Development of Hybrid System for SUV

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ABSTRACT

Toyota Hybrid System (THS), that combines a gasoline engine and an electric motor was installed in the Prius, which was introduced in 1997 as the world’s first mass-produced hybrid passenger car, and was vastly improved in 2003. The new Prius gained a status of highly innovative and practical vehicle.

In 2005, combined with a V6 engine, THS had a further evolution as a Hybrid System for SUV, which was installed in the RX400h and Highlander Hybrid to be introduced into the world.

This report will explain "new THS" which achieved both V8 engine power performance and compact class fuel economy, while securing the most stringent emission standard, SULEV.

INTRODUCTION

Faced with growing public concern about atmospheric contamination and global warming by carbon dioxide (CO₂), automobile manufacturers are now required to further reduce automobile exhaust gas and CO₂ emissions through improvement of fuel efficiency. A hybrid system that combines an internal combustion engine and an electric motor is recognized as a very effective means for satisfying the above requirements. Toyota developed in 1997 the world’s first mass-produced hybrid system, called the Toyota Hybrid System (THS). Since then, vehicles incorporating a hybrid system (hybrid vehicles) have rapidly expanded the market (Fig.1) and thus contributed to conservation of the global environment. However, only a limited number of hybrid passenger vehicle models are available today, making it difficult for some customers to find the models they need. Most hybrid systems produced today are installed in small-sized vehicles. Their performance is insufficient for driving the type of heavy-duty vehicles that emit larger amounts of CO₂ than small and medium-sized vehicles. This paper presents and discusses a new hybrid system that Toyota has developed by further improving the conventional Toyota Hybrid System in order to expand the use of hybrid systems in sports utility vehicles (SUVs).
Table 2 Specification of THS-II(SUV)

<table>
<thead>
<tr>
<th>ITEM</th>
<th>THS-II(SUV)</th>
<th>THS-II(Prius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENGINE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>3.3L gasoline</td>
<td>1.5L gasoline</td>
</tr>
<tr>
<td>Maximum output (kW/rpm)</td>
<td>155/5600</td>
<td>67/5000</td>
</tr>
<tr>
<td>Maximum torque (Nm/rpm)</td>
<td>286/4400</td>
<td>115/4200</td>
</tr>
<tr>
<td>FRONT MOTOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Permanent magnet motor</td>
<td>Permanent magnet motor</td>
</tr>
<tr>
<td>Maximum output (kW/rpm)</td>
<td>123/4500</td>
<td>90/1200-1540</td>
</tr>
<tr>
<td>Maximum speed (rpm)</td>
<td>12450</td>
<td>0400</td>
</tr>
<tr>
<td>Maximum torque (Nm/rpm)</td>
<td>223/0-2800</td>
<td>340/0-1000</td>
</tr>
<tr>
<td>REAR MOTOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Permanent magnet motor</td>
<td>-</td>
</tr>
<tr>
<td>Maximum output (kW/rpm)</td>
<td>50/4600-5100</td>
<td>-</td>
</tr>
<tr>
<td>Maximum speed (rpm)</td>
<td>10500</td>
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</tr>
<tr>
<td>Maximum torque (Nm/rpm)</td>
<td>130/0-610</td>
<td>-</td>
</tr>
<tr>
<td>BATTERY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Nickel-metal hydride</td>
<td>Nickel-metal hydride</td>
</tr>
<tr>
<td>Maximum output (kW)</td>
<td>45</td>
<td>25</td>
</tr>
<tr>
<td>10 second rating output (kW)</td>
<td>36</td>
<td>21</td>
</tr>
</tbody>
</table>

1-1. ENGINE

Increasing engine output is most important for improving the power performance of a vehicle. A 3.3L, V6 engine was designed so that it could drive even a heavy-duty SUV of FF system. This engine was basically the same as the RX330 engine, with the exception of intake and exhaust systems that were redesigned for further reduction of exhaust emissions. The variable valve timing (VVT) of the new engine was also changed to decompress the engine cylinders, thereby to minimize engine vibration during starting and stopping.

