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Guidelines for Measurement of Quantity-of-Electricity in Fuel Consumption Test for HEVs

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Hybrid electric vehicles (HEVs) are one of the most energy efficient vehicles for urban traffic use. Most of the HEVs on the current market are non-externally chargeable hybrid electric vehicles. ISO standardizing for the fuel consumption test methods for this type of vehicle has just been completed. However, as HEVs are still in the development stage, the standard only covers the basic aspects of the test method and the accuracy of quantity-of-electricity measurements needs to be considered. In this paper, we discuss the effect of the accuracy of quantity-of-electricity measurements on fuel consumption measurements. We also propose measurement guidelines for achieving the required accuracy for the resultant fuel consumption for every HEV

Keywords: HEV, Energy Consumption, Efficiency, Energy Storage, State of Charge,

1. INTRODUCTION

Achieving energy savings in the transportation sector, especially for vehicles, is a priority in the context of global warming. Hybrid electric vehicles (HEVs) are anticipated to improve the energy efficiency of vehicles designed for urban use. Fuel cell electric vehicles (FCEVs), which are expected to achieve the highest energy efficiency, and emission-free vehicles will require a hybrid system in order to be sufficiently efficient for practical urban use. Therefore, a hybrid system is essential for the producing energy efficient vehicles for urban use. Hybrid electric vehicles that have no off-vehicle charge capability are expected to become widespread since they are not much more expensive than conventional vehicles; these vehicles are already becoming widespread in the US and Japan due to a sudden rise in oil prices.

It is essential to develop a test method for evaluating the energy efficiency of HEVs since it is important to be able to do things such as classify vehicles according to efficiency and to confirm their efficiency level for green tax certification. In fuel consumption test of HEVs, the effect of the energy to or from the on-board energy storage systems makes it difficult to evaluate the fuel economy of an HEV.

ISO FDIS 23274[1)] defines following three procedures to obtain fuel consumption of HEVs without the SOC change (ΔSOC or ΔQ) effect of on-board energy storage systems during the test period:

1. Estimation of fuel consumption under no RESS (Rechargeable Energy Storage System) effect condition (ΔSOC=0 or ΔQ=0) from several test results by the linear regression method.
2. Compensation of one test result using the resultant coefficient of the fuel consumption vs. ΔSOC obtained by the first procedure.
3. Application of the test result with a negligibly small ΔSOC.

As the latter two procedures are based on the first procedure (linear regression method) the accuracy of HEV fuel test should be basically discussed in relation to the linear regression method.

In the present report, the principle of the linear regression method and the factors that affect test accuracy are discussed [2, 3)]. In our previous report, we discussed the accuracy of the three procedures mentioned above, and we also discussed the RESS efficiency, which is potentiality one of the key factors for determining total test accuracy.

Fuel consumption tests for HEVs require quantitative measurement of electrical charge “to” and “from” RESS, and errors in this measurement will reduce the total accuracy of the test. In this report, we propose guidelines for performing quantity-of-electricity (quantity of electrical charge; expressed in Ah) measurements to ensure a high total accuracy of fuel consumption tests

2. OVERVIEW OF FUEL CONSUMPTION TEST METHODS FOR HEVs

2.1 Review of Linear Regression Methods

Hybrid electric vehicles have two power units (e.g. an ICE (Internal Combustion Engine) and a motor) as shown in Fig. 1, and the RESS is used as a temporary energy buffer. We assume that at the beginning of the

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test the battery SOC and the fuel level have the levels depicted in Fig. 1. In case c), both SOC and the fuel consumption increase after the test, because part of the fuel is consumed in order to charge the battery. By contrast, in case a), the fuel consumption is reduced because the vehicle is assisted by battery. In case b), there is no change in the SOC, and the vehicle is powered by fuel alone. The fuel consumption in case b) does not involve the RESS effect.

