

A Study on Improvement of Fuel Economy of Heavy Duty Hybrid Trucks with New Type of Hybrid Electric Assist Engine System

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ABSTRACT

In order to improve the fuel economy of the heavy duty trucks at a highway driving condition, the heavy duty hybrid trucks with new type of hybrid electric assist engine system were proposed at the previous report. The new system consists of a downsizing diesel engine with a two-stage charging structure, which has an electric supercharger with bypass circuit and a conventional turbocharger, the hybrid electric motor and the small-capacity battery. The electric power consumption of an electric supercharger is equivalent to the amount of the regeneration power produced during high-speed driving where the opportunity of the regeneration is small.

In this report, an electric supercharger for the heavy duty hybrid truck was produced experimentally. First, the engine performance and exhaust emissions were investigated using the 4 cylinder diesel engine equipped with an electric supercharger. Next, the fuel economy of this heavy duty hybrid truck driving in a Japanese in-city mode and a Japanese interurban mode was investigated by using the "Hybrid Powertrain Test Bed System".

CITATION: Okui, N., "A Study on Improvement of Fuel Economy of Heavy Duty Hybrid Trucks with New Type of Hybrid Electric Assist Engine System," *SAE Int. J. Commer. Veh.* 9(2):2016, doi:10.4271/2016-01-2358.

INTRODUCTION

The carbon dioxide emitted by Japan's transportation sector accounts for 20% of the country's total emissions. Automobile manufacturers are currently engaged in research and development related to fuel-efficient and hybrid vehicles, with a goal of improving engine efficiencies and thus reducing carbon dioxide emissions [1]. Trucks account for a high percentage of these carbon dioxide emissions, so considerable effort is being made toward applying hybrid technology to small- and medium-size trucks. The authors have been conducting research related to the simultaneous improvement of the fuel efficiency and emission characteristics of hybrid trucks through the optimization of the hybrid control [2], [3], [4], [5]. Large trucks operate mainly at constant high speeds and so present fewer opportunities for energy regeneration. Therefore, if the fuel efficiency of these vehicles is to be improved through hybridization, it would be necessary to increase the sizes of the motors and batteries [6], [7], [8], [9], [10], [11], [12], [13], [14]. Since this would give rise to issues such as reduced load space and a higher purchase price, there has been little progress towards the commercialization of large hybrid trucks. The authors, therefore, are proposing a new-type of hybrid system [15]-[16], specifically for large hybrid trucks, which differs from a conventional hybrid system where the aim is to improve fuel efficiency for high-speed operation by reducing the weight of the hybrid system. This new hybrid system is based on the concept of improving fuel efficiency by operating the engine in the high thermal efficiency range by increasing the air flow into the combustion chamber regardless of the engine's rotational speed. The regenerative

energy produced by the electric motor during high-speed operation is used mainly in the electric supercharger, this being an auxiliary device with a low power consumption.

This report describes the verification of the improvement in fuel efficiency, etc. It describes the prototyping of the electric supercharger, which is central to the application of this new-type hybrid technology to diesel engines, as well as the testing of a large virtual hybrid truck equipped with the new hybrid system, using a hybrid power train bench-testing system [17]. The virtual truck was subjected to the operating patterns of the Japanese heavy-vehicle fuel-efficiency and emissions tests.

CONCEPT OF NEW-TYPE HYBRID SYSTEM

The conventional hybrid system applied to passenger cars as a means of improving fuel efficiency is shown in the upper half of [Figure 1](#). Regenerative energy is used to power the electric motor linked to the driving axle, with large amounts of energy consumed by every assist, thus necessitating a large battery. On the other hand, as shown in the lower half of [Figure 1](#), the "new-type hybrid system" proposed previously utilizes an electric supercharger (eSC) with a high-voltage driving battery acting as the power supply. This system compensates for the lack of engine torque encountered in the transient state when a small-displacement engine is employed. The axle-driving electric motor is mainly responsible for regeneration/generation while providing torque assist to compensate for the torque shortfall that occurs during acceleration with the small-displacement engine. Since

the electric supercharger consumes less power than the axle-driving electric motor, the power regenerated/generated by the axle-driving electric motor during high-speed operation, albeit with a relative low charge frequency, is considered sufficient to secure the output performance. Consequentially, the battery used to temporarily store the regenerative energy can be relatively small, and thus, the load space required by large trucks is not compromised.

