

Development of New Plug-In Hybrid System for Compact-Class Vehicle

Shinji Ichikawa, Hiroaki Takeuchi, Shigeru Fukuda, Shigeki Kinomura, Yoshiki Tomita,
Yosuke Suzuki, and Takahiko Hirasawa
Toyota Motor Corporation

ABSTRACT

A next-generation plug-in hybrid system has been developed for the new Prius Prime. The objective of this development was to maximize the performance of the Toyota Hybrid System II (THS II) developed for the new fourth generation Prius HV, while achieving even better dynamic performance in electric vehicle (EV) mode. These objectives were accomplished by the adoption of new components and systems, as well as refinements to existing hybrid vehicle (HV) components. This paper describes the development of this new plug-in hybrid system.

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1. INTRODUCTION

Automakers are expanding the availability of plug-in hybrid vehicles (PHVs) to help satisfy increasingly stringent automotive environmental standards around the world.

As part of this trend, the development of the new Prius Prime aimed to achieve an appealing vehicle capable of meeting the expectations of customers by combining world-class environmental performance (i.e., power consumption efficiency and fuel economy) with greatly improved dynamic performance in electric vehicle (EV) mode. This paper describes the development of this new plug-in hybrid system, as well as its components and systems.

2. DEVELOPMENT OBJECTIVE

2.1 Dynamic Performance in EV Mode and Environmental Friendliness

The first objective of this development was to create a highly efficient system with greatly improved dynamic performance in EV mode, while maximizing the performance of the hybrid system components in the new fourth generation Prius hybrid vehicle (HV) to maintain high-performance in HV mode [1]. At the same time, this development also aimed to improve the driving feeling of the PHV in EV mode. This high EV mode performance was achieved by increasing the output current and battery voltage of the power control unit (PCU), adding a new Dual Motor Drive System with a one-way clutch installed on the transaxle, and adopting a high-capacity battery pack system. In addition, a new battery warm-up system was developed to help improve EV mode dynamic performance in cold temperatures.

2.2 Charging System

Charging is an essential function for PHVs. This development increased the efficiency of the charging system and boosted the output of the charger with the aim of minimizing increases in charging time caused by the expanded EV mode range.

The charging system also features a new charging function based on weekly scheduling. The new function includes a timer and coordinated control between the pre-air conditioning and battery warm-up system to help improve user friendliness.

3. CONFIGURATION OF PLUG-IN HYBRID SYSTEM

Figure 1 shows the configuration of the plug-in hybrid system.

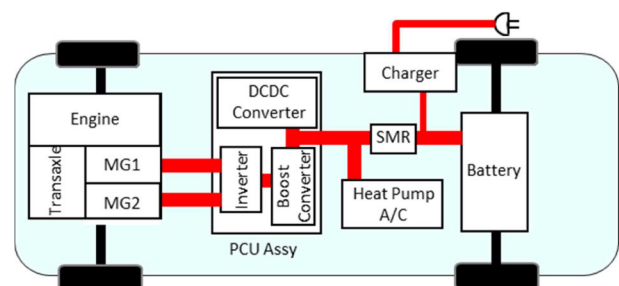


Figure 1. Configuration of new plug-in hybrid system.

The engine in the new Prius Prime is the same 2ZR-FXE engine used in the Prius HV. This engine has a peak thermal efficiency of 40%[2].

The configuration of the plug-in hybrid system is essentially the same as in the Prius HV [1]. However, to improve performance in EV mode, the output of the boost converter in the PCU was increased. A new Dual Motor Drive System was also adopted, which is capable of using the generator in addition to the motor to drive the vehicle in EV mode. These improvements helped to greatly enhance EV mode performance.

The traction battery system features a larger capacity battery than the Prius HV, which helps to substantially extend range in EV mode. A new battery warm-up system was also developed to improve EV mode performance in winter. At the same time, a higher efficiency charger was developed to minimize increases in charging time caused by the larger battery capacity. The following sections describe the details of these components and systems.

4. TRACTION BATTERY SYSTEM

4.1 Structure of Battery System

Figure 2 shows the layout of the parts in the battery system. Control devices such as the battery ECU are consolidated at the top of the system and the battery stack is installed at the bottom. This layout reduces the length of the battery and allows a storage space to be provided in the vehicle behind the battery. The air-cooling system is applied to this system. The electric heater elements of the battery warm-up system are installed below the battery stack to save space while providing efficient battery warm-up.

