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Hybrid-electric road vehicles — Guidelines for charge balance measurement

Véhicules routiers électriques hybrides — Lignes directrices pour le mesurage de la balance de charge

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Introduction

On the fuel consumption test of non-externally chargeable *hybrid-electric vehicles* (HEV), it is essential to measure the charge balance in a rechargeable energy storage system (RESS) during a test period in order to compensate the effect of energy change in a RESS on fuel consumption. ISO 23274, which defines a basic fuel consumption test method for non-externally chargeable HEVs, does not define required accuracy on a current measurement system but defines required accuracy on charge balance as required accuracy for the total current measurement system; so the required accuracy of current sensor or current measuring system for each test should be individually managed.

To investigate the required accuracy on a current measuring system is a complicated task, due to the fact that the effect of current measurement error on fuel consumption test accuracy depends on both vehicle characteristics and test cycle. As the charge balance is normally obtained by integrating battery current (remainder of “accumulated value of charging current” minus “accumulated value of discharged current”) and as the battery current is composed of intermittent huge charging current, intermittent huge discharging current and small current with long duration time, it is necessary to pay special attention to managing the d.c. stability in the current measurement system to keep the required accuracy.

In consideration of these backgrounds, this Technocal Report describes detailed guidelines for charge balance measurement methods (including requirements for current measuring systems) to fulfil the required total accuracy prescribed in ISO 23274.

Hybrid-electric road vehicles — Guidelines for charge balance measurement

1 Scope

This Technical Report describes procedures of charge balance measurement to ensure necessary and sufficient accuracy of a fuel consumption test on *hybrid-electric vehicles* (HEV) with batteries, which is conducted based on ISO 23274 (see Bibliography).

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
charge balance
⟨of a battery⟩ change of charge in a battery during test period

NOTE Normally expressed in ampere-hours.

2.2
energy balance
⟨of a battery⟩ change of energy in a battery during test period

NOTE 1 Normally expressed in Watt-hours.

NOTE 2 For practical use, following approximate definition is made: “charge balance of battery multiplied by the nominal voltage, normally expressed in Wh (ISO 23274)”.

2.3
energy efficiency
Wh efficiency
efficiency of the battery, based on energy for a specified charge/discharge procedure, expressed by output energy divided by input energy

2.4
coulomb efficiency
Ah efficiency
efficiency of the battery, based on electricity (in coulomb) for a specified charge/discharge procedure, expressed by output electricity divided by input electricity

3 Outline of error in HEV fuel consumption test

As shown in Figure 1, the relationship of fuel consumption and charge balance is estimated by the linear regression method, using test results in a scheduled driving test, to obtain resultant fuel consumption. The regression line is scattered by errors caused by various factors. Factors that affect the fuel consumption test have been classified according to the following three types:

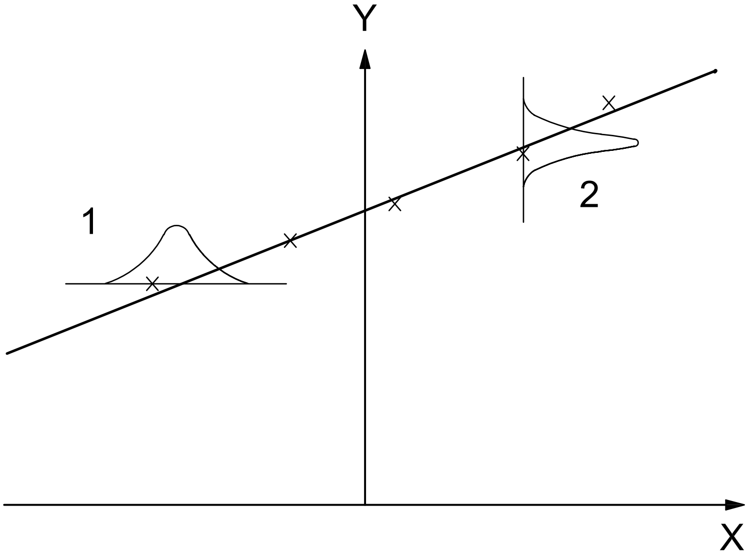
a) errors in the fuel consumption measurement;

b) errors caused by the load simulation on the chassis dynamometer;

c) errors in the charge balance measurement.

