

Advanced Transient Simulation on Hybrid Vehicle Using Rankine Cycle System

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ABSTRACT

A hybrid simulation model in the transient bench was developed to realize the characteristics of the transient behavior and the fuel economy equivalent to that of a real vehicle. The motors and the batteries that were main components of the hybrid vehicle system were simulated as constructive modules, the functions of which have the integrated control and the input/output (I/O) function with real components. This model enabled us to accommodate a variety of auxiliary (AUX) I/O flexibly. The accuracy of the model was verified by the transient characteristics of the engine and the fuel economy result through correlation with a mass-produced vehicle. Furthermore, the flexibility of the model to a variety of AUX I/O was examined from the simulation test of the vehicle equipped with the waste heat recovery (WHR) system. As a result, it was concluded that the transient engine characteristics of transient bench showed a good agreement with that of a real vehicle and simulated fuel economy within $\pm 1\%$ accuracy.

1. INTRODUCTION

The reduction in the amount of CO₂ by the improvement of the exhaust emission and fuel economy has become a very important issue because of a focus on global environment protection and a reduction in the use of the natural resources. In recent years, we have seen an increasing urgency to prevent further global warming, and system research that takes full advantage of various fuels, combustions and mechanisms has been actively done all over the world. In this trend, hybrid vehicles (HEVs) that combine an engine with an electric motor have been sold in many countries in the world and become popular because of power and fuel economy performance. Automobiles with low fuel consumption such as HEV have successfully complied with strict emission regulations in each country, while achieving both good power performance and improved fuel economy.

It is predicted that regulations will focus more on reducing CO₂ emission in the future and the improvement of automotive fuel economy is becoming an important theme in the effort to improve the global environment. One approach is the research that recovers and reuses the wasted heat of the engine by using Rankine cycle to improve the automotive fuel economy dramatically [1, 2]. Honda R&D has already proved the significant improvement in thermal efficiency by installing the system on an actual vehicle [3, 4].

In order to bring such a power train for the next generation to the market, it is important to evaluate the balance of competing goals for improved fuel economy, low exhaust emissions and power performance accurately and at the development phase as early as possible. Therefore, a transient bench that allows us the evaluation of power plant without the need of manufacturing a real vehicle is an extremely useful tool. In general, the transient bench that is able to simulate a variety of driving conditions is often used for a racing simulation such as Formula-1 and the endurance simulation [5, 6].

This study aimed at the development of the hybrid simulation model to evaluate the fuel economy and the transient characteristics in the power train research for the next generation. Important research considerations in establishing the test bench system are to improve the reproducibility of the transient characteristic, the accuracy of the fuel economy, and the expandability. For the improved reproducibility of the transient characteristic and the accuracy of fuel economy, it is necessary to verify the correlation of the modeled components with that on a real vehicle. The improvement of expandability has to be attempted after the reproducibility and the accuracy are established. For this, it would be effective to construct the hybrid simulation model with both the integrated control function in the hybrid system and the I/O function with real components.

In this study, the correlation was examined with the Honda Stream as a mass-produced conventional vehicle and the Honda Civic-Hybrid as a mass-produced HEV. Moreover, the flexibility to a variety of AUX I/O was examined through the simulation results of the vehicle equipped with WHR system.

2. TRANSIENT BENCH SYSTEM

On the transient bench, real components used were engine and engine control unit (ECU) . However, the air conditioner compressor and the power steering pump usually installed in the engine were detached. The transmissions such as manual transmission (MT), automatic transmission (AT) and continuous variable transmission (CVT) were modeled according to the respective vehicles. A transmission control unit (TCU) was set up in coordination with each engine type in a highly sophisticated and complicated architecture. Accordingly, only the controls demanded for the driving mode were modeled.

In order to evaluate a whole vehicle model with high reliability, it is important to clarify which can be simulated, and which real components to use, and to understand the difference between reality and simulation in each component [7, 8, 9]. In the first step of verification, the accuracy of simulation model for the components of mass-produced vehicle such as transmission, vehicle and driver were verified in terms of the transient characteristics and the fuel economy. Secondly, the accuracy of the components of HEV such as transmission, motor and battery was verified with a similar method. The accuracy of vehicle simulation for mass-produced vehicles was proven by verifying the major component models each in turn. After that, a system flexible to a variety of AUX I/O was realized by verifying the transient characteristics and the fuel economy when a WHR system was added to mass-produced vehicle. The evaluation approach would realize a systematic verification of the simulation model. Table 1 denotes the combination of the real components and the simulation models.

