1. Abstract
As the demand for so-called eco-cars has been increasing recently, new hybrid transaxle P610 has been developed to achieve outstanding fuel economy and an excellent driving performance. P610 was installed in the 4th generation Prius, the first car to implement TOYOTA’s new development strategy, TNGA (Toyota New Global Architecture). In order to accomplish the goal, radical reduction of mechanical loss, size and weight, dual-axle motor structure are adopted to draw out the potential capability of the THS (Toyota Hybrid System) to the maximum extent possible. Furthermore, placing the compact power train low, which is realized by installed the PCU (Power Control Unit) on top of the transaxle, led to provide the low center of gravity of the vehicle and excellent driving performance.

2. Introduction
Since the world’s first mass production hybrid system was developed and installed in the 1st generation Prius in 1997[1,2,3], increased environmental awareness led to raise the demands for the vehicle to have superior fuel efficiency and cleaner exhaust gases. As the eco-cars become popular, the customer's needs for various performances except for fuel efficiency, such as driving performance and styling, has been increasing. And the automakers need to put together the various performances in a high level. Then TOYOTA implements the new development strategy, TNGA, to the new generation Prius.

This paper describes the main features and performances of the newly developed hybrid transaxle P610 for compact vehicles which is installed in the new Prius.

3. Development Objectives
The development goal for P610 is (1) reducing the overall length of the transaxle to fit in the new platform, (2) reducing the weight and low mechanical loss to contribute to fuel economy and (3) improving the NV (Noise and Vibration) performance to keep the vehicle quiet.

4. Basic Specifications and Structure
Figure 1 and 2 show the main cross section and schematic diagram of P610. Table 1 details its major specifications.

P610 consists of a 4 axle structure of torsional damper with a torque limiter, input shaft, planetary gear for torque split, generator, motor, reduction device, differential device. The planetary gear functions as a power split device that divides the engine power into the driving power for the vehicle and the generator. The motor is positioned on a separate axle from the engine, as the motor reduction device, the parallel shaft gear, is adopted. The counter driven gear receives power from both the engine and motor, and transmits their powers to the differential gear.

Table 1. Specifications of new hybrid transaxle

<table>
<thead>
<tr>
<th>Transaxle</th>
<th>P610</th>
<th>P410</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Class</td>
<td>Compact</td>
<td></td>
</tr>
<tr>
<td>Displacement</td>
<td>1.8 L</td>
<td></td>
</tr>
<tr>
<td>Max. Power</td>
<td>72 kW</td>
<td>73 kW</td>
</tr>
<tr>
<td>Max. Torque</td>
<td>142 Nm</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Synchronous AC motor</td>
<td></td>
</tr>
<tr>
<td>Max. Power</td>
<td>53 kW</td>
<td>60 kW</td>
</tr>
<tr>
<td>Max. Torque</td>
<td>163 Nm</td>
<td>207 Nm</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>17000rpm</td>
<td>13500rpm</td>
</tr>
<tr>
<td>Motor Reduction Gear Ratio</td>
<td>3.117</td>
<td>2.636</td>
</tr>
<tr>
<td>Differential Gear Ratio</td>
<td>3.476</td>
<td>3.267</td>
</tr>
<tr>
<td>Weight Including ATF</td>
<td>-5.6 kg</td>
<td>-</td>
</tr>
<tr>
<td>Overall Length</td>
<td>-47 mm</td>
<td>-</td>
</tr>
</tbody>
</table>
5. Compactness and Weight Reduction

Based on the adoption of the new gear train, new motor and a dual-axle motor structure, P610 accomplished the compactness and weight reduction although P610 has similar torque capacity from the former P410. The overall length of P610 is much shorter than the former P410 by 47mm and the number of component parts and weight are also reduced by 20% and 6.3 % respectively. Details of reduction size and weight technology are introduced below.

5-1. PCU Installation

As shown in Figure 4, the PCU is installed on top of the transaxle in order to keep the powertrain compact. This allowed the auxiliary battery, which was in the luggage area for the former Prius, to fit in the engine compartment. Also, it contributes to shorten the power cable and expand the trunk room. Furthermore, placing the power train low led to achieving a low center of gravity of the vehicle and helps dynamic performance.

