Fuel Consumption Improvements by Applying IVT Technology to Commercial Vehicles

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Abstract:

A highly efficient, fully optimised Commercial Vehicle powertrain can be configured to operate the engine on its ultimate efficiency line for fuel economy and emissions by utilising a high torque capacity variable drive transmission.

The Torotrak full-toroidal traction drive Infinitely Variable Transmission (IVT) has previously been applied to cars and Sports Utility Vehicles (SUV's) delivering 20% fuel economy improvements.

This technology has now been applied to a European mid-sized bus providing a measured fuel saving of 19% over the UK official bus test cycle when compared to the standard production model.

The fuel economy benefit is achieved through substituting the conventional fixed ratio automatic transmission with a 'geared neutral' IVT, so eliminating the torque converter, removing emission spikes generated by gear shift torque interruptions and providing a high overdrive ratio.

For heavy duty commercial vehicles, the 'two regime' IVT utilised in the bus application is extended into either three or four regime powersplit designs to optimise transmission efficiency and accommodate the higher engine torques and tractive effort requirements.

This paper describes the operation of the IVT and the fuel economy benefits achieved in the European bus application together with the arrangements for the three and four regime designs.

Keywords: Fuel economy, IVT, traction drive, powersplit

1. Introduction

The Torotrak full-toroidal traction drive technology is a simple variable drive technology with a variety applications ranging from low power auxiliary drive units through to multi-regime main drive transmissions suitable for passenger cars, SUVs, buses, trucks and Off-Highway vehicles.

The heart of the system traction drive is the Variator. The Variator can be utilised either as a direct drive unit (for example, as an auxiliary drive or CVT), 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- and Off-Highway vehicles).

A key characteristic of the Torotrak Variator is its ability to be scaled which leads to the broad range of applications irrespective of power level. The torque and power capacity of the Variator is determined by a number of factors including:

1. the number of toroidal 'cavities' in the Variator (single or twin cavities),
2. the number of rollers in each cavity (two or three) and
3. 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 Variator technology:

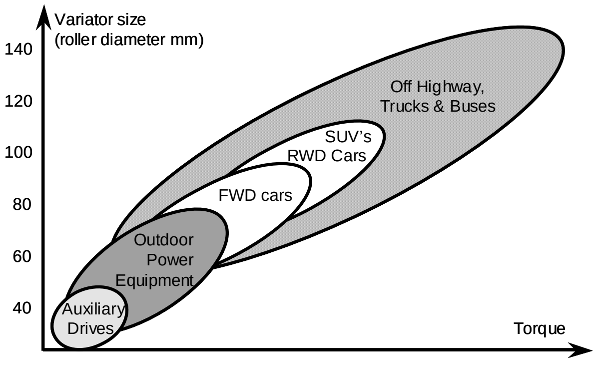

Figure 1: IVT Applications

In each of the market sectors described above, Torotrak has active projects with customers who are applying the company's IPR and know-how.

2. The Full Toroidal Traction Drive Variator

The full-toroidal traction drive Variator comprises toroidally shaped metal discs and rollers arranged with either a single or twin identical ‘cavities’. Each cavity therefore consists of an input disc driven by the engine and an output disc which is ultimately connected to the road wheels (Figure 2).

The space between each pair of discs forms a hollow doughnut shape or toroid. Within each toroidal space are the rollers – either two or three rollers per cavity. The rollers transfer the power and torque from the input discs to the output discs. The angle of the roller determines the ratio of the Variator and hence, with the roller at a small radius (near the centre) on the input disc and at a large radius (near the edge) on the output disc, the Variator produces a “low” ratio. Moving the roller across the discs to a large radius at the input disc and corresponding low radius at the output produces the “high” ratio and provides the full ratio sweep in a smooth, continuous manner.

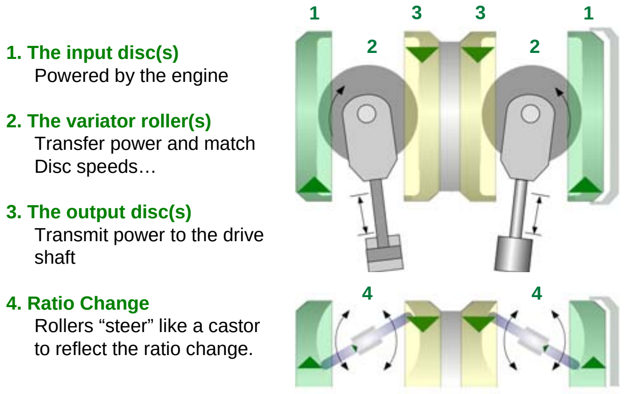

Figure 2: Full Toroidal Torque Controlled Variator

Force is applied to the rollers via hydro-mechanical actuation via a piston (one per roller) producing the tangential force on the contacts and the discs are clamped together with an end load arrangement to produce the normal load. Application of these forces reacts torque between the input and output discs of the Variator ultimately delivering wheel torque to the road.

