

# **Developments in Full-Toroidal Traction Drive Infinitely & Continuously Variable Transmissions**

**By**

**Chris Brockbank, BSc  
Business Manager  
Torotrak (Development) Ltd  
Leyland, UK**

**Chris Greenwood, BSc  
Technology Director  
Torotrak (Development) Ltd  
Leyland, UK**

# 1 Introduction

## 1.1 Abstract

The Torotrak full-toroidal traction drive technology has been proven in a range of applications, the most familiar of which being V8 SUV's where double figure fuel economy improvements have been delivered in a durable, smooth and refined package.

Demonstrating the flexibility of the technology, Series Production has now commenced of full-toroidal Infinitely Variable Transmission (IVTs) in the Outdoor Power Equipment market.

Novel transmission architectures, new approaches to roller control and improvements in hydraulic design and operation have delivered significant parts count and cost reductions together with system efficiency, performance and package improvements.

The result is a family of new transmission design concepts in both "clutch start" Continuously Variable Transmission and "geared neutral" Infinitely Variable Transmission format.

Applications are from high torque RWD / SUV vehicles to low torque FWD vehicles.

This paper describes the new designs, transmission layouts, roller control mechanisms and quantifies the functional performance and cost benefits of the developments in the vehicle applications.

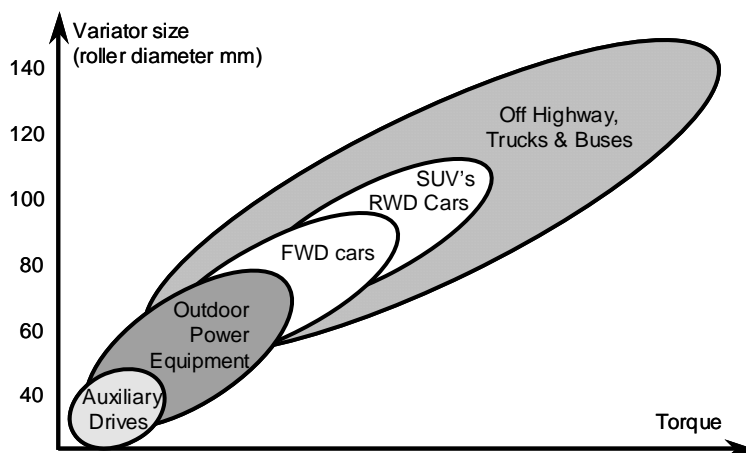
## 1.2 One Technology, Many Applications

The Torotrak full-toroidal traction drive Variator system is a simple variable drive technology with many applications ranging from low-power ancillary drive-units through to multi-regime transmissions suitable for passenger cars, SUVs, buses, trucks and off-highway vehicles.

The Variator can be applied either as a direct drive-unit (for example, as an auxiliary drive), in a single regime shunt (for a low-power off-highway vehicle application), as a twin regime shunt (for typical automotive applications) or as a variable component within a multi-regime shunt (for high torque on-road and off-highway vehicles).

A key characteristic of the Torotrak Variator is its ability to be scaled which leads to a broad range of applications irrespective of power level. The torque capacity of the Variator is determined, amongst other factors such as the shunt design and mechanical layout, by the number of 'cavities' within the Variator (single or twin cavity), the number rollers per cavity (typically two or three) and by the size of the discs and rollers; increasing the roller diameter increases the torque capacity of the unit.

Figure 1 below describes the applicability of the Torotrak full-toroidal Variator technology:



**Figure 1 - IVT Applications**

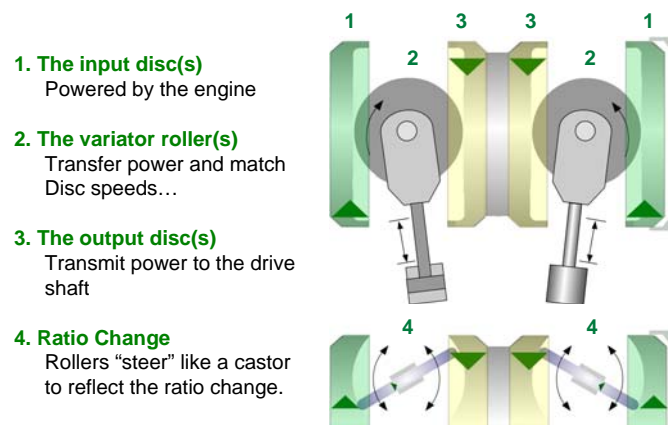
In each of the market sectors described above, Torotrak has active projects with customers who are applying the company's IPR and know-how. Two areas of particular interest are the low-power Outdoor Power Equipment (OPE) market and the mainstream automotive industry. In these two sectors, Torotrak have developed two new roller control mechanisms namely the 'two roller' design for low power and torque applications and the Epicycoidal Roller Control (ERC) system for high power and torque applications. These new roller control systems deliver cost, weight, package and efficiency improvements that make the Torotrak's Variable drive system competitive and compact – confirming the applicability of the Torotrak IVT high power & torque RWD vehicles and enabling the use of the technology in FWD vehicles in both IVT and CVT format.

### 1.3 Torotrak Infinitely Variable Transmission

Before describing the new roller control solutions, it is worth reviewing the basic functionality of Torotrak's IVT technology.

