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Investigation of CO_2 emissions in usage phase due to an electric vehicle - Study of battery degradation impact on emissions -

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Abstract

The CO_2 emissions due to an electric vehicle in usage phase were estimated in this study. In usage phase, there is a possibility that indirect emissions due to electric vehicles are increased by the variation of vehicles' performance, such as electricity consumption. In this paper, the impact of battery degradation on the vehicle's indirect emissions was focused on and the variation of energy efficiency, and influence of battery replacement of an electric vehicle were investigated. Battery degradation is one of several significant factors that can influence indirect emissions, because batteries are the single energy source of electric vehicles and batteries' degradations will influence vehicles' performance directly. In addition, batteries are large components in electric vehicles and their replacements also have large impacts on indirect emissions. The variation of energy efficiency by battery degradation was investigated by drive tests with a test electric vehicle. Both the timing and impact of battery replacement on indirect CO_2 emissions were estimated through the test of Li-ion battery cells. From the results, it was expected that battery replacement would have larger impact on indirect CO_2 emissions than the variation of energy efficiency. The obtained estimation of indirect CO_2 emissions for 100,000 km driving was compared with the emissions from an internal combustion engine vehicle.

Keywords: Electric vehicle, CO_2, lithium battery, degradation

1 Introduction

The transport sector of Japan emits a large amount of CO_2 and reducing CO_2 emission due to vehicles is a significant challenge. In the 2011 fiscal year, the total amount of CO_2 emission from the transportation sector was 0.22 billion tons. 90% of the emissions were caused by vehicles [1]. Electric vehicles that emit no CO_2 directly are expected to be a key technology for reducing CO_2 emissions.

To estimate the effectiveness of electric vehicles in CO_2 reduction, indirect emissions due to electric vehicles should be clarified. Electric generators that consume fossil fuel emit CO_2. The emissions due to electricity that electric vehicles consume need to be taken into account as indirect emissions. The estimations of such indirect emissions are carried out through investigations of the electricity

consumption of electric vehicles and energy efficiency of electric generators [2].
Battery degradations have the potential to influence indirect emissions in the usage phase of electric vehicles, and case studies regarding CO_2 emissions should take into account battery degradations. A large capacity battery is the single energy source of every electric vehicle. The variation of battery performance, such as efficiency, in use will influence the amount of CO_2 emission caused by the usage of electric vehicles. For instance, the internal resistance of batteries increase as the progress of batteries' degradations.
In this study, CO_2 emission due to an electric vehicle in usage phase will be estimated by taking into account the degradation impact of a large capacity battery. Firstly, the CO_2 emission without the consideration of battery degradation will be estimated. Secondly, two possible ways in which batteries' degradation influences CO_2 emissions will be investigated and numerically-estimated. CO_2 emissions due to both a test electric vehicle and an internal combustion engine vehicle in usage will also be compared.

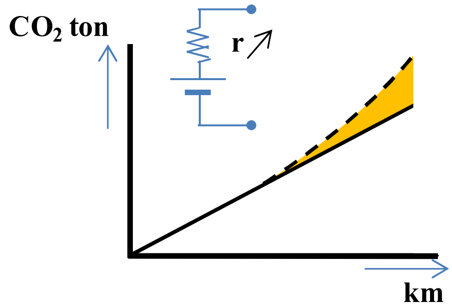
2 Procedure

2.1 Estimation of CO_2 emission in usage phase

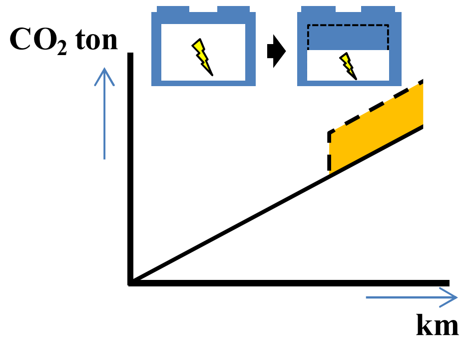
CO_2 emissions in an electric vehicle were estimated from the electric energy consumption Wh/km that was measured by a test electric vehicle. In this case study, the estimation was based on a Japanese usage case. The test electric vehicle was tested in Japanese specific mode (JC08[3]) to reflect the Japanese situation in the estimation. The test vehicle was charged by using a normal charge (not quick charge), and charging loss was also taken into account.

