

Development of Multi Stage Hybrid Transmission

Koichi Okuda, Yuji Yasuda, Masatoshi Adachi, Atsushi Tabata, Haruhisa Suzuki,
and Kiyonori Takagi
Toyota Motor Corporation

Tomoo Atarashi and Ryuta Horie
AISIN AW Co.,LTD.

ABSTRACT

Toyota Motor Corporation developed the Multi Stage Hybrid System for the Lexus flagship LC500h coupe with the aim of achieving an excellent balance between fuel economy and acceleration performance. The Multi Stage Hybrid Transmission used in this new hybrid system includes a shift device located immediately after the power split device and motor.

Compared with previous hybrid systems, acceleration performance is improved by increasing the driving force at low and medium vehicle speeds in lower gears, fuel economy and heat management performance are improved by reducing electrical loss by selecting the optimal gear depending on the driving state. The Multi Stage Hybrid Transmission uses a shift device with a wide gear ratio range to maximize both fuel economy and acceleration performance.

The transmission was designed to achieve the appropriate size to be mounted in a new platform, as well as class-leading low noise levels for adoption in luxury vehicles. It also includes a quickly responsive and accurate hydraulic control system that achieves excellent shift performance.

This paper describes the hardware of the Multi Stage Hybrid Transmission.

CITATION: Okuda, K., Yasuda, Y., Adachi, M., Tabata, A. et al., "Development of Multi Stage Hybrid Transmission," *SAE Int. J. Alt. Power*. 6(1):2017, doi:10.4271/2017-01-1156.

1. INTRODUCTION

In 2006, Lexus introduced the GS450h, equipped with the Lexus Hybrid Drive (LHD) system developed for rear-wheel drive (RWD) passenger vehicles. This system was later adopted for the all-wheel drive LS600h in 2007 as well. At the core of system was the hybrid transmission with a two-stage motor speed reduction device [2]. While providing superior fuel economy, the acceleration performance of this hybrid system is also highly regarded by drivers of competing vehicles. Since the introduction of these vehicles, various refinements have been applied to the hybrid transmission, adding to the already major contributions made towards reducing CO₂ emissions.

However, in recent years, increasing awareness of environmental pollutions have created growing demand for various types of low-emission vehicles, as even more stringent emissions regulations are being announced across the globe. In an effort to develop and popularize vehicles with even higher environmental performance, automakers around the world have been actively developing eco-friendly vehicles, and a wide range of systems have been launched. Competition in the market is has never been higher. Even in the luxury coupe market, dominated by vehicles with excellent dynamic performance, hybridization has become a trend, as still higher levels of fuel economy and acceleration performance are in demand.

To achieve supreme balance between fuel economy and acceleration performance in the RWD coupe market, Toyota has developed the Multi Stage Hybrid System. By combining this system with a V6 engine, the all new LC500h achieves a 0-to-60 mph time of 4.7 seconds and 30.0 mpg of combined fuel economy, all the while meeting SULEV requirements for exhaust emissions. At the core of this system is the newly developed Multi Stage Hybrid Transmission, including a shift device located immediately after the power split device and motor.

2. DEVELOPMENT OBJECTIVES

The development objectives of the Multi Stage Hybrid Transmission (L310) are as follows.

1. The adoption of a shift device with a wide gear ratio range to maximize the potential fuel economy and acceleration performance of the transmission, and a step ratio that ensures high quality shifts.(Section 4)
2. The adoption of a quickly responsive and accurate hydraulic control system to achieve high quality shifts. (Section 5)

3. A design that achieves the appropriate size for mounting in a new platform. (Section 6)
4. Gear noise characteristics that achieve class-leading levels of noise and vibration performance (Section 7).

3. STRUCTURE AND BASIC SPECIFICATIONS

Figure 1 shows the main cross-section and figure 2 shows a schematic diagram of the L310. Table 1 lists the Clutch Applications and Shift Assignments and table 2 lists the main specifications. The L310 consists of a power split device, motor, generator and, the shift device that changes the output rotation of the power split device and the motor rotation, a hydraulic control system that controls the shift device, as well as mechanical and electrical oil pumps to generate the required oil pressure. The power split device, the motor, the generator and the shift device are mounted on the same axis as the engine crankshaft.

The L310 transmission shifts gears via coordinated control of the generator and the shift device, and acts as an electrically-controlled continuously variable transmission.

