

# Fuel Consumption Test Method for 4WD HEVs – On a Necessity of Double Axis Chassis Dynamometer Test –

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Concerns regarding global climate change have caused the transportation sector to look for alternatives to petroleum as a fuel for vehicles of all types. Hybrid electric vehicles (HEVs) have been recognized as being particularly efficient for urban traffic use. In the last few years, Four wheel drive (4WD) transmissions have been developed for heavy passenger vehicles. As these vehicles become more popular, there is a need for accurate fuel consumptions test methods. Clearly the most accurate fuel consumption measurements would be obtained by using dual axis dynamometers, but these systems are not always available. Single axis dynamometers are commonly used for evaluating fuel consumption, but these are inadequate for 4WD vehicles without adjustments to account for the uncertainty that will result from disabling one of the drive axles.

This paper describes a method for extrapolating fuel consumption results from single axle chassis dynamometer testing to estimate the fuel consumption of 4WD vehicles. A simple method is proposed that will allow reasonable estimates of fuel consumption for 4WD vehicles to be made from single axle dynamometer testing.

This paper also describes methods to reduce the uncertainty in 4WD chassis dynamometer testing by paying particular attention to road load, tire conditions and restraint characteristics.

**Keywords:** HEV, Energy Consumption, Efficiency, Chassis Dynamometer, State of Charge

## 1. INTRODUCTION

Energy efficiency evaluation of HEVs is important to classify the vehicles by efficiency performance or to confirm the efficiency level to clear the certain level such as the threshold level for green tax. Basic fuel consumption test method for HEVs has been established as ISO standards (ISO 23274). In the last few years, 4WD HEVs have been developed and are becoming popular among heavy weight passenger vehicles such as SUVs. As for the vehicles in this category, HEVs with an electric 4-wheel drive system should be accepted due to its high efficiency and high traction performance on the low  $\mu$  roads.

Basically, a fuel consumption test of 4WD HEVs should be conducted on double axes chassis dynamometer. But, single axis chassis dynamometers are commonly used for the test, due to the two main problems lying on double

axes chassis dynamometer application. First problem is high cost and non popularity of double axes chassis dynamometer. It is common to evaluate 4WD ICEVs on a single axis dynamometer by modifying the 4WD system to 2WD system. The second one is the difficulty in double axes chassis dynamometer applications. Although double axes chassis dynamometer has various factors that generate load or mechanical loss errors anew, no clear method is determined for the test on the double axes chassis dynamometer. Because of high efficiency of HEVs, resultant fuel consumption of the test is deeply affected by these load or loss errors generated in the test. So, the newly generated errors are very huge problems for fuel consumption test of HEVs.

In this paper, the above mentioned two problems are discussed: The first one is on 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 condition). We propose simple test method to check if the result on single axis chassis dynamometer is equal to the one on double axes chassis dynamometer or not. As this test can be conducted on a proving ground (no double axes chassis dynamometer is required) only by measuring battery current history (no fuel consumption

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measurement is required), it is useful for those who have no double axes chassis dynamometer facilities.

The second one is on the application of double axes chassis dynamometer to have enough repeatability in the resultant data. Guideline of double axes chassis dynamometer application will be proposed to ensure test repeatability in above mentioned test. As HEV power train is efficient, fuel consumption of HEVs is sensitive to road load. So, it is important to manage tire loss variation in test periods and the management on vehicle restraint procedure is also important to keep the test vehicle in adequate condition.

**2. PROBLEMS OF 4WD HEV FUEL TEST**

HEVs are classified to following three types by their traction style.

- o 2WD HEVs without traction control system
- o 2WD HEVs with traction control system
- o 4WD HEVs (normally, with extra motor for electric 4WDfunction)

And chassis dynamometers (CHDYs) are roughly classified to following three types.

- o Single axis CHDY (for 2WD HEVs)
- o Double axes CHDY consisted by electrically linked two single CHDYs
- o Double axes CHDY with one dynamometer and mechanically linked two rollers

Concerning double axes CHDY (for 4WD HEVs) two dynamometer type CHDY is commonly used. So, we only discuss on single axis CHDY and two dynamometer type double axes CHDY.

Table 1 shows problems on CHDY simulation in each

case. Simulation on both traction and braking has no problem on double axes CHDY. On the contrary, 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.

Figure 1 shows possible combinations of HEV operating modes (normal/maintenance mode) and CHDY types. 4WD HEV can operate in normal mode

Vehicle type	Vehicle simulation in <i>Traction control / Braking control</i>	
	Double axes CHDY	Single axis CHDY
2WD HEV without cooperative control	OK / OK	OK / Incomplete
2WD HEV with cooperative control	OK / OK	Incomplete / Incomplete (control should be modified)
4WD HEV	OK / OK	Incomplete / Incomplete (to be modified to 2WD / control should be modified)