2.2 Influence of battery degradation

The impact of battery degradation on CO_2 emissions in usage was investigated by experimental results from both the test vehicle and a test battery cell. The internal resistance of batteries increase as the degradation proceeds. The internal resistance can affect the efficiency of function of batteries. The energy consumption due to the internal resistance will change from its unused condition. Consequently, CO_2 emission will be increased. Degraded batteries lose their capacities. The reduction of batteries' capacity can shorten ranges of electric vehicles. Thus, the usability of vehicles becomes worse and this could be a motivation to replace batteries.



(a) Image for the increase of CO_2 emission due to internal resistance variation



(b) Image for the increase of CO_2 emission due to battery replacement

Figure 1 Image for the increase of CO_2 emission due to battery degradation

From these perspectives, battery degradations have a potential to increase CO_2 emissions in usage. Fig. 1 displays the image of the both possibilities to gain CO_2 emission in usage.
In this study, the actual variation of both energy consumption and range of a test electric vehicle were measured to observe the degradation impact in-use. In addition, replacement condition of batteries was estimated by carrying out the experiment of Li-ion battery cells.

3 Experimental setup

3.1 Measurement of electric energy consumption

A commercial electric vehicle available in Japan was tested. The specification of the test electric vehicle (EV) is represented in Table 1.

Table 1 Specification of the test electric vehicle

Weight	1,110kg
Battery type	Li-ion battery
Battery capacity	16kWh
Range	160km(10/15mode)
Electric energy consumption	125Wh/km

The electric energy consumption Wh/km was measured with the test schedule in fig.2. In this case study, the test vehicle was driven in JC08 mode after the vehicle was fully charged. After the drive, the vehicle was fully charged again. During the charge, the input power toward the charger in the vehicle was measured in order to obtain the AC energy consumption.

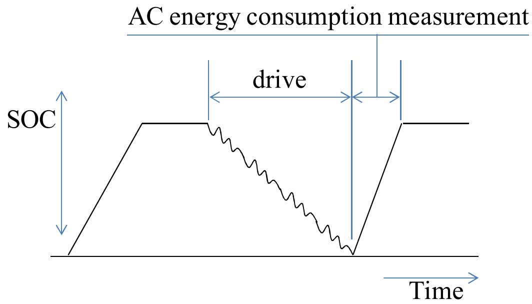


Figure 2 Test schedule for electric energy consumption

3.2 Experimental investigation of battery degradation impact

3.2.1 Observation of variation of the test electric vehicle's performance in usage

The basic vehicle performances, such as electric energy consumption and range, of the test electric vehicle were routinely measured in order to observe their variation in usage. The electric vehicle was tested in accordance with the test for electric vehicles approved by the Japanese government [3]. The vehicle was cyclically driven with JC08 until the charge was completely depleted from the full charge condition.

3.2.2 Experimental prediction of variation of the test electric vehicle performance

In order to predict the variation of the test electric vehicle performance in its life time, a degradation test of a Li-ion battery cell was conducted. Testing a battery pack on the vehicle consumes experimental resources. Thus, a simple test method with a Li-ion battery cell was employed. The test cell was set in a chamber in which ambient temperature was kept at 25 deg. C which is the standard test temperature for Japanese vehicle approval test. The cell was electrically loaded under the condition with the specific charge/discharge pattern which was actually measured from the test electric vehicle (Fig 3). Fig 4 shows the voltage variation of 2 cycles with the specific pattern.

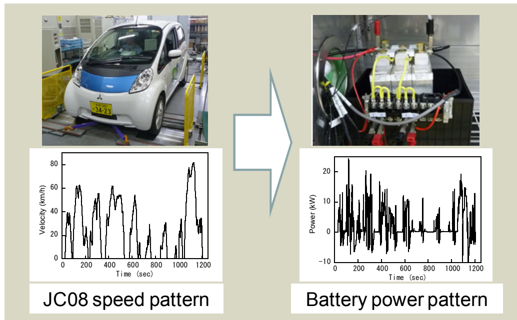


Figure 3 measurement of a specific charge/ discharge pattern from the test electric vehicle

