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Fuel Consumption Test Method for HEVs -Error Estimation and Test Procedure for Better Accuracy-

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Abstract

Energy efficiency evaluation of HEVs is important to classify the hybrid vehicles by efficiency or to confirm the efficiency level to clear the certain level such as the threshold level for green tax. But, actual fuel consumption test for HEVs has various problems to be solved. One is the effect of charge balance of RESS on fuel consumption and the other huge subjects is effect of the fluctuation of the load or mechanical loss of chassis dynamometer due to the high efficiency of HEVs. The effect of the fluctuation of dynamometer load or mechanical loss of the system becomes to be more significant according to the popularizing trends of 4WD HEVs.

In this paper, firstly we summarize the above subjects and its effects on test results, and secondary we discuss following two subjects: 1) Optimum restraint condition for minimizing mechanical loss fluctuation generated by front axle. 2) How to reduce the deviation of loads (including fluctuation or variation of mechanical losses generated by the tire)

Keywords: Hybrid Electric Vehicle, Standardization, energy consumption, efficiency, PHEV

1 Introduction

Energy efficiency evaluation of HEVs is important to classify the hybrid vehicles by efficiency performance or to confirm the efficiency level to clear the certain level such as the threshold level for green tax, by the scale common or equivalent to another type of vehicles. But, actual fuel consumption test for HEVs has various problems to be solved. First one is the effect of charge balance of rechargeable energy storage system (RESS) on fuel consumption. Basic solution for this subject had been given by standards (ex. ISO 23274 or SAE J 1711). One of the other huge subjects is effect of the fluctuation of the load or mechanical loss of chassis dynamometer (CHDY) due to the high efficiency and low fuel consumption of HEVs. The effect of the fluctuation of dynamometer load or mechanical loss of the system becomes to be more significant according to the popularizing trends of 4WD HEVs among heavy weight passenger vehicles such as SUVs. Basically, 4WD HEVs should be tested on double axes CHDY, but double axes CHDY has various factors that generate load or mechanical loss errors anew. Furthermore no clear method is determined for the test on the double axes CHDY. Because of high efficiency of HEVs, resultant fuel consumption of the test is deeply affected by these load and loss errors generated in the test. So, the newly generated errors are very huge problems for fuel consumption test of HEVs.

We proposed guideline of charge balance measurement to have enough accuracy in fuel consumption test on various HEVs[1] and the method to confirm the validity of the test result of 4WD HEV obtained on single axis chassis dynamometer (the HEV is modified to 2WD configuration)[2]. And we also discussed on the fluctuation of mechanical losses generated by tire side force of 4WD HEV tested on double axes CHDY. We found that conventional restraint system have the tendency to generate the fluctuation of tire losses due to hysteresis of steering system and we proposed the restrain procedure to reduce the fluctuation of tire losses (lateral stiffness of front axle is improved to minimize unexpected slip angle fluctuation and the lateral stiffness of rear axle is lowered to minimize rear tire slip angle).

In this paper, firstly we summarize the subjects mentioned above and its effects on test results. Secondary, we discuss following two subjects;

1) Optimum restraint condition for minimizing mechanical loss fluctuation generated by front axle
2) How to reduce the deviation of loads (including fluctuation or variation of mechanical losses generated by the tire)

2 Cancelation of RESS effects

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

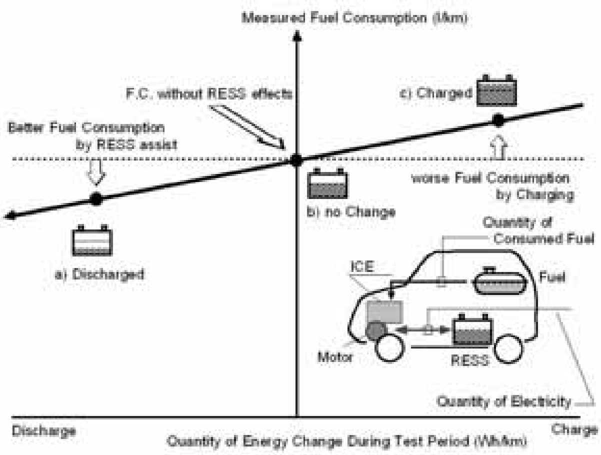

Figure 1: Effect the energy change in the RESS on fuel consumption in HEVs

2.1 Review of linear regression methods

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.

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

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 (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 Charge balance measurement

The regression line will be all so scattered by the errors in charge balance measurement.

The allowable error in the electricity consumption (Ah/km) can be estimated directly using the information in Fig. 2. Figure 2 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.