Table 1: Feasibility of traction/braking simulation on CHDYs

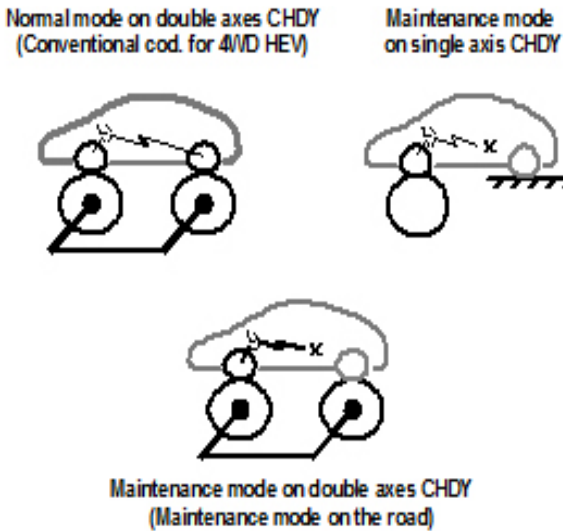


Figure 1: Combinations of vehicle operating modes and CHDYs

only on double axes CHDY. Normal mode on double axes CHDY simulates normal driving conditions of 4WD HEV on the roads. Condition of maintenance mode on single axis CHDY is available only in this combination (cannot be provided on the road). Maintenance mode on double axes CHDY simulates the driving condition in maintenance mode on the road. So, normal operating model on double axes CHDY and

maintenance operating mode on double axes CHDY can be realized without CHDY.

### 3. POSSIBILITY OF SIMPLIFIED TEST ON SINGLE AXIS CHASSIS DYNAMOMETER

Figure 2 shows variation of battery SOC (variation of quantity of electricity, variation of charge balance), variation of total charged quantity of electricity (total charged charge) and variation of total discharged quantity of electricity (total discharged charge) during 10-15 mode driving schedule test of a HEV in the market. In this paper, we call “quantity of electricity” to “charge” and also call “change of quantity of electricity” to “charge balance”, to simplify. Total charged charge and total discharged charge correlate with amount of energy spent by motor. Energy spent by motor gives amount of replaced energy to be spent by internal combustion engine (ICE) with energy in electric power train. Namely, efficiency of HEV depends on total discharged charge, so, this value will be proper indicator for efficiency level of HEV.

We try to apply this indicator to verify the fuel consumptions of HEV in two different operating mode and or CHDY types. Namely, if total discharged charge of two test of a HEV conducted under different operating mode and or CHDY types, is equivalent, hybrid system works in the same way and resultant fuel consumption of two tests will be the same. To confirm this feasibility,

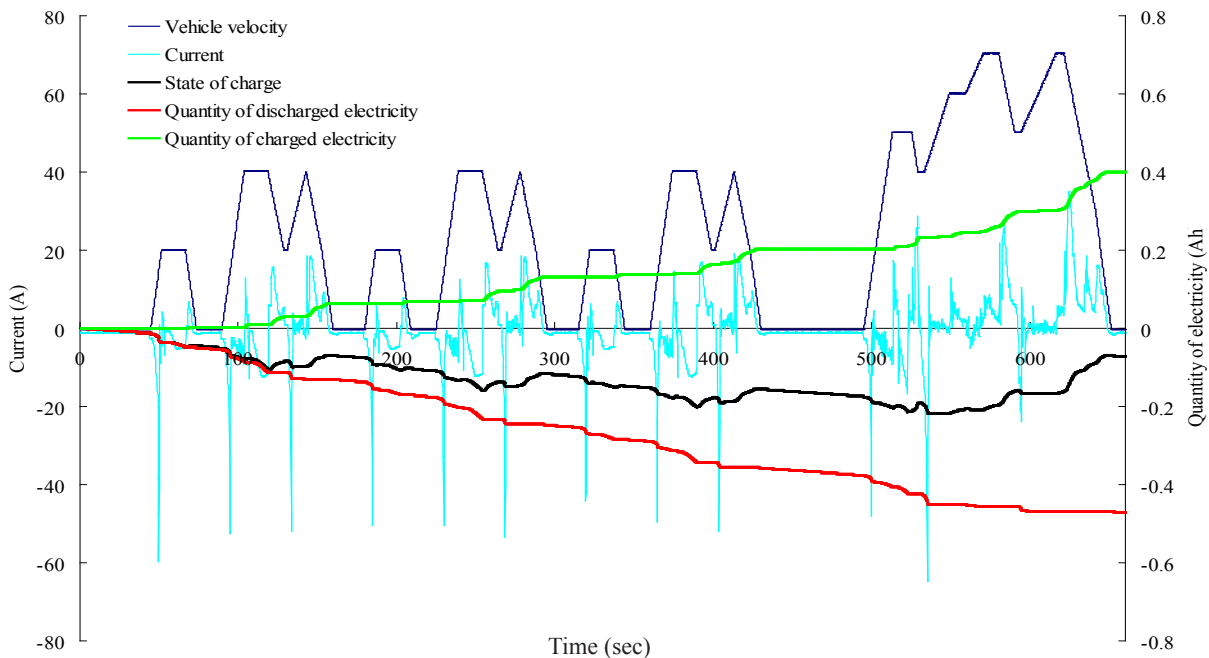


Figure 2: Variation of total charged/discharged charge during 10-15 mode test

10-15 mode scheduled driving tests of 2WD HEV under both normal operating mode and maintenance mode are conducted on double axes CHDY. These conditions are similar to driving condition under normal mode and maintenance mode on the flat road respectively. Resultant total discharged charge is shown in Figure 3a, and result of fuel consumption is shown in Figure 3b. As the total discharged charge and fuel consumption of one test depend on charge balance of the battery during test, these values are estimated by result of several tests under different charge balance. Charge balance independent value is obtained as Y axis crossing point of each regression line [1], [2]. Result shows that total charged charges of two test results are similar. This means hybrid system will work similarly and fuel consumption in these two conditions will be similar. This result can be confirmed by Figure 3b.