Whereas the first two types of error scatter the regression line vertically, the third type of error scatters the line horizontally as shown in Figure 1. Thus, the third error indirectly affects resultant fuel consumption, while the first two errors directly affect fuel consumption.

As mentioned above, when the fuel consumption of HEVs is expressed as a linear equation in the charge balance of the battery, ΔQ, the gradient of the regression line will be a function of the distance covered and the average ratio of the electric power train efficiency to the ICE power train efficiency during the test period. Consequently, the effect of the third type of error on the resultant fuel consumption will strongly depend on the test vehicle and the test cycle. Thus, the required accuracy for charge balance measurement will be strongly dependent on the test cycle and the characteristics of the test vehicle. So, it is important to ascertain the required accuracy for the charge balance measurement that will ensure that the resultant fuel consumption test for a specific test cycle and vehicle meets the required accuracy. 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.



Key

X charge balance per distance of battery in Watt-hours per kilometre or ampere-hours per kilometre

Y fuel consumption in litres per kilometre

1 electricty measurement error

2 fuel measurement error + load simulation error

Figure 1 — Relationship of the three error factors on tests

4 Guideline for measurement

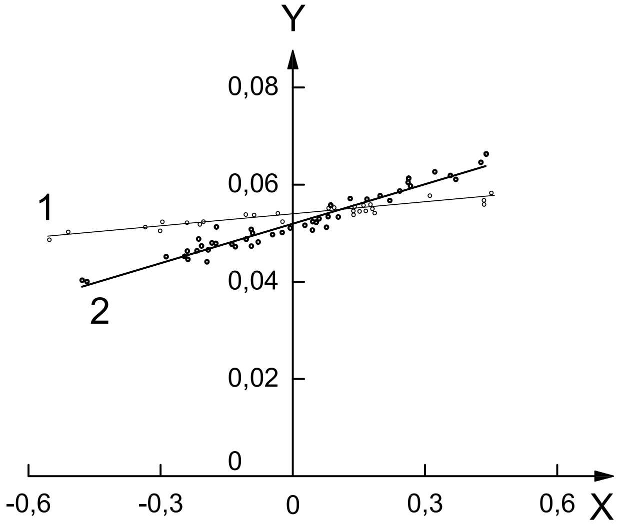
4.1 General

Investigations into the required accuracy for charge balance measurement systems and procedures for retaining the required accuracy are described in 4.2 to 4.4.

4.2 Normalization to reduce the effect of the test cycle

Figure 2 shows fuel consumption vs. ΔQ characteristics of an HEV on the market during the Japanese 10-15 mode and the U.S. urban dynamometer driving schedule (U.D.D.S.). 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 test cycles or to check whether the regression line of a new result is reasonable by comparing it with a standard regression line for another test cycle.



Key

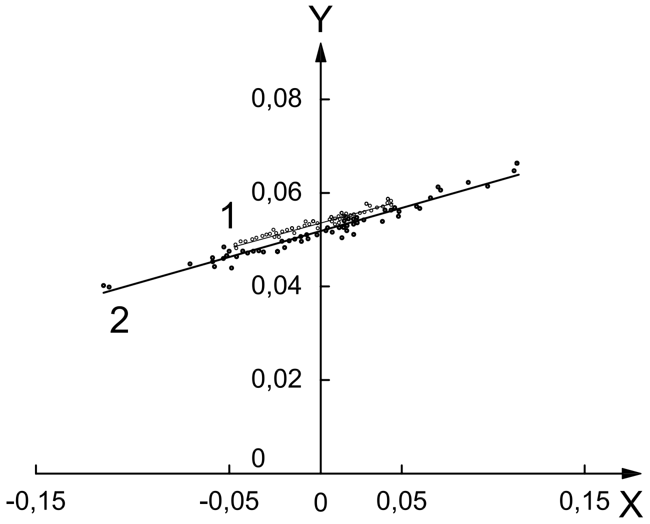
X charge balance, ΔQ in ampere-hours

Y fuel consumption in litres per kilometre

1 U.D.D.S.

2 10-15 mode

Figure 2 — Fuel consumption — ΔQ characteristics in two test modes



Key

X charge balance per distance in ampere-hours per kilometre

Y fuel consumption in litres per kilometre

1 U.D.D.S.

2 10-15 mode

Figure 3 — Fuel consumption — Charge balance per distance characteristics in two test modes

Figure 3 shows fuel consumption vs. charge balance per distance characteristics of the HEV shown in Figure 2. 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 test cycle for the HEV.