Automotive applications of the Torotrak IVT typically comprise a torque controlled full-toroidal traction drive Variator in a two-regime configuration.

The Variator itself is the core of the IVT and consists of two engine driven input discs and two output discs which are ultimately connected to the road wheels. Between the two sets of discs are six rollers – three per cavity. These two sets of three rollers transmit power between the toroidal discs. Force is applied to the rollers by hydraulic cylinders which react torque between the input and output discs. Figure 2 details the full-toroidal torque controlled Variator:



**Figure 2 - Full Toroidal Torque Controlled Variator**

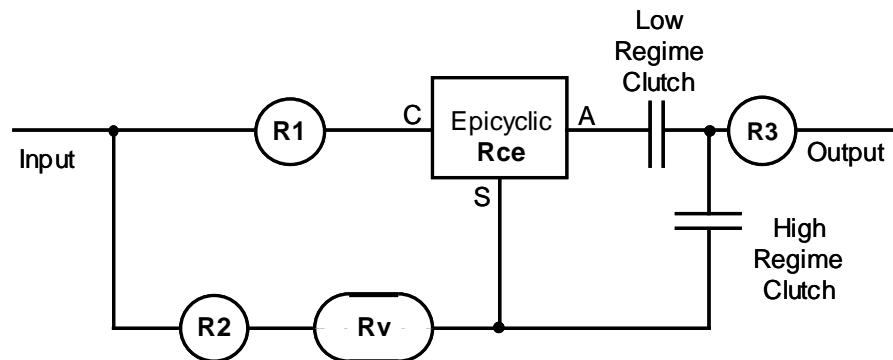
The unique characteristic of the Variator is 'torque control' rather than 'ratio control'. Transmissions are traditionally ratio controlled whereby a specific ratio is selected which results in an engine speed and wheel torque. The Torotrak IVT is torque controlled, whereby the desired wheel torque and consequent vehicle acceleration are selected and the ratio of the transmission then changes to satisfy these requirements. The rollers "self steer" in response to the changing speeds of the input and output discs.

The Variator alone cannot provide neutral and reverse drive, nor can it provide the ratio spread to achieve high overdrive ratios. However, the unique torque control capability of the Torotrak IVT allows the Variator to be incorporated within a split-power mechanical shunt arrangement to provide forward and reverse rotation, generation of high output torques in 'low regime', extraordinary overdrive capabilities in 'high regime' and the 'geared neutral' function of a zero output speed. A separate starting device is therefore not required.

Investigating the transmission arrangement in more detail, the mechanical shunt is achieved by connecting the engine to both the planet carrier of a mixing epicyclic and the input of the Variator. The output from the Variator is connected to both the sun gear of the epicyclic and the output shaft of the

transmission through a wet plate clutch (the high regime clutch). The annulus of the epicyclic is also linked to the output shaft of the transmission through another wet plate clutch (the low regime clutch).

A typical automotive IVT layout is given below :



**Figure 3 – Torotrak IVT Layout**

The epicyclic is configured to allow the summation of the two driven members to produce a zero speed condition on the third member, resulting in a geared neutral transmission.

A typical automotive IVT therefore has two operating regimes; low regime is a recirculating power system providing geared neutral, forward and reverse drive; high regime extends the ratio of the transmission in forward drive to provide high overdrive capability.

The IVT arrangement is not limited to two regimes; other applications have been designed to sweep the Variator ratio a number of times in order to achieve the desired power density and to deliver high tractive effort. For example, an off-highway IVT application can be configured with four regimes, which allows the Variator to sweep four times as the IVT shifts from full reverse to full forwards

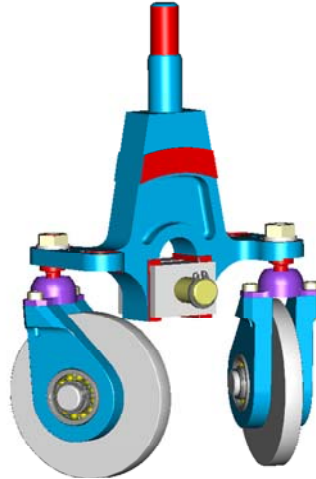
## 1.4 Outdoor Power Equipment Applications

Torotrak has recently announced the first commercial launch of the full-toroidal technology in a high volume, compact, traction drive IVT for use in the commercial and domestic garden tractor market in USA and Europe.

The Outdoor Power Equipment (OPE) market is led by the USA where approximately 2 million commercial and domestic Ride-On lawn mowers are sold each year. The existing variable drive transmission for this market is the hydrostatic transmission. The Torotrak IVT provides increased control, features and functionality over the hydrostatic drive and in order to compete in this cost competitive market, both the transmission and the Variator required significant simplification in both design and operation.

To succeed in this highly competitive market sector, significant redesign and invention were required to achieve the stringent cost, weight and package targets. The result is a highly simplified, single regime IVT with a single cavity “two roller” Variator design that is ideal for low power and torque applications.

The base principles of operation of the Variator are maintained with the castor angle generated by an offset on the carriage stem with the rollers pivoting about a central pin and forces applied through a single yoke. The result is a significant cost and weight saving due to the reduced parts count and simplicity of the parts and control system.