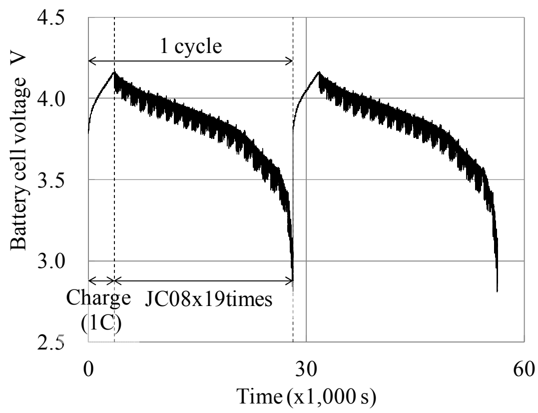


Figure 4 Variation of voltage of the test cell

Table 2: Specification of the test Li-ion battery cell

Battery type	Li-ion battery
Capacity	26Ah
Voltage	3.75V

4 Experimental results

4.1 Electric energy consumption

The measured results of electric energy consumption are indicated on Table 3. From the test results, the CO_2 emission against driving length was estimated. Fig. 5 shows the results. 6.5 tons was estimated as an amount of indirect emission due to the vehicle during the drive for 100,000 km. 100,000 km is assumed as a durability requirement for typical passenger vehicles in Japan [4]. 0.000550 ton/Wh was the Japanese average value for electric generations in the 2011 fiscal year [5]. This value was used as the CO_2 coefficient for this estimation.

Table 3: measured results of electric energy consumption

Charge type	Normal charge (AC 200V)
electric energy consumption	118.3Wh/km

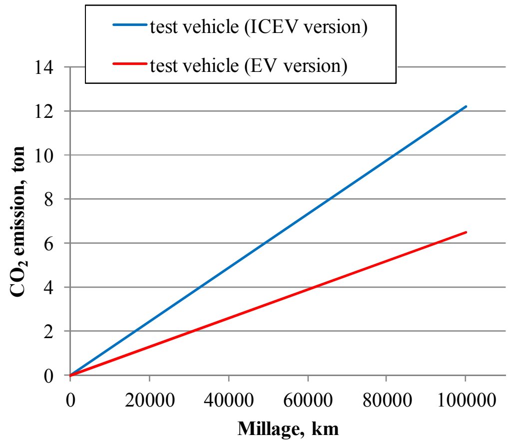


Figure 5 CO_2 emission comparisons in usage phase between the test vehicle and an ICEV

In Fig. 5, the estimated result by the internal combustion engine vehicle whose type is same with the test vehicle is plotted. Its fuel consumption was 19.0 km/L. The petroleum CO_2 coefficient was 0.00232 ton-CO_2/L [6]. In comparison of the both case, it is expected that the test vehicle can reduce CO_2 emission by 5.2 ton against the internal combustion engine vehicle.

4.2 Experimental investigation of battery degradation impact

4.2.1 Observation of variation of the test electric vehicle's performance in usage

The electric energy consumption and range of the test electric vehicle were routinely measured. The variation of range is displayed in Fig.6. The range of the test vehicle dropped down sharply at the beginning of the test. The range was reduced by 20% from the initial condition during 6,000km driving.

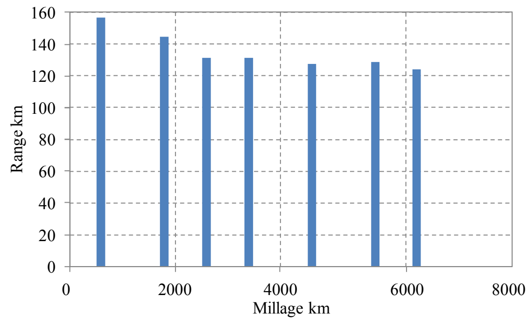


Figure 6 Range variation of the test vehicle

The variation of electric energy consumption is displayed in Fig.7. The electric energy consumption had no sharp variation relatively. It can be seen that the electric energy consumption went up gradually against the millage.

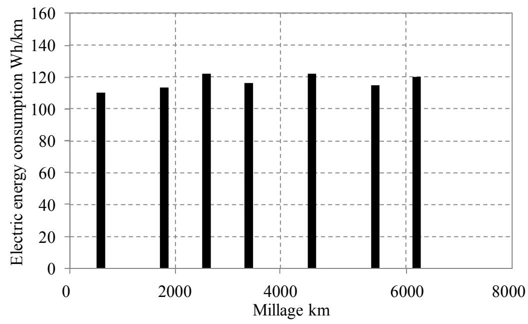


Figure 7 Electric energy consumption variation of the test vehicle

4.2.2 Experimental prediction of variation of the test electric vehicle performance

In order to predict the variation of the test vehicles performance that is affected by battery degradation, the Li-ion battery cell was tested. The test cell was electrically loaded under the condition with the pattern that was shown in Fig. 4. The capacity variation is displayed in the figure. The cell was loaded with a static battery tester. Thus, the cycle of charging and discharging were represented by an assumed driving length with the test vehicle. The x-axis shows the assumed millage.