1-2. FRONT MOTOR

As in the case of THS-II(Prius), THS-II(SUV) uses a permanent magnet motor. Since the motor produces most of the driving power as shown in Fig. 3, a large-torque, high-power motor is required to increase the power performance.

On the other hand, due to limited allowances for space and weight a vehicle does not allow the mounting of a large electric motor. The following two techniques enabled THS-II(SUV) to resolve the above contradictory problems. One is use of a system operating voltage higher than the rated voltage of the battery. Using the same technique as that used in THS-II(Prius), the electric power voltage from the battery is boosted to drive the motor and generator. For THS-II(SUV), the power density has been enhanced further by boosting the voltage of the motor and generator from 500 V in THS-II(Prius) to a maximum of 650 V.

The other is installation of a gear for reducing motor speed. This speed reduction gear allows the motor to run at a high speed with a low torque value, even when large output torque is required to the drive shaft. THS-II(SUV) has an output power 2.5 times and a power density 3 times higher than those of the THS-II(Prius) (Fig.4,5).
1-3. GENERATOR

The generator is a permanent magnet motor with the maximum operating voltage of 650 V. An output torque larger than that in THS-II(Prius) was required for the generator to be compatible with the output torque of the 3.3L, V6 engine, which would usually cause both the generator dimensions and weight to increase. In designing THS-II(SUV), the torque margin of the generator for engine output torque was reduced as much as possible to minimize the generator dimensions and weight. The generator is also required to supply sufficient electric power to drive the front motor and the rear motor, as will be discussed later. To meet this requirement, the generator has been designed so that it runs at a higher speed than the THS-II(Prius) generator. For the generator, the same material; magnetic steel sheet, and the same coil turns as those for the front motors are used in order to reduce cost and the number of parts. The overall dimensions of the THS-II(SUV) generator per engine output has been reduced more than 30% compared to the THS-II(Prius) generator (Fig. 6).

![Fig.6 Relation of Engine Power and Generator Size](image)

1-4. REAR MOTOR

For installation in an SUV, the hybrid system should be of a 4WD design. When compared with 2WD vehicles, conventional 4WD vehicles are disadvantageous in acceleration performance, passenger space, and vehicle weight due to installation of an additional propeller shaft and related components. To overcome these shortcomings, THS-II(SUV) uses a motor-powered rear wheel drive unit as does the Estima-Hybrid which began mass-production in Japan in 2001. Similarly to the Estima-Hybrid, a permanent magnet motor drives the rear wheel drive unit. The motor has dramatically increased its output thanks to increase of the maximum operating voltage to 650 V and the use of optimal coil turns for this voltage (see fig. 6).

![Fig.6 Rear Motor Torque Profile](image)

1-5. BOOST CONVERTER CIRCUIT

THS-II(SUV) also uses the same boost converter circuit as that used in THS-II(Prius). This circuit boosts the voltage to a maximum of 650 V to dramatically increase the output power of the front motor, generator, and rear motor, and at the same time making them easy to install due to size and weight reduction.

1-6. BATTERY

Similar to THS-II(Prius), THS-II(SUV) uses a nickel-metal hydride battery. In order to secure an acceleration performance sufficient for the weight of an SUV, a battery composed of 240 cells is used. This battery has a short time rating of 45 kW and 10 second rating of 36 kW. The size of each cell has been minimized to allow for installation in an SUV equipped with three rows of passenger seats. The above design considerations have made it possible to locate the battery beneath the second passenger seats without sacrificing the passenger space, as shown in Fig. 8. To reduce the battery pack dimensions, the main relay, rush-current suppressing resistor, and current sensor have also been rearranged.
1-7. COOLING SYSTEM

The cooling system separately circulates engine cooling water and electric component cooling water, which is the same design as that for THS-II(Prius) with the exception of a multifunctional radiator installed for common use by both cooling systems for simplification of system installation.