**Figure 4 – Two Roller Control Mechanism**

This 'two roller' Variator design has been validated and Series Production has commenced through Infinitrak, a US based joint venture company between Torotrak and MTD Inc. of Ohio.



**Figure 5 – Infinitrak Production IVT**

The 'two roller' Variator design has now been applied to higher power and torque applications for FWD vehicles.

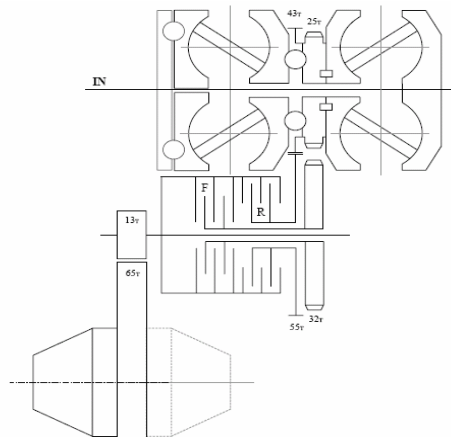
## **2 Toroidal Continuously Variable Transmission (T-CVT)**

For entry-level front wheel drive vehicles, the traditional approaches to an automatic transmission solution are unattractive on the grounds of cost and weight. A fresh concept is required. The result is the Toroidal Continuously Variable Transmission (T-CVT).

One factor already discussed that determines the Variator size (and hence transmission size) is the roller diameter. Another key parameter is the number of rollers in the Variator. Torotrak have focussed on simple 'two roller' Variator design with the effect of a significant reduction in the complexity of the Variator and its control system and a corresponding impact upon the transmission cost and weight.

This T-CVT solution combines the proven two roller design with the developments from the high end automotive products. The change to a CVT from an IVT retains the smooth seamless driving experience whilst dispensing with the mechanical componentry associated with the split power path shunt. A simple, cheap, small and lightweight automatic transmission solution is created.

Figure 6 shows the principle details of this transmission.



**Figure 6 – Toroidal Continuously Variable Transmission (T-CVT) layout.**

The T-CVT comprises of four key elements:

- Torotrak's twin cavity 'two roller' full-toroidal traction drive Variator.
- A clutch pack
- A simple hydraulic valve block
- A conventional final drive gearset

One of the innovative aspects of the T-CVT is the position of the clutch pack compared to conventional CVTs. The Variator input is connected directly to the engine with the clutch pack located on the Variator output. This is the same position as the regime clutches for traditional IVTs, therefore their torque capacity is not in doubt. However, this arrangement provides two key benefits.

First, with a direct connection, the Variator rotates whenever the engine is rotating – even in neutral – resulting in a robust Variator that cannot be damaged by “shock loading” on launch.

Second, the clutch pack has been designed to contain two clutches – one for forward drive and a second for reverse operation. The drive from the Variator to the clutch pack is simply achieved via a chain for forward drive and a gear for reverse drive.

Hence for forward drive, the forward clutch is engaged and the vehicle drives forward. Changing the Variator ratio provides the smooth variable drive across the full ratio spread of the transmission. For reverse, the reverse clutch is engaged but the Variator ratio is not varied but is maintained at the low ratio providing a fixed reverse ratio i.e. the vehicle speed changes with engine speed.

Therefore, unlike alternative variable drive transmissions, there is no need for additional gearing for reverse providing simplification and a corresponding reduction in parts count resulting in cost and weight benefits. The standard final drive unit is connected directly to the output of the clutch pack.

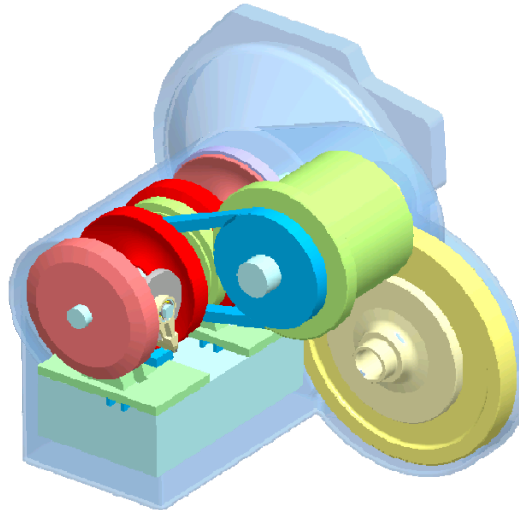
Further cost and weight saving arises from the two roller Variator configuration. A twin cavity arrangement is used to handle the power and torque requirements of A & B segment FWD vehicles.

The axial load required by a traction drive Variator is proportional to the torque being transmitted by the Variator. The optimum efficiency of the Variator is achieved by careful control of this axial load, which has traditionally been provided by hydraulic pressure. The T-CVT can be configured with either a hydraulic axial loading mechanism or with a simple mechanical ball & ramp assembly which automatically applies force proportional to the torque being transmitted. The ball & ramp system has transmission cost, weight and size benefits with minimal reduction in Variator efficiency. If the application requires ultimate Variator efficiency it is of course possible to retain the hydraulic axial loading arrangement.

