{Amount of power supplied to battery [kWh]}} \times 100 \quad (3)$$

Fuel economy declines due to an increase in internal resistance for the following reasons.

The first reason is that both the charge and discharge efficiency of the battery decline. Figure 6 shows the efficiency values derived using Equations 1 and 2 above. In particular, the decrease in the discharge efficiency is quite pronounced. To clarify this effect, Fig. 7 shows the total battery energy and internal resistance loss per increase in internal resistance. The increase in internal resistance during discharge makes it more likely that the lower limit voltage will be reached, thereby limiting and reducing the current. The engine then must compensate for the insufficient battery power. As a result, the total battery discharge greatly reduces as the internal resistance rises. In contrast, during charging, the internal resistance can increase to 200% without reaching the upper limit voltage limit so the total energy input will rise in this range. However, when the internal resistance increase exceeds 300%, the upper limit voltage limit is reached and the energy input from charging then decreases. Nonetheless, this decrease is smaller than the total output. The loss increases for both energy input and output. Consequently, in the case of Equations 1 and 2 above, the increase in internal resistance has a larger adverse effect on discharge efficiency compared to charge efficiency.

The second reason is that when the internal resistance increase reaches 300% or higher, the power for charging the battery when the vehicle decelerates is limited. Figure 8 shows the charge efficiency (derived from Equation 2) and the permissible recovery rate of regenerated power (derived from Equation 3) per increase in internal resistance. It is possible to recover all regenerated power when the battery is new, but the permissible recovery rate is greatly reduced when the internal resistance increases. This results in a reduction in fuel economy.

Finally, the third reason for the reduction in fuel economy is that the engine ON time increases. Figure 9 shows the engine running time and increase as the internal resistance rises. This graph indicates that the engine running time increases in accordance with the internal resistance, which has an adverse effect on fuel economy. Furthermore, increased engine cranking also reduces fuel economy. However, compared to the three reasons described above, the adverse effect of additional engine cranking is only minor.

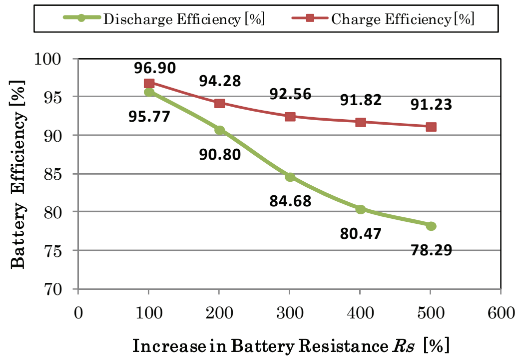


Figure 6: Charge and Discharge Efficiency when Internal Resistance Increases

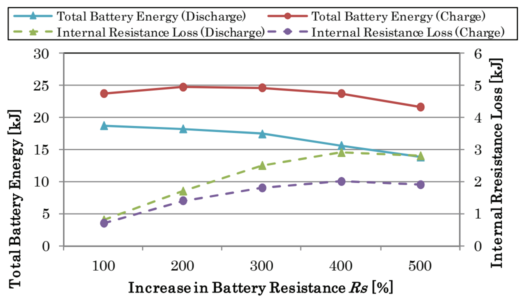


Figure 7: Total Battery Energy and Total Internal Resistance Loss during Charge and Discharge when Internal Resistance Increases

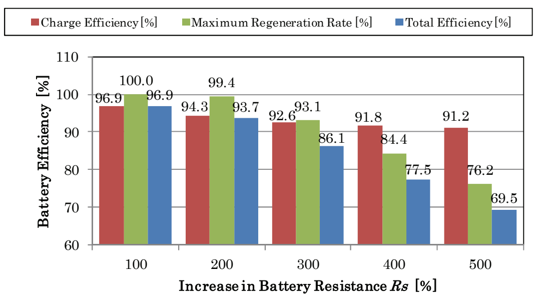


Figure 8: Charge Efficiency and Permissible Recovery Rate of Regenerated Power per Internal Resistance Increase