1-7. SYSTEM CONFIGURATION

The arrangement of ECUs, which has been substantially modified from the THS-II(Prius) design, is shown in Fig. 9.

Major modifications are described below:

- Relocation of MG-CPU in inverter box

Differing from the THS-II(Prius) design, in which the HV-ECU comprised an HV-CPU and MG-CPU, the MG-CPU has been relocated in the inverter box to integrate the motor, generator, and rear motor controls. As a result, the need for inverter powering wire harness has been eliminated.

- Integration of HV-CPU and engine CPU into single ECU (THS-ECU)

To simplify installation and reduce cost, the engine CPU and HV-CPU have been integrated into a single ECU with a common power source circuit.

- Elimination of battery-CPU

Except for sensing functions, the SOC processor, cooling fan controller, and other functional units have been separated from the battery pack and relocated in the HV-CPU. As a result, the need for the battery-CPU has been eliminated, which has led to reduced cost and dimensions of the battery pack.

As previously discussed, the output power of electric components has been dramatically increased from THS-II(Prius). In THS-II(SUV) the measures taken for balancing motor power with generator power, as well as the scheme for controlling the system within the rated specifications of electric components are greatly changed.

3. 4WD CONTROL

The new hybrid systems are installed in FF type 2WD vehicles and 4WD vehicles consisting of a specially designed rear wheel drive unit.

3-1 ALLOWABLE RATIO OF POWER SPLIT BETWEEN FRONT AND REAR WHEEL DRIVE UNITS

Front wheel drive units have been designed to allow FF vehicles to achieve the fullest performance. On the other hand, the output power of the rear wheel drive unit is slightly limited due to restricted installation space in the body. However, since the rear motor has an output power of 50 kW or 130 Nm, power can be delivered to the front and rear wheel drive units at a ratio of nearly 1 to 1, as long as the accelerator pedal is held at about 50% stroke (see Fig. 10).
The new hybrid system uses an electronic 4WD system. Its front and rear wheel drive units are driven independently by two electric motors (front and rear motors). The power split ratio between the front and rear motors is managed by controlling the output torque of these motors. Differing from conventional 4WD vehicles that use a hydraulic control system, the new hybrid system directly controls the electric power to be transmitted to the front and rear wheel drive motors. Therefore, the new hybrid system quickly responds to power split ratio command signals (see Fig. 11) and thus maximizes fuel efficiency, as well as stability and controllability of the vehicle.

When a vehicle runs at a constant speed in the 4WD mode, the front motor is driven by the engine and generates the rear motor drive power. This causes electrical energy to flow between the front and rear motors and increases power loss in the electrical system, resulting in overall efficiency reduction. To eliminate this disadvantage, the new hybrid system has been designed to operate in the FF mode when the vehicle runs at a constant speed. Since either the FF or 4WD mode can be selected quickly as has already been discussed, sufficient vehicle stability and controllability are always obtained, even if the vehicle runs in the 4WD mode only when necessary. To keep proper stability and controllability, the vehicle is driven in the 4WD mode during acceleration, skidding, and right/left turns. 4WD mode is also used during deceleration in order to recover kinetic energy as electrical energy.

The front and rear wheel drive units have individual performance limits. Taking this fact into account, the power split ratio is finally determined so that the fuel efficiency and power performance are maximized while giving the top priority to vehicle stability and controllability.

4. POWER PERFORMANCE

As discussed in Section 2, the output of each electrical component has been dramatically increased from that in THS-II(Prius) while suppressing weight increase to a minimum. Thus, a new hybrid system suitable for installation in SUVs has been developed successfully.

4-1. SYSTEM OUTPUT POWER

In THS, the engine and battery produce the vehicle drive power, while the electric motors and generator are used to merely transmit the power, as can be understood from Fig. 12.
A combination of the engine and battery can produce a maximum output power of 200 kW, which is comparative to the output capacity of a gasoline engine having a displacement of nearly 4L (see Table 13).