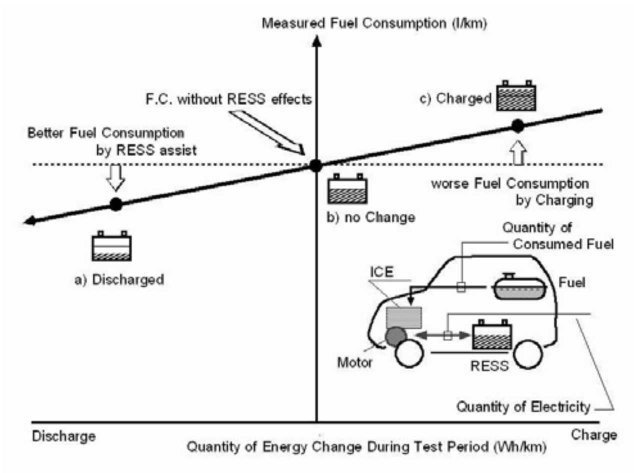

Fig.1 Effect the energy change in the RESS on fuel consumption in HEVs

The following relationship for the energy consumption of the electric power train and the fuel consumption of the thermal power train of HEVs was introduced in a previous paper by us[4].

$$FCm = FCo - \eta_{RESS} \cdot \frac{\eta_E}{\eta_G} \cdot \frac{1}{\gamma} EnrgyCm \quad (1)$$

Where,

- FCo : fuel consumption for the gasoline-only mode during the test period
- FCm : fuel consumption for the mixed (gasoline and electric) mode during the test period
- $EnrgyCm$: energy consumption for the mixed (gasoline and electric) mode during the test
- η_{RESS} : efficiency of the RESS
- η_G : average efficiency of the thermal power train during the test period
- η_E : average efficiency of electric power train during the test period
- γ : volume energy density of gasoline

Equation 1 shows that the fuel consumption measured in the test (FCm) is a linear function of the energy consumption ($EnrgyCm$) measured in the test. The coefficient of first-order term depends on the efficiency of the RESS, the ratio of the efficiency of the electric power train to that of the thermal power train and the energy density of gasoline. Thus, the coefficient depends on the characteristics of the HEV. The zero-order term (FCo in Eq. (1)) consists of fuel consumption in no RESS change.

The linear regression method is performed as follows: Several data sets for ΔE_{RESS} vs. consumed fuel are obtained by performing several driving schedule tests for different initial SOC in the RESS, so that the consumed fuel for various ΔE_{RESS} (energy change in RESS) conditions can be obtained. The regression line can be obtained from these data sets, and its zero-order term (FCo in Eq. (1)) represents the RESS-free fuel consumption. The coefficient of the first-order term (gradient of the regression line) is the correction factor (or the correction coefficient), which is the key factor for estimating the RESS-free fuel consumption in a single test, such as in the cold start test [2] (2nd procedure mentioned above).

Concerning the system that has batteries as RESS, energy consumption ($EnrgyCm$) is hard to apply due to the fact that efficiency of battery (Wh efficiency) varies dynamically corresponding to the load. On the other hand, since the coulomb efficiency (Ah efficiency) of recently developed batteries (such as Ni-MH or Li-ion batteries) is nearly 1, the quantity of electricity change (ΔQ) or the electricity consumption (consumption of quantity-of-electricity; ECm) should be applied rather than the energy consumption. Equation (1) can be expressed in terms of the electricity consumption by using the following approximation for the energy consumption,

$$EnrgyCm \cong V \cdot \frac{\Delta Q}{L} \quad (2)$$

Where,

- V : system voltage (V)
- ΔQ : quantity of electricity change during the test period (Ah)
- L : distance covered during the test period (km)

Equations (1) and (2) can be combined to produce the following equation:

$$FCm = FCo - \eta_B \cdot \frac{\eta_E}{\eta_G} \cdot \frac{V}{\gamma} \cdot \frac{\Delta Q}{L} \quad (3)$$

Where, η_B is coulomb efficiency of the battery.

Assuming that several driving schedule tests have been conducted and data sets for fuel consumption vs. ΔQ are obtained from the test results, the points on these plots will be distributed along the line defined by Eq. (3). Equation (3) shows that the gradient of the regression line is proportional to η_E / η_G (the average efficiency ratio of the electric power train to the thermal power train during the test period). In addition, the vertical-axis intercept of the line indicates the resultant fuel consumption without the RESS effect.

In this report, the polarity of ΔQ is taken as positive when the battery energy is increasing (charging), in accordance with battery charging conventions.

2.2 Necessity for Guidelines

The regression line will be scattered by errors caused by various factors. Factors that affect the fuel

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consumption test have been classified according to the following three types:

1. Errors in the fuel consumption measurement.
2. Errors caused by the simulation in the chassis dynamometer.
3. Errors in the quantity-of-electricity measurement.

Whereas the first two types of errors scatter the regression line vertically, the third type of error scatters the line horizontally as shown in Fig. 2. Thus, the third error affects resultant fuel consumption indirectly, while the first two errors directly affect fuel consumption.