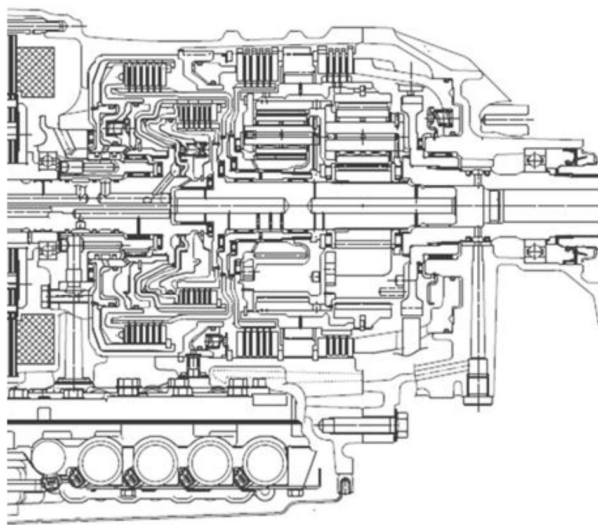
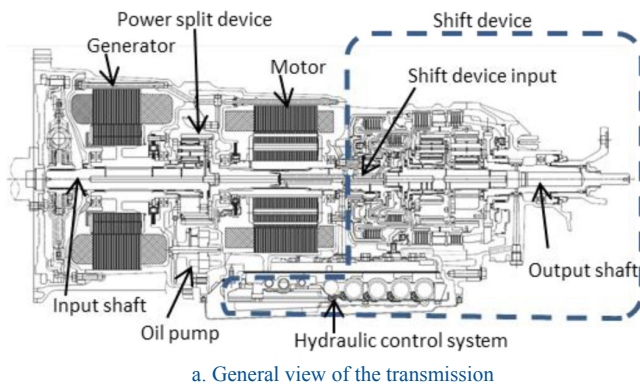


Figure 1. Cross-section (L310).

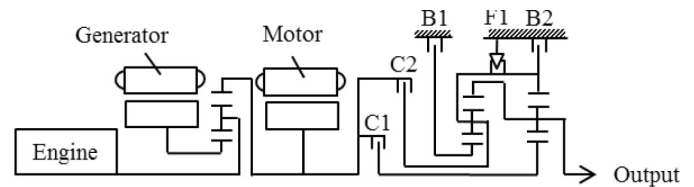


Figure 2. Schematic diagram of L310.

Table 1. Clutch Applications and Shift Assignments.

		Clutch application				
		C1	C2	B1	B2	(F1)
R		○				
	1st	○			○	○
	2nd	○		○		
	3rd	○	○			
	4th		○	○		

Table 2. Main specifications.

Transmission		L310 (New)	L110 (Previous)
Engine	Displacement	3.5 L V6	
	Max. power	220 kW	213 kW
	Max. torque	350 Nm	348 Nm
Motor	Type	Permanent magnet motor	
	Max. power	132 kW	165 kW
	Max. torque	300 Nm	300 Nm
	Max. speed	9,300 rpm	14,400 rpm
Power split device gear ratio		0.436	0.436
Two-stage motor speed reduction device gear ratio		-	1.9 3.9
Shift device gear ratio		3.538 1.888 1.000 0.650	1.87 1.88 1.53 -
Differential gear ratio		3.357	-

Figure 3 and 4 show the main difference between the L110 (previous transmission) and the L310 (new transmission).

The L110 can carry out two-stage shifting of the motor rotation speed. In comparison, the L310 includes the shift device located on the output shaft of the power split device. This configuration enables multi-stage shifting of the output rotation speed of the power split device and motor rotation.

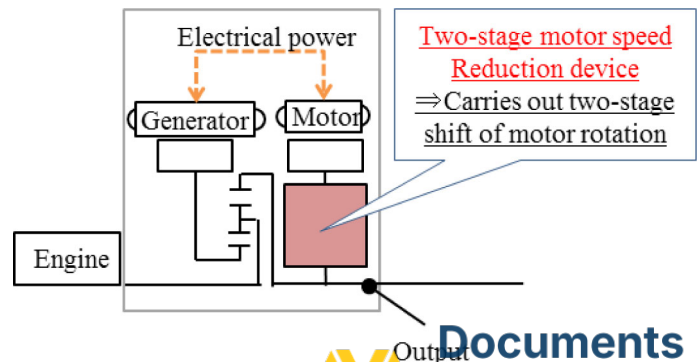


Figure 3. L110 (Previous transmission).

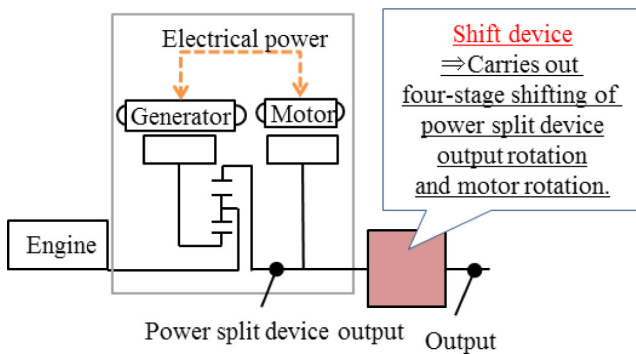


Figure 4. L310 (New transmission).

Figure 5 shows the relationship between theoretical efficiency and gear ratio. Theoretical efficiency here is efficiency of the transmission calculated with a certain power conversion loss between mechanical and electrical power in motor/generators.

