

# Development of the Transfer Unit for the Toyota Land Cruiser

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## 1. Introduction

As the world's third biggest carmaker, Toyota Motor Corporation is offering a broad range of 4WD vehicles worldwide.

Our lineup currently consists of more than 35 different models using various types of 4WD technology.

Fig. 1 shows a selection of some popular models.

Full-time	Stand-by	Rear Motor
Land Cruiser	Vitz	Estima Hybrid
RAV4	Platz	Alphard Hybrid
RX300	Wish	
4Runner	Corolla	
Crown	Ipsun	
Caldina	Raum	
Alphard	Gaia	
Verossa	Noah	
Brevis	Avenis	
Altezza	Allion	
	Camry	
...	...	

Fig 1. Toyota worldwide 4WD lineup

Especially in recent years, the so-called SUV segments have shown considerable growth. Along with this popularity, customer requirements in terms of driving stability, ride comfort, and quietness have become stronger than ever before. Against this background, many carmakers have developed SUV models derived from passenger cars, and new SUVs from various companies continue to enter the marketplace almost every month.

Toyota has therefore developed the latest Land Cruiser with the aim of maintaining its leading position as full-fledged offroad vehicle, while at the same time competing with passenger-car-derived SUVs in terms of driving stability and ride comfort. In addition to the rugged characteristics and off-road reliability that have made the Land Cruiser range famous over the last 53 years, a drastic improvement has been achieved in terms of driving stability and Noise and Vibration (NV) against the previous model. This article introduces the newly developed Transfer Unit, named VF4, which has greatly contributed to the achievement of these targets.

## 2. Outline

### 2.1. Development targets

The following targets were set at the start of development of the VF4 Transfer Unit Series:

1. Improved driving stability and traction performance.
2. Downsizing & mass reduction.
3. Maintain good NV performance.
4. Improved shift operation and shifting performance.

### 2.2. Outline of VF4 Series

Table 1 shows the outline of the VF4 Series.

- The part-time version VF4AM is currently only used in vehicles sold in Japan and USA. The switchover between 2WD mode and 4WD mode is by means of an electric actuator. Additionally, the same actuator is operating the High-Low reduction gear, as well as the center differential Lock.
- The full-time version VF4B is standard on the Land Cruiser sold in Europe. The High-Low reduction gear and the center differential Lock are operated manually by means of the shift lever. In case the customer selects the option of the Brake Control System for his vehicle, the center differential Lock operation will be electrical instead of manual.

		Part-time	Full-time		
		VF4AM	VF4B	VF4BM	
4WD	2WD	Electrical			
	High	Electrical	Manual	Manual	Electrical
	High-Lock	Electrical	Manual	Electrical	Electrical
	Low	Electrical		Manual	Electrical
	Low-Lock	Electrical	Manual	Electrical	Electrical
JPN		Surf	Prado		
USA		4Runner V6		Lexus GX470	4Runner V8
EU			Land Cruiser	Land Cruiser	

Table 1. VF4 Series applications

### 2.3. Basic structure of VF4 Series

The cut model of the VF4AM Transfer Unit is shown in Fig. 2. The improvements in the structure over the previous version are as follows:

- Adoption of Torsen-C as center differential.
- Full motor shift by 2 motor actuators.
- Integrated 2WD/4WD and center diff Lock mechanisms.
- Shortening of full length by 50mm.

By adopting these points, the torque capacity improved by 25% and the mass reduced by 2kg compared to the previous model.

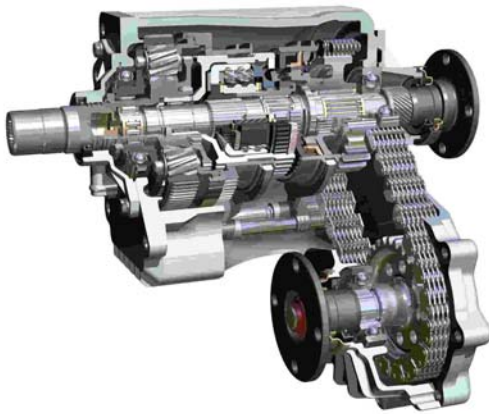


Fig 2. Cut model of VF4AM

### 3. Selection of traction distribution device

#### 3.1. Theoretical background of traction force distribution

In order to improve the vehicle's handling, a traction force distribution control depending on the driving condition and a device that highly responds to the situation are needed. The required characteristics and degrees of influence are reviewed below. The reasons for selecting Torsen-C are also described.

