

# Development of the New Light-Duty Hybrid Truck

Koichi Yamaguchi\*

Hino Motors, Ltd., developed the new light-duty hybrid truck whose traction motor, inverter, and traction battery were completely redesigned for maximizing output and efficiency. It also succeeds in balancing low fuel economy and low exhaust emissions by utilizing a combination of a new hybrid system control with a specially developed diesel engine.

**Keywords:** Hybrid Electric Vehicles, Parallel HEVs, Fuel Economy, NiMH

## 1. INTRODUCTION

Recently, the regulation of CO<sub>2</sub> reduction and exhaust emission reduction of the vehicles has been strengthened in order to improve worldwide environmental issues and, as the countermeasure, development of gasoline engine electric hybrid systems has been positively promoted for passenger cars. On the other hand, for commercial vehicles, diesel engines have been continuously used due to the merit of fuel efficiency. Each manufacturer of diesel engines is pushing ahead with the development of clean engines to comply with exhaust emission regulation which has been becoming very stringent on a global basis.

The hybrid system of Hino Motors, Ltd., combines its clean diesel engine with a hybrid system for keeping the balance of further improvement of fuel efficiency and exhaust emission reduction.

Hino Motors, Ltd., paid attention to the diesel hybrid system earlier and had started research on it in 1981. As a result, we succeeded in the practical use of the heavy-duty diesel hybrid route bus and put it on the market in 1991 for the first time in the world.

Then, Hino added medium-duty hybrid trucks (class 5) and large sized sightseeing hybrid buses to its product line-up, and put light-duty hybrid trucks (class 3~4) on the market in November 2003, which is expected to contribute to the improvement of the environment in the city (Figure 1).

This light-duty hybrid truck attracted the attention

of transportation and Japanese convenience store industries, who were increasingly keen to reduce their own environmental effects of pollution and CO<sub>2</sub>. Thus approximately 4,300 trucks has been operating until the end of September 2008, and more than 5,500 hybrid vehicles have been operating, including medium-duty trucks and heavy-duty large buses (Figure 2).

We developed the new light-duty hybrid truck at the end of the year 2006 (Figure 3).

Through the development of this light-duty hybrid truck, we have achieved 1.4 times fuel efficiency in the maximum compared to prior models.

We introduced newly developed hybrid systems as follows.

## 2. EXAMINATION OF A HYBRID SYSTEM

The best merit of hybrid vehicles is fuel efficiency. But, regarding diesel electric hybrid for commercial vehicles, it is technically different from gasoline electric hybrids for passenger cars. It is necessary to comply with exhaust emission regulations due to the combination with diesel engines, and further, necessary to improve fuel efficiency which is a feature of diesel engines.

However, commercial vehicles are heavy, and its gross vehicle weight reaches twice its original vehicle weight depending on the payload.

Besides, the loads of vehicle are greatly changed by body applications, such as garbage trucks and refrigerator trucks, etc.

We have to satisfy the stable improvement of fuel efficiency without being influenced by the above conditions.

\*Hino Motors, Ltd.  
191-8660, 3-1-1 Hino-dai Hino-shi, Tokyo, Japan  
Phone: 042-586-5231  
Fax: 042-586-5913  
koichi.yamaguchi@hino.co.jp

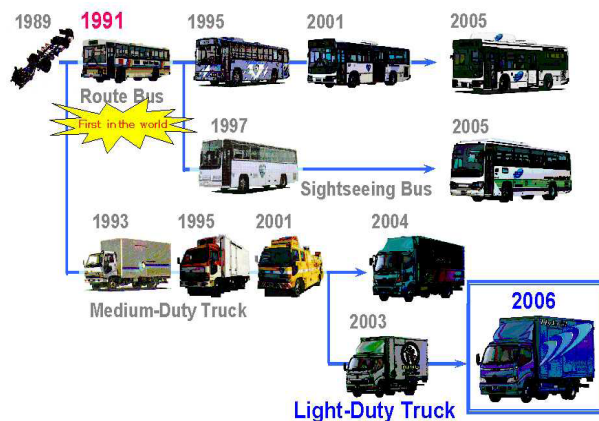


Figure 1: History of Hino's hybrid vehicle

Furthermore, because of the peculiar long mileage and long life of commercial vehicles, it must have high reliability based upon simple and strong systems.

Moreover, because the vehicle has a purpose to load cargo, most of the space is for the customer, and all hybrid units must be as small as possible and must be lightweight.

In order to satisfy all these conditions, we examined the system to optimize again.

There are three types of hybrid systems: parallel, series, and series-parallel systems (Figure 4).