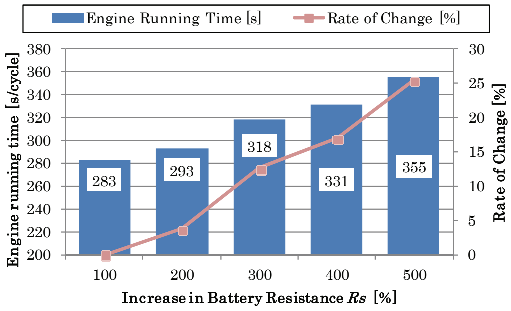


Figure 9: Increase in Battery Resistance and Engine Running Time

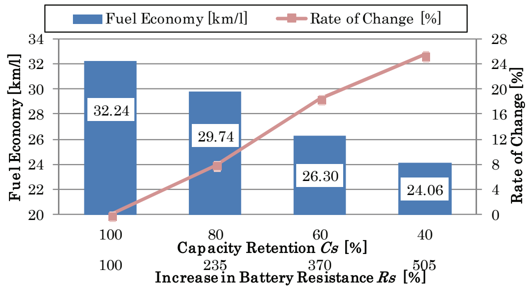
4 Effects of Simultaneous Deterioration in Capacity and Internal Resistance on Vehicle Performance

This section describes the results of an evaluation of simultaneous deterioration in battery capacity and internal resistance deterioration to reproduce actual usage conditions more closely. Table 5 compares these two types of battery deterioration. This table was created by referring to the results of a lithium-ion battery storage capacity loss test and then adopted in this analysis [4].

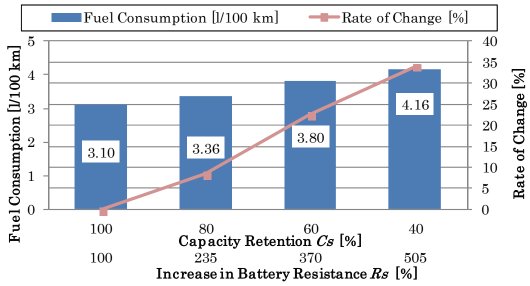
Figure 10 shows the relationship between the internal resistance increase *Rs* (with simultaneous deterioration in battery capacity) and fuel economy, fuel consumption. These results confirmed that simultaneous deterioration has a larger adverse effect on vehicle performance than the independent deterioration described in the previous sections. This can be explained by a combination of the previous results and observations of the adverse effects of these two battery deterioration phenomena.

Table 5: Relationship between *Cs* and *Rs* of Deteriorated Lithium-ion Batteries (Mn-type LIB)

	New	⇒		Deteriorated
Cs	100%	80%	60%	40%
Rs	100%	235%	370%	505%



(a) Fuel Economy



(b) Fuel Consumption

Figure 10: Effect of Battery Deterioration on Vehicle Performance under Actual Usage Conditions

5 Study of Permissible Battery Deterioration

This section examines the permissible battery deterioration, with a focus on well-to-wheel CO_2 emissions [5] and fuel consumption. The results of the analysis are summarized in Fig. 11. Battery deterioration that results in a 20% reduction in vehicle performance compared to a vehicle with a new battery can be defined as the permissible deterioration [6]. As shown in the figure, a 350% increase in internal resistance does not present any problems (when the battery capacity has deteriorated to approximately 60% of the initial value).

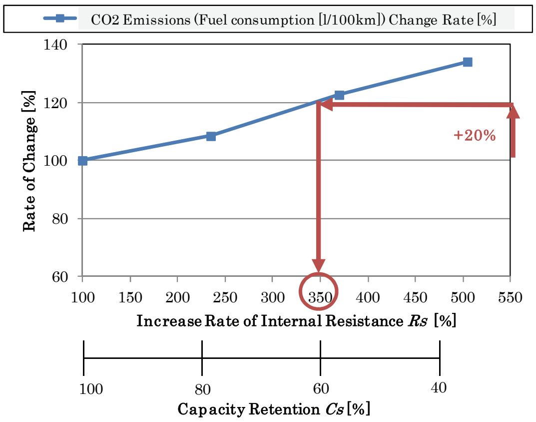


Figure 11: Examination of Permissible Battery Deterioration under Actual Usage Conditions

6 Conclusion

1. It was confirmed that deterioration in the battery capacity has only a minor adverse effect on the fuel economy and CO_2 emissions of an HEV.
2. In contrast, deterioration in the battery internal resistance has a large adverse effect on the fuel economy and CO_2 emissions of an HEV. Test results and analysis showed that this is directly caused by reductions in the charge and discharge efficiency, an increase in the engine running time due to greater limitations on battery discharge, and a decrease in the permissible recovery rate (an index that expresses how much the battery can be charged from the available power (through regeneration and the like) from the standpoint of input performance).
3. CO_2 emissions and fuel consumption were e valuated as indices of the effect on vehicle performance to examine the permissible battery deterioration. This research determined the permissible vehicle performance reduction to be 20%. It was confirmed that a 350% increase in internal resistance (with capacity retention of approximately 60% compared to a new battery) results in a 20% reduction in vehicle performance. Therefore, it is proposed that 350% internal resistance increase can be used to determine the permissible deterioration of lithium-ion batteries in an HEV.

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