### Table 13 System Power

<table>
<thead>
<tr>
<th></th>
<th>THS-II (SU)</th>
<th>LS 430</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine Type</strong></td>
<td>V6</td>
<td>V8</td>
</tr>
<tr>
<td><strong>Displacement</strong></td>
<td>3.3L</td>
<td>4.6L</td>
</tr>
<tr>
<td><strong>Engine Maximum Power</strong></td>
<td>155kW</td>
<td>210kW</td>
</tr>
<tr>
<td><strong>Battery Maximum Power</strong></td>
<td>45kW</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Power</strong></td>
<td>200kW</td>
<td>216kW</td>
</tr>
</tbody>
</table>

#### 4-2. STEPLESS SPEED REDUCTION GEAR

The continuous speed reducing function of THS permits a wide engine speed range, which implies that the engine speed can be controlled independently of vehicle speed. Therefore, unlike a step change gear type vehicle in which the engine speed drops immediately after up-shifting, THS does not stall the engine power (Fig. 14).

A hydraulic system, such as a CVT, is not used in THS to change the engine speed. Therefore, the engine speed can be changed very quickly and hence a necessary amount of engine power can be obtained in a moment (see Fig. 15).

#### 4-3. ASSIST BY REAR MOTOR

Since a 4WD model system consists of a rear motor, the excess electric power that would be generated by the generator or stored in the battery in a 2WD model system when it is driven at a low-speed can be transformed by the rear motor to drive power (see Fig. 16).

It is a matter of common knowledge that the power performance of a 2WD model system is higher than that of a 4WD system mainly because the former is lighter than the latter. When a 4WD and 2WD model systems are compared with each other, the 4WD has higher power performance than the 2WD, despite the fact that the former is heavier than the latter by the weight of the rear wheel drive unit.
4-4. ACCELERATION TIME

As discussed above, the 3.3L, V6 engine of the new hybrid system can provide a power performance equivalent to that of a 4L gasoline engine (see Fig. 17). Particularly, the acceleration of the new hybrid system from 30 mph is far better than that of 4L gasoline engine. 2WD model systems also exhibit an excellent power performance since they include a high-powered front motor.

5. FUEL EFFICIENCY

A vehicle having THS-II-R achieves remarkable fuel economy in the same class of SUVs as a result of combining a newly developed hybrid system with an existing engine which was not developed for hybrid vehicles originally (Fig. 18).

Table 19 shows a comparison of fuel economy between the new SUV with THS-II(SUV), LEXUS RX-330 with 3.3L, V6 engine, which is the same engine and body as the new SUV, and LEXUS RX-300 with 3.0L, V6 engine, which is the same body.

Fig. 17 Acceleration Time

Fig. 18 Fuel Economy of EPA Combined Mode

Fig. 20 shows fuel economy measurement results for various US certification modes. Data are shown for a range of vehicles. In comparison to fuel economy under official fuel economy evaluation conditions at 75°F, though fuel economy worsens as atmospheric temperatures fall in conventional vehicle, the percentage in the new SUV doesn’t change so much (Fig. 21, e.g. 50°F and 25°F). This is a result of the effective engine drive by the hybrid system in lower temperature as well as in normal conditions.

Fig. 21 FE % Difference to FTP

However, comparing savings in fuel use of the new SUV to the conventional vehicles (Fig. 22), the new SUV shows similar savings in the amount of fuel used per 1,000 miles over official test modes, cold tests, hot tests and the US06 mode, a market check on the cleanliness of exhaust emissions under aggressive driving conditions (Fig. 23). Thus, although fuel economy may vary widely, fuel savings are nearly constant. This illustrates that fuel economy is a poor metric as its relationship to actual fuel consumption and CO₂ formation is non-linear.
6. EXHAUST EMISSION

6-1. EMISSION STANDARD

The THS-II(SUV) system complies with the strictest emission regulations that are currently being proposed in the various countries such as SULEV in California, Euro 4 in Europe, and J-SULEV in Japan. The basic system of the hybrid vehicle that we recently developed is common to all these destinations. This system meets the emission regulations of Japan, United States, and Europe. This was achieved by optimizing the amount of noble metals in the catalyst, under floor catalyst and fuel tank system, etc.