Under the series system, the engine can be a low output

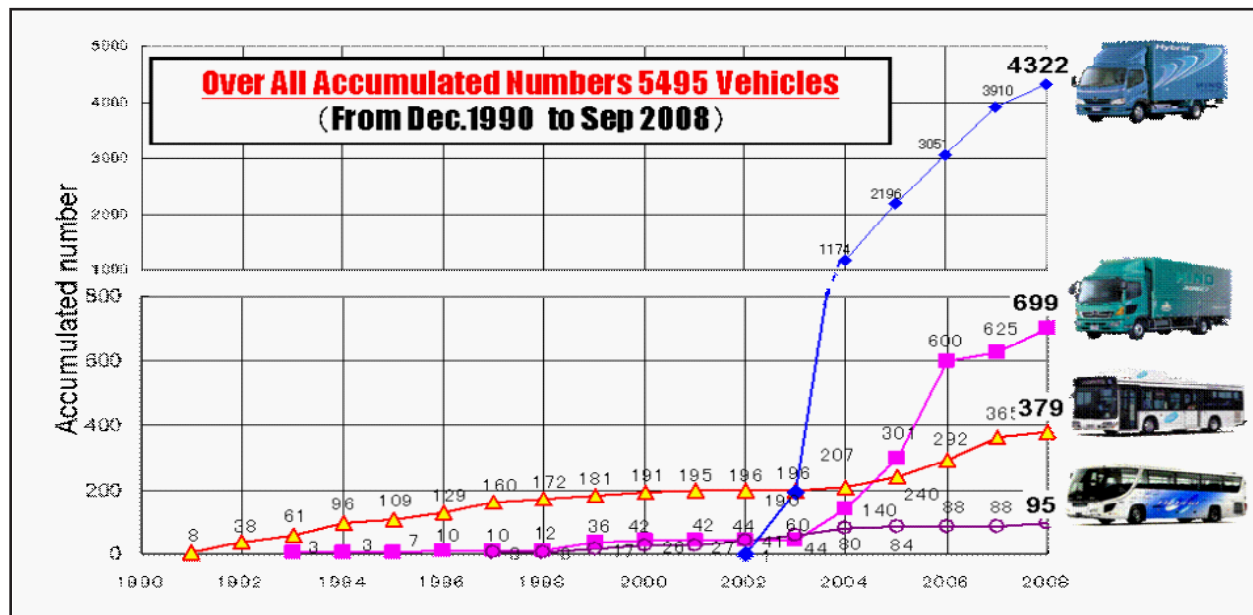


Figure 2: Accumulated numbers of Hino's hybrid vehicles



Figure 3: New light-duty hybrid truck

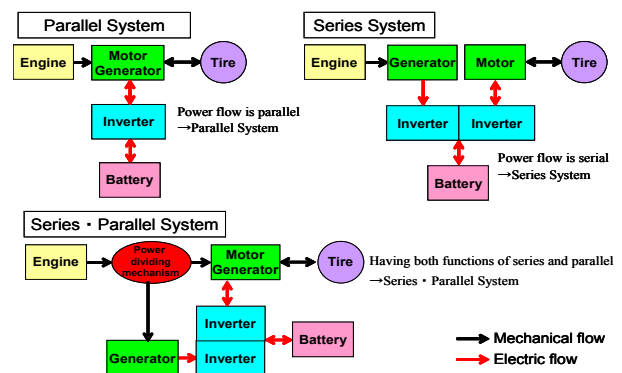


Figure 4: Kind of hybrid system

type because it is used only to drive the generator. But a high output Traction Motor is necessary in order to provide total power to the drive tire for the use of commercial vehicles which are heavyweight and are in use under heavy load frequently.

In connection with this, high output Inverter and Traction Battery are necessary, and moreover, both Generator and Traction Motor are also needed; it is difficult to install them to the light-duty truck due to the problem of installation space and mass, etc.

In addition, because the electrical energy generated by the Generator is stored in the Traction Battery and then converted into the Traction Motor to drive the tires, the system has the problem of the total efficiency becoming low, if the efficiency of each component is not high enough.

On the other hand, as for series-parallel system, engine power is divided into tire driving force and Generator driving force by the power distribution mechanism.

This divided engine power is added up to the Traction Motor power which drives the tires and is converted to the power to generate electric power with Generator.

The greatest feature of the series-parallel system is that the engine can operate with a fuel-efficient line. And this system is the most suitable for the engine, especially a gasoline engine, with bad fuel efficiency zone in low rotation and low load.

In the case of the diesel engine, since there are few zones where fuel efficiency falls extremely like the gasoline engine, it is not necessary to operate with a line.

Because this system has a complicated structure that consists of the power dividing mechanism, Generator and Traction Motor, and moreover the needs of some hybrid units, it has problem of installation space and mass, etc. Accordingly, there is no advantage in terms of cost-benefit performance.

In contrast, since the parallel system requires only one Traction Motor/Generator, the mechanical structure is simple. And the engine is operated mainly for the running vehicle.

Since a Traction Motor is operated to assist driving force at the time of starting the engine and acceleration when fuel is much consumed, only low output Generator, Inverter, and Traction battery are sufficient for them.