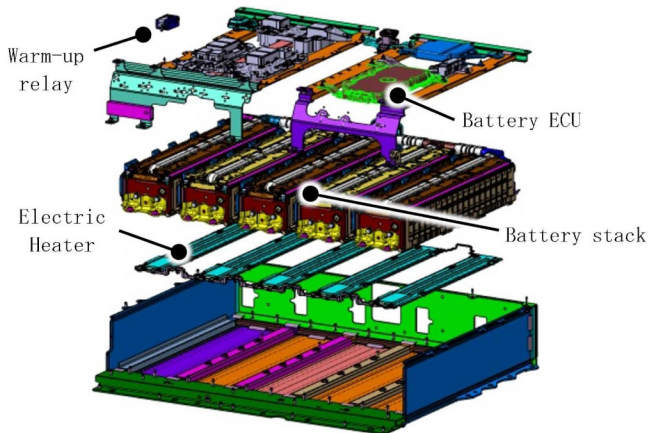


Figure 2. Internal structure of battery system.

Table 1. Main specifications of battery system.

	New system	Previous system	Difference
Total electric energy [kwh]	8.8	4.4	Approximate 2x increase
Weight [kg]	120	80	Approximate 1.5x increase
Volume [L]	145	87	Approximate 1.6x increase
Voltage [V]	351.5	207.2	—
Cells	95	56	—

Although the total energy of the new battery system is approximately twice as high as the previous system, the new component layout and an optimized frame structure kept the increase in weight to approximately 1.5 times and the increase in volume to approximately 1.6 times (Table 1). The developed structure also enables a flat luggage compartment surface with enough space to fit two golf bags.

4.2 Battery Warm-Up System

Battery output generally becomes restricted in low temperatures. When a battery is cold, output is reduced even when the state of charge (SOC) is high. For hybrid vehicles, this means that the engine may have to be started to satisfy the power demand from the driver (Figure 3).

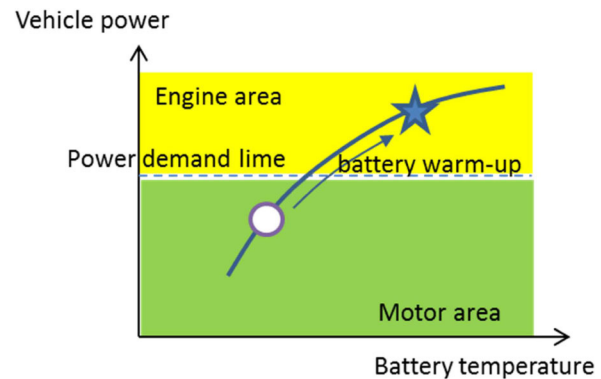


Figure 3. Illustration of output increase with battery warm-up system.

Therefore, an electric heater is installed in the new Prius Prime below the battery stack to warm up the battery in cold climates (Figure 2). During charging, the electric heater is controlled to maintain the battery at the appropriate temperature. This increases battery output as shown in Figure 3 and allows a more higher battery output power in EV mode.

Figure 4 shows the electric heater pattern. The heater pattern has a variable areal density that optimizes the amount of heat generation over 35 areas and ensures that the cells in the battery pack are warmed up uniformly.

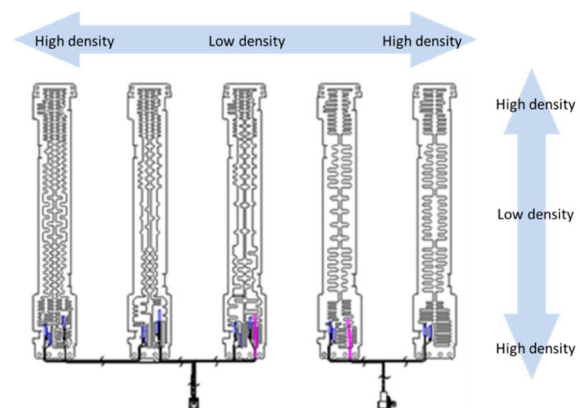


Figure 4. Electric heater pattern

The pattern applies higher heater output to the corners to counteract the increased cooling that occurs in areas of the battery case with larger surface area exposure. Lower heater output is applied to the center of the battery, where heat is more likely to accumulate.

Figure 5 shows an example of the battery warm-up system operation. Under normal charging conditions, the system automatically maintains the target battery temperature. When a scheduled departure is set using the timer function, the warm-up system operates automatically by calculating the necessary heater start time to achieve the target battery temperature at the scheduled departure time. This ensures that the battery is warmed up without wasting energy.