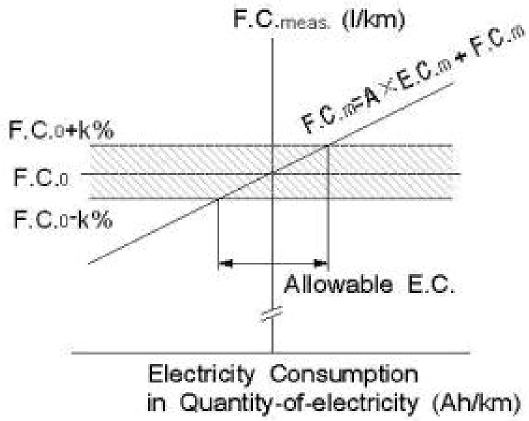

Figure 2: Allowable error in charge balance measurement

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 ΔEb 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.

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

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

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)

Vav : 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 equation 9 gives allowable error in total current measuring system, system should have accuracy less than 10% to 1% of "δI". This requirement is also valid for long term DC stability, because charge balance is obtained by integrating the current data.

2.3 Discussion of accuracy in existing test methods

Figure 3 shows variation of charge in succeeding 10.15-mode scheduled driving test. After several cycles, fuel consumption reaches steady state level, but charge value is still increasing. This reason is that the coulomb efficiency of this system is not 100%, overcharge is necessary to maintain the SOC level in the steady state.

Measured energy level has a tendency to increase more rapidly even in steady state conditions, due to low energy efficiency.

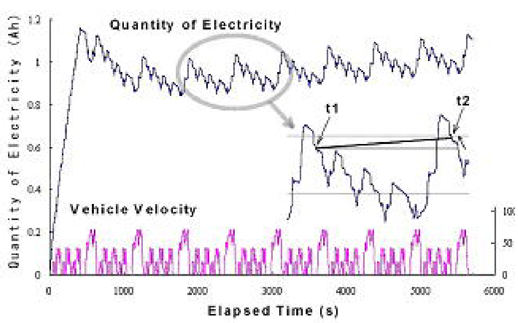

Figure 3: Variation charge in succeeding mode test

Figure 4 demonstrates the relationship of the phenomenon. In the steady state (after long driving) additional energy is consumed to maintain the SOC of RESS to target level. Concerning the fuel consumption v. s. energy change of RESS, energy change data will scattered not on the Y axis but slightly right side of Y axis. This offset shows the energy spent for RESS itself. As for the charge, some RESS does not show the 100%, but shows around 100%, rough estimation of RESS independent fuel consumption without any compensation by coulomb efficiency.

Some test method define the condition of steady state, by the condition that change of energy of RESS in each test cycle is less than 1% of driving energy (or energy of fuel spent in the driving cycle). This allows additional error on conventional error such as CHDY simulation error, fuel consumption measurement error or error on charge balance measurement. As this allows offset error to evaluate too high, some additional requirement may be needed.

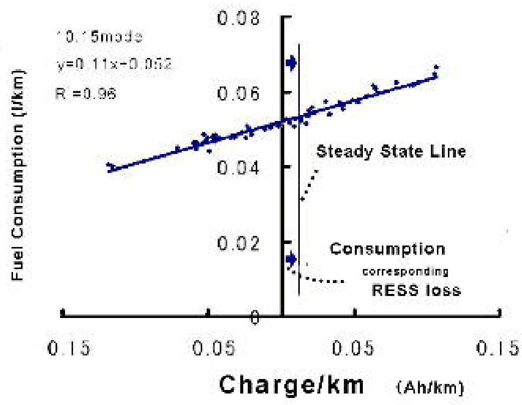

Figure 4: Offset of charge balance

3 Necessity of double axes tester

Single axis CHDY has some problems. Even for 2WD HEVs, braking simulation is incomplete. As the service brake on non traction axis is not active, the system has a possibility to have additional regenerative energy as a part of energy to be consumed by the service brake on non traction axis. 2WD HEVs with traction control system can not work on the single axis CHDY in its normal operating mode. Vehicle velocity will be limited by its traction control function if the HEV is operated on the single axis CHDY due to tremendous slip ratio among front tires and rear tires. In most cases, 2WD HEVs with traction control system has a function to cancel the function cooperated with non traction axis such as traction control system. This cancellation function is prepared for maintenance use on drum tester, and is enabled in "maintenance mode" (vehicle