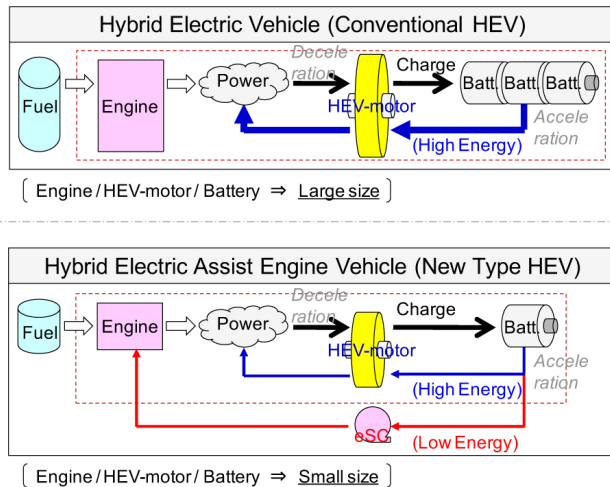


Fig.1. Concept of New Type HEV system



Fig.2. Electrical Supercharger (eSC)

Table 1. Specification of Electric Supercharger

Structure	Permanent Magnet Motor
Driving Voltage	DC Max. 230V
Inverter	IGBT
Rated Speed	65,000rpm
Rated Power / Torque	2.5kW@65,000rpm / 0.37Nm
Max. Power / Torque	3.0kW@65,000rpm / 0.44Nm
Compressor	Magnesium Alloy / Impeller : $\Phi 65\text{mm}$

ELECTRIC SUPERCHARGER

The electric supercharger, a key element technology of the new-type hybrid system, given its suitability to large-displacement diesel engines, was prototyped. The appearance of the electric supercharger is shown in Figure 2, and its specifications are summarized in Table 1. The electric supercharger motor was rated at a maximum of 3 kW at 65,000 rpm, and operated at 230 V, this being the voltage across the hybrid battery.

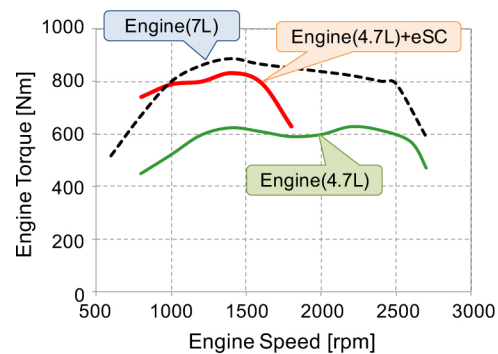


Fig.3. Engine Torque at Full Load Operation

Full-Load Operation Characteristics of Electric Supercharger

A 4.7-liter in-line four-cylinder diesel engine with an intercooled turbocharger (GH5, UD Trucks), capable of generating a maximum power output of 158 kW at 2500 rpm and a maximum torque of 628 Nm at 1400 rpm, was fitted with the electric supercharger and studied in terms of its full-load characteristics. The results are shown in Figure 3. The addition of the electric supercharger to the 4.7-L diesel engine produced a substantial increase in the torque at low engine speeds. In fact, the torque approached the full-load torque of a 7-L diesel engine. Thus, it was found that the addition of the electric supercharger enables significant engine downsizing.

Transient Response Operation Characteristics of Electric Supercharger

1. Accelerator opening: Fully closed to fully open

With the engine speed set to 1000 rpm, we studied the transient response torque when the accelerator was moved from the fully closed to fully open position in 0.1 s. This experiment was done under three conditions: with the electric supercharger power off (hereinafter, "Assist off"); with the electric supercharger powered on at the same instant as the accelerator is opened (hereinafter, "Assist on <together>"; and with the electric supercharger powered on before the accelerator is opened (hereinafter, "Assist on <steady>"). The results of our experiments are shown in Figure 4. The engine torque, amount of intake air, and charging pressure are shown in chronological order, from top to bottom. The torque rises immediately after the accelerator is fully opened with Assist on <together>. The same occurs with Assist off. The torque after 1 s differed greatly, however. Specifically, the torque was 369 Nm with Assist off and 492 Nm with Assist on <together>. This torque difference continued to increase with time. For Assist on <steady>, the increase in the torque immediately after the accelerator was fully opened rose approximately 0.1 s earlier than it did under the other conditions. The maximum amount by which the torque rose after 1 s was 552 Nm. As can be seen from the measured amount of intake air and the charge pressure, the electric supercharger instantaneously forced air into the combustion

chamber, even when the engine was operating at low speed and under a low load, that is, even when it is difficult to recover energy from the exhaust gas.

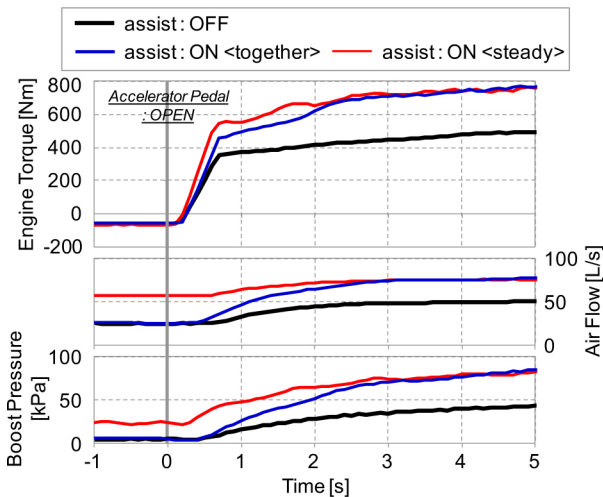


Fig. 4. Performance of eSC System by Step Acceleration (1,000rpm, Acc :OFF→WOT)