In order to discuss the accuracy of the charge balance 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 charge balance per distance ($\Delta Q/L$) rather than as a function of the charge balance, ΔQ.

Physically, it indicates that the fuel consumption is not a function of the charge balance per distance [i.e. charge balance in battery divided by distance travelled (Ah/km)] but rather that it is a function of the energy balance per distance [energy change in battery divided by distance travelled (Wh/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 for clarifying the energy level in the battery [i.e. the state of charge of the battery (SOC)]. On the contrary, the coulomb efficiency of a battery is usually close to unity, making the charge balance (integrated value of current) a suitable parameter for clarifying the energy level of a battery.

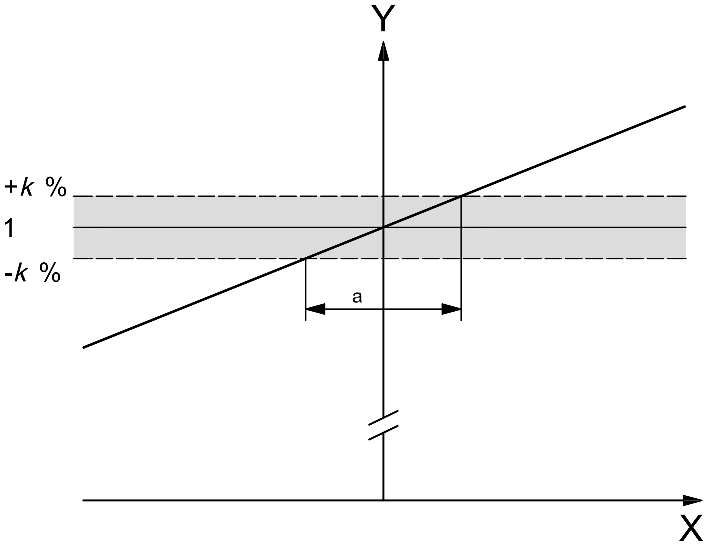
As the purpose of using the linear regression method is to estimate the fuel consumption under the conditions of no energy change, it is not essential to apply the energy balance or energy as a scale to confirm no energy change. However, if we discuss the quantity of energy change in the battery during 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 “charge balance” and the nominal voltage of battery.

4.3 Guideline to define the accuracy of the current measuring system required by the corresponding test cycle

As mentioned above, the effect of charge balance per distance (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 test cycles on the same HEV. So, the influence of the charge balance measurement error on fuel consumption is also dependent on the HEV to be tested. That is, the allowable error for the charge balance measurement or the required accuracy of the current measurement system has to be discussed by taking into account the HEV characteristics.

Figure 4 shows relationship between energy balance of battery, ΔEb, and measured fuel consumption [expressed as a ratio of measured fuel consumption (FC_{meas}) to true fuel consumption (FC_0)]. As shown in Figure 4, the allowable energy change in the battery, ΔEb, for a fuel consumption error of less than k % of the fuel consumption 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 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.

In the meantime, the allowable error in the charge balance per distance (Ah/km) can be estimated directly using the information in Figure 5. Figure 5 shows the estimated fuel consumption (l/km) for different charge balance per distance values (Ah/km) obtained using the linear regression method. The linear regression line shows the relationship between fuel consumption and charge balance per distance 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 charge balance per distance for achieving a fuel consumption error of less than k %. It should be noted that we can define the allowable error only for the charge balance per distance and that it is not possible to define the allowable error in the current measurement system at this stage.