control algorithm is modified). Braking simulation is also incomplete for HEVs of this type.
As 4WD HEV has extra motor(s) on non main traction axis, it can not work on the single axis CHDY. 4WD HEV can also work on single axis CHDY if HEV is set in its maintenance mode. As the HEV acts as 2WD HEV in maintenance mode, total traction/regeneration power of the HEV will decrease and braking simulation will also be incomplete.
In spite of some problems laying on single axis CHDY, 4WD HEV has a tendency to be tested on single axis CHDY due to low cost and popularity of the system. So, it is important to provide a method that can confirm the validity of the test result of 4WD HEV obtained on single axis chassis CHDY.
As for FF base HEVs, brake system is designed so that regenerative braking covers without mechanical brake, in normal operating conditions. So, test on single axel CHDY can obtain enough data concerning regenerative energy.
On the contrary, FR or FR based 4WD needs 2 axis CHDY, because of needs of braking power in front wheels. Figure 5 shows the braking behaviour of EV track for delivery use.

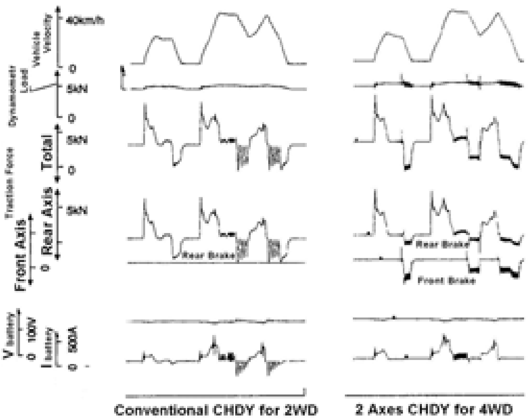

Figure 5: Behaviour of Brake on chassis dynamometer

4 Fluctuation of mechanical losses

Fuel consumption of HEV is sensitive to road load variation due to high efficiency of hybrid system. So, road load setting (including mechanical loss measurement) of CHDY should be done carefully. As for 4WD HEVs, four tires are active in CHDY tests; despite of only two tires on traction axis are active in 2WD HEVs. So, fluctuation in mechanical losses of tires of 4WD HEVs are larger than that of 2WD HEVs. Therefore it is necessary to manage the mechanical losses carefully in 4WD HEV test on double axes CHDY.
Variation of mechanical loss of tire during test can not be compensated, therefore mechanical loss especially variation of mechanical loss have to be minimized or managed.

4.1 Load fluctuation generated by tier side force

One of the other instable losses in double axes CHDY will be caused or generated by restraint equipment. As all four tires on 4WD HEV are active on double axes CHDY, test vehicle has to be restrained by restraint equipment as shown Figure 6. Generally, vehicle is pulled to forward and backward by two sets of cross wires. Conventional restraint equipment has stiff spring on the restraint pole, and pre tension is set by the spring.

Figure 6: conventional restraint procedure

If test vehicle is restrained roughly, vehicle will have yaw angle. This yaw angle causes two unstable phenomena; one is side force of tires and the other is lateral movement or yaw angle movement. Latter one is generated as following manner; during accelerating period and decelerating period, tensions of restraint wires varies by traction force or braking force, vehicle moves so that tension will be balanced if the tensions of restraint wires are not symmetry. To avoid vehicle movement, test vehicle should be set correctly symmetry and wire tension should also be set correctly.

4.1.1 Effect of side slip angle in the wheel without steering system

Typical drag force generated by side slip of rear tires is tested, by motoring only rear axle by

CHDY for small yaw angle. Variation of drag force is neglect ably small in a small yaw angle. So, as for tested vehicle, rear tire shift within ±2cm causes no significant drag force variation. On the centrally, vehicle has to be set within ±2cm shift from right position. Out of this position, significant drag force variation will caused by small lateral movement.

4.1.2 Effect of slip angle due to hysteresis in steering system

Front axle has a steering system, and steering system has hysteresis. In last report, we discuss about hysteresis in steering system, and showed that this hysteresis has a possibility to generate unsteady side force on the tire on steering axle. As shown in figure 7, this side force can be minimized by applying steering torque periodically with decreasing its amplitude gradually (we call this operation as “hysterics minimization (of steering system)”. But side force has possibility to vary within hysterics in lateral force by the force applied to tire in acceleration or deceleration operation.

