

Development of Innovative Toyota 10-Speed Longitudinal Automatic Transmission

Seiji Masunaga, Terufumi Miyazaki, Yohei Habata, Kazuhiko Yamada, Yoshio Hasegawa,
 Takahiro Kondo, Ichiro Kitaori, and Akira Takeichi
 Toyota Motor Corporation

ABSTRACT

Toyota Motor Corporation has developed an innovative 10-speed longitudinal automatic transmission called the Direct Shift-10AT. The Direct Shift-10AT is a significant contributor to the excellent dynamic performance of the Lexus LC500. A wide gear spread with close gear ratios allows for rhythmical shifting, smooth and powerful acceleration from a standing start, along with quiet and relaxed high-speed driving due to low engine speeds. The lock-up area is expanded to a wider range of vehicle speeds (excluding low-speed regions such as when starting off), by the adoption of a multi-plate lock-up clutch, a newly developed torque converter, and a high-precision controller. As a result, the shift control can match the driver's intended operation more directly because the main cause of the response delay (transient changes in engine speed (flare)) is eliminated. Furthermore, fuel economy is improved due to the adoption of low friction clutches. Emotional driving performance is achieved using a support control that responds to the driver's intention and the driving situation, cooperative control with the powertrain, and one of the world's quickest shifting automatic transmissions. This support control adopts an individual driving force control for each driver by estimating the driver's intention based on the accelerator operation and vehicle state to seamlessly select a shift pattern. This paper describes the gear ratio design method, new control technology, and vehicle performance of the Direct Shift-10AT.

CITATION: Masunaga, S., Miyazaki, T., Habata, Y., Yamada, K. et al., "Development of Innovative Toyota 10-Speed Longitudinal Automatic Transmission," *SAE Int. J. Engines* 10(2):2017, doi:10.4271/2017-01-1099.

1. INTRODUCTION

The new 10-speed automatic transmission (AT) for rear-wheel drive (RWD) vehicles called the Direct Shift-10AT (model code: AGA0) was developed as a core unit to support performance enhancements of next-generation Lexus. The AGA0 will be used in the new Lexus LC500. The Lexus LC500 is a flagship luxury coupe which was developed as a grand tourer with excellent dynamic performance. AGA0 greatly contributed to "sharper and more refined driving" of Lexus LC500.

Automatic transmissions can make a major contribution in creating appealing vehicle performance and driving pleasure. In particular, each gear ratio and shift control are important factors for achieving rhythmical shifting with a good tempo, as well as for ensuring a direct response to accelerator inputs from the driver.

This paper describes the development concept of the AGA0 transmission, the gear ratio design method that was adopted to help achieve appealing dynamic performance, and the new shift control technology.

2. DEVELOPMENT CONCEPT

The AGA0 transmission was developed to achieve the following five objectives.

1. Rhythmical shifting with a good tempo: each gear ratio was optimized to achieve rhythmical shifting with a good cadence within the same engine speed range during acceleration. In particular, the shifting time (i.e., the time required for the rotation speed of the AT input shaft to synchronize before and after a shift) when an upshift is performed with the power on (i.e., a power-on upshift) was shortened to achieve rhythmical and incisive shifting.
2. Smooth and powerful acceleration from a standing start and low noise when cruising at highway speeds: a wide gear spread was achieved by enlarging the low-speed side and high-speed side gear ratios.
3. Dynamic performance that matches the driver's intention: the optimum gear is selected to match the intention of the driver by estimating the acceleration based on the operation of the accelerator and brake pedals, as well as the current speed and acceleration of the vehicle.
4. Direct response to accelerator operation: the AGA0 transmission features a multi-plate lock-up clutch and a newly developed torque converter with a new dynamic lock-up damper, which substantially expands the lock-up area compared to the previous 8-speed AT (model code: AA80). In addition, a greatly refined shift control logic was adopted to achieve a direct response to accelerator operation during multiple shifts when a power-on downshift is carried out.

- Excellent fuel economy: in addition to a lightweight and compact gear train, the AGA0 transmission helps to greatly improve the fuel economy of the vehicle by adopting technologies such as the new torque converter that expands the lock-up area and low-friction clutches.

3. GEAR RATIO DESIGN

Each gear ratio was designed to help achieve the first two objectives of the AGA0 transmission development concept: rhythmical shifting with a good tempo, as well as smooth and powerful acceleration from a standing start and low noise when cruising at highway speeds. This section focuses on the gear step and gear spread design methods within the gear ratio design process for the AGA0 transmission.

3.1 Gear Step Design Method

The gear steps were designed to achieve rhythmical shifting with a good tempo within the same engine speed range during acceleration.