As a result, the parallel system is the most suitable

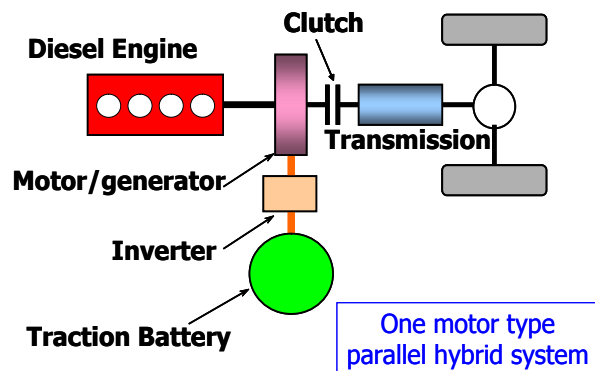


Figure 5: General outline of Hino hybrid system

for commercial vehicles with diesel engines.

In accordance with the above examination, we decided to use one motor parallel system for our hybrid system. We have adopted this one motor parallel system from the initial stages of development. As of late, many hybrid systems have been developed but we verified again that one motor parallel system is the best for diesel hybrid systems for commercial vehicles.

A conceptual diagram is shown in Figure 5.

### 3. EXAMINATION OF PERFORMANCE OF HYBRID SYSTEM

The fundamental idea of the hybrid system is to collect the energy, which used to be thrown away as heat when braking at the time of deceleration, as electric energy and reuse it as torque assist the engine.

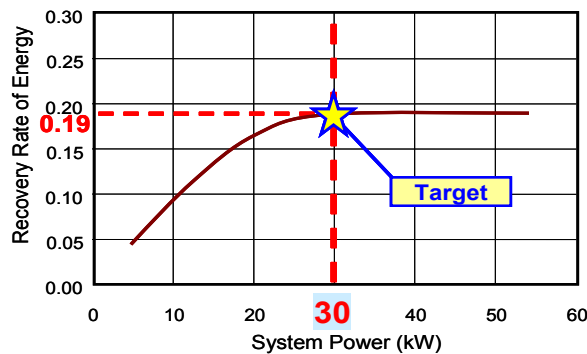
Therefore, in order to improve fuel efficiency, it is important that we know “how to collect decelerated energy” and “how to consume collected energy efficiently.”

In order to materialize these, “optimization of the system output,” “upgrading of system efficiency,” and “optimization of engine torque assist zone” are necessary, and “weight saving of the system” is also an important factor in order to improve fuel efficiency.

Contents of examination for those four items are shown as follows.

#### 3.1 Optimization of System Output

In case of the light-duty truck, the maximum recovery rate of energy city driving mode is 19%. (Recovery rate of energy means usable recovered energy quantity vs. required energy quantity to run the vehicle.)



$$\text{Recovery Rate of Energy} = \frac{\text{Regenerative Energy}}{\text{Driving Energy}}$$

Figure 6: Relationship between system output and energy recovery rate

The curve in Figure 6 shows the system output of a hybrid (i.e. output of Traction Motor and Traction Battery) plotted on the horizontal axis and the energy recovery rate on the longitudinal axis.

This curve has an inflection point and the energy recovery rate becomes flat beyond a certain output. In other words, this shows that the energy recovery rate does not increase, even if a large output system is installed.

Therefore, it shows clearly that the optimal system output is 30kW for a light-duty truck.

### 3.2 Upgrading of System Efficiency

The square of conversion efficiency when deceleration energy is converted to electric energy and the stored energy is converted to torque that assist the engine act on one-motor parallel type hybrid systems, which we adopted.

Therefore, fuel efficiency differs greatly from how much we improve the efficiency of the Traction Motor-Generator, Inverter and Traction Battery, which are main components.

For example, assuming that the efficiency of Traction Motor-Generator and Inverter is 92%, the efficiency of the Traction Battery is 90% and deceleration energy is 100, storable energy will go down to approximately 83%.  $(100 \times 0.92 \times 0.9 = 0.828)$

Because the same efficiency is applied, when it is used as torque that assists an engine, it will fall to about 69%.

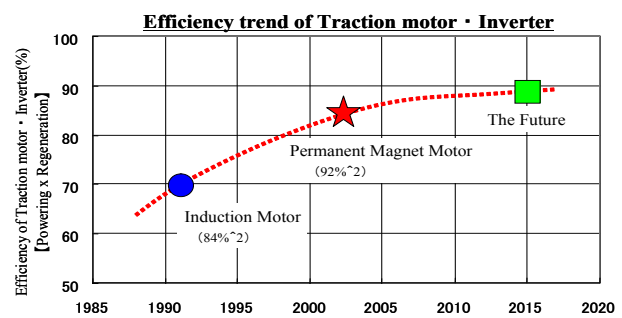


Figure 7: Trend curve of the efficiency of Traction Motor/Generator + Inverter

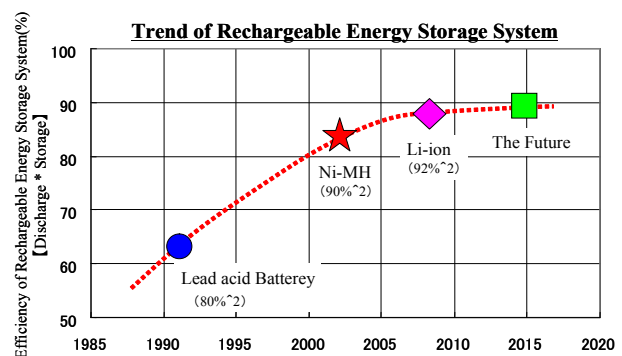


Figure 8: Trend curve of the efficiency of Traction Battery

The curves in Figure 7 and 8 show the efficiency of the components that we researched at present.