The consequence of the simplified roller control and the mechanical axial load mechanism is a particularly simple hydraulic control system. A single proportional pressure control valve supplies both

the Variator control and the active clutch pistons; and two hydraulic switches are necessary to select between forward and reverse clutches and to define the direction of force applied to the Variator.

Figure 7 details the simple and modular T-CVT. The clutch pack, hydraulic valve block and final drive elements can be rotated around the Variator to achieve the best packaging solution for the vehicle application.



**Figure 7 – Toroidal Continuously Variable Transmission.**

The main dimensions for a typical T-CVT in a small car applications are:

	<b>T-CVT 1</b>	<b>T-CVT 2</b>
Roller Diameter	60 mm	70 mm
Length (RFoB)	325 mm	345 mm
Weight	43 Kg	50 Kg
Ratio Spread	6.25	6.25
Power capacity (Gasoline)	50 kW	75 kW
Torque capacity(Gasoline)	100 Nm	150 Nm
Engine capacity(Gasoline)	~ 1.0 L	~ 1.6 L

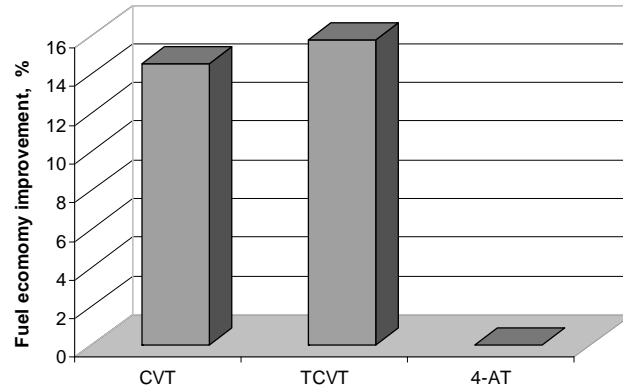
Therefore a lightweight automatic transmission solution for small front wheel drive cars is achieved.

## **2.1 T-CVT Fuel Economy**

Torotrak have well proven software modelling tools to simulate variable drive transmission performance including validated models of Variator behaviour.

To evaluate the performance of a vehicle fitted with a T-CVT, Torotrak have created a generic vehicle model comprising an engine, four speed automatic transmission and torque converter including the transmission shift map and torque converter lock up schedule. An overlay comparison has also been made to the same vehicle and engine with a belt CVT transmission.

Considering fuel efficiency, the T-CVT offers an advantage over the belt CVT because the full toroidal traction drive Variator is more efficient, has a greater ratio spread and lower hydraulic power requirements than the belt drive Variator in small transmission applications. The implementation of torque control strategy in the T-CVT results in more accurate control of the load applied to the engine, hence better control of the engine operating condition. However, both the T-CVT and the belt CVT have much better fuel efficiency than the 4 speed automatic transmission because, in both cases, the engine can be operated at its best specific fuel conditions most of the time. The comparison between these transmissions for the Japanese J10-15 fuel cycle is shown in figure 8.



**Figure 8. Fuel efficiency comparison for J10-15 fuel cycle.**

### 3 Epicycloidal Roller Control (ERC)

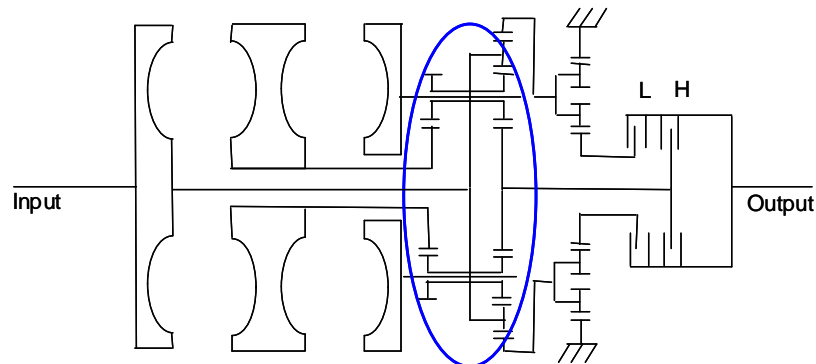
As previously discussed at the CTI Innovative Automotive Transmission conference in Berlin, with the IVT proven as concept, Torotrak's design team focussed on optimising the cost, weight, package and efficiency if the IVT to deliver production ready IVT designs suitable for series production.

#### 3.1 Conventional Variator Configuration

As described, the conventional Torotrak Variator comprises two toroidal cavities with three rollers per cavity. Each roller is attached to a reaction piston via a carriage assembly and piston stem. Hydraulic pressure from a common source is applied to each of these six reaction pistons with the magnitude of the applied pressure defining the torque reacted in the disc / roller contacts within the Variator.

The benefit of employing an individual piston for each roller is automatic equalisation of force distribution – in essence the Variator is operating as an assembly of six independent 'sub-Variators' running on common discs.