We try to check if the result of 4WD HEV on single axis chassis dynamometer is equal to the one on double axes chassis dynamometer or not, by using this verification method. Following three tests were conducted using 4WD HEV in the market:

1. Normal mode on double axes CHDY corresponding to conventional operation.
2. Maintenance mode on double axes CHDY corresponding to maintenance mode on the road.
3. Maintenance mode on single axis CHDY (conventional condition on single axis tester).

Resultant total discharged charge is shown in Figure 4a. As the test vehicle is operated not by automated actuator but by an operator, fuel consumption data is scattered comparing to Figure 3a, b (operated by automated actuator). There is clear difference between normal operating mode and two maintenance modes. By this result, we can estimate that working condition of the hybrid system in the tested driving schedule is different in normal operating mode and maintenance mode. Figure 4b shows resultant fuel consumption data obtained by the test. Unexpectedly fuel consumption data has little correlation with total discharged electricity. We can suppose the reason of this difference by Figure 4c which shows total charged charge during decelerating periods and total discharged charge during accelerating periods. As for decelerating periods, hybrid system works in different working conditions in each combination of operating mode and CHDY. Moreover total charged charge data have a tendency to scatter in two separate working areas. We assume that both regenerative operation and assisting operation are different in each combination of operating mode and CHDY. We can confirm only the fact that this HEV needs the test on double axes CHDY, if the result on conventional conditions in this scheduled driving cycle is needed. So, this procedure can check only if test on double axes CHDY is needed or not.

As pre described procedure needs double axes CHDY, the procedure has no effect for those who has no chance to conduct a test on double axes CHDY, and also has no effect for those who has a chance to conduct a test on double axes CHDY because fuel consumption test can be conducted on double axes CHDY directly. Test “3” can be conducted only on the CHDY, but test “1” and test “2” can be conducted both on CHDY and on the flat road (or proving ground). So, some test can be conducted without CHDY.

As mentioned in Figure 4c, difference in hybrid system operation is occurred in accelerating period and decelerating period. We propose simple test method on proving ground to check if the result on single axis chassis dynamometer is equal to the one on double axes chassis dynamometer or not. As the scheduled driving cycle test is difficult to conduct on proving ground, we adopt simple 4 mode scheduled driving cycle with constant acceleration and constant deceleration of which acceleration/deceleration rate is similar to