Especially because of the efficiency of Traction Motor/Generator, in accordance with its characteristics (which differs in the rotation range from load range), it is important in the system design to secure a wide range of high efficiency, maintain the efficiency at a high level, and match the high efficient zone to the zone used by light-duty truck.

Taking these into consideration, we examined the unit which secures maximum system efficiency this time.

### 3.3 Optimization of Engine Torque Assist

Figure 9 shows examples of specific fuel consumption maps of the diesel engine.

Diesel engines consume large quantities of fuel in a high torque range. And combustion efficiency in the low rotation and low load range is the lowest.

On one hand, from fuel consumption distribution of how it's used in the market, fuel is consumed most at

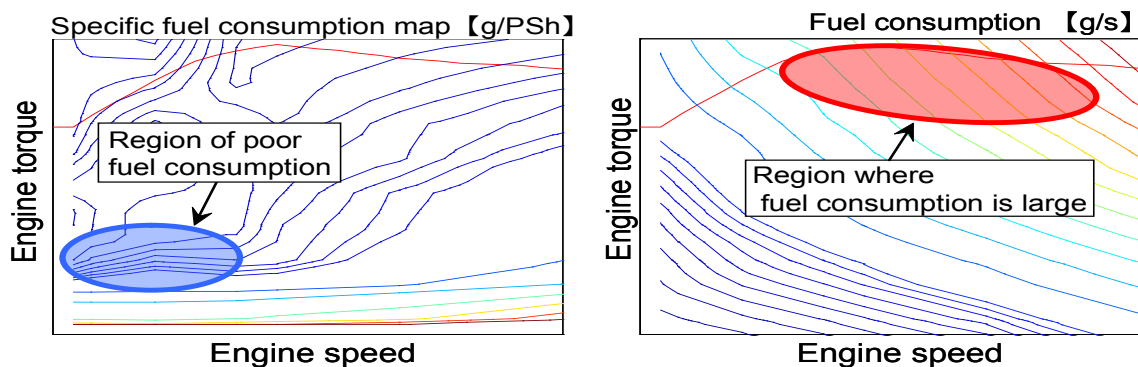


Figure 9: Example of specific fuel consumption map of a diesel engine

the time of start and acceleration (Figure 10). And it is confirmed that load frequency distribution greatly changes, depending on the gear stages as shown in Figure 11.

Considering these points, we examined the torque assist zone by the Traction Motor. In particular, we made the most of the characteristic of the Traction Motor where high torque can be generated in a low rotation zone, but output becomes constant and torque decreases in medium/high rotation zones and sets the torque assist zone in the low rotation zone where start and acceleration is performed.