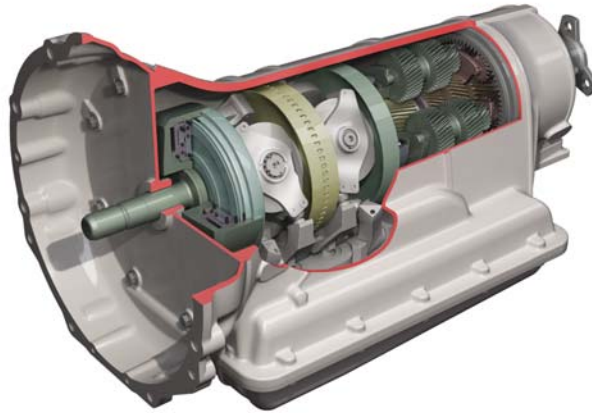
However the inevitable down side is the need for six independent roller control systems resulting in both a high parts count and providing problems for taking the drive off the Variator output / centre disc. Hence the output from the Variator must be taken via a transfer drive and lay shaft or an epicyclic gear set configured for coaxial connection to the shunt gearing. The epicyclic version is preferred for RWD applications since it provides a compact cross-section ideal for installation in modern, low intrusion transmission tunnels. The arrangement of a typical IVT based around a conventional Variator configuration can be seen in the pre-production IVT layout drawing in Figure 9:



**Figure 9 - Pre Production IVT Layout**



The hardware for this design has been realised and previously reported and provides a fuel economy improvement of over 10% when compared to the 'state of the art' six speed step automatic transmissions in a premium SUV.



**Figure 10 - Pre Production IVT**

The three obvious targets for simplification were therefore:

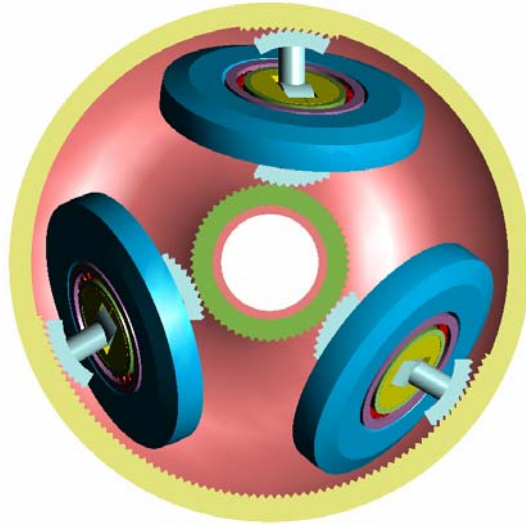
- Elimination of the output epicyclic gear arrangement by applying a direct connection to the centre discs;
- Elimination of the individual roller pistons; and
- Simplification of the roller.

### **3.2 ERC Variator Configuration**

The alternative is to provide a single control system rigidly connected to each roller. Without equalisation such a system must rely on mechanical accuracy to achieve adequate load distribution

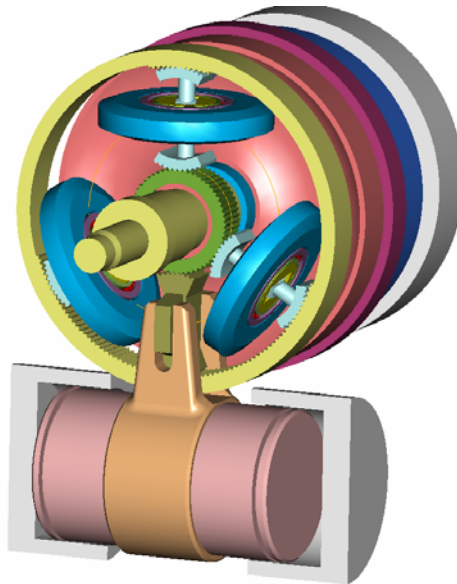
In the ERC Variator, the simplification objectives have been achieved by linking the rollers to a mechanical system that distributes the required reaction forces from a single hydraulic piston. Steering geometry must be provided by the connection to each roller while distribution of power flow is maintained by accurately fixing the relative position of each roller assembly.

The concept is best realised by exploiting the inherent accuracy obtained from conventional involute gearing. Each roller is mounted on and steered by the planet of an epicyclic gear train. The sun and annulus gears position the planet / roller assemblies and, since no other connection is necessary, a conventional carrier is not required as shown in Figure 11:



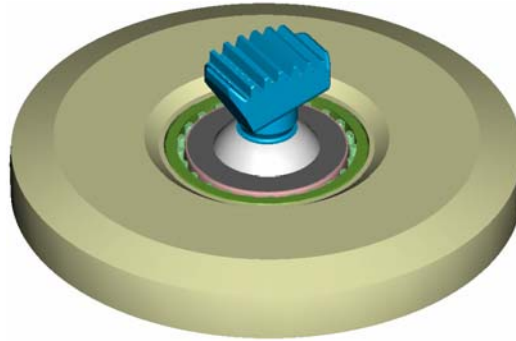
**Figure 11 – ERC Assembly**

Control input is made via a fourth planet which is connected by a sliding linkage to the single hydraulic ram. Motion of the ram creates the necessary displacement of the control planet, which is then replicated at each roller by the resulting sun and annulus rotations as illustrated in Figure 12:



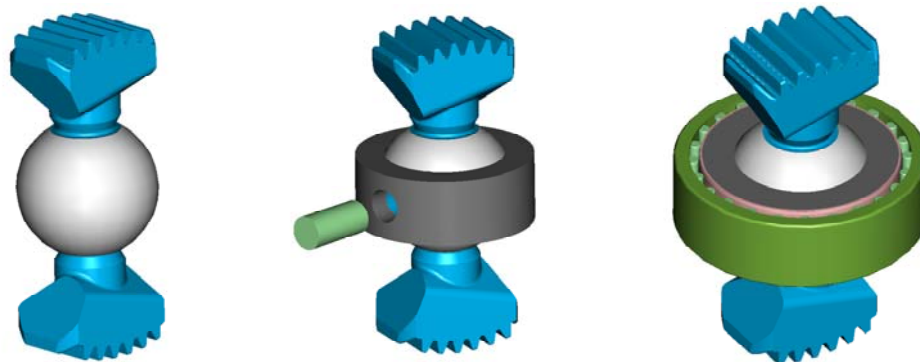
**Figure 12 – ERC and Control Cylinder**

The roller is mounted on combined spherical and needle bearings Figure 13:



**Figure 13 – Roller Mounting**

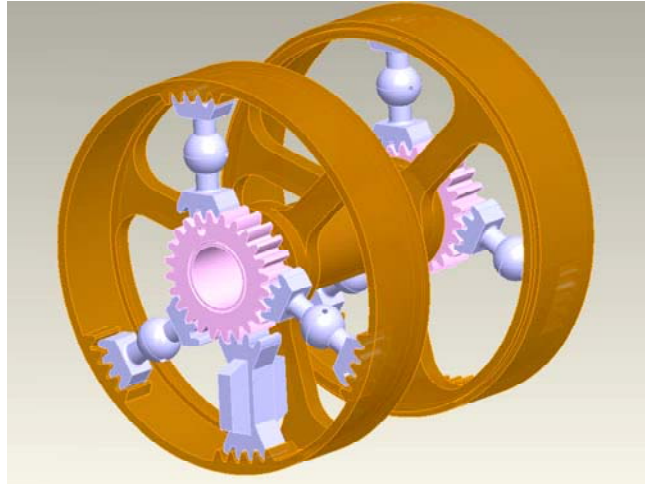
The planet gear teeth extend over a narrow arc which is sufficient to permit the limited deflection required to steer the roller. The two geared segments and the centre of the spherical bearing are linked by the planet body (Figures 14). Rotation of the spherical bearing is constrained to the roller precession axis by pinning its outer ring to the spherical body (Figure 15). The roller is supported on a needle bearing that is pressed onto the spherical bearing and into the roller (figure 16).



**Figures 14, 15 & 16 – Planet Gear & Spherical Bearing Arrangement**

The rollers are free to comply with the Variator disc geometry by a combination of axial and radial movement permitted by the epicyclic spur gears and the needle roller bearing. Roller reaction is taken via the spherical bearing while its locking pin provides the steering connection to the planet.

Although each Variator cavity requires an epicyclic to support its three rollers, only one epicyclic is connected to a control ram. This epicyclic is located in the 'open' cavity which facilitates its connection to the control cylinder which can be mounted on the transmission casing. The 'enclosed' cavity, located within the output drum, receives its control demand and reaction forces via connections to its sun and annulus gears as shown in Fig 17:

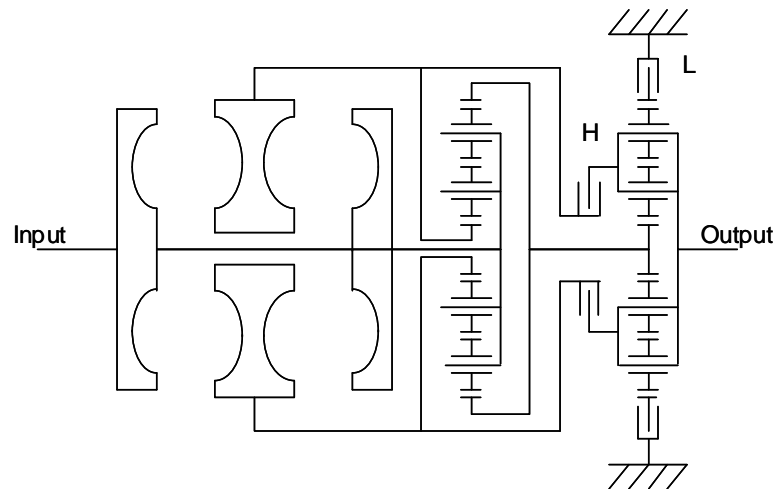


**Figure 17 – Sun and Annulus Gear Arrangement**

Since the sun and annulus rotations in each cavity are identical, all six rollers operate together.

The ERC Variator is therefore fully co-axial and no longer requires the inefficient output gearing of the earlier, conventional configuration. It is simplified by the elimination of all high regime gearing, allowing the Variator to be directly connected to the transmission output. Low regime is provided by shunt and reversing epicyclics. Two multi plate clutches select either regime.