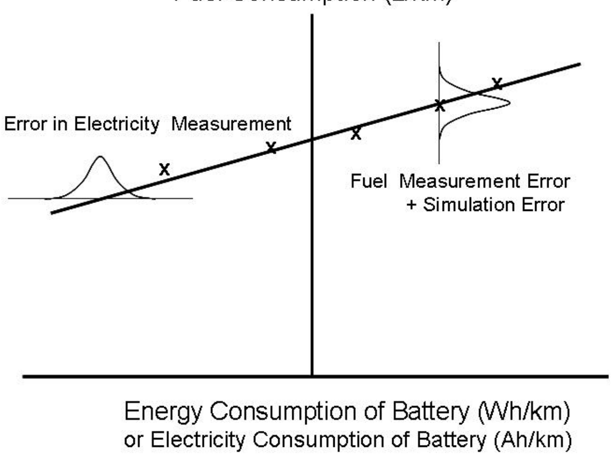

Fig. 2 Effect of the three types of error on the HEV test

As mentioned above, when the fuel consumption of HEVs is expressed as a linear equation in ΔQ, the gradient of the regression line will be a function of the distance covered and the average efficiency ratio of the electric power train to the thermal power train during the test period η_E / η_G. Consequently, the effect of the third type of error on the resultant fuel consumption will depend strongly on the test vehicle and the test mode. Thus, the required accuracy for quantity-of-electricity measurement will be strongly dependent on the test mode and the characteristics of test vehicle. So, it is important to ascertain the required accuracy for the quantity-of-electricity measurement that will ensure the resultant fuel consumption test for a specific test mode and vehicle, corresponding to the required accuracy in fuel consumtion. In addition, it is important to define the procedures for measuring current and data processing to ensure that the final result meets the required accuracy.

3. OVERVIEW OF MEASUREMENT GUIDELINES

In this paper we propose the following guidelines for the quantity-of-electricity measurement for ensuring that the required accuracy for measuring the fuel consumption of HEVs is achieved. An overview of the guidelines is as follows. The following procedures should be performed systematically in the order given below:

1. Normalize the data to obtain the test-mode-independent value.
2. Define the accuracy of the current measurement system corresponding to the test mode, so that the required accuracy for the fuel consumption test can be achieved.
3. Confirm DC stability and nullify DC offset to ensure that the result is sufficiently accurate.
4. Compensate charging/discharging of coulomb efficiency of battery system (if necessary).

Each step is explained in detail in the following sections.

4. NORMALIZATION TO OBTAIN TEST-MODE-INDEPENDENT VALUE

Figure 3 shows the fuel consumption vs. ΔQ characteristics of a HEV on the market during the Japanese 10.15 mode driving schedule test and the U.S. LA4 mode driving schedule test. The two resultant regression lines exhibit remarkable differences in their gradients (i.e. the first-order coefficients of the linear regression lines). This fact makes it difficult to compare test results for the same vehicle in different driving schedule tests or to check whether the regression line of a new result is reasonable by comparing it with a standard regression line for another driving schedule test.

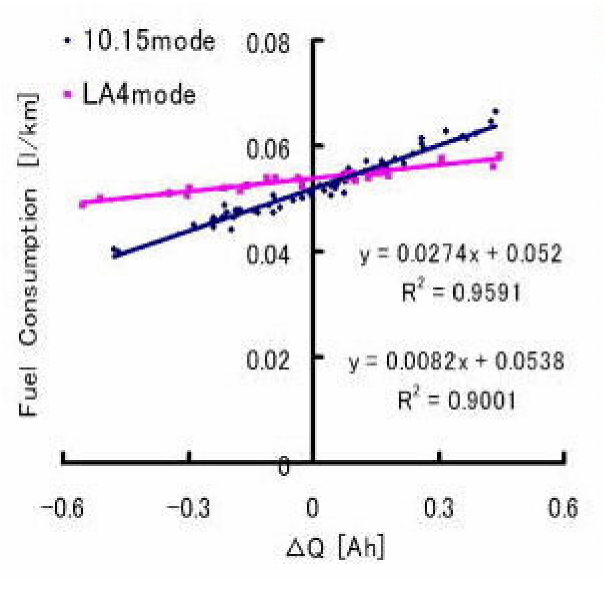

Fig. 3 Difference in gain to ΔQ

Equation 2 implies that the actual fuel consumption of HEVs is a function of $\Delta Q \cdot V/L$ (energy consumption) or $\Delta Q/L$ (electricity consumption) and that the ratio of the fuel/electric energy consumption is proportional to the ratio of the efficiencies in the thermal/electric

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propulsion systems. Figure 4 shows the fuel consumption vs. electricity consumption characteristics of the HEV shown in Fig. 3. The two regression lines show no remarkable differences in their gradients, so that it is possible to estimate the validity of a newly obtained result by comparing it to the standard regression line of another driving schedule test for the HEV.