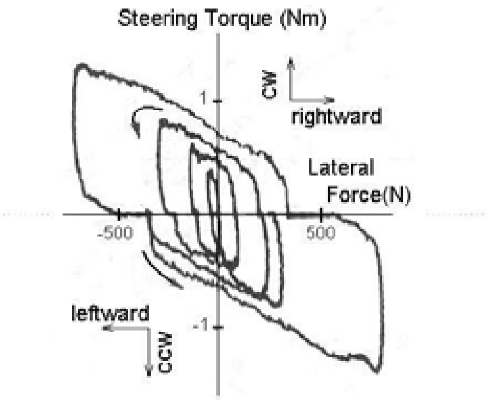

Figure 7: Hysteresis in the steering system

4.1.3 Restraint procedure to improve load fluctuation

In latest report, we tried to find proper restraint procedure, and introduced stiffness improved restraint procedure for front side and increased lateral compliance for rear restraint. Front wires are fastened at their cross point by fastener as shown in figure 8. Lateral compliance is increased by putting box shape wire portion among vehicle rear side and restraint pole, to enable the rear wheel to follow the right track for less side force.

Figure 8: restraint with improved lateral stiffness

We had checked 4 restrain procedures and had found that type 4 in figure 9 (improved stiffness in front restraint system and improved compliance in rear restraint system) can put stable condition as shown figure 10.

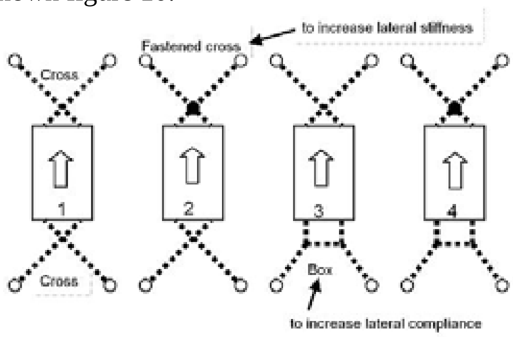

Figure 9: Restraint system on the test table

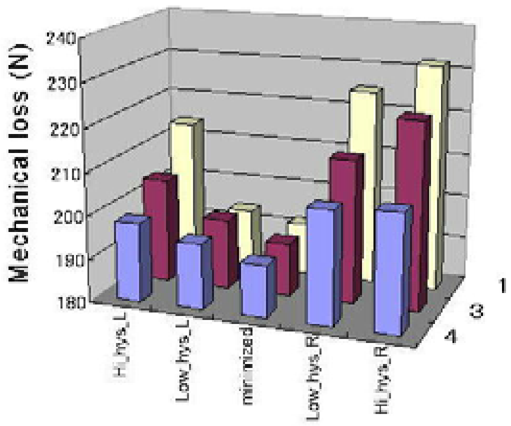

Figure 10: Effect of restraint system on mechanical loss fluctuation

As shown in figure 8, we accomplished restraint system with high stiffness by adding a fastener on wire crossing point of conventional restraint system to make two rigid triangle and we can get fine result. This restraint procedure has small backlash in the centre due to the size of fastener. We tried to cancel this backlash to get more result in ideal conditions. We made ideal restraint system with enough lateral stiffness (see figure 11) and tried to test. But we found that too high stiffness of front axle makes frequent steering operation due to self aligning torque generated in actual test period even after enough "minimizing operation of hysteresis in steering system" and this leads unexpected fluctuation of mechanical losses. At this moment, we can not find clear stiffness condition to realize stable test. But it will be right that some backlash may be needed for stable operation.

Figure 11: Rigid restraint system to find proper lateral stiffness

4.2 Load fluctuation generated by tier rolling losses

The CHDY simulates road load and the kinetic energy of the vehicle. As the road load data is obtained by coast down test after enough pre-running (for warm up) and certain load compensated by mechanical loss of vehicle-chassis dynamometer system shall be set to be absorbed by dynamometer, so that the obtained road load will be reproduced, we have to be careful that tire loss will be well simulated under coast down test conditions and dynamometer setting conditions. If tire behaviour on the chassis dynamometer is different from the one on actual road, this deference will be one of the factors that degrade the test accuracy.

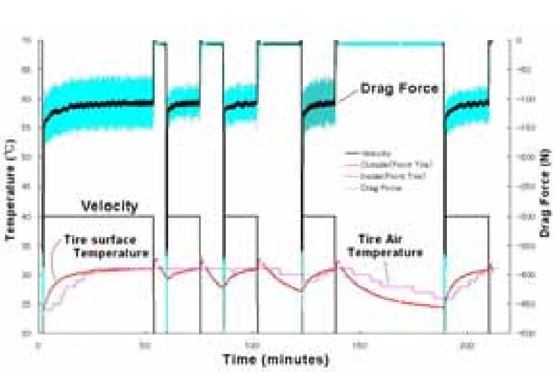

Figure 12: variation of tire drag force and tire temperature under free rolling conditions

Figure 12 shows variation of tire drag force and tire temperature under free rolling conditions. (Vehicle is set on the chassis dynamometer with its gear is set to "neutral position", and its tires are driven by chassis dynamometer at a constant velocity of 40km/h. Drag force is measured as a traction force). Two tire temperatures are measured, one is surface temperature on tier side wall and the other is temperature of air in the tire. As the volume of the air in the tire is huge, air temperature has huge time lug. However, tire surface temperature seems to be varying without time lug.