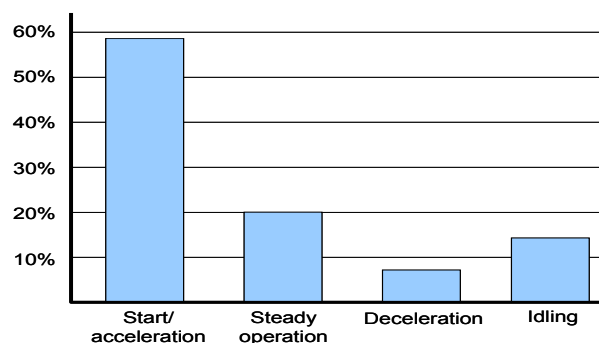


Figure 10: Fuel consumption in vehicle operation

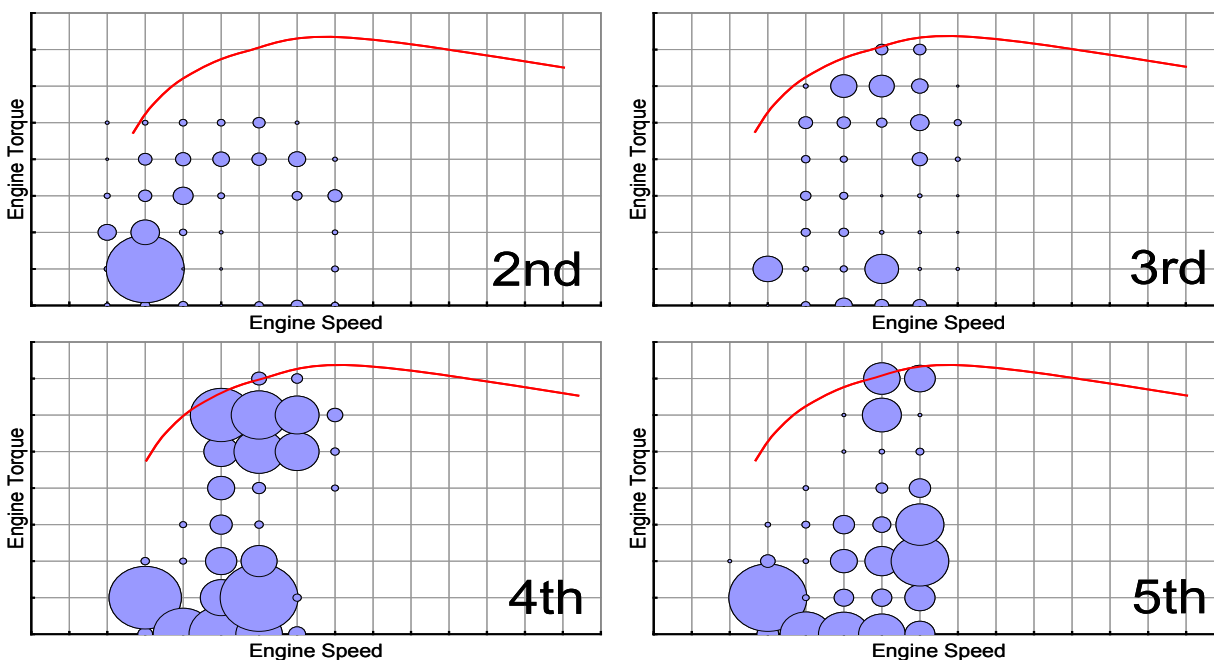


Figure 11: Engine load frequency distribution by transmission gear position engaged



We examined the torque assist zone so that the vehicle can run only by engine in the steady run area where fuel consumption is relatively low, by setting the torque assist zone variable in accordance with the gear stage.

The graph of torque assist zone of the engine examined this time is shown in Figure 12.

### 3.4 Examination of System Weight Saving

In case of the light-duty truck, it is known that if the vehicle mass increases by 200kg, fuel consumption gets worse by 3%. Therefore, weight saving of the Hybrid System is important in order to improve fuel efficiency.

We determined the system mass target as 200kg and tried to carry out weight saving of each components, reducing the quantity of packaging and parts items. As a result, we have exceeded our target and achieved 195kg.

## 4. DEVELOPMENT OF HYBRID UNIT

We studied the Hybrid Unit in order to satisfy the issues examined above.

Here, we introduce Traction Motor, Inverter and Traction Battery and packaging (PCU), which are main components that we adopted for weight saving.