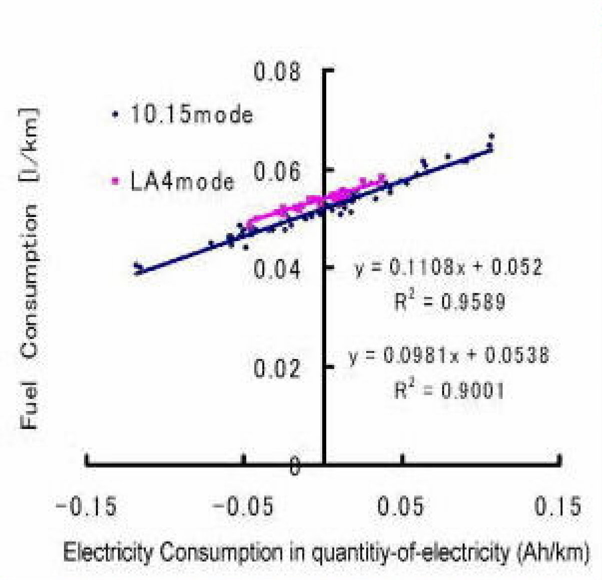

Fig. 4 Effect of normalization of ΔQ

In order to discuss the accuracy of the quantity-of-electricity measurement by referring to the accuracy of the fuel consumption test, the linear regression method should be applied to the fuel consumption as a function of electricity consumption ($\Delta Q/L$) rather than as a function of the quantity-of-electricity change (ΔQ). Physically, Eq. (1) indicates that the fuel consumption with change in Q is not a function of the electricity consumption (i.e. quantity-of-electricity change in battery (Ah) / distance traveled (km)) but rather that it is a function of the electric energy consumption (energy change in battery (Wh) / distance traveled (km)). But the energy efficiency of the battery (the Wh efficiency) depends on loads and it varies dynamically corresponding to the charging/discharging current and battery conditions. So, it is difficult to apply integration of the power as a scale to clarify the energy level in battery (equivalent to battery state of charge). So, it is difficult to apply integration of the power as a scale for clarifying the energy level in the battery (i.e. the state of charge of the battery). On the contrary, the coulomb efficiency of a battery is usually close to unity, making the quantity-of-electricity (integrated value of current) a suitable parameter for clarifying the energy level of a battery.

As the purpose of using the linear regression method is to estimate the fuel consumption under the conditions of no change in energy, it is not essential to apply the quantity-of-electricity or energy as a scale to confirm the no change in energy condition. However, if we discuss the quantity of energy change in the battery during the test, the charging/discharging energy should be measured by taking into account the charging/discharging efficiency, or an approximate energy should be calculated as a product of the "quantity of electricity change" and the rated voltage of battery.

4. GUIDELINES FOR DEFINING THE REQUIRED ACCURACY FOR THE CURRENT MEAS.

In the actual HEV fuel test, the accuracy requirement for the current measurement system is one of the key parameters for ensuring the accuracy of the fuel test result. As the characteristics of HEVs are complex and unclear, test methods discussed in the standards or regulations do not specify a required accuracy for the current measurement, but only for the quantity-of-electricity measurement or the permissible energy change during the test. In any case, it defines common values that may be sufficient for every HEV. This means that it may be too strict for some HEVs.

As mentioned above, the effect of electricity consumption (i.e. the coefficient of the first-order term of the linear regression line) on the fuel consumption depends on the characteristics of the HEV, and is approximately the same level for different driving schedule tests on the same HEV. So, the influence of the electricity measurement error on fuel consumption is also dependent on the HEV to be tested. That is, the allowable error for the electric energy measurement or the required accuracy of the current measurement system has to be discussed by taking into account the HEV characteristics.