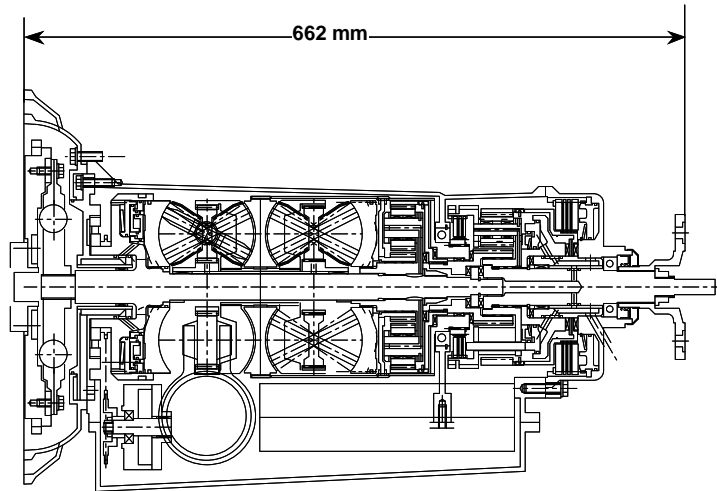
The associated shunt gearing is shown schematically in Figure 18:



**Figure 18 – Shunt Gearing Schematic**

The outcome from the ERC design study was a significant reduction (>30%) in component count producing a 20% reduction in Variator cost, when compared with a conventional Variator. In addition, the ERC Variator configuration also allows the elimination of the high regime epicyclic gearset leading to a 10% improvement in IVT mechanical efficiency in high regime.

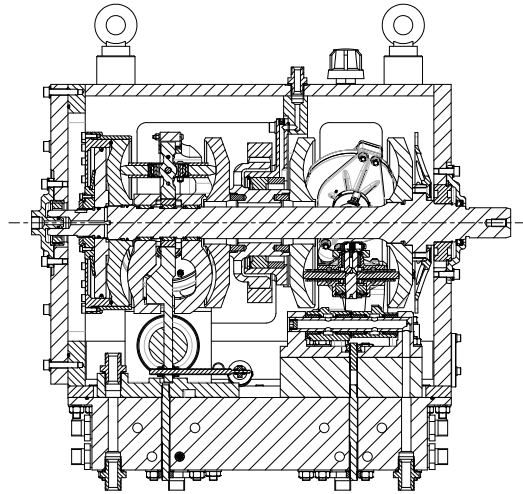
Therefore, the ERC IVT exhibits a 5% reduction in overall length and a 10% reduction in package volume requirement when compared to the pre-production IVT layout. For a particular application when compared to the existing 6AT, the revised shunt layout and the elimination of one epicyclic gearset has reduced the overall transmission length by 53mm, down to 662mm, producing an enhanced fuel economy benefit of 14%.



**Figure 19 – Transmission Layout using ERC Variator**

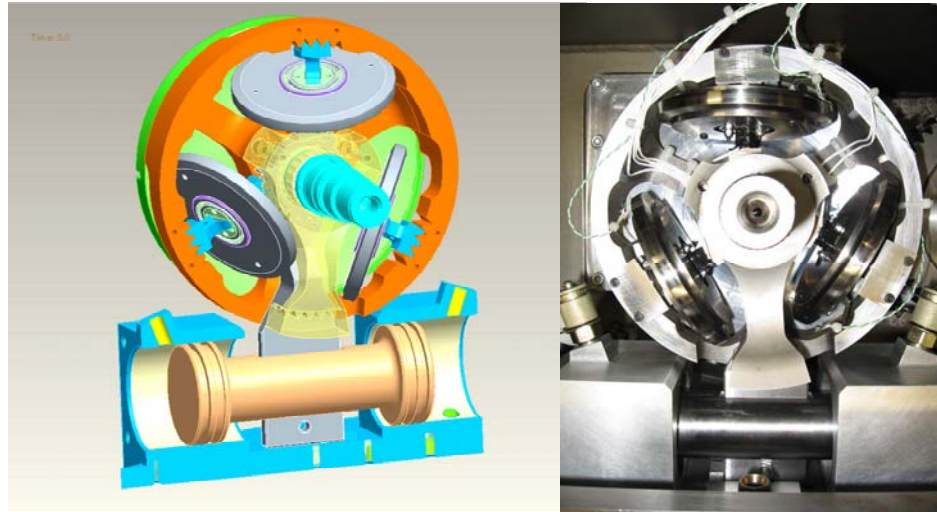
## 4 ERC Test Programme

Having quantified the benefits of moving to an ERC arrangement, Torotrak has set about proving the concept. As a first stage, a standard twin cavity Variator test module was converted to ERC operation in the front cavity alone – once the roller control mechanism is proved in a single cavity arrangement, a twin cavity arrange will follow.



**Figure 20 – ERC Single Cavity Module**

Figure 21 below details the ERC schematic and corresponding hardware :



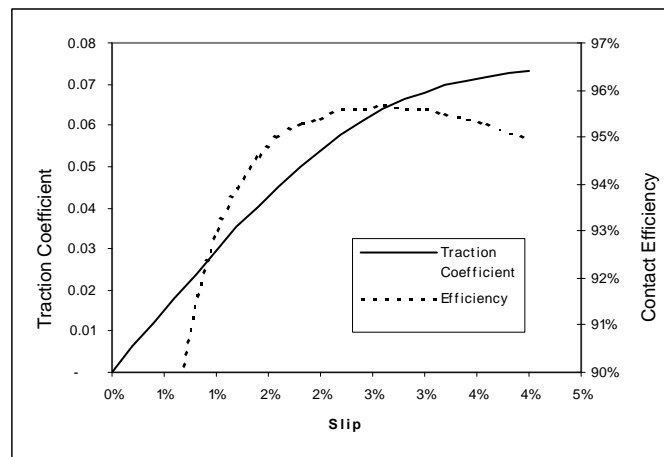
**Figure 21 – ERC Schematic & Hardware**

The ERC system requires each roller to run at the same 'ratio angle' (i.e. the relative angle to the rotating axis of the Variator) in order to provide equal load distribution between the rollers.