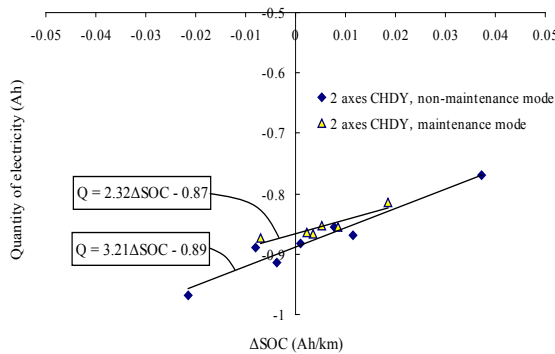


Figure 3a: Total discharged charge in two operating modes

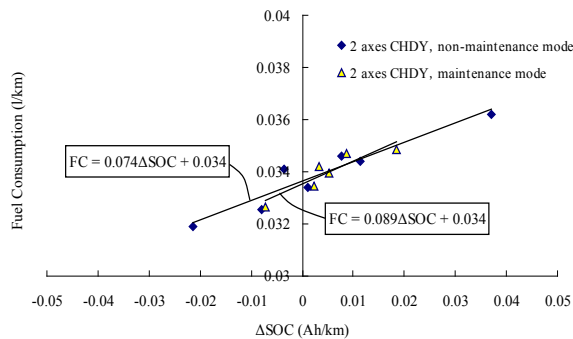


Figure 3b: Fuel consumption of 2WD HEV in two operating modes

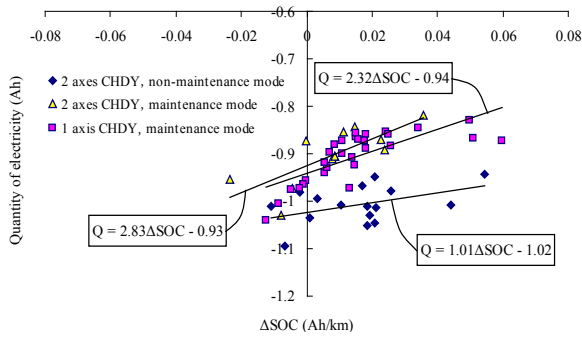


Figure 4a: Total discharged electricity in 10-15mode tests on three combinations

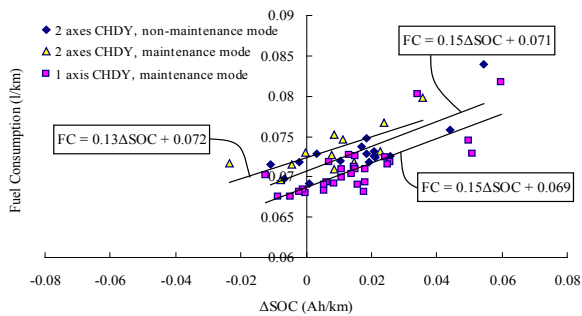


Figure 4b: Fuel consumption of 4WD HEV in 10-15mode tests on three combinations

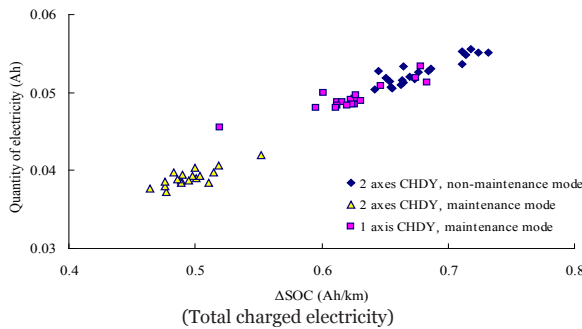
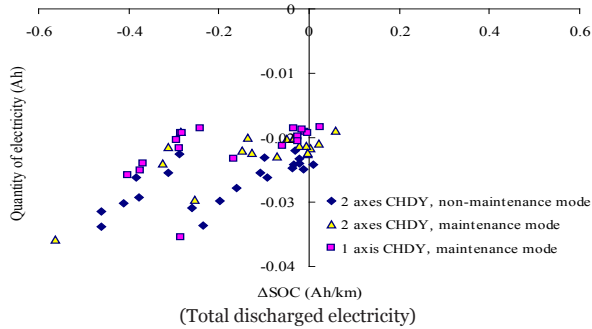


Figure 4c: Total discharged/charged charge of 4WD HEV during 10-15 mode test

maximum acceleration/deceleration rate of scheduled driving cycle to be tested. Maximum velocity of the simple 4 mode is set to the maximum velocity of the scheduled driving cycle to be tested.

The test should be conducted as follows. Posts corresponding to start point, end of accelerating period, beginning of decelerating period and stopping point are set on the proving ground, and vehicle is driven using acceleration/deceleration indicator so that the pre determined acceleration/deceleration level can be obtained (refer to Figure 5). Test under normal mode and test in maintenance mode should be conducted and each total discharged charge during the test should be measured. If total discharged charges in two tests (test “1” and test “2”) are similar, we can confirm that hybrid system of the tested HEV works similar both in normal operating mode and maintenance mode (as for driving on flat road). We have to conduct a similar test on single CHDY (test “3”) to confirm the effect of rear service brake on single axis CHDY.

The test is conducted by simulating the flat road by double axes CHDY. Figure 6a shows the result of the simulation test. Total discharged charges in each vehicle operating mode are different. This means that this hybrid system does not work at similar condition in each test, and test result in maintenance mode on single axis CHDY is not equal to the one in conventional mode on double axes CHDY. Namely, test shall be conducted on double axes CHDY. To confirm validity of this procedure, fuel consumption in each condition is measured. As shown in Figure 6b, resultant fuel consumption data is scattered, but there are a small differences in each test conditions.

This test can be conducted on a proving ground (no double axes chassis dynamometer is required) only by measuring battery current history (no fuel consumption measurement is required), it is useful for those who has no double axes chassis dynamometer facilities.

#### 4. EFFECT OF RESTRAINT PROCEDURE OF TEST VEHICLE ON ERROR

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 is active in 2WD HEVs. So, 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.