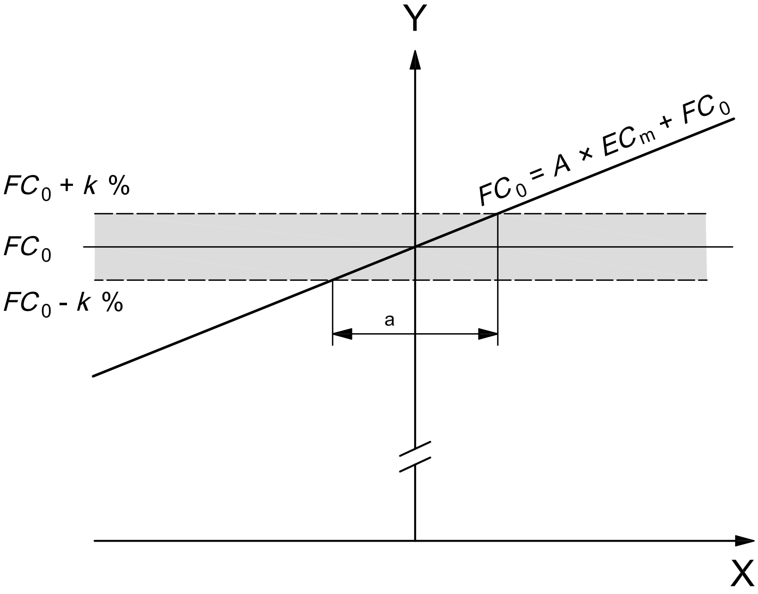
Key

X energy balance of battery, ΔEb

Y FC_{meas}/FC_0

[a] Allowable ΔEb

Figure 4 — Allowable error in energy balance of battery, ΔEb



Key

X charge balance per distance, EC_{m} in ampere-hours per kilometre

Y FC_{meas} in litres per kilometre

[a] Allowable EC_{m}.

Figure 5 — Allowable error in charge balance per distance

The allowable error for the current measurement system is defined in the following manner. Assuming that we can obtain a linear regression line as shown in Equation (1) for several data sets of ΔQ vs. consumed fuel by performing several test cycles for different initial SOCs, then:

$$FC_{\mathrm{m}} = A \times EC_{\mathrm{m}} + FC_{\mathrm{est}} \tag{1}$$

where

FC_{m} is the measured fuel consumption (l/km) for different ΔQ;

EC_{m} is the measured charge balance per distance (Ah/km) for different ΔQ;

FC_{est} is the estimated fuel consumption for $\Delta Q = 0$ (coefficient of constant term, l/km);

A is 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 charge balance per distance to δX (Ah/km). The allowable error of charge balance per distance can be expressed as follows.

$$A \times \delta X \leqslant \frac{k}{100} \times FC_{\mathrm{est}} \tag{2}$$

$$\delta X \leqslant \frac{k}{100} \times \frac{FC_{\mathrm{est}}}{A} \tag{3}$$

where

k is the required accuracy for the fuel consumption test (%);

δX is the allowable error for the charge balance per distance (Ah/km).

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

$$\delta X = \int_0^T \frac{\delta I}{L}\, dt = \frac{\delta I \times T}{L} \tag{4}$$

$$\delta I = \delta X \times \frac{L}{T} = \delta X \times V_{\mathrm{av}} \tag{5}$$

where

T is the test duration time in hours (h);

L is the distance covered during the test (km);

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

Equations (3) and (5) lead to Equation (6). Equation (6) gives the allowable error for the current measurement, δI, as a product of the allowable error in the charge balance per distance and the average velocity of the test cycle.

$$\delta I \leqslant \frac{k}{100} \times \frac{FC_{\mathrm{est}}}{A} \times V_{\mathrm{av}} \tag{6}$$

Since the coefficient of the first-order term of the linear regression line (fuel consumption/charge balance per distance) can be determined only after the test, the allowable error for the corresponding current measurement system cannot be determined before the 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 test cycle. The accuracy of the current measurement system should be determined using this provisional value, and the actual allowable error in current measurement system should be checked after the test by using the obtained resultant coefficient to confirm the accuracy of the system.

4.4 d.c. stability confirmation and d.c. offset nullification

As mentioned in the previous subclauses, ΔQ for the linear regression operation is calculated by integrating the battery current successively during the test period. HEVs 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 electric vehicles, that is, the duration under approximately zero current conditions is appreciable, in spite of the high flowrate operation under peak power assist conditions. Since ΔQ is the integrated value for the intermittent charging current and the intermittent discharging current, and has a long integration time for small currents, d.c. offset in the current measuring system has the possibility of being one of the major factors affecting the error.

As a result of the short durations for high-peak currents, the long durations for low currents and the long integration times, it is essential to confirm the d.c. level stability of the current measurement system and to cancel the remaining d.c. offset value in the current measurement system more accurately. It is appropriate to confirm the d.c. level stability and to nullify the d.c. offset using the following steps.

Step 1 Before starting the test, the current measuring system should warm up for the period recommended by the measuring system manufacturers.