##### 1. Review of required distribution characteristics.

Fig. 3 shows the tire friction circles (Kamm'scher Kreis) and the two-wheel dynamic cornering model that are both well known from literature. When the traction force  $F$  of the front and rear wheels is set as  $(F_f, F_r)$ , the cornering force  $C$  as  $(C_f, C_r)$ , the distance  $L$  from the center of gravity as  $(L_f, L_r)$ , the load  $W$  as  $(W_f, W_r)$ , the road

surface friction coefficient  $\mu$  as  $(\mu_f, \mu_r)$ , and the centrifugal force acting on the vehicle as  $(F_m)$ , the yaw moment of the cornering vehicle is expressed as  $M_c$  in the following formula.

$$M_c = C_f \times L_f - C_r \times L_r$$

$M_c = 0$  : Equilibrium state (no yaw movement)

$M_c > 0$  : Over-steering (OS) tendency

$M_c < 0$  : Under-steering (US) tendency

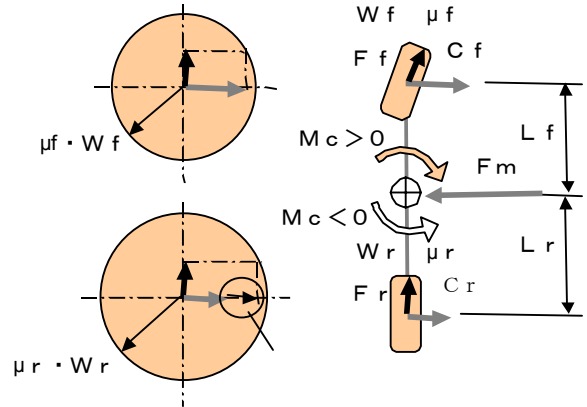


Fig 3. Tire friction circles and dynamic cornering model

Moreover, the cornering forces that can be generated on the front and rear wheels are expressed with the following formulae from the characteristic of tire friction circles.

$$\bullet \text{ Front wheel : } C_f = ((\mu_f \cdot W_f)^2 - F_f^2)^{1/2}$$

$$\bullet \text{ Rear wheel : } C_r = ((\mu_r \cdot W_r)^2 - F_r^2)^{1/2}$$

Here,  $W_f$ ,  $W_r$ , and  $\mu$  ( $\mu_f$ ,  $\mu_r$ ) are values that change with the vehicle acceleration state and with the road surface conditions. In order to utilize the tire friction circles efficiently, control of traction force distribution according to these situations is required.

The calculation results of the torque distribution ratio that is required to realize the equilibrium state ( $M_c = 0$ ) are shown in Fig. 4. The horizontal axis shows the vehicle's longitudinal acceleration. The vertical axis shows the torque distribution ratio.

For a given road friction  $\mu$ , and at maximum lateral  $G$ , the vehicle can generate more longitudinal  $G$  as the torque is shifted to the Front. This result indicates that the traction distribution device should be able to control mainly rear-biased torques.

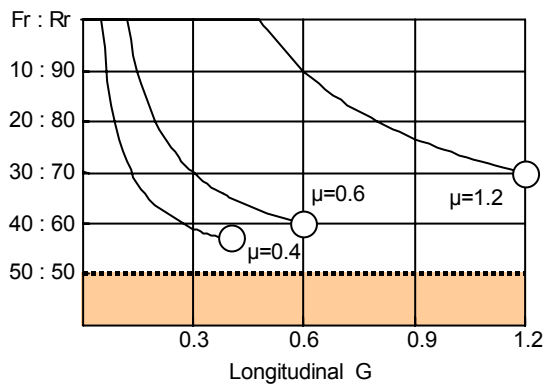


Fig 4. Achievable longitudinal G at maximum lateral G

## 2. Influence of responsiveness of torque distribution

Fig. 5 shows the results of a response analysis of the distribution control (yaw rate feedback control), based on a controlled clutch system.

The vehicle is driven on a road surface  $\mu=0.6$ , along a constant radius of 80m, at an initial speed of 30km/h. As the throttle is opened gradually, the vehicle builds up speed, resulting in an increase of yaw rate.