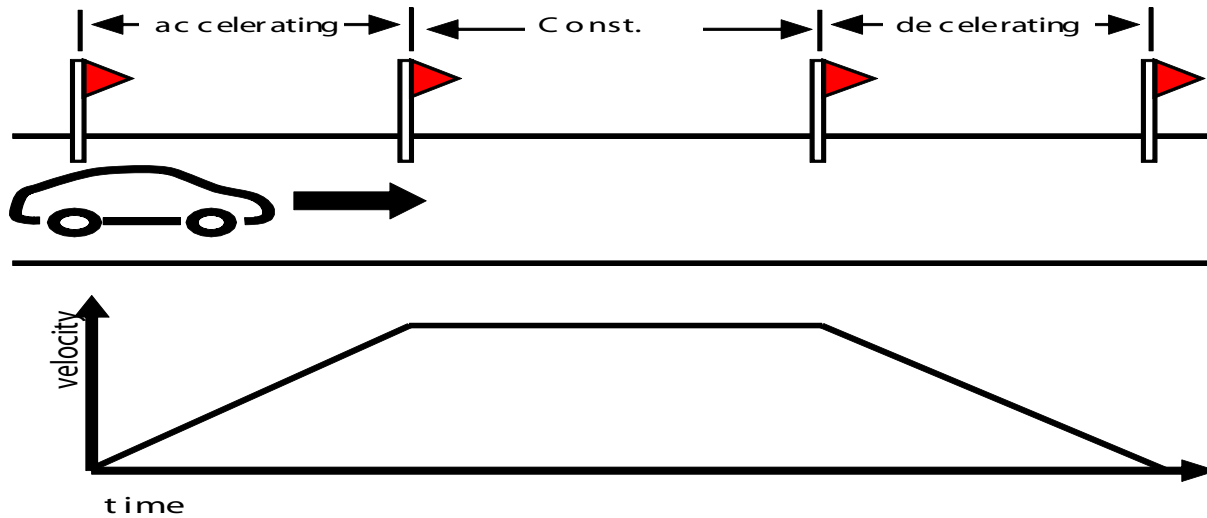


Figure 5: Outline of mode and target of simplified test

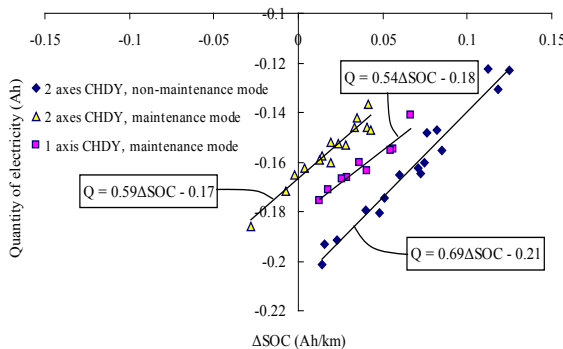


Figure 6a: Total discharged charge in simplified tests on three combinations

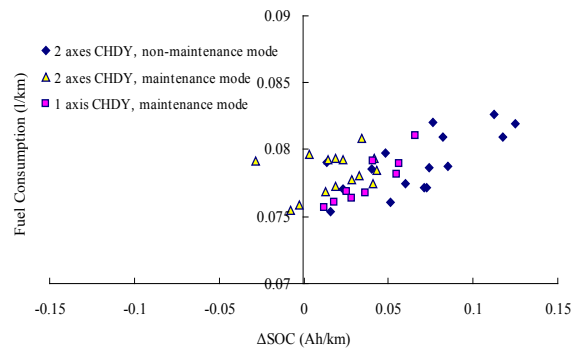


Figure 6b: Fuel consumption of 4WD HEV in simplified tests on three combinations

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 7. 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.

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 Effect of Side Slip of Rear Tires

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. Figure 8 shows typical drag force generated by side slip of rear tires. Variation of drag force is neglect ably small in a small yaw angle. So, as for tested vehicle, rear tire shift within  $\pm 2\text{cm}$  causes no significant drag force variation.

#### 4.2 Effect of Steering System Hysteries

Front axle has a steering system, and steering system has hysteries. To clarify the effect of steering system hysteries on restraint procedure, especially on

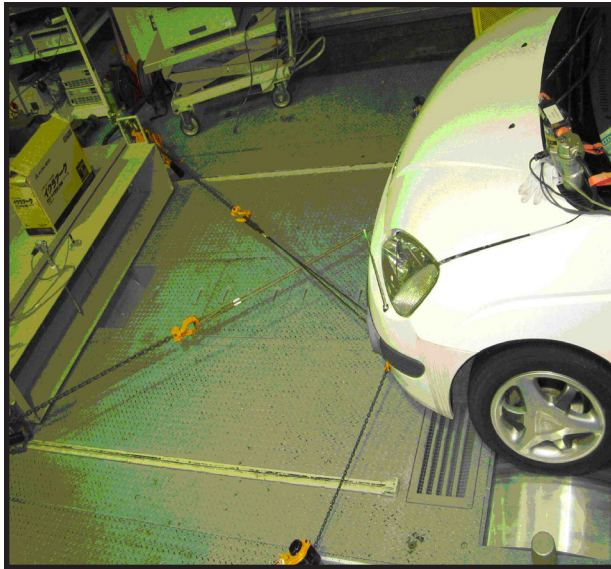


Figure 7: Conventional restraint procedure for vehicle

mechanical loss (drag force and side force), simplified test is conducted [3]. Block diagram of test system is shown in Figure 9. Test vehicle is fixed only by pivot which is set center of rear axle, and lateral displacement of vehicle front is limited by wires shown in Figure 9. Lateral force is measured as a differentiation of two wire tensions measured by load cells. Vehicle lateral displacement and yaw angle is measured by X-Y tracker with angular displacement measurement function (tracker measures XY displacement and angular displacement of the mark attached on the object to be measured, dynamically). Front wheels are set on the drum of CHDY and are rotated at a constant velocity by CHDY. Amount of mechanical loss is measured by CHDY as a drag force.