Hence the success of the ERC roller control mechanism can be measured in terms of the variation in actual ratio angle achieved for each roller i.e. the effective equal distribution of transmitted power.

One of the fundamental principles of traction drives is the relationship between traction coefficient and relative slip between the surfaces in the contact. As described in Figure 22 with increasing slip between in the contact, the traction coefficient increases up to a maximum where peak traction is achieved. Increasing the relative slip between the contacts further will result in a lower traction coefficient resulting in a 'Traction Slide' in the contact. Safe operation of the Variator requires traction coefficients to the left of the peak traction condition.

It can also be noted that contact efficiency increases as the traction coefficient approaches the peak value.

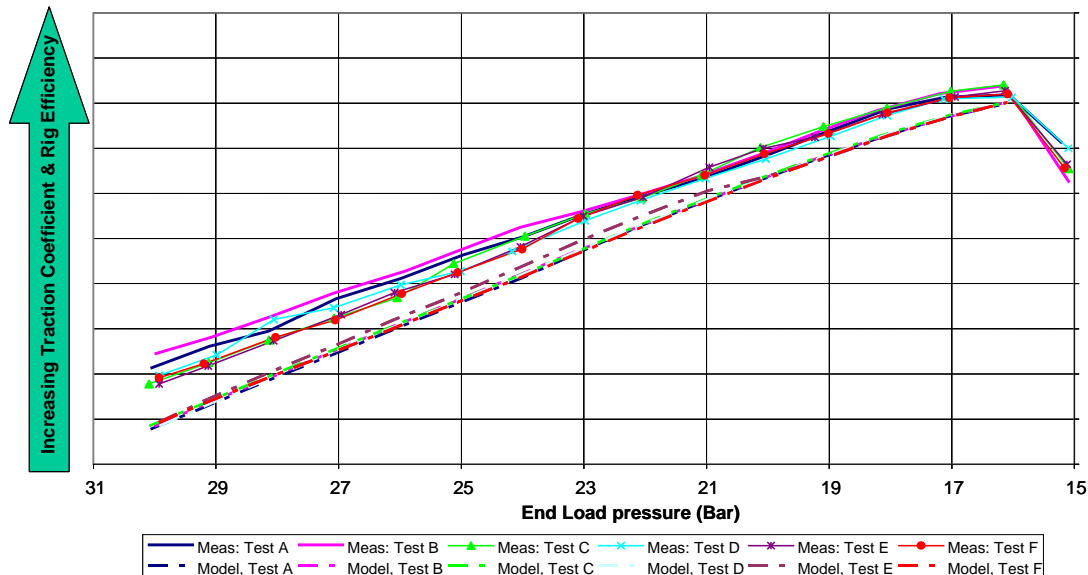


**Figure 22 –Graph of traction curve and contact efficiency**

Hence, if the rollers are correctly positioned, the efficiency of the Variator will be maximised without precipitating a Traction Slide.

Therefore to demonstrate effective load sharing, increasing the traction coefficient in each contact by reducing the End Load will produce a rise in traction coefficient at each roller with a consequent increase in total Variator efficiency. So Variator efficiency is an indicator of roller synchronisation.

Figure 23 describes both the simulation and the rig test results. In both simulation and test, a reaction pressure of 14.4 bar was applied to the Variator with an End Load pressure of 31 bar resulting in a calculated and measured Variator efficiency. The End Load pressure was gradually reduced whilst maintaining the reaction pressure until the measured efficiency peaked and reduced.



**Figure 23 – ERC Test & Simulation Results**

Figure 23 demonstrates the correlation between the simulated and measured data with respect to the Variator efficiency, the relative increase with respect to reducing End Load and, critically, the “knee” point where the Variator efficiency peaks.

Hence, the ERC system is clearly providing roller synchronisation as a result of accurate roller control.

## 5 Conclusion and Summary

Torotrak have developed two new Variator roller control methods namely the ‘two roller’ design and the ERC mechanism, both of which have been realised in hardware. The two roller design is now in Series Production and the ERC system has successfully completed the first series of testing.

The new designs provide significant parts count and cost reductions together with system efficiency, performance and package improvements and have enabled the technology to be applied to both existing and new applications.

## 6 Contact Details

This paper was presented with the aid of animations. To obtain a copy of the PowerPoint slides and animations please contact:

Torotrak (Development) Ltd  
1 Aston Way, Leyland, Lancashire, PR26 7UX, UK  
Tel: +44 (0)1772 900900, Fax: +44 (0)1772 900929

email: [marketing@torotrak.com](mailto:marketing@torotrak.com)  
[www.torotrak.com](http://www.torotrak.com)