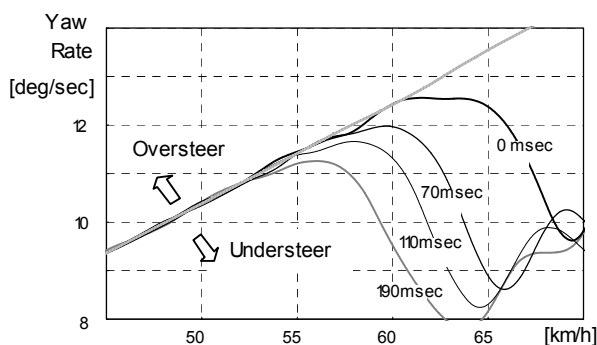


Fig. 5. Yaw rate simulations

As long as the yaw rate shows a fixed relation to the vehicle speed, the vehicle is in a stable condition. As from a certain vehicle speed, the yaw rate collapses, which means that the car can no longer keep the circular path and understeers straight ahead. Compared to a realistic response time for a controlled clutch of 70 milliseconds, a great improvement can be seen when the system response is set to 0 milliseconds. That however is just a hypothetical case, since the controlled clutch will need some response time in any case.

The results for Torsen-A, Torsen-B and Torsen-C are shown in Fig. 6.

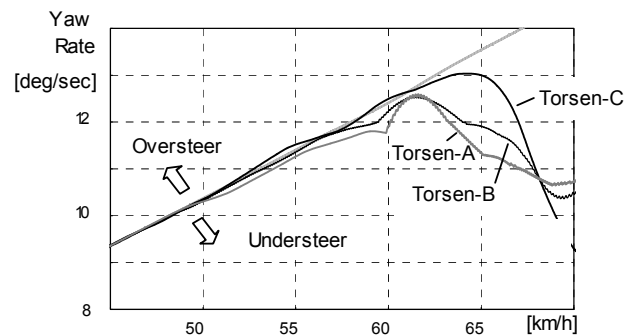


Fig. 6. Yaw rate with Torsen

As can be seen, these mechanical torque-sensing devices have a good response in general. Especially Torsen-C stands out by the fact that it can keep the vehicle in a stable yaw condition for longer than even our hypothetical (0 msec) controlled clutch could do. This means that we have found a mechanical system that can compete with sophisticated electronically controlled systems, at a much lower complexity and cost. These effects were confirmed in an actual vehicle evaluation in the initial stages of the development.

## 3.2. Drivetrain downsizing

Based on the appeal of the Torsen technology as described above, any influence on the design of the front drive system was checked. From the distribution characteristics shown in Fig. 7, Torsen-A and Torsen-B cannot avoid generating a front-biased distribution, most notably when the rear wheels start to lose traction. In comparison to the previous model (using an open 50:50 center differential), that would result in a bigger front diff in order to cope with that torque. Torsen-C however allows a design that will largely remain rear-biased, even when the rear wheels lose traction. For this reason too, Torsen-C is a good candidate to increase the system's functionality without having to add any mass elsewhere in the car.

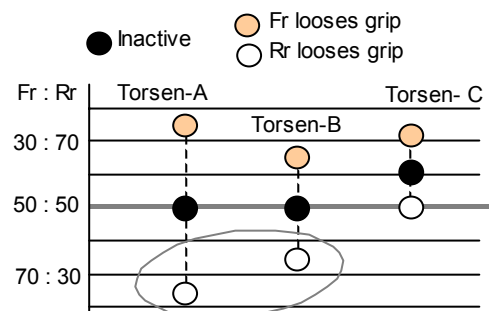


Fig 7. Distribution ratio with Torsen

### 3.3. Practical traction performance

A comparison of low- $\mu$  climbing performance is shown in Fig. 8. The open-type center differential as used in the previous model quickly reached its limits, unless the driver operated the Lock function. With the new model, adopting Torsen-C, the vehicle can cope with a much wider variety in road friction conditions without any action required from the driver. The absolute maximum climbing performance remains unchanged when operating the Lock function. In summary, the practical traction performance of the new model has become more convenient thanks to the adoption of Torsen-C.