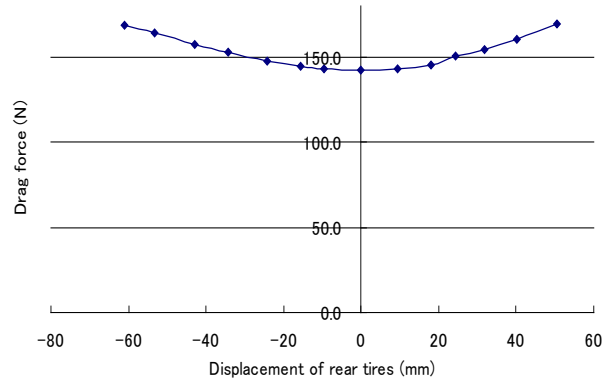


Figure 8: Effect of yaw angle on drag force of rear tires

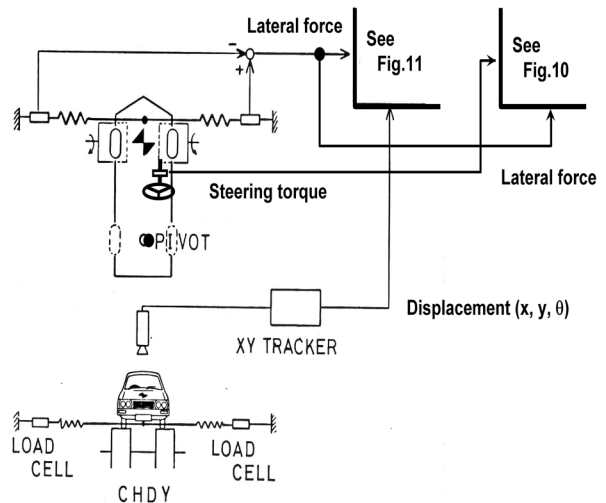


Figure 9: Block diagram of the test on hysteresis of steering system

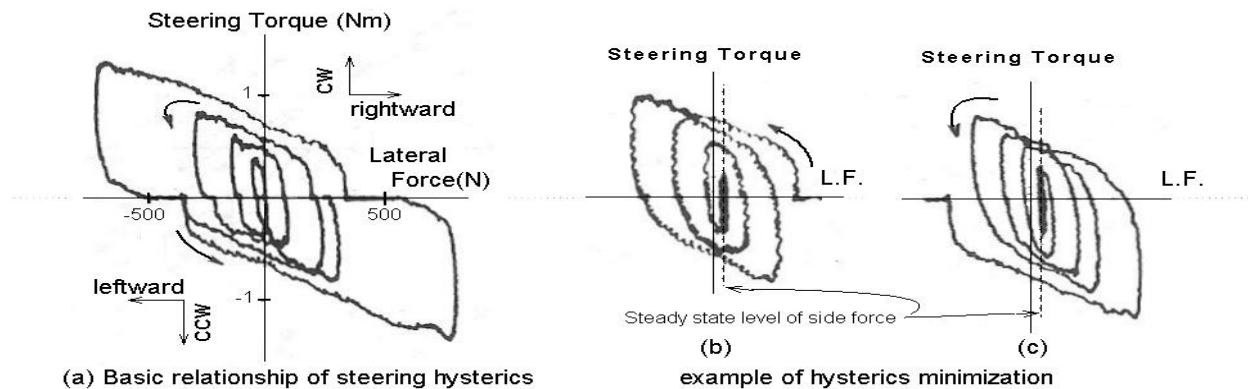


Figure 10: Hysteresis in steering system

Figure 10 shows relationship between steering torque and side force generated on front axle. Steering torque is measured by steering wheel with torque transducer replaced for original steering wheel. Steering torque vs. side force characteristics has hysteresis; therefore tire side force has possibility to vary within hysteresis in side force. After vehicle is restrained on CHDY system, steering force should be applied periodically with decreasing its amplitude gradually to minimize the hysteresis in side force (see Figures b and c). In this paper we call this operation as “hysteresis minimization (of steering system)”.

Figure 11a shows characteristics of side force (equivalent to lateral force necessary to restrain the test vehicle) vs. lateral displacement of front axle. Vehicle lateral position is changed step by step, and lateral displacement, side force and drag force (mechanical loss of front axle and drum) is measured under three steering conditions; just after hysteresis minimization, maximum hysteresis condition after steering rightward (CW) and the same condition after steering leftward (CCW). Curves upper portion in Figure 11 indicate variation of drag force corresponding steering angle, and two short segment of line on the curb indicate maximum hysteresis condition on both direction. Due to this hysteresis in steering system, test vehicle has possibility to run with any steering angle between these

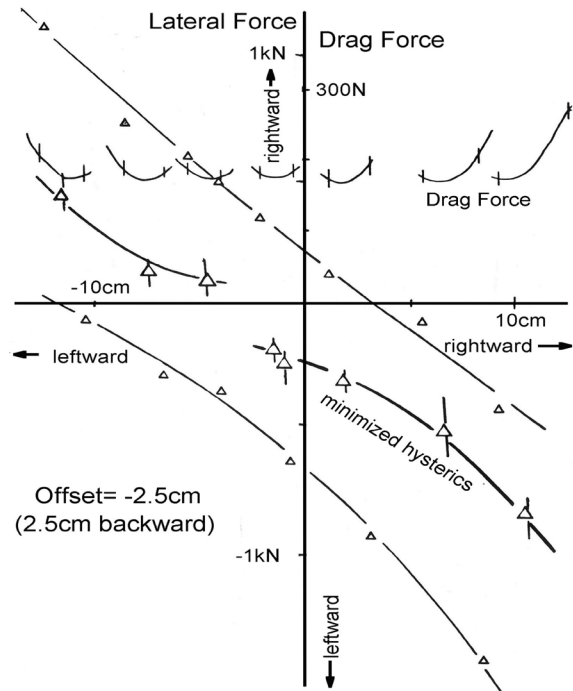


Figure 11b: Effect of hysteresis in steering system (vehicle is set 25mm backward)