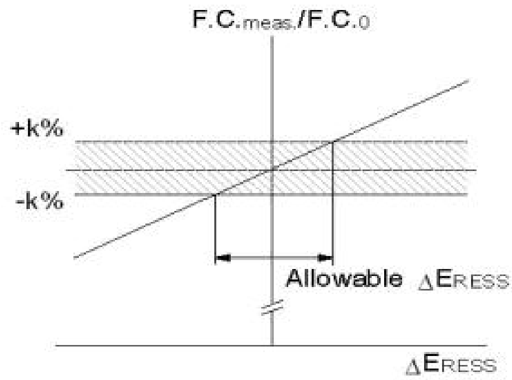

Fig. 5 Allowable error in ΔE_b

As shown in Fig. 5, the allowable energy change in the battery (ΔE_b) for a fuel consumption error of less than k% fuel consumption error can be calculated using the relationship between the electric energy and the consumable fuel energy. But such an energy-based discussion will be problematic, since it requires use of

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an approximation to calculate the energy change in the battery and of a conversion to evaluate the two energy sources (electric energy and fuel energy) on the same table. So, a discussion based on energy is not suitable for an actual test, because of its complicated operation and the uncertainty in the operation process.

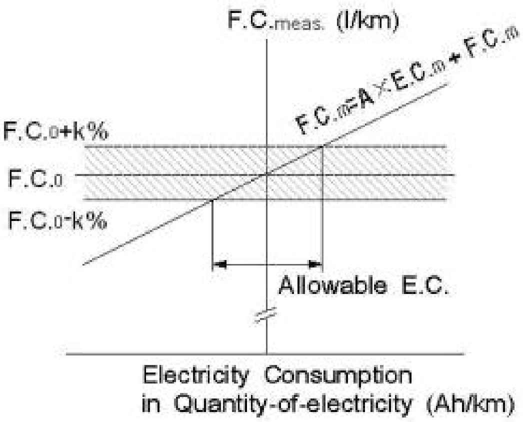

Fig. 6 Allowable error in electricity consumption

In the meantime, the allowable error in the electricity consumption (Ah/km) can be estimated directly using the information in Fig. 6. Figure 6 shows the estimated fuel consumption (l/km) for different electricity consumptions (Ah/km) obtained using the linear regression method. The linear regression line shows the relationship between fuel consumption and electricity consumption directly, that is, the effect of the thermal/electric system efficiency and the energy conversion ratio are already taken into account. Thus, we can define the allowable error in the electricity consumption for achieving a fuel consumption error of less than k%. It should be noted that we can define the allowable error only for the electricity consumption and that it is not possible to define the allowable error in the current measurement system at this stage.

The allowable error for the current measurement system is defined in the following manner. Assuming that we can obtain a linear regression line corresponding to Eq. (1) for several data sets of ΔE_b vs. consumed fuel by performing several scheduled driving tests for different initial SOCs, then

$$F.C._m = A \cdot E.C._m + B = A \cdot E.C._m + F.C._{est} \quad (4)$$

Where,

$F.C.m$: measured fuel consumption (l/km) for different ΔQ

$E.C.m$: measured electricity consumption (Ah/km) for different ΔQ

B, $F.C.est$: estimated fuel consumption for ΔQ=0 (coefficient of constant term, l/km)

A : coefficient of the first-order term of linear regression line (l/Ah)

We set the required accuracy for the fuel consumption test to k%, and the allowable error for the electricity consumption to δX (Ah/km). The allowable error of electricity consumption can be expressed as follows.

$$A \cdot \delta X \leq \frac{k}{100} \cdot F.C._{est} \quad (5)$$

$$\delta X \leq \frac{k}{100} \cdot \frac{F.C._{est}}{A} \quad (6)$$

Assuming that the average allowable error in measured current is δI, δI can be expressed as follows.

$$\delta X = \int_0^T \frac{\delta I}{L} dt = \frac{\delta I \cdot T}{L} \quad (7)$$

$$\delta I = \delta X \cdot \frac{L}{T} = \delta X \cdot V_{av} \quad (8)$$

Where,

T : test duration time in hours (h)

L : distance covered during test (km)

V_{av} : average velocity of the test vehicle during the test (L/T (km/h))

Equations (6) and (8) lead to Eq. (9). And Eq. (9) gives the allowable error for the current measurement (δI) as a product of the allowable error in the electricity consumption and the average velocity of the scheduled driving test.

$$\delta I \leq \frac{k}{100} \cdot \frac{F.C._{est}}{A} \cdot V_{av} \quad (9)$$

Since the coefficient of first-order term of linear regression line (fuel consumption/electricity consumption) can be determined only after the test, the allowable error for the corresponding current measurement system cannot be determined before test. This drawback can be overcome by using the following procedure.