Step 2 The d.c. offset value for the current measurement system immediately before the test, I_{OB}, and the one immediately after the test, I_{OE}, can be measured with the main key turned off (see Figure 6a).

Step 3 The difference of the d.c. offset for before and after test($|I_{\mathrm{OB}} - I_{\mathrm{OE}}|$) can be checked to see if it is smaller than the allowable error for the current measurement system [refer to Equation (6)]. If the system is sufficiently stable (i.e. $|I_{\mathrm{OB}} - I_{\mathrm{OE}}| <<$ the allowable error for the current measurement system), step 4 can be performed to cancel the d.c. offset value for the current measurement system. If it is not sufficiently stable, the variation of the d.c. offset value can 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 can be performed:

a) if the offset value moves gradually in one direction (simple drifting), and its drift rate is almost constant [refer to Figure 6b)], nullification (step 4) can be performed without carrying out any additional operation;

b) if the d.c. offset value fluctuates irregularly and the variation exceeds the allowable error for the current measurement system [refer to Figure 6c)], it is clear that sufficient accuracy cannot be achieved by the system. The current measuring system has to be re-adjusted or reconstructed so that sufficient stability can be obtained.

Step 4. Nullification of the offset value of the current measurement system: prior to performing the integrating operation of the measured battery current for obtaining the electric charge change, ΔQ, the offset value of the measured battery current data can be compensated by cancelling the average offset. The nth compensated current data, i_{n0}, is expressed as follows, using the nth measured current data, i_n:

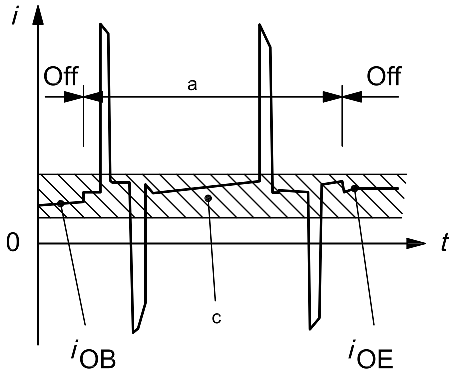
$$i_{n0} = i_n - \left[i_{\mathrm{OB}} + \left(\frac{i_{\mathrm{OE}} - i_{\mathrm{OB}}}{N - 1} \right) \times (n - 1) \right] \tag{7}$$

where N is the total number of sampling points during the test.

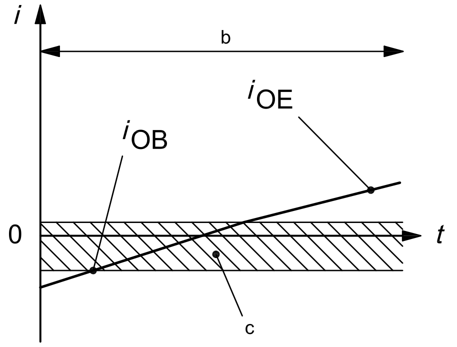
For the sufficiently stable condition ($\left| I_{\mathrm{OB}} - I_{\mathrm{OE}} \right| <<$ allowable error), it is enough to cancel the whole current data with average offset value. Namely, i_{n0} is expressed for all "n" as shown in Equation (8):

$$i_{n0} = i_n - \left(\frac{i_{\mathrm{OB}} + i_{\mathrm{OE}}}{2} \right) \tag{8}$$

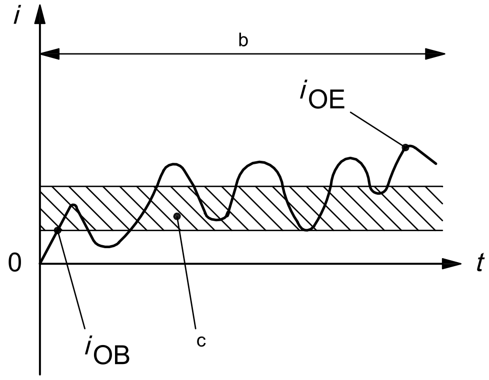
This nullification process is essential for achieving a sufficiently small resultant offset value relative to the allowable error for the current measurement system if the current measurement system has an offset value.



a) Normal operating condition



b) Serious drift



c) Unstable condition

a Key on.

b Key off.

c Allowable error.

Figure 6 — Conditions of d.c. offset pattern

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