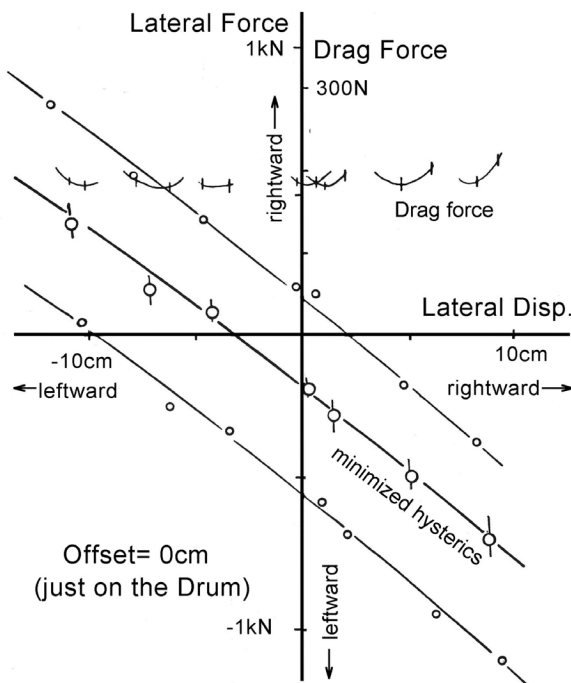


Figure 11a: Effect of hysteresis in steering system

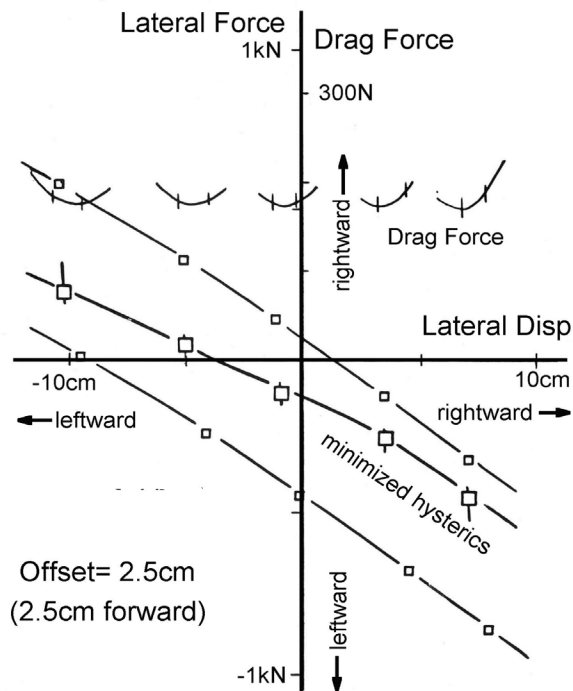


Figure 11c: Effect of hysteresis in steering system (vehicle is set 25mm forward)



two short segment of line (force necessary to restrain the vehicle will move between upper line and lower line in Figure 11). As a result, drag force will fluctuate and resultant fuel consumption data will be degraded. This figure also shows that lateral force is balanced not under the condition in which vehicle lateral displacement are zero but under the condition vehicle is set about 3cm leftward. (Vehicle is designed to run straight forward on the road with cross-grade.)

Figure 11a shows result of the test conducted under the condition that front axis of vehicle is just on the drum center. In practical test conditions, it is difficult to set vehicle front axis just on drum center. In some case, vehicle will be set forward or backward in some length. Figure 11b shows result of similar test under the condition vehicle is set 2.5cm backward, and Figure 11c is the result for 2.5cm forward. When vehicle is set backward, steering system will be unstable due to the small pneumatic trail. On the contrary, stable area will increase when vehicle is set forward.

### 4.3 Modification on Restraint Procedure to Improve Test Condition

Fuel consumption test of HEV needs at least four to five test results to estimate battery independent fuel consumption value by linear regression method. In fuel consumption test of 4WD HEVs, we have some experience on step-like change in resultant fuel consumption. In many cases, fuel consumption is shift to worse and the situation is succeeding until test vehicle is re-restrained or re-adjusted in its restraint condition. We thought that one of the reasons of this trouble will be increase of mechanical losses caused by restraint system during test. We tried to modify the restraint procedure to have stable mechanical loss. Conventional restraint procedure and following three modified restraint procedures are tested to confirm their effects.

1. cross(front) + cross (rear) conventional one
2. fastened cross (front) + cross (rear)  
increase lateral stiffness (front)
3. cross (front) + box (rear)  
increase lateral compliance (rear)
4. fastened cross (front) + box (rear) 2 + 3

Tested restraint procedure are shown Figure 12. Restraint type, of which wires are fastened at crossing point, is a one of the practical procedure to improve lateral stiffness. Generally, additional restraint wires which restrain just lateral movement were used to increase lateral stiffness. As additional wires have a possibility to affect the other wires, no additional wire is used to clarify the essence of restraint system.

Figure 13 shows relationship of fuel consumption and mechanical loss obtained from test in four restraint procedures. To clarify the effect of mechanical loss, road-load compensation by mechanical loss was accomplished only once, and every test is conducted in a same road-load and mechanical loss compensation. Mechanical loss of each test is measured just after each test (Mechanical loss of each test shows no average value during test). Mechanical losses vary about 20N, and fuel consumption data scatter about 5%. Conventional restraint generates additional mechanical loss, and makes resultant fuel consumption value scattered. Conventional restraint (front) with rear compliance is similar to conventional one. Fastened cross restraint (front) does not generate so much mechanical loss and does not make fuel consumption value to be scattered. Rear compliance by "box" improves fuel consumption stability. So, "fastened cross (front) + box (rear)" restraint system is suitable for restraining 4WD HEV.

This result can be well understood by the following figure. Figure 14 shows variations of mechanical loss of restraint system. Valley at the center is corresponding to the condition just after "hysteresis minimizing" operation. Next to the center is the result having small hysteresis conditions (steering force is released quickly after enough steering force is applied). Most out side is the result having large hysteresis conditions (steering torque is released gradually, after enough steering force is applied).

Due to the low stiffness of "conventional restraint procedure" (cross + XX), if test vehicle moves laterally during accelerating /decelerating period, vehicle has a tendency to keep the hysteresis in steering system high. On the contrary, fastened cross restraint of which lateral stiffness is improved, will keep the hysteresis in the steering system low, so that un-expected mechanical loss increase is not occurred.

