

A Study on High-Accuracy Test Method for Fuel Consumption of Heavy-Duty Diesel Vehicles Considering the Transient Characteristics of Engines

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ABSTRACT

In the conventional approval test method of fuel consumption for heavy-duty diesel vehicles currently in use in Japan, the fuel consumption under the transient test cycle is calculated by integrating the instantaneous fuel consumption rate referred from a look-up table of fuel consumptions measured under the steady state conditions of the engine. Therefore, the transient engine performance is not considered in this conventional method. In this study, a highly accurate test method for fuel consumption in which the map-based fuel consumption rate is corrected using the transient characteristics of individual engines was developed. The method and its applicability for a heavy-duty diesel engine that complied with the Japanese 2009 emission regulation were validated.

The proposed test method comprises four processes: (i) obtaining experimental data for deriving the formula of transient correction factor (*TCF*); (ii) performing simulation for obtaining calculated data for deriving *TCF* formula; (iii) deriving this formula; and (iv) performing simulation of the fuel consumption by correcting the instantaneous fuel consumption by using *TCF* formula in addition to the conventional simulation method. In process (iii), the *TCF* formula is derived by multiple regression analysis with instantaneous data of the following explanatory variables: measured engine speed and its rate of change, measured torque and its rate of change. The ratio of measured instantaneous fuel consumption and estimated instantaneous fuel consumption based on the look-up table were considered as the objective variables.

The evaluation results of fuel consumption after the correction for the transient characteristics of the test engine showed that the calculation results with the correction were strongly correlated with experimental results. Thus, the proposed correction method for calculated fuel consumption effectively considered the transient characteristics of the engine. In addition, the engine speed and its rate of change and torque and its rate of change were established to be important parameters for deriving the *TCF* formula.

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INTRODUCTION

Japan introduced a fuel consumption standard for heavy-duty diesel vehicles ahead of the world in 2006. At the same time, Japan commenced conducting a fuel consumption test [1]. Figure 1 shows the outline of this test method [2], which is based on an ancient method [3], [4], [5], that is, the fuel efficiency during driving in a test cycle is calculated according to the simulated fuel consumption. In this case, the map of fuel consumption (hereinafter referred to as the fuel consumption map) corresponding to the engine speed and torque as measured using an engine test cell under steady-state conditions is referred according to the engine speed and torque conditions (hereinafter referred to as the simulation method). In particular, as shown in Figure 2, the test cycle simulating urban driving and interurban driving is converted into the engine test cycle (every second); thereafter, the instantaneous fuel consumption during operation in the obtained test cycle is read from the fuel consumption map. By integrating the instantaneous fuel consumption, the fuel

consumption of the test cycle as a whole and the fuel efficiency [km/L] are calculated. However, this test method does not take into account the transient characteristics of the engine. That is, the test method is based on the assumption that the fuel efficiency calculated by the simulation method (hereinafter referred to as the calculated fuel efficiency) is equivalent to the fuel efficiency measured during transient operation in the same test cycle.

Similar test methods of fuel consumption for heavy-duty diesel vehicles will be applied in the United States and Europe [6], [7], [8], [9]. In these test methods, fuel consumption and greenhouse gas emission are also calculated based on the fuel consumption map measured under steady-state condition using engine test cell.

Against the background of increasingly stringent emission regulations worldwide, the demand for improving fuel efficiency is growing. In this context, it is essential to install a turbocharger in the engines of heavy-duty vehicles for achieving high boost and high

exhaust gas recirculation (EGR) with reduced displacement. Under the transient operating condition of the engine when the accelerator is depressed, the delays in the response of boost and transient control of the EGR ratio cause the state to be different from the operation state at the same engine speed and torque under the steady-state condition. In other words, in the case of the recent high-boost engines, the calculated fuel efficiency easily deviates from the measured one.

A Method to correct the deviation between the measurement and calculated fuel consumption had been developed in studies [8] [9]. In these report, however, correction factor taking account of transient characteristics of an engine is calculated only as a total cycle value by measuring and calculating fuel consumption in the World-wide Harmonized Transient Cycle (WHTC). This method, therefore, cannot correct calculated fuel consumption accurately when the engine test cycle is changed from WHTC.

In this study, a diesel engine that is used in heavy-duty vehicles and complies with the post new long-term emission regulation (Japanese 2009 regulation) was used to evaluate the calculated fuel consumption by the conventional method shown in Figure 1 and the measured fuel consumption using engine test cell and determine the deviation between the two. Thereafter, methods of calculating the fuel consumption with higher accuracy by including correction for the fuel consumption based on the transient characteristics of individual engines were considered in order to propose an alternative to conventional method in each area.