First, the target vehicle acceleration was designed. This was accomplished by defining a target acceleration that creates a feeling of continuous acceleration when the driver accelerates with a constant accelerator pedal angle. As a method of expressing subjective characteristics, the Weber-Fechner law is well known way of empirically deriving the relationship between an actual stimulus and the perception of that stimulus. This law is expressed as shown in Equation (1), in which the change in perception ΔE is proportional to Weber's ratio for the degree of the stimulus R ($\Delta R/R$).

$$\Delta E = k' \frac{\Delta R}{R} \quad (1)$$

where, k' is a proportionality constant. In this research, the change in perception is the acceleration perceived by the driver ΔV and the stimulus is the vehicle acceleration G . If k is adopted as the proportionality constant, the following equation is obtained.

$$\Delta V = k \frac{\Delta G}{G} \quad (2)$$

Therefore, the target acceleration was designed by empirically calculating the proportionality constant k to create a constant acceleration perceived by the driver ΔV . Figure 1 shows the designed target vehicle acceleration. The figure indicates that the rate of change in vehicle acceleration required to achieve a continuous acceleration feeling increases when the vehicle acceleration is high.

Next, the target time for the upshift start interval during acceleration was designed. With the previous AT, the upshift start interval during acceleration was lengthened in accordance with the vehicle speed to generate larger driving force using the low-speed side gear.

In contrast, the AGA0 transmission was designed to achieve rhythmical shifting with a good cadence. Therefore, a constant target time for the upshift start interval during acceleration was empirically

derived. Figure 2 compares the changes in rotation speed of the AT input shaft when accelerating from a standing start for the AGA0 (solid line) and AA80 (dotted line) transmissions.

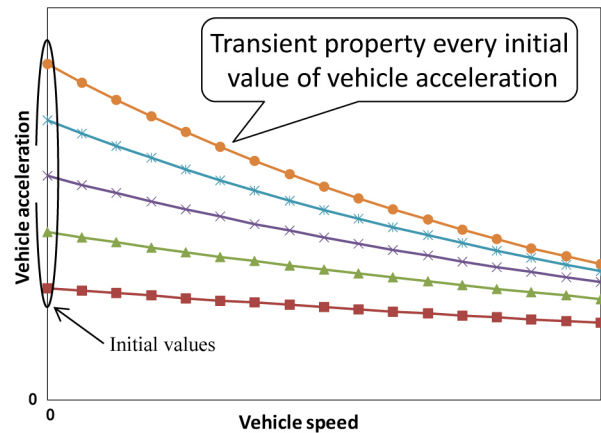


Figure 1. Target acceleration to achieve continuous acceleration feeling.

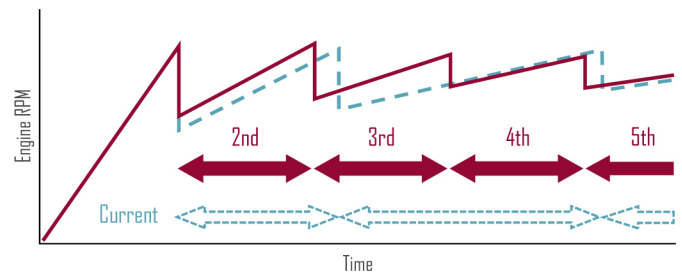


Figure 2. Comparison of AT input shaft rotation speed when accelerating from standing start.

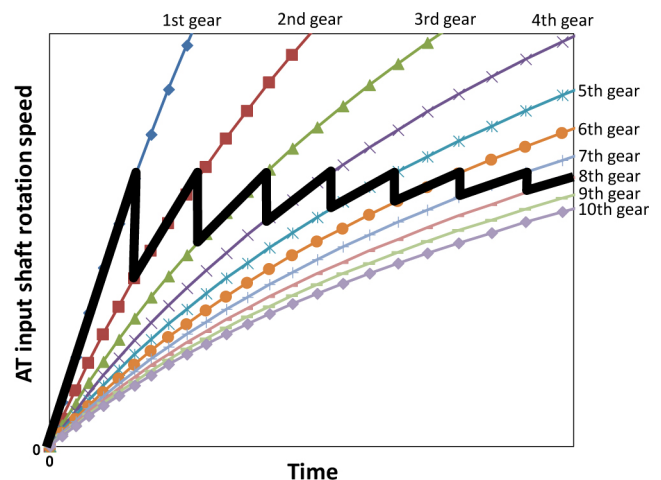


Figure 3. AT input shaft rotation speed when accelerating from standing start.

The gear step design achieves both the designed target acceleration and target upshift start interval time, while ensuring that changes in engine speed occur within the same range. Rhythmical shifting with a good tempo was achieved by setting a cross gear ratio that brings each gear ratio closer together. Figure 3 shows the changes in rotation speed of the AT input shaft when accelerating from a standing start with the designed gear ratios and upshift timings. This figure indicates that the upshifts are carried out within a certain AT input shaft rotation speed range.

3.2 Gear Spread Design Method

This section describes the gear ratio design method applied to the lowest and highest gears.