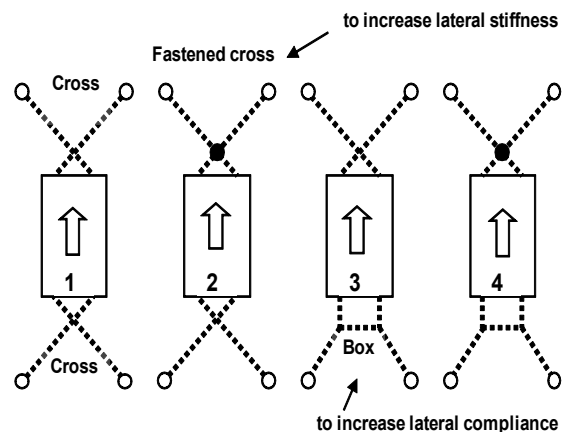


Figure 12: Restraint system to be tested

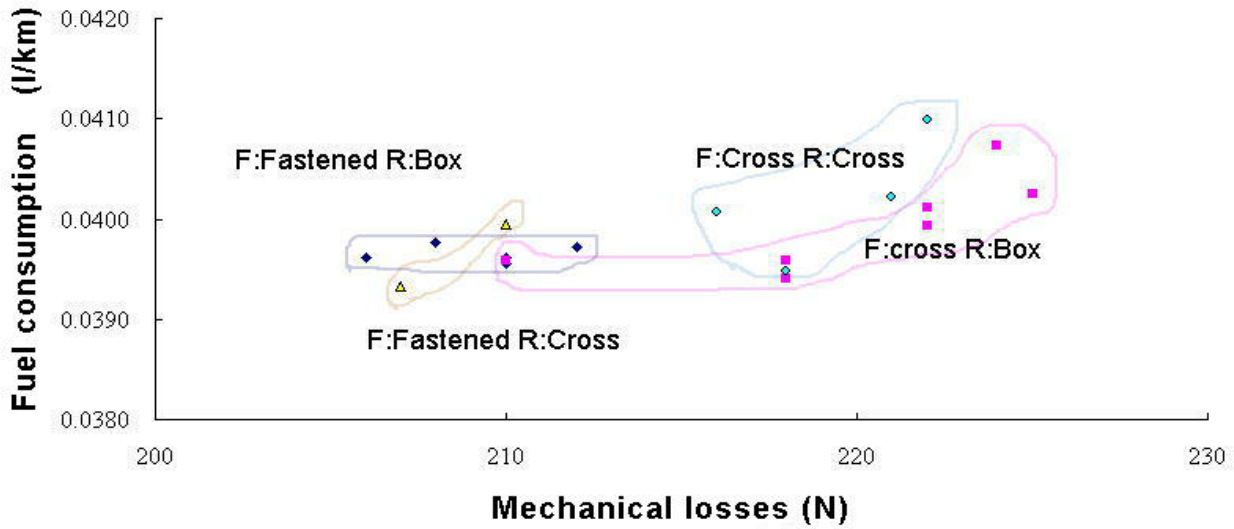


Figure 13: Effect of restraint system on mechanical loss and fuel consumption

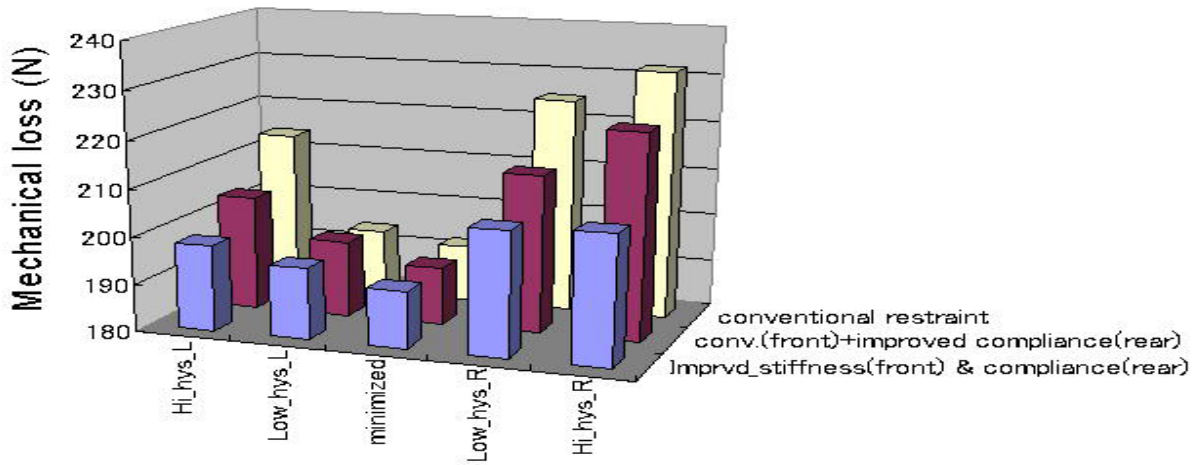


Figure 14: Effect of restraint system on fluctuation of mechanical loss



Figure 15: Example of basic restraint procedure

“Fastened cross restraint” is applied to improve lateral stiffness of restraint system without special additional equipment on the test vehicle. But, stiffness is degraded by the fastener. Basically, center of front portion of the vehicle should be restrained directly, using the additional device as shown Figure 15.

### 5. CONCLUSION

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 condition) is discussed.. We propose simple test method to check if the result on single axis chassis dynamometer is equal to the one on double axes chassis dynamometer or not, by checking

the total discharge electricity during the test conducted on proving ground. Only basic confirmation on this procedure was accomplished at this time.

As HEV power train is efficient, fuel consumption of HEVs is sensitive to road load. But in practically, it is hard to get enough repeatable data in 4WD HEV test on double axes chassis dynamometer. We found that restraint system in double axes chassis dynamometer causes fluctuation of mechanical loss, and this is caused by hysteresis of steering system. We propose the method to reduce the fluctuation of mechanical loss by modifying the restraint system.

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