

Development of a Fuel Economy and Exhaust Emissions Test Method with HILS for Heavy-Duty HEVs

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ABSTRACT

The objective of this study was to develop a test method for heavy-duty HEVs using a hardware-in-the-loop simulator (HILS) to enhance the type-approval-test method. To achieve our objective, HILS systems for series and parallel HEVs were actually constructed to verify calculation accuracy. Comparison of calculated and measured data (vehicle speed, motor/generator power, rechargeable energy storage system power/voltage/current/state of charge, and fuel economy) revealed them to be in good agreement. Calculation error for fuel economy was less than 2%. To establish an HILS method, the following items were carried out: (a) Typical HEV models for the HILS system were proposed to enable them to be adapted to all types of heavy-duty HEVs which will be launched over the next few years in Japan; (b) Test procedures for HEV components such as engines, motors/generators and batteries were proposed to measure the parameters of HEV models; and (c) A verification procedure for the HILS system was developed.

INTRODUCTION

Japan's exhaust emissions test method for heavy-duty vehicles was transferred from the steady 13 mode to the transient JE05 mode in response to new long-term

regulations adopted in 2005. The new legislation also demands a test method for hybrid electric vehicles (HEVs) that supports JE05. HEVs, which consist of an engine and various other elements such as a generator (GE), a motor/generator (MG) and a rechargeable energy storage system (RESS), are designed to reduce fuel consumption and exhaust emissions by operating these elements to match given traveling conditions. This type of vehicle should be thus evaluated as a vehicle system, not as a separate engine. Various types of heavy-duty HEVs with different gear ratios and bodies are predicted to emerge in the future. A type-approval test requiring a chassis dynamometer (CD), however, would considerably increase man-hours and costs.

The authors have previously suggested a "system bench method" ⁽¹⁾ as an alternative to the exhaust emissions test method for vehicle systems, in which the entire hybrid system is operated on an engine dynamometer (ED). This method has been in operation since June 2004 as "National Automobile Environment No. 60," notified by the Ministry of Land, Infrastructure and Transport (MLIT). Since then, adoption of the revised law on Rational Use of Energy has required heavy-duty vehicles to display their fuel efficiency, so the method has been in operation as "National Automobile Environment No. 278" for fuel consumption tests since March 2006. When alternative approaches

are used for this fuel efficiency method, however, (a) the fuel economy figure is greatly affected by the operation accuracy of the ED, (b) the types of HEVs that can be tested are limited, and (c) the fuel consumption for 3 types of certification test modes (JE05 mode, urban mode and city-to-city traveling mode) must be measured. In addition, the RESS's state of charge (SOC) must be calibrated for individual vehicles with different specifications such as transmission. For these reasons, several problems have become apparent, such as an inability to reduce testing man-hours.

This situation prompted the authors to study a test method as an alternative to the "system bench method," in which a "hardware-in-the-loop simulator (HILS)" is employed. In this study, we confirmed that simulated runs with an HILS achieved an accuracy that made them suitable for applicable to certification testing for both parallel and series HEVs (P-HEVs and S-HEVs) ^{(2),(3)}. In this paper we propose a test procedure that will assist with the certification and standardized testing of HEV models. The results are reported below.

OUTLINE OF THE HILS METHOD

For fuel efficiency testing of conventional heavy-duty vehicles, the loading conditions of the engine (rpm, torque) are determined using a conversion program ⁽⁴⁾, and the vehicle's fuel economy is calculated from the loading conditions and a fuel map. The loading conditions are reproduced on the ED for a separate engine to measure the mass of exhaust emissions. The HILS method, as represented in Figure 1, substitutes the HILS for the conversion program. In the case of HEVs, the loading conditions of the engine are determined using vehicle-specific control logic, so they are calculated for the HILS, a combination of individual element models of the actual electronic control unit (ECU) and the HEV. After the loading conditions are determined, fuel economy and exhaust emissions are evaluated.