In the AGA0 transmission, the 1st gear is used exclusively for standing starts, while 2nd gear to the highest gear is designed primarily for regular driving situations. Since the AGA0 transmission features a lock-up area that is much larger compared to the AA80 transmission, the 2nd gear ratio was designed to achieve the necessary driving force requested when accelerating, without having to use torque amplification from the torque converter. The other gear ratios were designed by using the gear step design method, described in the previous section, relative to the 2nd gear ratio.

Subsequently, the gear ratio of the highest gear was designed as follows. The objective of the highest gear ratio was to ensure both low noise and good fuel economy when cruising at high speeds. In addition, the gear ratios were also designed so that the available driving force capable of efficiently accelerating the vehicle at high speeds can be obtained. The most suitable gear ratio was designed by identifying the optimum target engine speed for high-speed cruising based on noise and vibration (NV), performance, and engine efficiency.

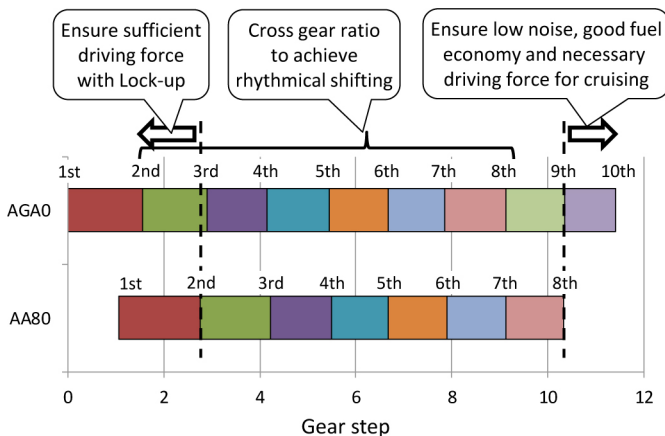


Figure 4. Gear ratio design method.

Here, Figure 4 summarizes the gear ratio design method for each gear. This figure demonstrates that the low-speed side and high-speed side gear ratios of the AGA0 transmission have been enlarged compared to the AA80 transmission.

4. TRANSMISSION SYSTEM

The AGA0 transmission was designed to achieve both the gear steps and gear spread described in the previous section. Compared to the AA80 transmission, an additional gear was required to help shorten the upshift start interval during acceleration. Another additional gear was also required on the high-speed side to reduce noise and improve fuel economy when cruising at highway speeds. For this reason, the AGA0 transmission was constructed as a 10-speed AT. This section describes the configuration of the AGA0 transmission system. Figure 5 shows a cutaway view of the transmission.

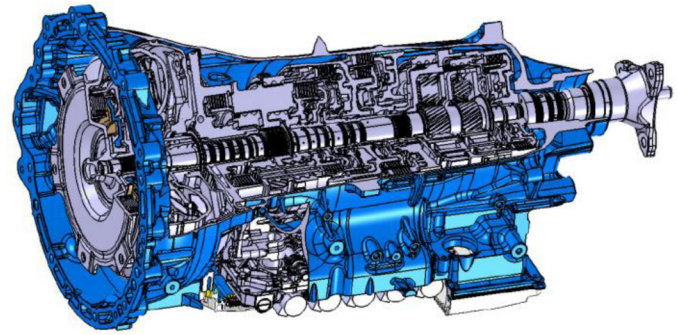


Figure 5. Cutaway view of the AGA0 transmission.

4.1 Configuration of the 10-Speed Automatic Transmission

The AGA0 transmission consists of four newly designed planetary gears and the same number of friction elements as the AA80 transmission to achieve the targeted gears for an AT with 10 forward speeds. The developed transmission is also among the lightest in its class due to a structure in which the sun gear of the rear planetary gear is capable of engaging the same element from the inner and outer sides using the C1 and C2 clutches, and the adoption of aluminum members. The axial length and middle diameter of the AGA0 transmission are the same as the AA80 transmission, which helps to facilitate easier mounting. Table 1 lists the technical data of the AGA0 transmission, Table 2 shows the engagement of the friction elements and the gear ratio of each gear, and Figure 6 shows a schematic of the gear train.

Table 1. Technical data of the AGA0 transmission.

Item	Value
Engine	2UR-FSE
Transmission model code	AGA0
Drivetrain layout	RWD
Torque converter layout	3-element, 1-stage, 2-phase (with lock-up mechanism)
Transmission layout	Electronically controlled planetary gears
AT fluid (ATF)	Genuine Toyota World Standard (WS)
Oil capacity [L]	8.59

Table 2. Shift pattern of the AGA0 transmission.

	C1	C2	C3	C4	B1	B2	Gear ratio	Step
Rev		○	○			○	5.169	
1st	○	○				○	4.923	
2nd	○				○	○	3.153	1.56
3rd		○			○	○	2.349	1.34
4th				○	○	○	1.879	1.25
5th		○		○	○		1.462	1.29
6th	○			○	○		1.193	1.23
7th	○		○	○			1.000	1.19
8th			○	○	○		0.792	1.26
9th	○		○		○		0.640	1.24
10th		○	○		○		0.598	1.07