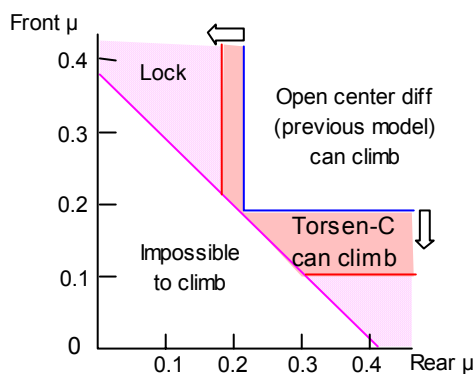


Fig. 8. Low- $\mu$  climbing (10 deg incline)

### 3.4. Reliability

The adoption of A-TRC (Active Traction Control) on a vehicle requires the drivetrain to cope with sudden changes in torque and speed induced by the brakes. This causes new challenges in terms of durability in off road use (high torque and high differential speeds) and fatigue strength.

As shown in Fig. 9 and 10, Torsen-C meets both criteria at the same time. Even though Torsen-B exceeds the fatigue strength target by a bigger margin than Torsen-C, it completely fails to meet the off road durability target. As a result, Torsen-C provides the best combination of off-road durability and fatigue strength.

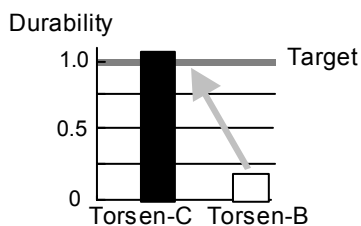


Fig. 9. Off-road durability

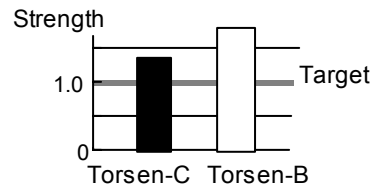


Fig. 10. Low Cycle Fatigue Strength

### 3.5. Synergy of Torsen and A-TRC

Active Traction Control (A-TRC) applies braking control independently to whichever of the four wheels might be slipping, thereby creating a limited slip differential effect. The brake torque  $T_b$  applied to the slipping wheel is transferred to a non-slipping wheel across the differential. The non-slipping wheel receives this torque as an additional traction torque  $T_t$ , as shown in Fig. 11, thereby improving the traction performance of the vehicle. In the previous Land Cruiser, with its open center differential, the brake torque induced by the A-TRC was transferred 1:1. Consequently, when one of the wheels was losing traction during off-roading, the additional torque that could be generated at the other wheel was nevertheless limited.

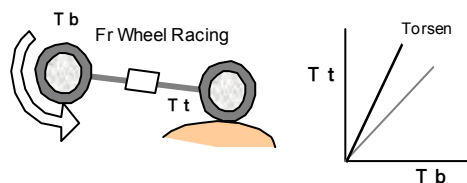


Fig. 11. Synergy of Torsen and A-TRC

Torsen-type differentials excel in this respect by the fact that the brake torque  $T_b$  is amplified by the Torque Bias Ratio (TBR) before it reaches the other wheel.

As a result, the A-TRC system gets more effective in enhancing the vehicle's traction performance when it is combined with a Torsen.

### 3.6. NV performance

Torsen-type limited slip differentials are using friction for their slip limiting function. This can cause NV concerns, especially when the vehicle is taking off with a differential speed over the center differential (e.g. during a minimal radius turn-in, up to about 10 km/h). This typically leads to a vertical vibration of the rear differential, which is then transmitted to the rear floor of the vehicle and felt there as a judder. The transmission path of such vibration is shown in Fig. 12.

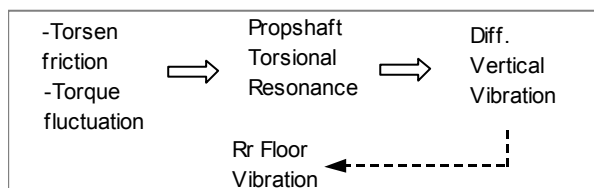


Fig. 12. NV transmission path

To find a countermeasure for this judder has been one of the most difficult engineering tasks during the development of the new transfer unit, especially because the countermeasure had to remain effective for the entire life of the vehicle.

Fig. 13. shows the results of a parameter study. Starting from a differential that had run a durability test, the components were replaced by fresh ones, one-by-one, and the vibration of the rear differential was measured with these new setups. This led to the conclusion that the Planet Gears and the Carrier were the main contributors to the vibration, while the Washers, the Sun Gear and the Internal Gear had no influence.

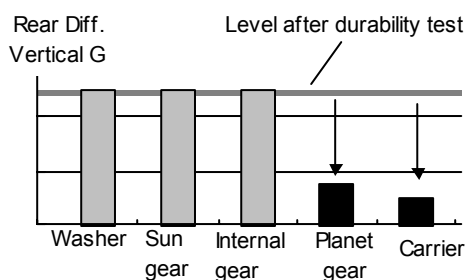


Fig. 13. Vibration reduction by fresh components

Once this was clear, the correlation between the vibration of the rear differential and the plateau ratio of the planet gears was established, as shown in Fig. 14.