While the L110 has a single efficiency curve, the L310 has multiple efficiency curves. This has the effect of improving the overall transmission efficiency and enhancing fuel economy.

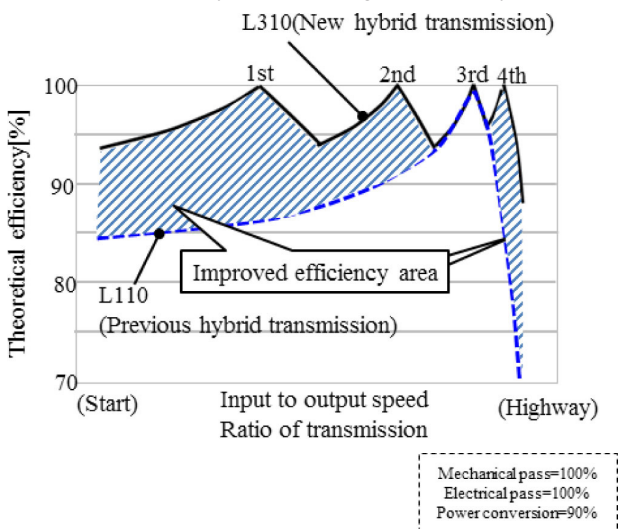


Figure 5. Improvement of theoretical efficiency of transmission.

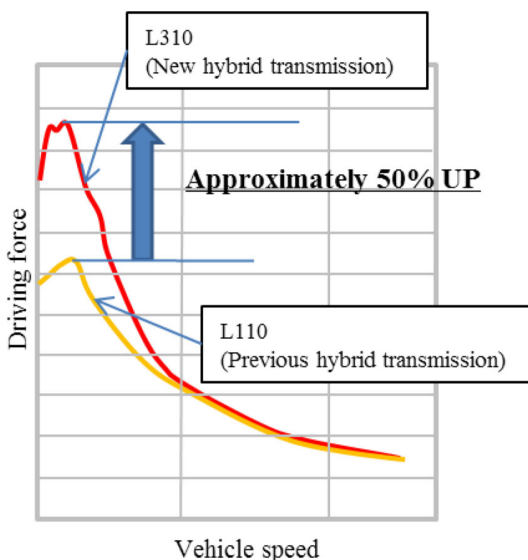


Figure 6. Driving Force Comparison of Hybrid transmission.

In addition, by reducing the rotation speed of the power split device and motor rotation, the L310 increases the driving force at low and medium vehicle speeds by enabling a lower gear ratio than the L110 (Fig. 6). This has the effect of improving acceleration performance.

4. SELECTION OF SHIFT DEVICE GEAR TRAIN

The shift device combines a gear ratio range that maximizes the potential fuel economy and acceleration performance of the Multi Stage Hybrid Transmission with a step ratio that ensures a smooth shift feeling. This section describes the design method of the gear train.

4.1 Gear Ratio Requirements of Highest Gear

During highway driving, theoretical efficiency at 3rd gear decreases, as shown in figure 5. The state in which the power split device operates during highway driving is shown in figure 7. Because the generator rotation speed becomes negative, large amounts of power is transmitted through the electrical path, which leads to reduced theoretical efficiency. Hence, theoretical efficiency can be improved by operating the generator at 0rpm, reducing electrical path transmitted power to 0. This can be achieved by operating the shifting device in overdrive.

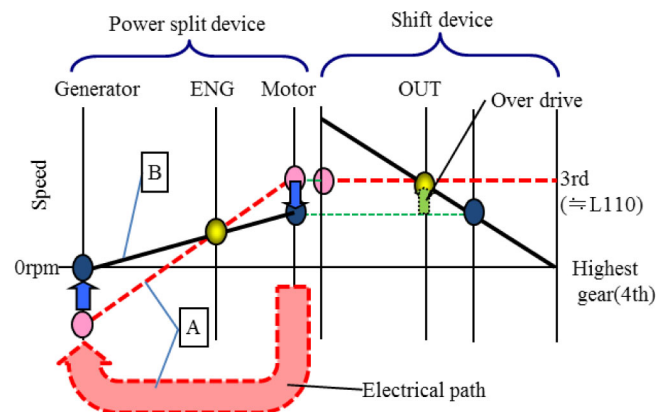


Figure 7. Power interaction diagram at highway driving.

The theoretical efficiency of the L110, as well as the usage frequency distribution of total gear ratio (=engine rotation speed/driveshaft rotation speed) was calculated for highway driving, assuming combination with an engine with large displacement. The results are shown in figure 8. It was determined that the optimal total gear ratio for the highest gear would lie between 1.0 and 2.0, which corresponds to shifting device gear ratio of 0.42 and 0.82, respectively. This gear ratio range covers approximately 70% of usage during highway driving.

By setting the high efficiency point (operation where generator rotation speed is 0rpm) in this gear ratio range, transmission efficiency will be improved over the majority of highway driving, leading to substantial fuel economy improvement.