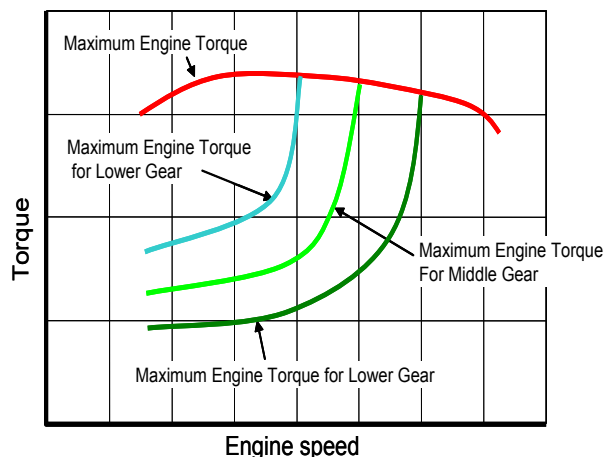


Figure 12: Torque profile of motor torque assist

	Motor
Type	IPMSM*
Max Power [kW]	36
Max Torque [Nm]	350
Mass [kg]	41

\*IPMSM : Interior Permanent Magnet Synchronous Motor

Table 1: Specifications of the Traction Motor

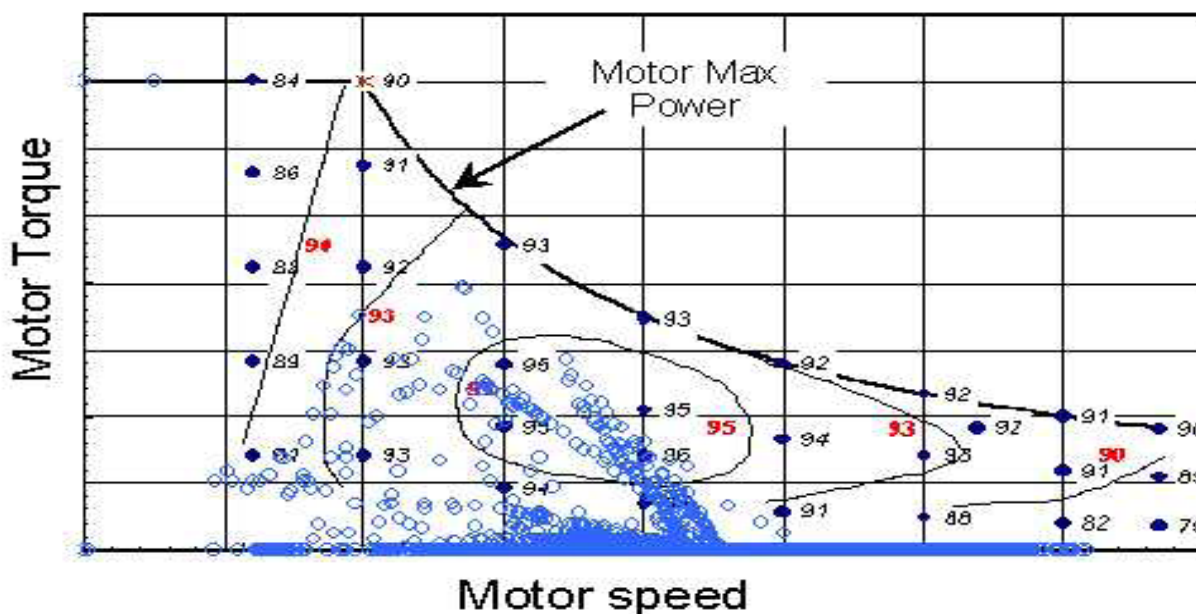


Figure 13: Efficiency Characteristic of Traction Motor and driving frequency

#### 4.1 Traction Motor

In order to satisfy the above mentioned hybrid system output and to attain downsizing and weight saving, we adopted the permanent reluctance electric motor with high power density. And the efficient zone of the Traction Motor was designed to match the zone of frequent operations by city traffic.

Specifications of Traction Motor is shown in Table 1 and its Efficiency Characteristic is shown in Figure 13.

In consideration of performance, function, transmission efficiency and the feasibility as a vehicle, we decided the arrangement of the Traction Motor in the power train, and so the rotor is directly connected to crankshaft and the stator is accommodated in the special housing in the periphery of the rotor.

External and cross section views of the Traction Motor are shown in Figure 14.

We made a structure with as minimal axial dimension as possible by preparing a special motor housing at the rear end of the engine, installing the rotor through the special shaft which is directly connected to crankshaft and fixing stator inside the motor housing.

We designed it so that the outer diameter of this motor housing was the same as the flywheel casing of a general light-duty truck to materialize lower floor and easy rear body. And we designed it to fix the stator in the motor housing, so that heat dissipation was improved. Both of these made us realize the encapsulated type of air cooling system without the special cooling system.

#### 4.2 Inverter

We decided to set the capacity of the Inverter as 64kW using the power element of 1200V-600A, taking into consideration the 30kW which is the required output of the Traction Motor and in view of common use with other heavy-duty vehicles.

The constant torque zone near low rotation must satisfy the low-temperature starting nature of the engine, since the engine is started with the Traction Motor which is a feature of this Hybrid System. Therefore, we considered making the inverter output a striking current at low temperature. Moreover, since downsizing and weight saving is required in order to install it to a light-duty truck, we made the design content as follows:

- o Power element is made 2 in 1
- o Downsizing of heat sink by water-cooling

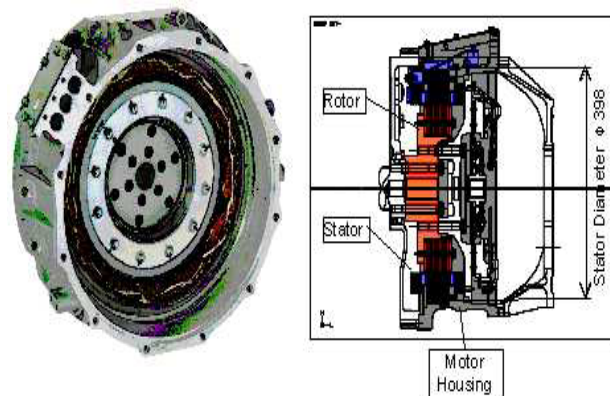


Figure 14: Traction Motor

system

- o Case is made of aluminum die cast

We were able to keep the mass to 15kg and the volume to 17 liters, thanks to these.

Specification of the Inverter is shown in Table 2 and its external view is shown in Figure 15.

#### 4.3 Traction Battery

The Traction Battery also needs to have an output capacity of 30kW in order to satisfy the system output of the HV mentioned earlier. Therefore, we decided to use the nickel metal-hydride battery which has high density and reliability.

Forty pieces of 7.2V modules connected in a series produce 288V, and the input-output feature was improved by reducing the internal modular resistance.

Table 3 shows the specification of the Traction Battery and Figure 16 shows its external view.

#### 4.4 PCU (Power Control Unit)

We adopted unit packaging components of the hybrid like the Inverter, Traction Battery, etc., in consideration of weight saving and easy rear body mounting. And we installed it to the left side frame between the wheelbase of the vehicle.

Making the optimum placement of each component, we were able to control the volume to 160 liters and the mass to 125kg.

We arranged the Traction Battery as a waterproof structure on the upper row of PCU, and the Inverter and ECU box on the lower row.