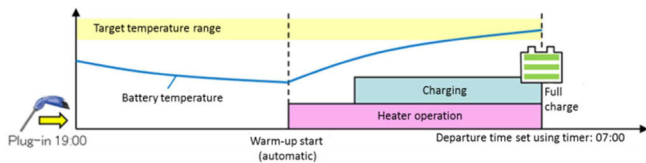


Figure 5. Operation after setting departure time using charging timer function.

5. PHV TRANSAXLE

5.1 Transaxle Structure

Figure 6 shows a cross-section of the PHV transaxle.

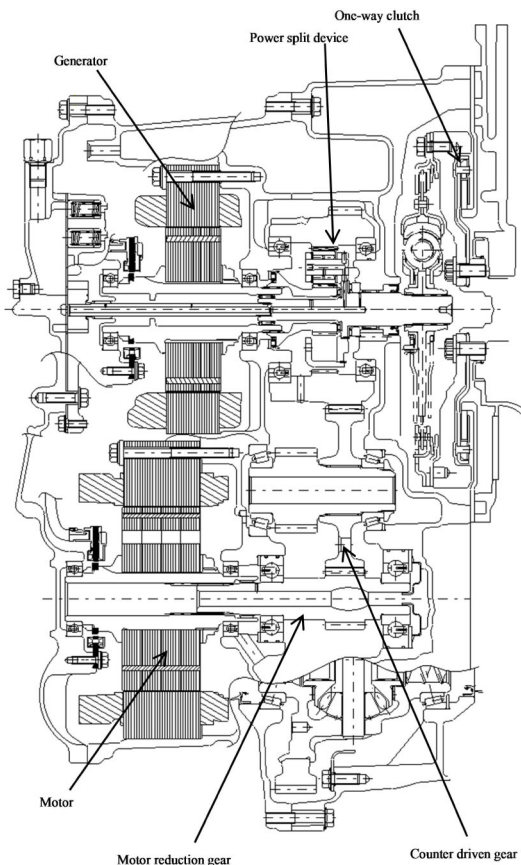


Figure 6. Cross-section of PHV transaxle.

The development objectives of the new PHV transaxle were as follows.

1. Help achieve powerful EV driving force by placing a one-way clutch between the engine and power split device to realize the Dual Motor Drive System, which enables the vehicle to be driven using two motors.
2. Help achieve powerful EV mode driving force and greatly extend the EV mode driving range by enhancing the cooling performance of the planetary gear and motor during EV mode through the use of an electric oil pump (EOP).
3. Utilize the existing components and capabilities of the HV transaxle in the Prius HV when possible to maintain high performance in HV mode while also greatly improving performance in EV mode.

The PHV transaxle has a four-axis structure and consists of a torsional damper with a torque limiter, one-way clutch, input shaft, planetary gear, generator, motor, reduction device, and differential device. The planetary gear functions as the power split device that determines whether engine power is supplied to the generator or used as vehicle driving force. The motor and motor reduction gear are laid out on a different axis to the input shaft, and the motor speed reduction device uses a parallel shaft layout. Power is applied from both the engine and motor to the counter driven gear, which transmits this power to the differential gear. The one-way clutch receives the reaction torque of the generator and transmits it to the tires when driving force is required in EV mode.

5.2 Dual Motor Drive System

Figure 7 shows a monographic chart of the power split device (planetary gear) when the Dual Motor Drive System is operating. The one-way clutch is placed to permit rotation in the forward direction of the engine on the carrier axis of the planetary gear, while preventing engine rotation in the reverse direction. If reverse direction torque is outputted from the generator on the sun gear axis, the one-way clutch on the carrier axis receives this reaction torque, and transmits the generator torque to the output connected to the ring gear axis. In addition to this generator torque, output of torque from the traction motor allows the vehicle to be driven using two motors.

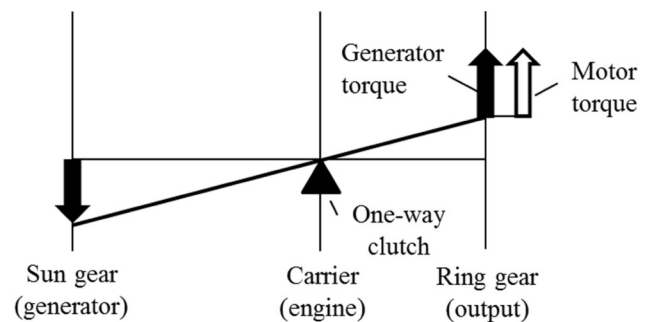


Figure 7. Monographic chart (Dual Motor Drive System)