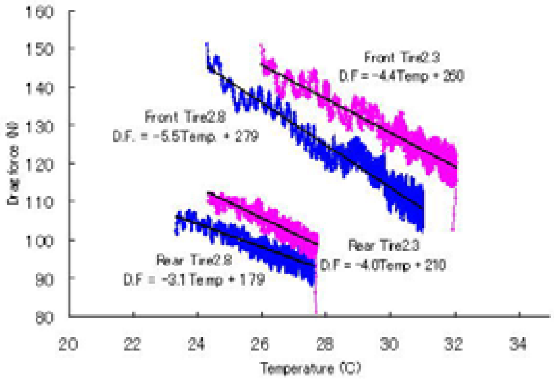

Figure 13: correlation of tire surface temperature and drag force

Figure 13 shows correlation of tire surface temperature and drag force in two tire pressure conditions (230kPa: recommended pressure. 2.8kPa: tested pressure to reduce tire loss). Low pressure tire has tendency to have higher drag force, but gain of the correlation factor has no significant variation among 4 conditions. As HEVs are highly efficient, fuel consumption has a tendency to be affected by road load or mechanical loss. For example, 10N increase of road load makes 5% degradation in fuel consumption of typical HEV. So, variation of tire loss (=drag force) both on chassis dynamometer and on road should be checked whether notable difference is exist or not.

We tried to estimate the variation of tire loss by watching tire surface temperature, but still we have no result. As the surface temperature of tire is deeply affected by velocity of wind, proper compensation with wind velocity will be required. Our target is to check the variation of tire loss in actual driving conditions and test conditions. At this moment, we have checked the variation of tire loss only in the test condition on 4WD chassis dynamometer (see figure 14). After 3, 6 or 9 cycles of 10.15-mode test, free rolling test was conducted to measure the rolling loss. This result shows that tire loss will vary widely in conventional pressure. This means resultant fuel consumption data varies widely corresponding to the cycle time of test cycle. High pressure tire can make this variation small, but we can not find proper pressure to be set, at this moment.

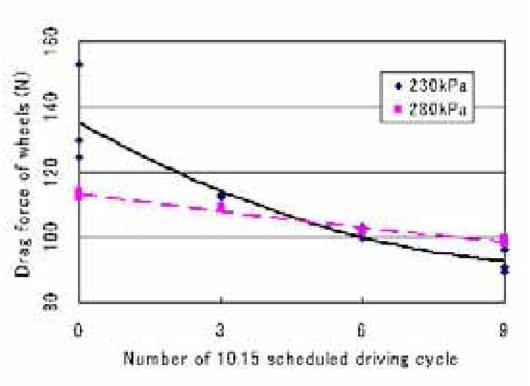

Figure 14: variation of tire loss in the test condition

5 Some Comment for PHE tests

Plug-in hybrid vehicle has some operating mode, some mode is EV like mode and the other is HEV like one. PHEVs have many possibilities in operation and there may be several procedure to evaluate there efficiency or performance. It may be difficult to evaluate their efficiency by one simple scale such as fuel consumption, because of their complex and various applications.

So, it is important to find basic values that can be used to calculate or estimate the basic characteristics of PHEVs. (It is better to have a flexibility to adopt various applications to be up near future.

As for basic values, SOC level of HEV mode (CS mode) and recharged energy will be one of the key values. SOC fluctuation or variation in long duration should be checked to find suitable rechargeable energy value, in addition to the charge balance value in each cycle.

Distance covered by CD mode and equivalent all electric range will be also one of the important key values, along with the quantity of fuel consumed in CD mode. As various concepts will be come up for PHEVs, we will need simple procedure to estimate these values, without succeeding long test on CHDY if possible. We think that result of one example test has few meaning for PHEV which may be used in various conditions.

6 Conclusion

Subjects that affect accuracy of efficiency test for HEV are summarized and rechecked referring to suitable portion of our study. We try to set a ideal restraint condition obtained last study, but we find that too high stiffness in restraint system lead us degraded result and find that small backlash is needed for better restraint system.

We try to clarify the effect of fluctuation of tire rolling loss on test accuracy. We can find possibility of degrading in the test result by this factor, but we cannot confirm in this moment.

Acknowledgments

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