5-2. Dual-Axle Motor Structure and Motor Reduction Device

In the former P410 the generator and the motor are installed in the same axle and adopts a planetary gear as the motor reduction device. The dual-axle motor structure of P610, the generator and motor are positioned on a separate axle and the parallel gear shaft is used as the motor reduction device, which reduces the overall length drastically. As shown in Figure 5, decreasing the motor max torque makes it possible to reduce the motor size. Furthermore, the new structure that the counter driven gear meshes both the engine counter drive gear and the motor counter drive gear also helps to shorten the overall length. Thus, revising the structure as described above enables the P610 to be installed in the new TNGA platform.
5-3. New Motor

A new motor has been developed for the fourth-generation Prius, with the goal of reducing mechanical loss, weight. For the drive motor, a segment coil type stator with distributed winding and a high-speed rotor has been developed. As a result, mechanical loss reduction of at least 20% compared to the P410 has been achieved. Furthermore, motor size reduction also helped reducing weight by at least 21% compared with the P410.

A segment coil stator with distributed winding has been developed for the drive motor shown in Figure 6. The main features of this stator are as follows: (1) Newly developed distributed winding aimed at increasing the high space factor and reducing mechanical loss. Switching from round wires to rectangular wires improved the space factor by at least 15%. Additionally, reducing coil wire usage through segment winding helped reduce weight and copper loss. (2) Newly developed coil wire suitable to segment winding. To improve the winding space factor, a new coating material was developed that can handle high voltage in thin film and offers improved weldability and processability. (3) Use of segment coil distributed winding. This type of winding has a structure in which many segments of coil are connected through welding. Here, mass producibility was achieved using innovative production technologies (such as narrow-gap multi-point welding and high-speed coil formation technologies).

A new high-speed, low-loss rotor was developed. To support the high-speed rotor shown in Figure 7, a locknut method was adopted for tightening the core. Furthermore, a magnetic circuit design was developed that improved the reluctance torque of the rotor core. This improvement was made possible by motor size reduction achieved through measures such as an increase in rotation speed. As a result, the volume of magnet used was reduced by at least 15% compared to the P410.

As for reducing loss, the harmonic component of the magnetic flux was substantially reduced by optimizing magnet position, thereby reducing iron loss. Furthermore, a thin electromagnetic steel plate and a new magnet material were developed, reducing motor loss.

5-4. Motor Cooling Structure

P610 adopts the fluid circulation structure by the pump driven by the engine as the cooling system for the generator and the motor. Compared to the former P410, it has the cooling structure pumped up by the gear, the cooling efficiency is improved and it makes the motor compact. Furthermore, the simple cooling structure contributes to the compactness and light weight of transaxle.

Figure 9 shows the cooling structure. The fluid pumped out is cooled by the fluid cooler installed on the outside of transaxle, and supplied to stator of the generator and the motor through the inner pipe. Additionally, the rotor core cooling structure led to significantly reduce the temperature of the magnet, and contents of the rare earth element in the magnet was reduced by at least 85% compared to the former P410.
5-5. New Differential Structure
The press-fitting and caulking method is adopted to secure the differential case and the ring gear. Figure 10 shows the differential structure. Compared to the former method of using bolts, the number of component parts and size is reduced and it results in the reduction of weight.

![Conventional Bolt vs Development Press-fitting and caulking](image)

Figure 10. New structure of differential

6. Mechanical Loss Reduction
P610 reduced the mechanical loss by 22% in Comb mode and by 21% in the NEDC (New European Driving Cycle) mode compared to the former P410. Figure 11 shows the mechanical loss of the transaxle.

Mechanical loss reduction is achieved by the newly developed motor reduction device shown in Figure 12 and by minimizing the size of bearings with the engine counter drive gear shown in Figure 13.

Figure 14 shows the flow of the fluid pumped up by the gear and stopped by the fluid dam in the transaxle. The fluid level and lubrication for the gear and bearing is optimized by the fluid catch tank which stores and distributes the fluid. As a result, the agitational loss by gear and bearing is minimized.

![Mechanical Loss](image)

Figure 11. Mechanical loss

![Motor reduction device](image)

Figure 12. Motor reduction device

![Downsized bearing](image)

Figure 13. Downsized bearing

![Conceptual diagram of fluid flow](image)

Figure 14. Conceptual diagram of fluid flow

7. Quietness
P610 is designed by dispersing the resonance frequency of the component parts, optimizing the stiffness of casing, adding the grinding process to the reduction gear to reduce the NVH (NV and Harshness). As mentioned, P610 adopts the structure that the counter
driven gear engaged with two gears, the engine counter drive gear and the motor counter drive gear, simultaneously for the compactness of transaxle. This results in settling the development target to prevent an increase of the engaging force. And, as shown in Figure 15, it is realized by optimizing the engaging point of two gears and rigidity of the counter driven gear.

8. Conclusion
The newly developed P610 has significant advantages in various performances such as overall length, weight, vehicle installation, mechanical loss etc, compared to the former P410. It's certain that TOYOTA makes various customers satisfied with the vehicles equipped with this new hybrid transaxle all over the world.

References