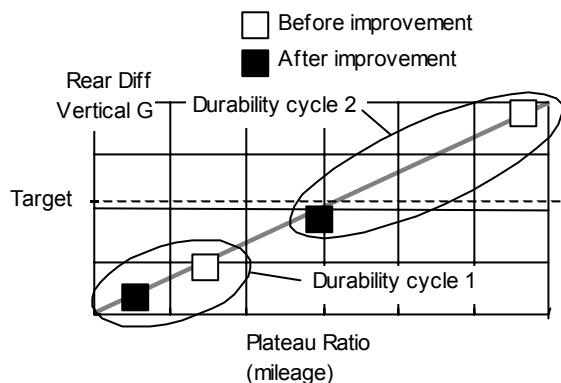
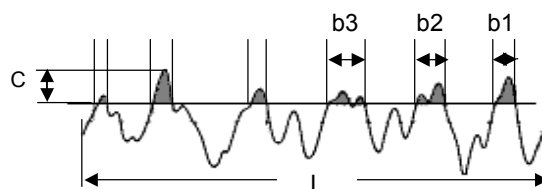


Fig. 14 Rear diff vibration against plateau ratio



Plateau ratio

$$T_p = (b_1 + b_2 + b_3 + \dots + b_n) / L \times 100$$

The targets could finally be met by means of a special processing, and by applying a coating on the outer diameters of the planet gears. This ensures that the plateau ratio, and thereby the vibration level, remains within the targets over the vehicles lifetime.

### 3.7. Selection of Torsen-C technology

In summary, our evaluations have led to the conclusion that the Torsen-C technology is the only one that meets all our targets for the Land Cruiser, as shown in Table 2.

	Control Stand-by	Control Full-time	Speed sensing LSD	Torsen-B	Torsen-C
Driving Stability	-	+	+	++	++
Light & Compact	++	-	-	-	++
Practical Traction	+	++	+	++	+
Reliability	-	-	-	-	++
A-TRC compatibility	-	+	-	++	+
NV during turning	+	+	++	-	+
VSC & ABS compatibility	+	++	-	+	+

Table 2: Criteria and judgements for Land Cruiser

The Toyota VF4 Series is the world's first application of the Torsen-C technology.

## 4. Presentation of Torsen-C

### 4.1. Outline of structure

The structure of a Torsen-C is fundamentally the same as that of a single planetary gearset, comprising an Internal Gear (IG), a planetary carrier, several Planet Gears (PG), and a Sun Gear (SG), as shown in Fig. 15.

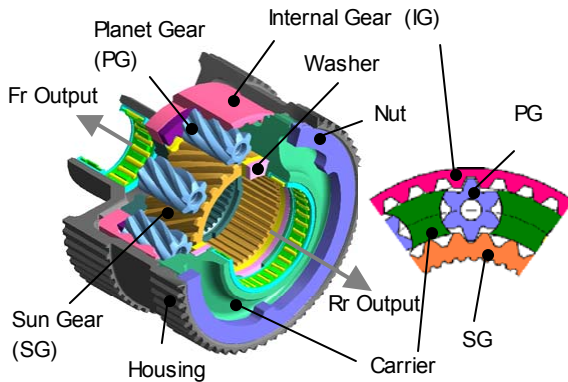


Fig.15 Basic structure of Torsen-C

The difference is that the Planet Gears can generate a friction force against the carrier on their outer diameter, because they are floating in the carrier, rather than being fixed by pins.

### 4.2. Main advantages

#### a. Lightweight and Compact

- The output components (IG, SG) overlap by their difference in diameter, making for a compact design.
- High torque distribution ratio is possible with just a single planetary gear mechanism.
- The structure combines the differential function and the limited slip function in the same hardware.

#### b. Excellent strength and durability.

- The design can be upgraded relatively easily, by increasing the number of Planet Gears.

#### c. Low cost.

- The Torsen structure is simple and easy to process. The system does not require any actuators or electronic control units.

### 4.3. Torque transmission route

A cross section of Torsen-C is shown in Fig. 16, and the principle of torque distribution is shown in Fig. 17.