	<b>Inverter</b>
<b>Type</b>	<b>IGBT</b>
<b>Capacity [kVA]</b>	<b>64</b>
<b>Sensor</b>	<b>Less Rotational Position Sensor</b>
<b>Cooling System</b>	<b>Water-cooled</b>

Table 2: Specifications of the Inverter

	<b>Battery</b>
<b>Type</b>	<b>Ni-MH</b>
<b>Voltage [V]</b>	<b>288</b>
<b>Capacity [Ah]</b>	<b>6.5</b>
<b>Power Density [W/kg]</b>	<b>1300</b>

Table 3: Specifications of the Traction Battery

We adopted the cooling system for the Traction Battery by forced air cooling and water cooling for the Inverters. We made the cooling system for the Traction Battery as “steam-water separate type,” and decided from the layout that the cooling air flowing from the Traction Battery side can also cool down the radiator for the Inverter cooling.

Figure 17 shows the configuration of PCU.

Figure 18 shows layout of installation to the vehicle.

## 5. THE VEHICLE WITH HYBRID SYSTEM AND ITS PERFORMANCE

### 5.1 Outline of Vehicle

Table 4 shows specification of the vehicle.

### 5.2 Evaluation of the Vehicle Performance

We evaluated the fuel consumption of the above vehicle according to driving on the actual road and its driving patterns.

The evaluation was carried out according to 4 different kinds of driving patterns, which cover how to drive light-duty trucks, after fully investigating the actual

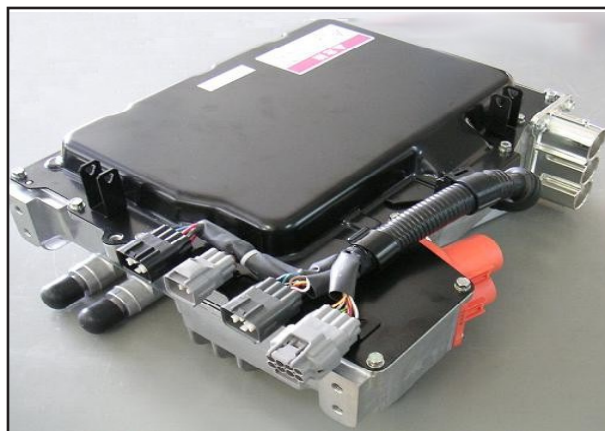


Figure 15: External view of the Inverter

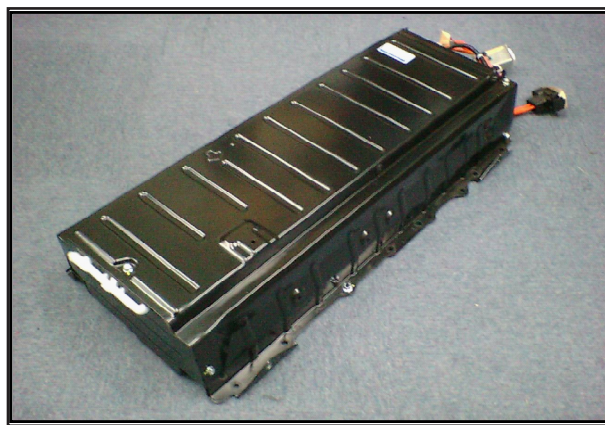


Figure 16: External view of the Traction Battery

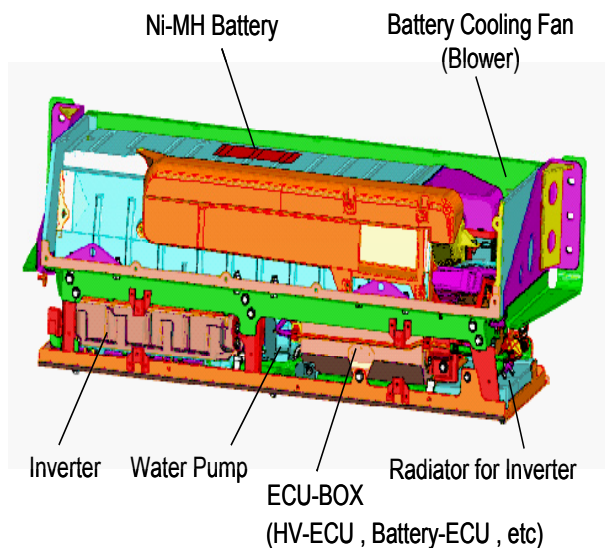


Figure 17: Inner structure of PCU (Power Control Unit)



market conditions.

Figure 19 shows evaluation pattern.

The result of fuel efficiency showed improvement from 1.25 to 1.45 times better than our previous light-duty trucks under the same test conditions carried out by us.

## 6. SUMMARY

We were able to develop a vehicle which can attain epoch-making fuel efficiency from the results of developing the hybrid system for light-duty trucks, which has a high effect on environmental improvement as low-pollution commercial vehicles, and also a combination with the newest diesel engine.