Since the coefficient of the linear regression line depends on the characteristics of the HEV, the coefficient of the linear regression line can be estimated by referring to the standard coefficient for a similar HEV. The allowable error for the current measurement system can be calculated using this estimated value and the average vehicle velocity during the driving schedule test. The accuracy of the current measurement system should be determined using this provisional value, and the actual accuracy of current measurement system should be checked after the test by using the obtained resultant coefficient to confirm the accuracy of the system.

5. DC STABILITY CONFIRMATION AND DC OFFSET NULLIFICATION

As mentioned in the previous sections, ΔQ for linear regression operation is calculated by integrating the battery current successively during the test period. Hybrid electric vehicles have intermittent battery currents having a high peak and a short duration. The duty ratio of the battery current is very small compared with the current in EVs, that is, the duration under approximately zero current conditions is appreciable, in spite of the high flow rate operation under peak power assist conditions. Since ΔQ is the average of the

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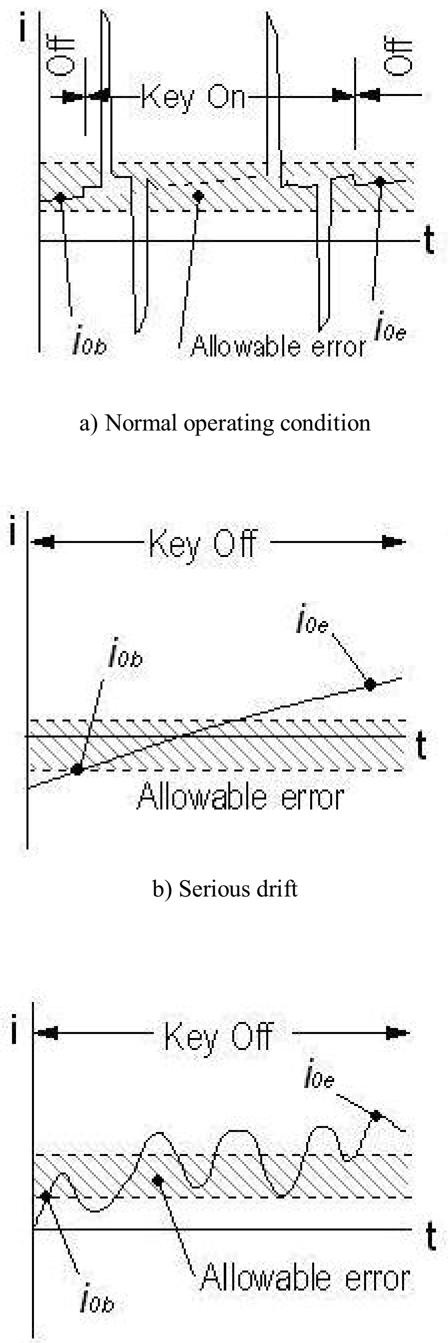
integrated values for the intermittent charging current and the intermittent discharging current, and has a long integration times for small currents, it is necessary to pay special attention to managing the DC stability in the current measurement system.

As a result of the short durations for high-peak currents and the long durations for low currents and the long integration times, it is essential to confirm the DC level stability of the current measurement system and to cancel the remaining DC offset value in the current measurement system more accurately. Confirming the DC level stability and nullifying the DC offset should be performed using the following steps:

1. Before starting the test, the current measuring system should warm-up for the period recommended by the measuring system manufacturers.
2. Before and after the test, the DC offset values for the current measurement system immediately before the test (I_{0B}) and the one immediately after the test (I_E) should be measured with the main key turned off (see Fig. 7a).
3. The balance of the DC offset for pre- and post-test, $|I_{0B}-I_{0E}|$, should be checked to see if it is smaller than the allowable error for the current measurement system. If the system is sufficiently stable (i.e. $|I_{0B}-I_{0E}| <<$ allowable error for the current measurement system), step 4 should be performed to cancel the DC offset value for the current measurement system. If it is not sufficiently stable, the variation of the output voltage for the zero input condition should be checked continuously for a period longer than the test period, to obtain a time history of the drift value. Depending on the resultant drift data obtained, one of the following two operations should be performed.
   a. If the offset value moves gradually in one direction (simple drifting), and its drift rate is almost constant (refer to Fig. 7b), nullification (step 4) should be performed without carrying out any additional operation.
   b. If the output for the zero input moves irregularly and the peak-to-peak of the output exceeds the allowable error for the current measurement system (refer to Fig. 7c), it is clear that sufficient accuracy cannot be achieved using the system. The current measuring system should be re-adjusted so that sufficient stability can be obtained.
4. Nullification of the offset value for the current measurement system. Prior to performing the integrating operation of the measured battery current for obtaining the quantity-of-electricity change, ΔQ, the offset for the measured battery current data should be compensated by canceling the average offset. The n-th compensated current data, i_{n0}, is expressed as follows, using the n-th measured current data, i_n:

$$i_{n0} = i_n - \left(\frac{i_{0B} + i_{0E}}{2}\right) \tag{10}$$

This nullification process is essential for achieving a sufficiently small resultant offset relative with the allowable error for the current measurement system (refer to Eq. 9) if the current measurement system has an offset value.



c) Unstable condition

Fig. 7 Variation patterns of DC offset for the current measurement system

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6. COMPENSATION OF THE CHARGE FACTOR OF BATTERY SYSTEM

As mentioned above, since newly developed batteries (such as a Ni-MH or a Li-ion battery) have high charge factor, the coulomb efficiency of such batteries can be considered to be unity under normal conditions. As for lead acid batteries or high performance batteries that have been used for a long period, the coulomb efficiency may be low or may be reduced to some extent, so the coulomb efficiency of battery should be checked. In a previous paper by us we proposed a procedure for checking the coulomb efficiency of a battery and a procedure for compensating the effect of this reduction in efficiency. They are given briefly as follows:

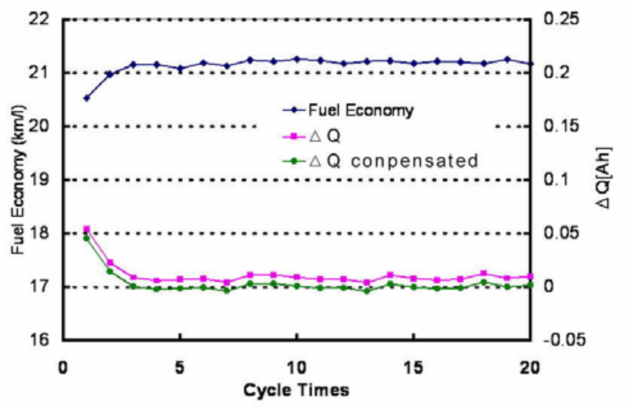

Fig. 8 Effect of the battery efficiency on ΔQ

Figure 8 shows the time history of fuel economy (1/fuel consumption) and *ΔQ* in successive 20 cycle tests of the 10.15 mode driving schedule tests of HEVs on the market. Since the fuel consumption and *ΔQ* reach steady-state conditions after four cycles, *ΔQ* does not reach zero, but rather reaches a value of approximately 0.01 Ah. This means the fact that the battery is slightly charged under the steady-state conditions due to loss from the battery system (including battery management system)

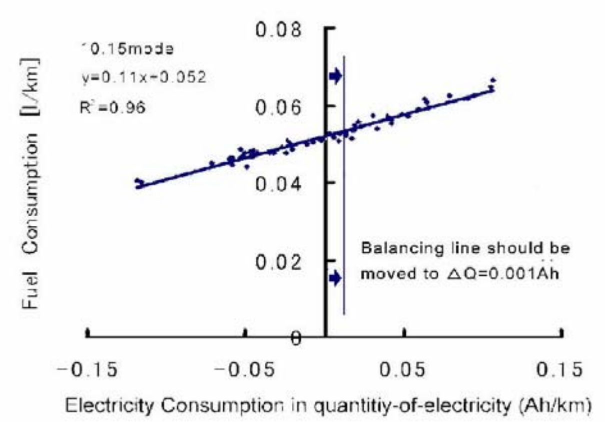

Fig. 9 Effect of ΔQ offset on the resultant fuel consumption

Although the equilibrium value of *ΔQ* in steady condition is not zero but 0.01 Ah, the fuel consumption with no battery change should be estimated using this value of *ΔQ*, as shown in Fig. 9. This results in the critical disadvantage that the steady-state value of the battery change must be measured, which requires a lengthy test until steady state is reached.

A practical procedure for compensation was proposed in last paper[4] and is described below.

7.1 Clarification of the Charge Factor of the Battery

As mentioned above, the efficiency of a battery can be obtained under long-duration steady-state conditions. But practically, it needs to be measured in one or two successive scheduled driving tests performed for the linear regression method.