Table 1 Combination of real components and simulation model

	Real	Simulation				
		Transmission	Vehicle	Driver		
Conventional Vehicle						
HEV Vehicle						
HEV Vehicle with WHR Sys.	 					

Figure 1 shows the outline of the torque and signal flow in the transient bench system. The torque calculated by the simulation was transmitted to an engine dynamometer and the engine was controlled by operating the throttle actuator from the driver model so that the required torque was generated.

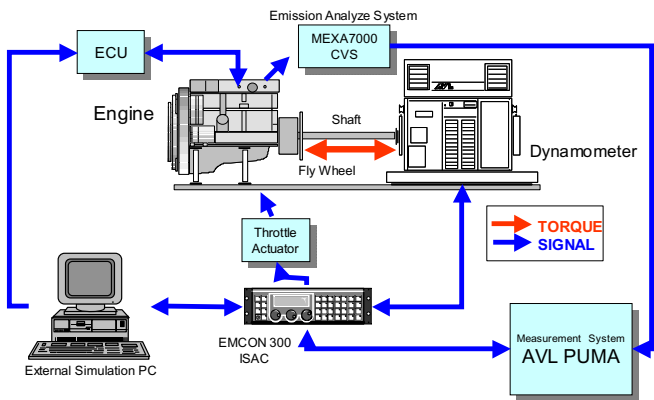


Figure 1 Outline of torque and signal flow in transient bench system

Figure 2 shows the I/O of the transmission model combined with HEV model. HEV model included component models such as motor and battery as functional modules. I/O unit sent the parameters and data necessary for control to the input port and the results of the calculation to the output port. This configuration of the model made it easy to analyze the energy of each part and understand the operation. And the correlation with a real vehicle and the verification of fuel economy could be done efficiently. In addition, it was even possible to apply a component under research as a module using the AUX I/O, regardless of a real component or the simulation model.

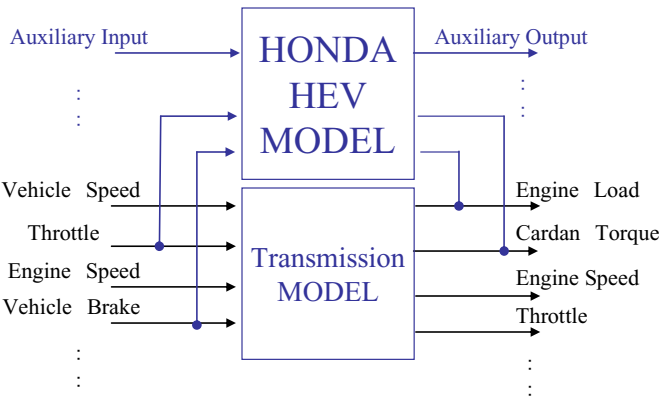


Figure 2 Simulation models in transient bench system

3. CORRELATION WITH MASS-PRODUCED VEHICLES

3.1 VEHICLE WITH MANUAL TRANSMISSION

At first, the correlation with the Honda-Stream (Vehicle Weight: 1590kg, Engine Volume: 1,998cm³) manual transmission (5MT) vehicle was verified on the transient bench. As basic components, the accuracy of simulation models for transmission, vehicle and driver needed to be evaluated and verified. As a first step of evaluation, constant speed driving and hot test mode were examined so as to eliminate the influence of temperature rise of cooling water to the transient characteristics and the fuel economy. Figure 3 shows the system diagram of a simulated vehicle with 5MT.

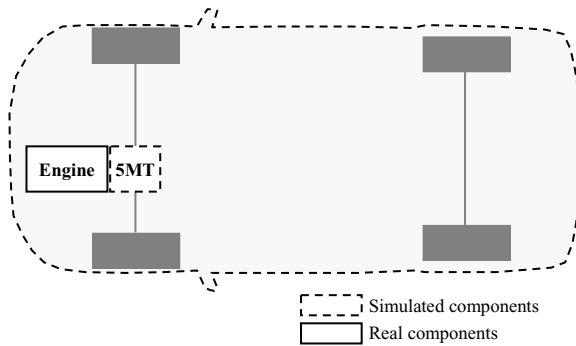


Figure 3 System diagram of simulated vehicle with manual transmission

Figure 4 shows the comparison result of the mass-produced vehicle with manual transmission and the transient bench in a hot European Community (EC) Mode. By matching the damped natural frequency and the damping rate of each gear, the engine speed change at a constant driving and a gear-shifting point exhibited the characteristics close to that in the chassis result. As a consequence, the coefficient of correlation in the transient characteristics was 0.96 and the difference in the fuel economy fell within $\pm 1\%$, which proved high reproducibility and accuracy.