In California, it obtained SULEV approval. The hybrid battery has a 10 year/120k miles warranty, and the vapor reduction tank system has been improved to satisfy the zero evaporative standard.

6-2. EXHAUST EMISSION REDUCTION

Fig.25 shows an overview of the exhaust system that complies with SULEV requirements. This system consists of a high-performance start catalyst with an ultra-thin wall and high cell density that is mounted close to the exhaust manifold. A front A/F sensor and a rear O₂ sensor are provided upstream and downstream of the start catalyst respectively.

Fig.26 shows the emission behavior of THS-II(SUV) SULEV system. HC/NOx emissions are reduced by taking advantage of the motor assist while the engine runs itself mainly to warm up the catalyst shortly after starting. Meanwhile, on the hybrid vehicle in which the engine is frequently started and stopped, the key point is how to minimize the exhaust emissions that are emitted when the engine is restarted.

The details of the various items for reducing the emissions are given below.

6-3. PRECISION ENGINE AND MOTOR COORDINATION CONTROL

6-3-1. Rapid catalyst warm-up after cold start

Following a cold start, during which the catalyst has not warmed up sufficiently and cannot properly reduce the exhaust. The system utilizes the motor assist to drive the vehicle, while the engine operates independently under
the conditions that are optimal for reducing the exhaust. Fig.27 shows the power management conditions when the vehicle is driven following a cold start. By maintaining a constant volume of intake air by the engine, the air-fuel ratio fluctuation has been restrained to minimize exhaust emissions. Furthermore, a rapid warm-up of the catalyst has been achieved by adopting the stoichiometric or lean air-fuel ratio and a considerable retarding of the ignition timing. Because the engine cannot be expected to provide power in the process, most of the power to drive the vehicle is provided by the motor assist.

![Fig.27 Power management after cold start](image)

6-3-2. Improvement in combustion after a cold start (for U.S.)

Fig.28 shows the improved combustion results following a cold start by Pre-heating and A/F lean feedback control (F/B). This improvement consists of A/F sensor warm-up. During pre-heating, precision air-fuel control is achieved, just after engine cold start.

![Fig.28 Improved Cold Start Combustion](image)

6-4. O₂ STORAGE MANAGEMENT OF THE CATALYST

The NOx emissions with the engine restarting is a serious issue for a hybrid system in which the engine is started and stopped frequently. During these conditions the O₂ storage capacity of the catalyst is in a saturated state. Fig.29 shows the concept of the O₂ storage management of the catalyst.

![Fig.29 Management of O₂ storage of catalyst](image)

6-5. SUPPRESSING CATALYST DETERIORATION

To meet the SULEV requirements by positively avoiding catalyst deterioration, the new hybrid system is equipped with A/F control logic system. It is widely known that 3-way catalyst deteriorates rapidly due to high temperature and lean ambience. In the new hybrid system design, catalyst temperature is estimated from engine load to control the air-fuel ratio in the catalyst so that a lean air-fuel ratio condition will not be created when the catalyst is highly heated.

CONCLUSION

A new power train containing two electric motors has been developed aiming at its application to FF type vehicles of the heaviest class.

- Introduction of a speed reduction gear and the use of higher operating voltage have increased the output density of the electrical system, yielding a power performance equal to or higher than that of conventional vehicles.

- The new 4WD design, in which the front and rear wheels are independently driven by two electric motors, has improved fuel efficiency while maintaining optimum vehicle stability and controllability. The rear motor assist function has also improved the power performance.

- A fuel efficiency outstandingly higher than that of gasoline-fueled vehicles of the same weight has been achieved.
• The new hybrid system meets the exhaust emission requirements of J-SULEV (Japan), SULEV (North America), and EURO 4 (Europe).

REFERENCES