7.1.1 Identification of Data Points which have the Same SOC Values

In order to compare the quantity-of-electricity for charging and that for discharging while the battery SOC recovers to its initial level, it is important to find the time, t2, at which it has the same SOC value (i.e. the same battery conditions) equal to that at the starting time (or selected time), t1.

Figure 10 shows the time history for the quantity-of-electricity, *Q*, during successive 10.15 mode tests. *Q* gradually increases after the battery reaches steady-state conditions. As the *Q* in this figure is a calculated value obtained by integrating the battery current, it does not represent the exact SOC value or battery energy level. Thus, the true battery energy levels at different two times that have the same *Q* value may be actually being different from each other. The time that has the same battery energy level equal to the one in staring time (or selected time) can be found as following manner.

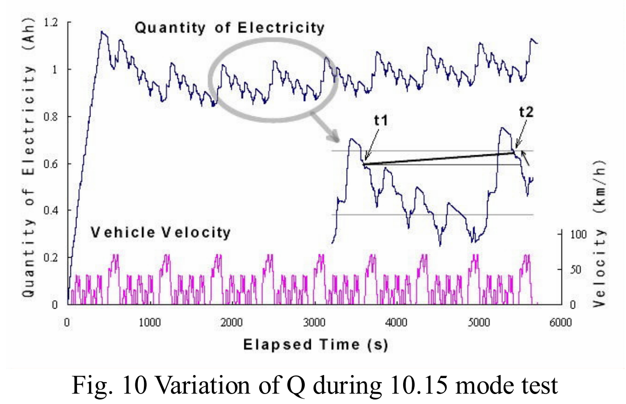

Fig. 10 Variation of Q during 10.15 mode test

The *V-I* characteristics of a battery are one of the simple and practical parameters for evaluating the health of a battery under dynamic load conditions. The times that have the same SOC levels can be found by checking if they have the same V-I characteristics or not (i.e. if they have the same health level or not). As *Q* usually varies strongly at the beginning of a test without proper preconditioning, the selected time

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should be chosen so that it lies in the steady-state condition region. The time that has the same Q value should be checked first, and the time to be checked is varied until the same "health" level can be achieved. If it is difficult to find an appropriate time, the starting time should be changed.

7.1.2 Definition of the Charge Factor of the Battery

Using t1 and t2 obtained by the above process, the charge factor (charging/discharging coulomb efficiency) of the RESS, κ, is determined by the following equation:

$$\kappa = \frac{\int_{t1}^{t2} I_d \, dt}{\int_{t1}^{t2} I_c \, dt} \qquad (11)$$

Where I_d is the discharging current and I_c is the charging current. The actual process for this accumulating step will be not an integrating operation but rather a sum-mention of I_d and I_c for every individual sampling time.

7.2 Compensation of Charge Current with Charge Factor

To obtain the ΔQ value for the linear regression method, knowing the accumulation process of the battery current (charging current, I_c, and discharging current, I_d) is essential. If the charge factors are not high enough, the charging current, I_c should be compensated by multiplying by κ in this step. The compensated I_c, I_{cc} is expressed as follows:

$$I_{cc} = k \cdot I_c \qquad (12)$$

If the accumulation process is performed using instruments such as an ampere-hour meter, the accumulation should be performed on I_c and I_d individually so that individual accumulated values for I_c and I_d can be obtained.

7. CONCLUSION

The error in the quantity-of-electricity measurement affects the total accuracy of fuel consumption tests of non-externally chargeable HEVs. Guidelines for ensuring the required accuracy for fuel consumption tests current measurement have been discussed. The following facts were found.

The effect of the error on quantity-of-electricity measurement depends on the vehicle characteristics and the driving schedule test. It is important to clarify the required accuracy of for the quantity-of-electricity measurement to ensure that the specified accuracy for the fuel consumption test for individual test mode and vehicle is achieved. In addition, it is also important to define the procedure for current measurement and processing of measured data to ensure that the required accuracy for the final result is achieved. The allowable current measurement error for various fuel consumption errors is found to be proportional to the average velocity (cruising velocity) of the driving schedule mode. Thus, an investigation of accuracy should be performed for each test mode. Concerning vehicle dependent factors, the difference in conventional HEVs on the market lies in the range 100 to 150%, but mild HEVs on the market are allowed a 10 times higher error compared to strong HEVs.

To keep the error within the pre-determined target level, extraordinary management is required to ensure DC stability and zero-level accuracy. A practical procedure for achieving sufficient accuracy is also proposed.

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BIOGRAPHIES

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