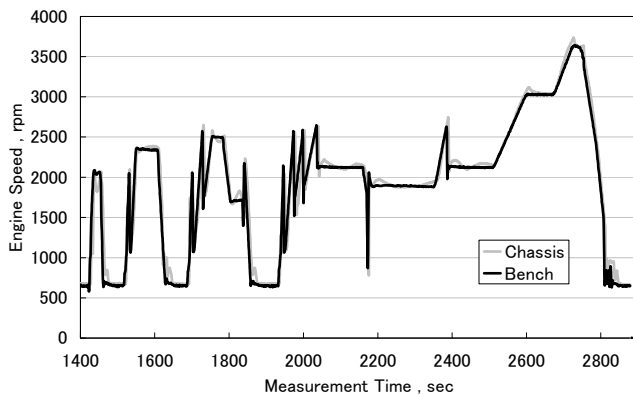


Figure 4 Transient behavior of engine speed in hot EC Mode

For the evaluation of the transient characteristics, the coefficient of correlation (CoC) in the engine speed defined in Equation (1) was used. JIS Z 8103 denoted that there was stronger correlation in the transient characteristics between a real vehicle and the transient bench, as CoC approached close to 1.0 [10].

$$CoC = \frac{\sum_{i=1}^n (NE_{vi} - \overline{NE_v})(NE_{bi} - \overline{NE_b})}{\sqrt{\sum_{i=1}^n (NE_{vi} - \overline{NE_v})^2 \sum_{i=1}^n (NE_{bi} - \overline{NE_b})^2}} \quad \dots(1)$$

CoC: Coefficient of Correlation

NE_v : Engine speed of vehicle (Chassis) test

NE_b : Engine speed of transient bench test

i : Sample number

3.2 VEHICLE WITH AUTOMATIC TRANSMISSION

In case of an automatic transmission (AT), all the controls were not modeled due to the complexity. Only Lock-Up control required in the driving mode was simply modeled. Figure 5 shows the system diagram of a simulated vehicle with AT.

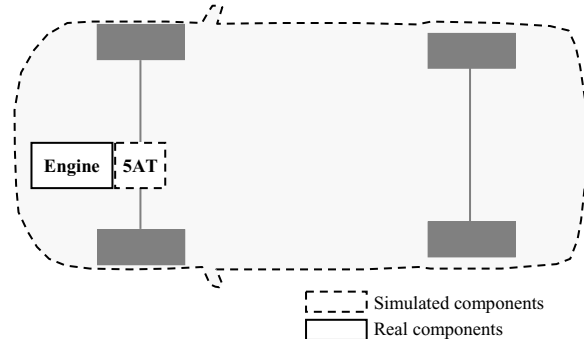


Figure 5 System diagram of simulated vehicle with automatic transmission

The comparison result of the mass-produced vehicle with AT and the transient bench in a Japanese 10-15 Mode is shown in Figure 6. The coefficient of correlation in the engine speed was 0.96 and the difference in fuel economy was within $\pm 1\%$. Thus, it was confirmed that only the modeling of basic control required for the mode driving could obtain high reproducibility and accuracy.

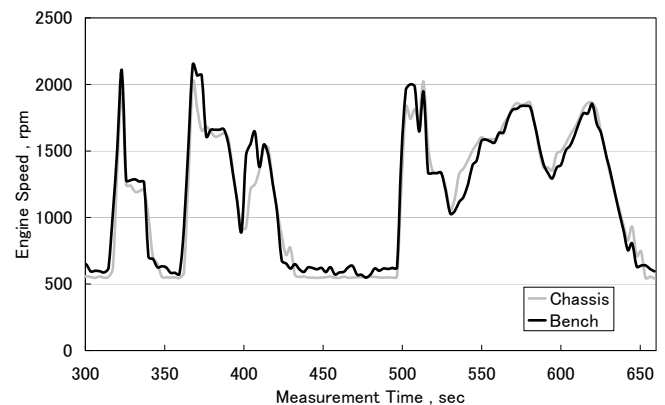


Figure 6 Transient behavior of engine speed in Japanese 10-15 Mode

The results above indicated that the simulation of transmission, vehicle and driver for the mass-produced vehicle was accurate, based on the reproducibility of the transient characteristics and the accuracy of the fuel economy.

3.3 VEHICLE WITH CONTINUOUS VARIABLE TRANSMISSION AND HEV

It was necessary to verify the correlation with a real vehicle on the battery and the motor that a conventional vehicle didn't have, when a HEV vehicle was evaluated on the transient bench [11, 12]. In order to realize HEV functions accurately on the transient bench, based on a real vehicle of the Honda Civic-Hybrid (Vehicle Weight: 1200kg,