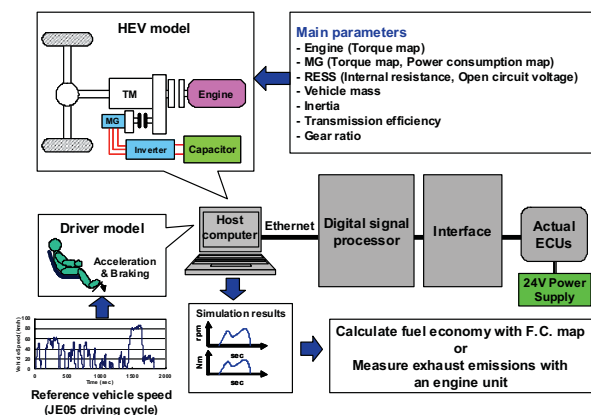


Figure 1. Outline of the HILS method for heavy-duty HEVs

VERIFICATION OF HILS SIMULATED TRAVELING

HEV UNDER TEST AND CONSTRUCTION OF HILS - To verify whether HILS has a simulated traveling accuracy that is usable in a certification test, we constructed HILS systems for a P-HEV equipped with an electric double-layer capacitor and for an S-HEV equipped with a lithium-ion battery whose specifications are shown in table 1 and compared the calculated values with their measured values. Both were equipped with a naturally aspirated diesel engine. As shown in Figure 2, we established an interface between the HILS and the digital signal processor (DSP) indicated in the specifications listed in Table 2, using a hybrid ECU and an engine ECU as the actual ECU. Within the DSP, the driver model carries out accelerating and braking operations to follow the reference vehicle's speed, while its operating signal is input into the actual ECU. After receiving a control signal from the ECU, the HEV model performs in the same manner as individual elements of the real machine and also returns a signal. The model step time was set at 500 μ s, taking into account the model's required maximum frequency and the communication speed required by the ECU.

Table 1. Specifications of the tested HEVs

Exterior		
Hybrid Type	Parallel	Series
Body	Vehicle Mass kg	4,580
	Total Vehicle Mass kg	7,990
	Vehicle Mass at Test kg	6,300
Fuel	Light Oil	Light Oil
Engine	Engine Type	Compression Ignition
	Displacement cc	6,925
	Cylinder	6
	Intake	Natural Aspiration
	Fuel Injection Pump	In-line Type
	Max. Power kW/rpm	152/3,000
	Max. Torque Nm/rpm	500/1,400
Transmission	Automated Manual Transmission	Single Speed
MG	Type	PM Synchronous
	Quantity	1
	Rated Power kW/rpm	55/4,060-9,000
GE	Type	PM Synchronous
	Rated Power kW/rpm	---
	Rated Power kW/rpm	40/1,400
RESS	Type	Electric Double Layer Capacitor
	Capacity	36F
	Total Voltage V	346
System Structure		

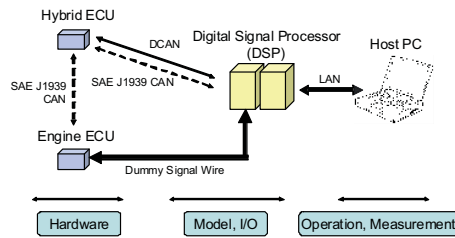


Figure 2. HILS system construction

Table 2. Specifications of the digital signal processor

Manufacture	FUJITSU TEN
CPU board	Pentium4 2GHz, 256MB memory equipped
CAN board	2ch
ADIO board	12bit, 32ch
CORE board	FPGA equipped, DIO 56ch
Quantity	2node
OS	RT-Linux

DEVELOPMENT OF HEV MODEL - An HEV model comprises individual elements such as the vehicle, MG, transmission, battery, engine and GE. Each element's performance can be expressed by inputting parameters into its map such as torque, fuel consumption and efficiency, and its inertia moment.