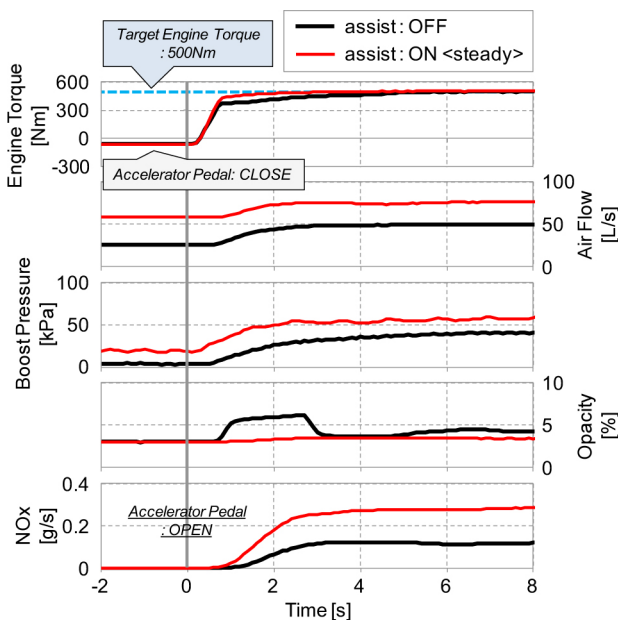


Fig. 5. Performance of eSC System by Step Acceleration (1,000rpm, Acc :OFF→500Nm)

2. Accelerator opening: ON to constant at 500 Nm

With the engine running at 1000 rpm, the transient response torque performance was studied when a control command was issued such that the target torque of 500 Nm would be attained immediately after the accelerator was opened fully (hereinafter, “Accelerator ON”), starting from the fully closed state. The experimental conditions were Assist off and Assist on <steady>. The results of our experiments are shown in Figure 5.

The engine torque, amount of intake air, charge pressure, smoke (opacity) at the engine outlet, and NOx values are shown in chronological order, from top to bottom. The exhaust gases were measured using an opacimeter (4390, AVL) and exhaust gas analyzer (MEXA-ONE-D1-EGR, Horiba). Under both conditions, the target torque of 500 Nm was attained about 5 s after Accelerator ON, but the torque with Assist on <steady> was always higher than that with Assist off. Regarding the amount of smoke, no change was observed even after Accelerator ON with Assist on <steady>, but the smoke concentration increased after Accelerator ON with Assist off. The NOx trend was opposite to that of the smoke, in that the amount of NOx with Assist on <steady> was always high. That is, during transient response operation, there is a shortage of air in the engine combustion chamber with Assist off. With Assist on <steady>, an air charge is forced into the chamber, such that no shortage arises and continuous burning is ensured.

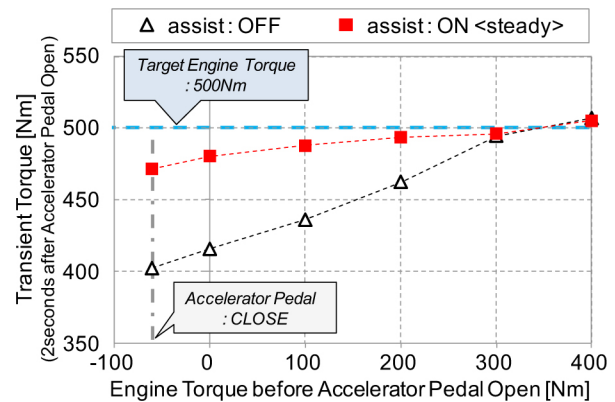


Fig. 6. Measurement Torque at 2sec after Acceleration Pedal Open (1,000rpm, Acc :OFF→500Nm)

The engine torque occurring 2 s after Accelerator ON was measured. For the torque immediately before Accelerator ON, we assumed six different values, namely, that with the accelerator fully closed, 0, 100, 200, 300, and 400 Nm. The acquired data was arranged in order as shown in Figure 6. The horizontal axis of the figure shows the torque immediately before Accelerator ON while the vertical axis shows the torque 2 s after full-opening of the accelerator. The torque with the accelerator fully closed was about -60 Nm. The torque 2 s after transitioning from this state to Accelerator ON was 402 Nm with Assist off and 472 Nm with Assist on <steady>. This confirms that the electric supercharger effectively improves the engine performance, given that the application of the supercharger developed substantial amounts of torque within a very short time. Note, however that the improvement in the transient response resulting from the use of the electric supercharger decreased during high-load operation with the torque immediately before the Accelerator ON. That is, during high-load operation, the exhaust gas flow is sufficient to fully enable the operation of the conventional turbocharger.