We kept on producing 100 units monthly of this

Vehicle	GVW* [tons]	4.5 ~ 6.5
	US Class	Class 3 ~ Class 4
	Load Capacity [tons]	2 ~ 3
	Transmission	5MT* or 6MT
	Destination	Japan
Engine	Displacement [cc]	4,009
	Max output [kW/rpm]	100 / 3,000
	Max torque [Nm/rpm]	353 / 1,600

Table 4: Specifications of the vehicle

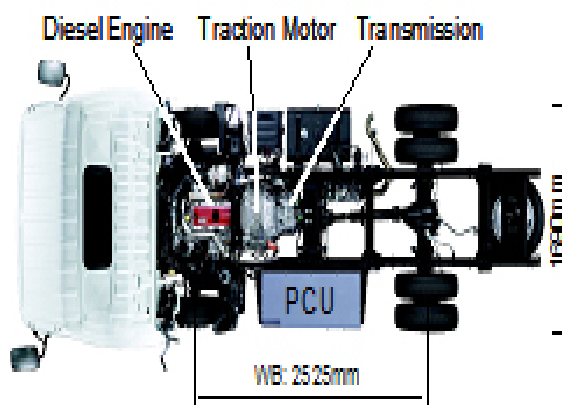


Figure 18: Overview of the new hybrid LDT

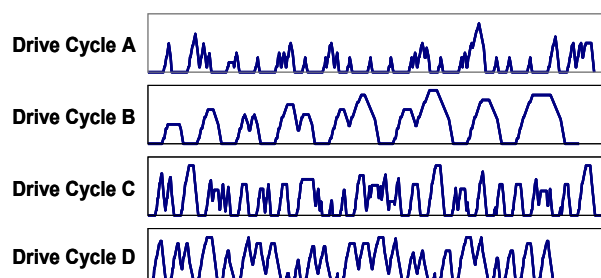


Figure 19: Driving pattern

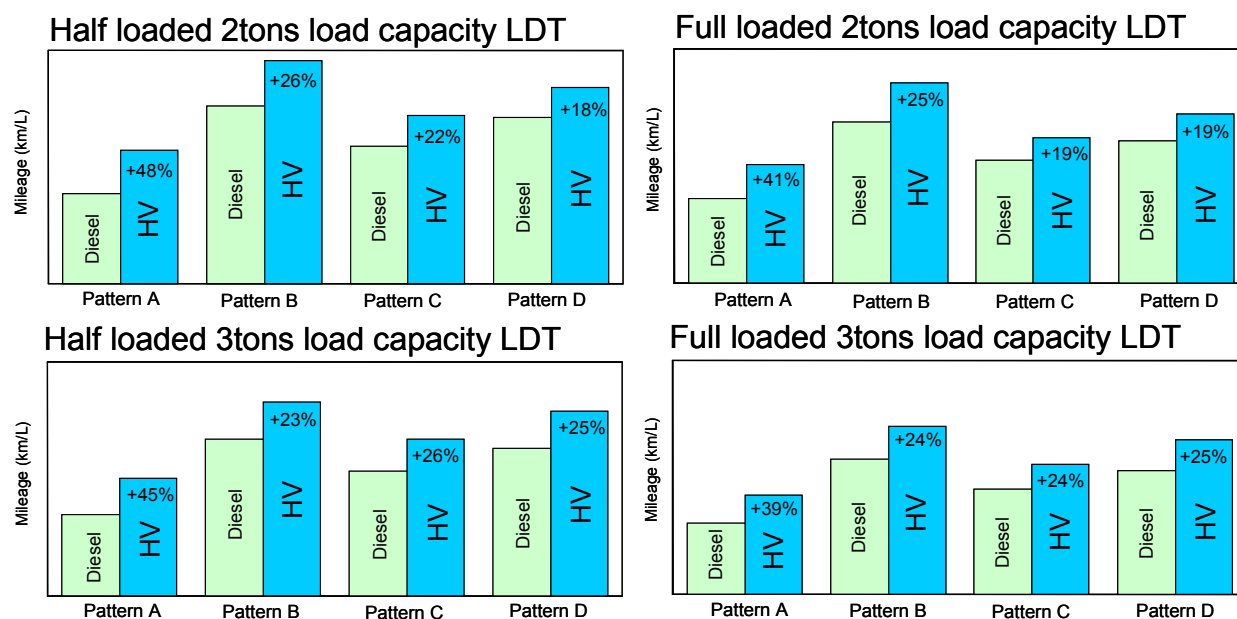


Figure 20: Results of fuel consumption testing

vehicle and they acquired a very good reputation from the market.

We believe that diesel engines will continue to exist since they do not require infrastructure development. In particular, for the environmental improvement centering city traffic, diesel hybrid vehicles which are excellent in epoch-making fuel efficiency, will be rapidly widespread in delivery trucks, route buses, etc., in the near future.

Hino Motors, Ltd., will further its effort in technical development as one of the top runners of the diesel hybrid for commercial vehicles.

#### **AUTHOR**



Koichi Yamaguchi, Chief Engineer in the Hybrid Vehicle Development Division, joined Hino Motors, Ltd., in 1992. He was immediately assigned to take charge of hybrid powertrain development. Mr. Yamaguchi has been working on hybrid vehicle development ever since. Hino Motors, Ltd., 3-1-1, Hino-dai, Hino-shi, Tokyo, 191-8660, Japan.

Phone: 81-42-586-5183, Fax: 81-42-586-5179  
koichi.yamaguchi@hino.co.jp  
<http://www.hino.co.jp/>