Vehicle model - Running resistance, R_r and accelerating resistance, R_a when the model travels on a flat road at a constant speed are expressed by Equation (1) and (2), respectively. As expressed by Equation (3), the difference between driving force, F and running resistance, R_r , is consumed during acceleration. Acceleration is calculated from Equation (4).

$$R_r = \mu_r mg + \mu_a AV^2 \text{ ----- (1)}$$

$$R_a = (m + m_r)\alpha \text{ ----- (2)}$$

$$R_a = F - R_r \text{ ----- (3)}$$

$$\alpha = \frac{F - (\mu_r mg + \mu_a AV^2)}{m + m_r} \text{ ----- (4)}$$

R_r : Running resistance N

R_a : Accelerating resistance N

μ_r : Rolling resistance coefficient

μ_a : Air resistance coefficient $N/m^2/(km/h)^2$

m : Vehicle's total mass kg

m_r : Rotating part equivalent mass kg

A : Frontal projected area m^2

V : Vehicle speed km/h

α : Vehicle acceleration m/s^2

F : Generated driving force N

g : Acceleration due to gravity m/s^2

MG Model - This model assumes that a difference between transient and steady efficiencies occurs in the order of 1 ms but does not occur in the order of 100 ms. Therefore, as shown in Figure 3, (a) drive/regenerative torque map and consumption/regenerative power map for rotational speed and torque command that were measured in a steady driving mode test, (b) inertia moment and (c) time constant are input as parameters, thereby reproducing the behavior of the MG model during actual vehicle movement with sufficient accuracy to permit it to be used as a test method for fuel economy and exhaust emissions. For reference, the GE model's basic principle is same as the MG's.

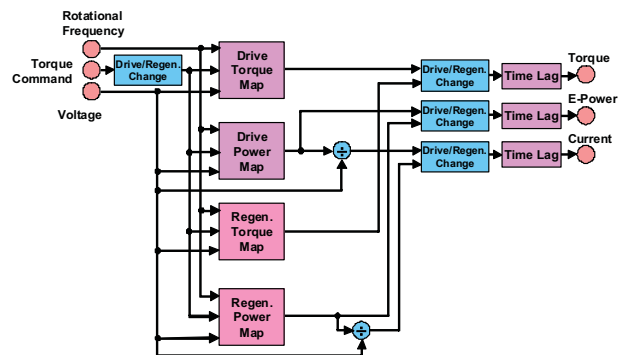


Figure 3. Outline of the MG model

Transmission model - For a clutch model, transfer torque is calculated from the difference between rotational speeds on the input and output sides and the clutch stroke. The load torque on the input side is determined by multiplying this torque by its gear ratio and transfer efficiency. In addition, the rotating speed on the input side is calculated by dividing this torque by the MG and the inertia moment for each gear step. As transfer efficiency, 0.98 was employed for the top gear and 0.95 for the other gears. These values were validated for their appropriateness and also used for a computational program in a fuel economy and exhaust emissions test method for conventional heavy-duty vehicles ⁽⁴⁾.

Battery model - The conceptual diagram is shown in Figure 4. The battery's discharge and charge power, as expressed by Equation (5), is calculated while taking into account the voltage variations that are the product of current and internal resistance. SOC is calculated by totalizing the currents in Equation (6), assuming a Coulomb efficiency of 100%. The battery's open-circuit voltage and internal resistance are determined from the SOC.

$$P = V_s I = (V_o - R_i I) I \text{-----(5)}$$

$$\text{SOC} = \text{SOC}_{\text{initial}} - \int_0^t \frac{I}{C_{\text{nominal}} \times 3600} dt \times 100 \text{-----(6)}$$

P:	Battery discharge and charge power	Wh
V _s :	Battery terminal voltage	V
I:	Battery current	A
V _o :	Battery open-circuit voltage	V
R _i :	Battery internal resistance	Ω
SOC:	Charged battery status	%
SOC _{initial} :	Initial charged battery status	%
C _{nominal} :	Rated capacity	Ah
t:	Elapsed time	s