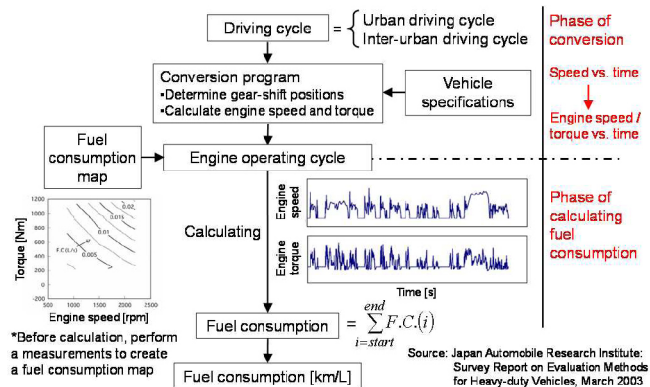


Figure 1. Simulation flow of fuel consumption for heavy-duty vehicles in Japan

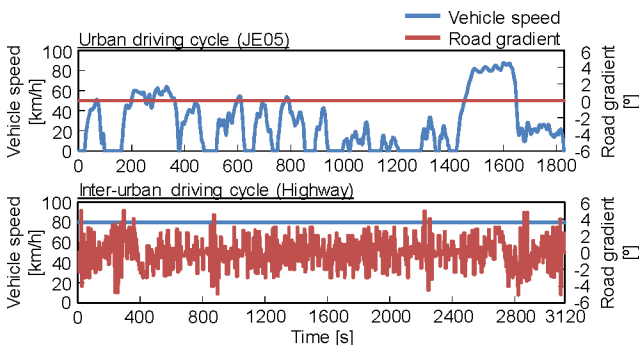


Figure 2. Test cycles of fuel consumption for heavy-duty vehicles

EQUIPMENT AND METHOD OF EXPERIMENT AND ANALYSIS

Engine Test Cell

Table 1 lists the specifications of the studied test engine. This engine is a production type in-line four cylinder turbo diesel engine with a total engine displacement of 2999 cm³. It is commonly used in heavy-duty vehicles complying with the post new long-term emission regulation. The aftertreatment system includes only the diesel oxidation catalyst (DOC) and the diesel particulate filter (DPF); the combined use of two-stage turbo charger system and EGR system is introduced to reduce NO_x.

Table 1. Specifications of test engine

Engine type	Water cooled, In-line 4-cylinder, 4-stroke cycle
Intake system	Two-stage turbocharger with intercooler
Fuel supply system	DI Common-rail
Displacement	2999 cm ³
Compression ratio	17.5
Bore x Stroke	95.4 mm x 104.9 mm
Maximum power	110 kW / 2800 rpm
Maximum torque	375 Nm / 1400-2800 rpm
Aftertreatment system	DOC, DPF
Emission regulation	Japanese 2009 (Post new long term)

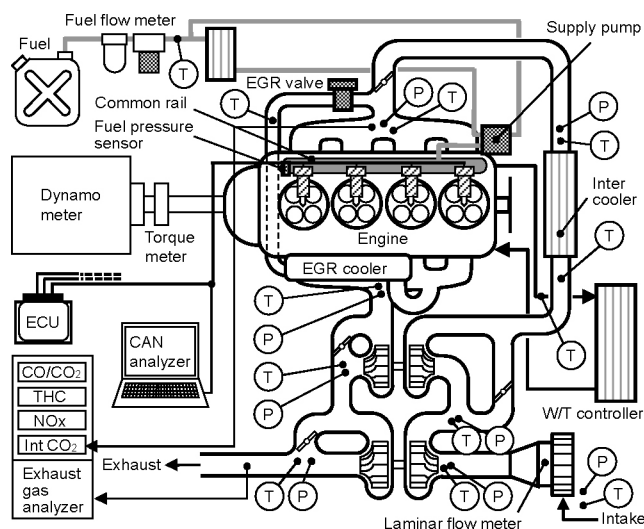


Figure 3. A schematic of the engine test cell

Figure 3 shows a schematic of the engine test cell. A positive-displacement flow meter (FP-2140H made by Ono Sokki Co., Ltd.) was used as the fuel flow meter. On the basis of fuel temperature detected with the temperature sensor installed close to the exit of the fuel flow meter, the measured fuel flow was converted into volume units at a fuel temperature of 288 K (15 °C) by referring to Table 2B of Attached Table II, JIS K2249-1987, "Table of Conversion Factor of Fuel Oil Temperature to Volume." In addition, the fuel flow was also evaluated in terms of mass by multiplying it with density at the

same temperature. The indicated value of fuel injection quantity from the engine control unit (ECU) could also be recorded by controller area network (CAN).

Simulation Code for Fuel Consumption

The simulation code for fuel consumption was chosen from among those provided in the webpage of MLIT [10]; the chosen code could be used for vehicles with manual transmission or automated manual transmission (FORTRAN version). This is an analytical model that predicts engine speed and torque for the lookup of fuel consumption from steady-state map. Note, however, that this code had been developed for the certification test, and hence, the test cycle and vehicle data cannot be provided freely. In this study, the source code was modified to allow calculation by taking into account the arbitrary test cycle data, vehicle data, and measurements of the engine's moment of inertia.