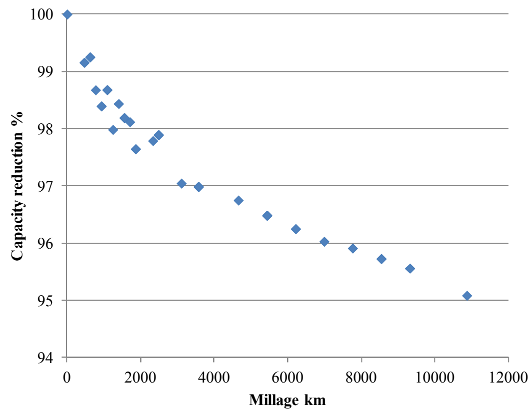


Figure 8 Capacity variation of the test cell against the assumed length

The capacity of the test cell dropped down relatively sharply at the beginning and proportionally decreased against millage.

5 Discussion

The results of both electric energy consumption and range imply that the reduction of battery capacity is more likely happened than the reduction of battery efficiency in usage phase. In this discussion, the impact of battery capacity reduction on the additional CO_2 emission in usage is investigated. Degraded batteries lose their capacities. The reduction of batteries' capacity can shorten ranges of electric vehicles. Thus, the usability of vehicles becomes worse and this could be a motivation to replace batteries. Firstly the replace timing is estimated and secondly the impact on CO_2 emission is estimated.

5.1 Estimation of battery replacement timing

In this part, the timing of battery replacement is estimated. For this estimation, a scenario for the battery replacement was set. In this scenario, the battery will be replaced when the range of the electric vehicle is reduced by 20% of the initial range.

By the 20% reduction of range from the initial condition, electric vehicles' usability for a large portion of users is reduced. In Fig. 9 shows the driving utility for daily trips in the Japanese market [3]. For instance, this graph means that 60% of the users in Japan utilize vehicles for trips within 40km a day. Referring other statistics, Japanese users tend to feed fuel while they preserve fuel in tanks which enables at least 100 km drive [7]. From this perspective, 72% of the vehicle users who drive within 60 km a day will be the majority of owners of the test vehicle of which initial range is 160 km. If the range was reduced by 20% of the initial range, the length for daily trips will be 28 km while they preserve electricity which enables at least 100 km drive. Thus, the 30% of the users (drawn with red allow on the figure) will feel inconvenient with the situation.

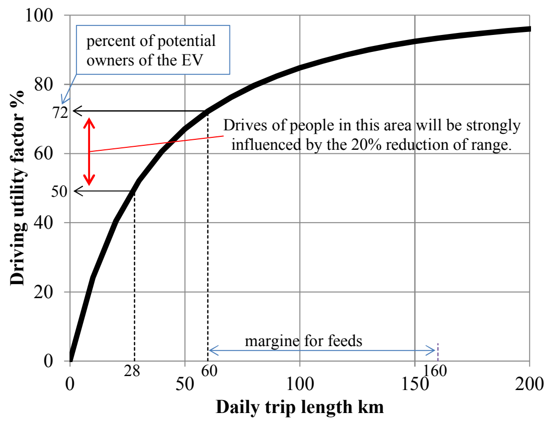


Figure 9 Japanese diving utility factors against daily trips

The timing that the test vehicle reduces 20% range was estimated by the Li-ion battery cell test. Fig. 10 shows the timing of when the test cell reduces 20% of capacity. When the 20% capacity reduction is assumed as the 20% reduction of the range, 70,000 km will be the timing for the 20% range reduction.

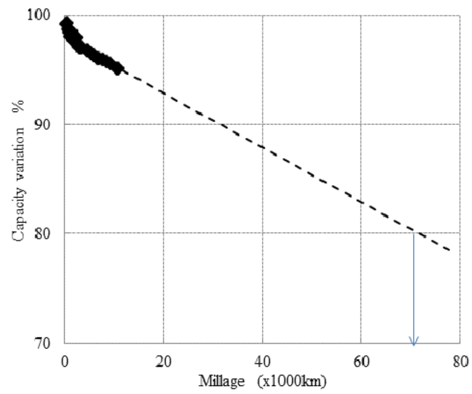


Figure 10 Experimental estimation of the timing for 20% reduction of capacity

5.2 Estimation of CO_2 emission due to battery replacement

CO_2 emissions due to battery replacement were estimated from the investigation of a battery production process. The electricity consumption in a battery production was obtained from the annual electricity consumption of a battery manufacturer's facility. The manufacturer assembles battery cells and modules from components (Fig. 11), such as electrodes and electrolyte. 800 kWh for 1 kWh of capacity of Li-ion battery production was used for the production process. The manufacturer is located in Tohoku, Japan. 0.000468 t-CO_2/kWh is assigned for the CO_2 emission coefficient of Tohoku Electric Power Company. 12,800 kWh will be used for the production of 16 kWh capacity batteries. Consequently, 6 ton of CO_2 is estimated as the emission due to the production.