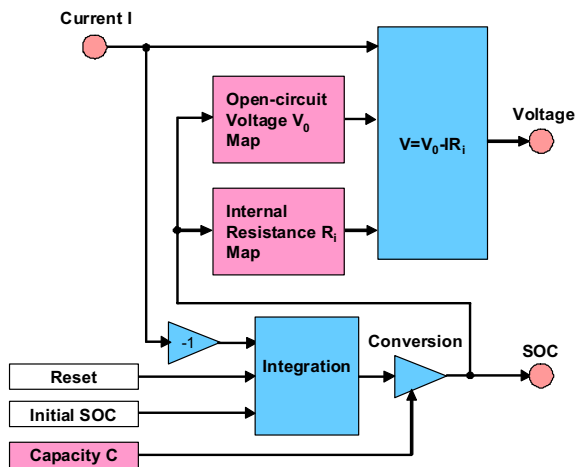


Figure 4. Outline of the battery model

Capacitor model - A conceptual diagram is shown in Figure 5. Its discharge and charge power is calculated using Equation (5) in the same way as in the battery model. Open-circuit voltage is calculated using Equation (7), since the capacitor's Coulomb efficiency is assumed to be close to 100%. The capacitor's energy is expressed in Equation (8), so SOC is calculated using Equation (9).

$$V_o = \frac{Q}{C_{\text{nominal}}} \text{-----(7)}$$

$$E = 0.5 \times C_{\text{nominal}} V_o^2 \text{-----(8)}$$

$$\text{SOC} = \frac{V_o^2}{V_{\text{max}}^2} \times 100 \text{-----(9)}$$

P:	Discharge and charge power	W
V _s :	Terminal voltage	V
I:	Current	A
V _o :	Open-circuit voltage	V
R _i :	Internal resistance	Ω
Q:	Electric charge	C
C _{nominal} :	Capacitance	F
E:	Electrostatic energy	J
SOC:	Charged status	%
V _{max} :	Maximal voltage	V

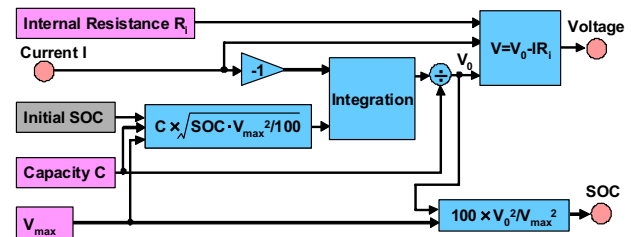


Figure 5. Outline of the capacitor model

Engine model - A conceptual diagram is shown in Figure 6. As simulated in the MG model, (a) the actual torque map (including negative torque due to friction) for a rotating speed and torque command, measured under a steady driving mode test, (b) the actual fuel flow rate for a rotating speed and actual torque, (c) the inertia moment and (d) the time constant and delay time are input as parameters. A separate engine model reproduces an inertia moment, so this engine model can be simulated, including transient energy at engine start/stop. For the time constant and delay times, values should be input that are consistent with data from actual vehicle movement. Under conditions associated with abrupt rotation and torque variations from shift and other operations, the simulation error for the model's behavior is predicted to increase, but can be ignored in terms of energy consumed by the overall running mode. In addition, the engine's difference between transient and steady efficiencies is greater than the MG's, but fuel economy during transient running, calculated with a fuel flow rate map determined in steady driving mode was confirmed to be in good agreement with the measured value. As a result, this calculation method is employed as a fuel economy type-approval-test method for conventional heavy-duty vehicles ⁽⁴⁾.