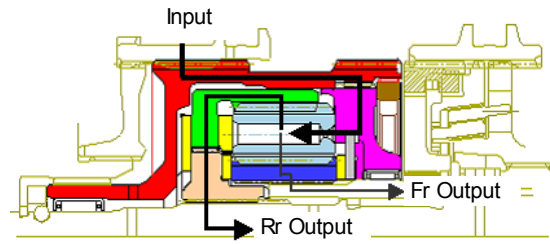


Fig.16 Torsen-C: Cross Section

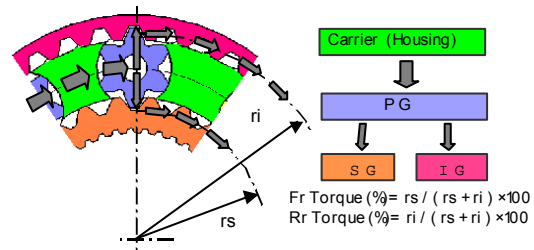


Fig.17 Principle of Torque Distribution

During straightline driving on a dry road, the force that is input by the planetary carrier is distributed 40/60 (Front/Rear), without involving any limited slip function. The distribution ratio corresponds to the ratio of the radii of Sun Gear (SG) and Internal Gear (IG). The 60% torque to the rear wheels is helpful for an appropriate turn-in steering response.

### 4.4. Limited slip mechanism

As known from Torsen-A and Torsen-B, the limited slip effect is generated by means of internal friction forces. In the case of the new Torsen-C, these friction forces are as follows:

- Tooth tip friction of Planet Gear (PG) against carrier.
- Tooth face friction of gear meshings (PG/SG & PG/IG).
- Thrust washers friction.

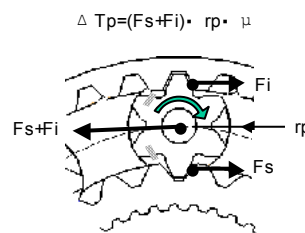


Fig.18 Effect of tooth tip friction



As can be seen from Fig 18, the tooth tip friction creates an additional torque  $\Delta T_p$  on the Planet Gear, and thereby modifies the torque distribution ratio in a direction that will limit the wheel slip.

In a similar way, the torque on the Sun Gear will be modified by the thrust washer friction by an amount  $\Delta T_s$  as exemplified in Fig 19.

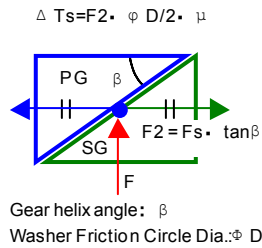


Fig.19 Effect of thrust washer friction

#### 4.5. Torque distribution ratio versus driving condition

The limited slip effects as explained above, and the changes in torque distribution that go with that, are summarized in Table 3.

Differential Condition	Drive	Coast
Front = Rear (e.g. straight line)	40 : 60	
Front > Rear (e.g. turning)	29 : 71	58 : 42
Rear < Front (e.g. Rear loses grip)	53 : 47	28 : 72

Table .3 Torque distribution in Drive and Coast

Torsen automatically adjusts the torque distribution ratio to one of these modes. When the vehicle tends to oversteer, the system will switch to the 53:47 mode, thereby preventing a spin. This allows the driver to enjoy the feeling of a RWD vehicle with enhanced safety and stability.

The nominal torque distribution ratio (40:60) can be adjusted in the design by varying the pitch diameters of Sun Gear and Internal Gear within certain limits. The distribution ratios in the other driving conditions can be tuned by means of the gear parameters and by the friction radii of the thrust washers, etc..

#### 5. Transfer Unit compact design

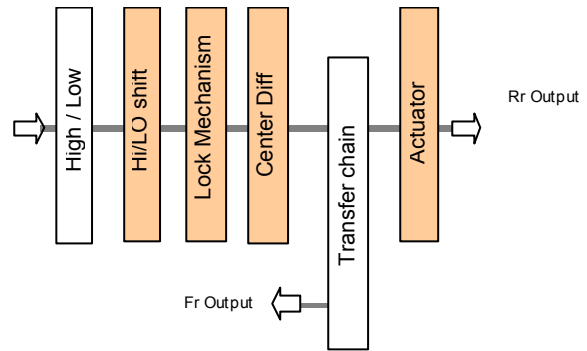
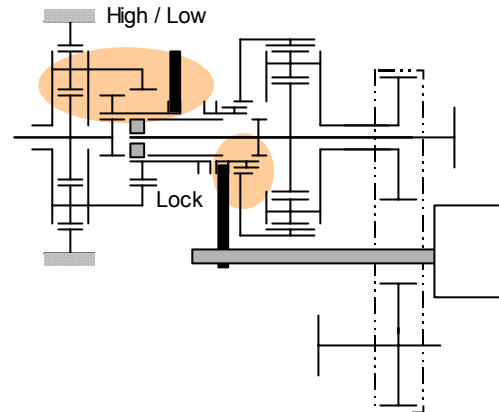