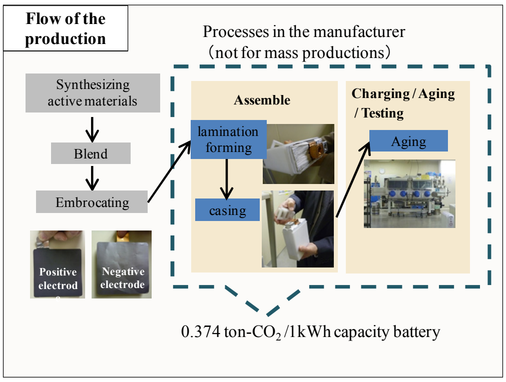


Figure 11 Production process flow for Li-ion battery in a manufacturer

As the consequent, 0.374 t-CO_2/1kWh was obtained as the CO_2 coefficients for the Li-ion battery production. Table 4 indicated CO_2 coefficients from different references.

Table 4: Comparison of CO_2 coefficient for Li-ion battery productions

In this study	0.374 t-CO_2/1kWh
Reference[8]	0.260 t-CO_2/1kWh
Reference[9]	0.191 t-CO_2/1kWh

5.3 Estimation of CO_2 emission increase due to battery degradation

From these results, CO_2 emission increase by the battery replacement was estimated. Fig. 12 shows the estimated result of CO_2 emission increase. In this estimation, the battery is replaced when the vehicle drives for 70,000 km. 6 ton CO_2 emission will be increased at this timing.

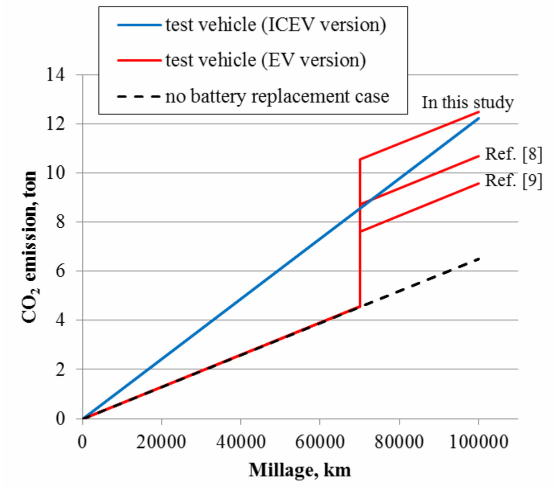


Fig. 12 Estimated result of CO_2 emission increase due to battery degradation

For the comparison, the estimated CO_2 emission from the internal combustion engine version of the same type with the test vehicle was plotted. In this case study, CO_2 emission due to the test vehicle exceeds that of the internal combustion engine version during the drive for 100,000 km. In the cases of CO_2 coefficients from other references, CO_2 emission due to the test vehicle was below that of the internal combustion engine version by 2-3 ton. To reduce CO_2 emissions due to the test electric vehicle successfully, the reduction CO_2 emission in the production of Li-ion batteries is important.

6 Conclusion

Electric vehicles are expected to be a key technology for CO_2 emission reduction in the transportation sector. In this study, CO_2 emission due to an electric vehicle in usage phase were estimated by taking into account the degradation impact of a large capacity battery. Firstly, it was estimated that the test electric vehicle without battery degradation influence has a potential to reduce CO_2 emission by 5.2 ton against the internal combustion engine vehicle during the drive for 100,000 km. Secondly, the CO_2 emission due to the test electric vehicle was estimated with taking battery degradation influence into account. In this case, the CO_2 emission has a potential to exceed that of the internal combustion engine version during the drive for 100,000 km. As a conclusion, to reduce the indirect emission of the test electric vehicle in usage phase successfully, battery degradation can become a significant issue.

To solve the problem, both the robustness of batteries and the reduction of CO_2 emission in battery productions are important.

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