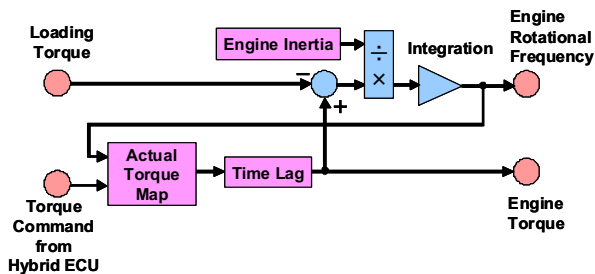


Figure 6. Outline of the engine model

HOW TO VERIFY SIMULATED RUNNING ACCURACY

Verification procedure - HILS was verified in comparison with measured values on the road and under the following procedures. First, the running resistance value of an actual vehicle value was calculated using a coasting test. The results confirmed that the coasting time, when the calculated value was input into the HEV model, agreed with the actual vehicle's coasting time. HILS's MG torque command, RESS power/current/voltage and engine rotating speed /torque command were compared with those of the actual vehicle under individual running conditions, constant acceleration and deceleration under fixed throttle opening and deceleration and the JE05 mode under fixed brake opening. As a result, the reproducibility of HILS as an actual vehicle was confirmed. In this case, the measured values were employed or throttle and brake openings and shift signal (hereafter referred to as operation amount on actual vehicle) to eliminate the effects of any difference between operations by a driver in an actual vehicle and a driver model. Fuel economies for JE05 and urban modes (644-1410 second section on JE05 mode) were verified.

Data Acquisition for Actual Vehicle

Test road - Data on an actual vehicle that form a comparison criterion for the verification of HILS calculated values were measured on our research laboratory's high-speed round course (an oval 5.5-km course, corner diameter 0.4 km and a north-south straight course of 1.1 km).

Vehicle conditions - Semi-loaded conditions were employed as the loading requirement. In addition, certification testing does not include drive loss due to accessories. For this reason, air was added from a nitrogen cylinder to compensate for losses by air braking, thereby eliminating the effect of compressor operation on fuel economy.

RESULT OF VERIFICATION OF SIMULATED TRAVELING ACCURACY

Parallel HEV

Verification of coasting time - Mass equivalent to rotating parts during coasting was calculated from the inertia moments of individual elements such as tires, brake drums, final gear and propeller shaft. Running resistance was determined from this mass equivalency and from vehicle mass and coasting time for an actual vehicle under test. After inputting the result into HILS, as shown in Table 3, the coasting time per 10 km/h proved to be consistent with the other coasting time within a range of 3%.

Table 3. Comparison of coast down times (P-HEV)

Vehicle Speed Range (km/h)	Coast Down Time		Difference	
	Actual (sec)	HILS (sec)	(sec)	(%)
95-85	10.9	10.8	-0.1	-1.1
85-75	13.0	12.8	-0.2	-1.6
75-65	15.5	15.1	-0.4	-2.6
65-55	18.3	18.2	-0.1	-0.5
55-45	22.2	22.0	-0.2	-1.0
45-35	27.0	26.9	-0.1	-0.5
35-25	33.6	33.0	-0.6	-1.8
25-15	40.2	40.4	0.2	0.4

Verification during constant-speed traveling - By inputting throttle opening under a constant vehicle speed into HILS, the efficiency of a power transmission system model can be confirmed. A test vehicle's speed when powered by only the MG is slow, so the vehicle was evaluated under two conditions: a reference vehicle speed of 20 km/h and 30 km/h. A comparison of measured and calculated values at 20 km/h is shown in Figure 7. The actual vehicle's speed closely agreed with HILS's in the period 50-90 seconds after throttle opening became constant. The MG torque command and capacitor power's absolute values are small. For this reason, the error rate is a little higher, but its absolute value remains small. There was no major difference between the capacitor's voltage drop speeds.

Based on the above result, we confirmed the appropriateness of the transmission efficiency of the drive system (transmission and final gear), and also the appropriateness of MG power generation for throttle opening at a constant vehicle speed.