Fig.20 Previous model

Fig. 20 shows the skeleton diagram and the functional block diagram of the previous transfer unit series.

As can be seen, all functional elements are arranged in series (High/Low planetary set → High/Low shift mechanism → Center Lock shift mechanism → Center differential (open type) → Front transfer system (chain) → Motor actuator), and each shifting mechanism is independent.

The new VF4 series has a more compact design as shown in Fig 21, mainly thanks to the adoption of the Torsen-C technology.

The center differential is reduced in diameter, and the shifting mechanisms are arranged at its outside, whereby they do not take up any axial space

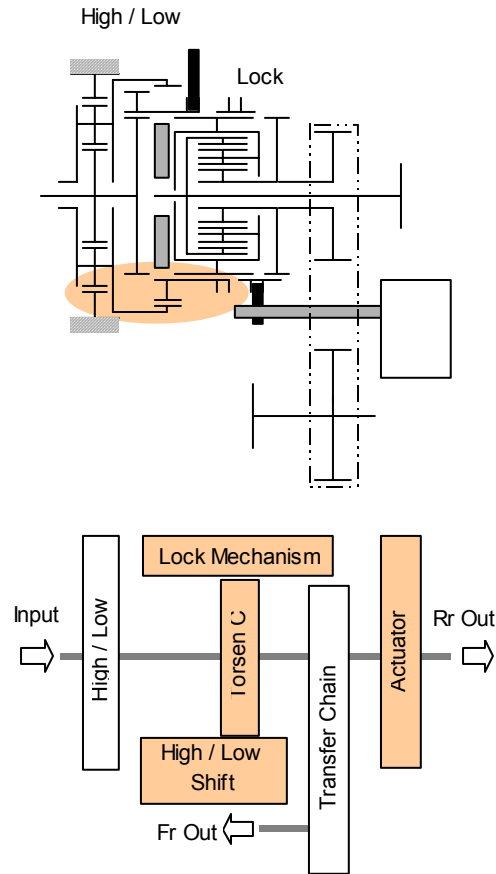
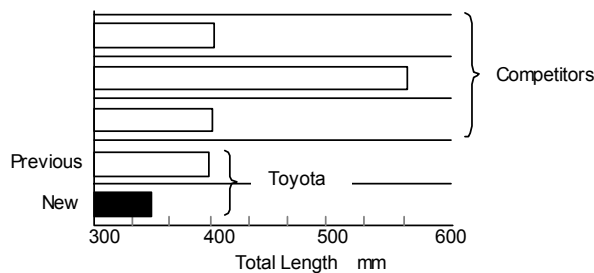
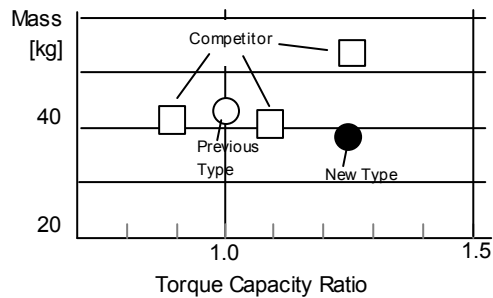


Fig.21: VF4 model

Consequently, this design is setting new benchmarks for torque capacity ratio and system mass.



## 6. Afterword

The VF4 series transfer unit used in the Toyota Land Cruiser is the world's first adoption of the Torsen-C technology. The main advantages of Torsen-C lie in its supreme reliability, compact design and system cost. Special countermeasures have been taken in order to guarantee a good NV behaviour throughout the vehicle's lifetime. Torsen-C is considered to be one of the best solutions for full-time 4WD systems at Toyota. Further vehicle applications are currently under development with the aim of offering reliable and comfortable 4WD to the customers worldwide.

The authors wish to express their gratitude to everyone in and outside the company involved in the development and production of this transfer unit.

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