Experiment and Analysis Method

In order to compare the calculated fuel efficiency with the fuel efficiency measured under various transient conditions (differences in the engine speed change and torque change) of the engine, fuel efficiency was calculated and measured using data of several virtual vehicles differing in dimensions, weight, transmission gear ratio, tire size, etc. Table 2 lists the specifications of the virtual vehicles. All of the data listed were used in the fuel consumption or emission gas certification test for this test engine. Additionally, 15 types of data were set in total for different payloads classified as empty, half, and full load.

As mentioned above, for the simulation, the fuel consumption map must be determined in advance. In order to eliminate the effect of interpolation accuracy on the map, a large number of measurement points were considered (203 points, including idling). The fuel consumption map was established from both types of data: measurement values from the fuel flow meter and indicated values of fuel injection quantity obtained from the ECU via CAN. Figure 4 shows the measurement points for the fuel consumption map and the measured results of the fuel consumption map with the fuel flow meter that was used as a reference for the simulation.

Table 2. Specifications of virtual test vehicles

No	Height [m]	Width [m]	Vehicle Weight [kg]	Max. pay load [kg]	Number of seats	Transmission gear ratio 1st, 2nd, 3rd, 4th, 5th, 6th	Final gear ratio	Dynamic rolling radius [m]
1	2.106	1.780	2482	2396	3	5.080, 2.816, 1.587, 1.000, 0.741	5.275	0.343
2	2.099	1.751	2356	2000	3	5.315, 2.908, 1.558, 1.000, 0.721	4.555	0.338
3	2.041	1.729	2652	2995	3	5.979, 3.434, 1.752, 1.000, 0.795	5.571	0.364
4	2.363	2.161	2979	3749	3	5.979, 3.434, 1.862, 1.297, 1.000, 0.759	5.125	0.366
5	2.454	2.235	3543	4275	3	5.979, 3.434, 1.862, 1.297, 1.000, 0.759	5.375	0.376

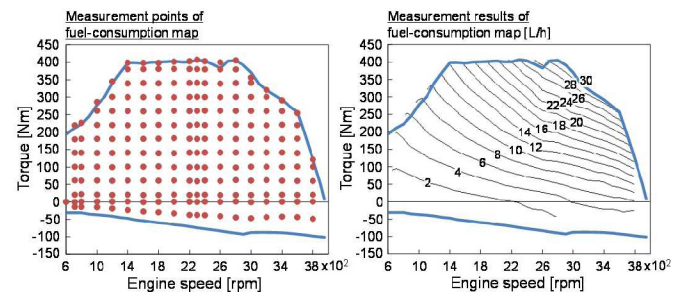


Figure 4. Measurement points (left) and results (right) of the fuel consumption map

SIMULATION METHOD CONSIDERING ENGINE TRANSIENT CHARACTERISTICS

Transient Correction Method in Simulation

In the case of the currently used engines, the operation states under steady-state and transient conditions tend to vary because of response delay or transient control of the engine intake and exhaust system and the EGR system. In particular, this phenomenon is conspicuous in engines with the high-boost and high EGR system.

Accordingly, a method of calculating the fuel efficiency with high accuracy was considered; in this method, fuel consumption was corrected (hereinafter referred to as the transient correction) on the basis of the transient characteristics of individual engines. Figure 5 shows a flowchart of this method. This method may be divided into three parts: Process (i), i.e., the experiment to acquire the measured data that are to be used to derive the Transient Correction Factor (TCF) calculation formula (TCF formula); Process (ii), i.e., the simulation to acquire the calculation data for deriving the TCF formula; Process (iii), i.e., the actual derivation of the TCF formula; Process (iv), i.e., the simulation method that comprises the conventional simulation method described in Figure 1 plus correction by multiplying the instantaneous fuel consumption by TCF.

In Process (i), the engine was operated over an arbitrary transient test cycle covering the wide operating range of the engine using engine test cell. Thus, the data on the instantaneous fuel consumption FC_{exp} (CAN), as calculated from the indicated value of fuel injection quantity obtained from the ECU via CAN, were obtained along with the engine speed N_e and torque T_e at the instantaneous moment (the sampling cycle 0.1 s). “(CAN)” means on the basis of CAN. Note that this method is based on a consideration that the indicated fuel injection quantity controlled by the ECU of this test engine under transient condition is defined by the arithmetic algorithm different from that under steady-state condition in order to obtain target torque.

In Process (ii), N_e and T_e obtained in Process (i) were set as the test cycle for the modified simulation code for fuel consumption. At the same time, the instantaneous fuel consumption FC_{cal} (CAN) was calculated by entering the fuel consumption map (CAN) derived from the fuel injection quantity obtained from the ECU via CAN and implementing the simulation code.