Figure 3 defines the forces in the Variator by considering a single roller. The piston is mounted at an angle to the Variator known as the Castor Angle. Application of the reaction force through the Castor Angle enables the rollers to ‘self steer’ in the Variator to a new angle of inclination hence achieving a new ratio.

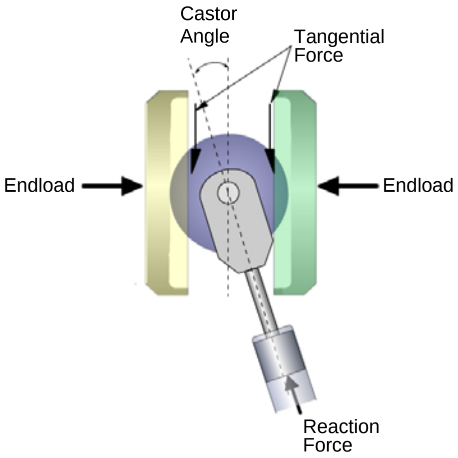

Figure 3: Variator Force Balance

The Torotrak Variator is torque controlled in that the required system torque is set by applying pressure to the pistons connected to the rollers and the Variator follows the ratio automatically.

Figure 4 explains this approach using a simplified single roller model.

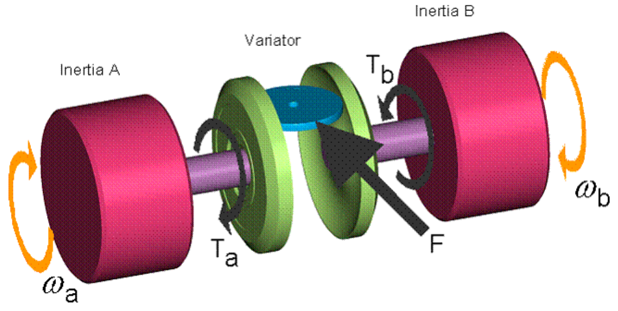

Figure 4: Torque control system balance.

Applying a reaction force F to the roller causes a reaction torque (Ta and Tb) at the Variator discs and consequently an acceleration of the two inertias (engine side inertia A and vehicle side inertia B). This may change the speed of the engine and/or vehicle inertia resulting in a change of Variator ratio. Due to application of the castor angle, this ratio change happens automatically. In the Torotrak Variator design described above, reaction force is applied hydraulically to individual roller carriage pistons.

Trapped between the rolling edge of the roller and the surface of the disc is a thin film of traction fluid which not only separates the components (ensuring that there is no metal to metal contact so eliminating component wear) but also transfers the forces between the rotating discs – see Figure 5. This is due to the long chain molecules of the traction fluid that interact with each other when the fluid is compressed resulting in a highly viscous state when under pressure.

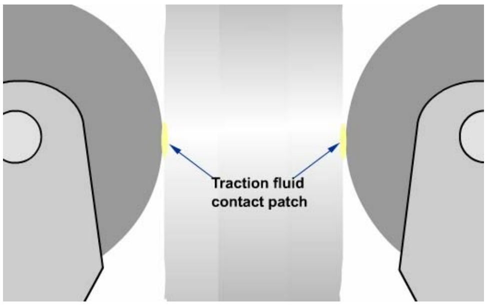

Figure 5: Traction Fluid Contact Patch

Therefore, as pressure is exerted at the contact points between the rollers and the discs, the oil resists the tendency to slide and transmits the force effectively.

The Variator provides a wide ratio spread itself but needs to be incorporated within a split-power mechanical shunt arrangement to provide neutral, forward and reverse rotation and generation of the required output torques.

Depending upon the arrangement, a single or multi regime 'Geared Neutral' Infinitely Variable Transmissions (IVT) or a clutch start Continuously Variable Transmission (CVT) results.

3. Incorporating a full-toroidal Variator into a 'Geared Neutral' IVT

Incorporating a 'Geared Neutral' arrangement (using a epicyclic gear set in a mechanical shunt) with a variable drive system dispenses with a separate launch device and produces an Infinitely Variable Transmission (IVT) rather than a traditional CVT.

In a typical IVT arrangement, the engine is connected 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 in Figure 6:

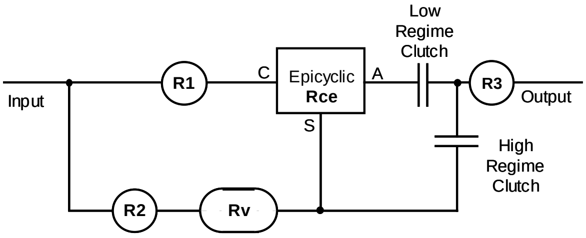

Figure 6: Typical 2-regime IVT shunt arrangement

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 (circa 100kph / 1000 rpm).

As the vehicle accelerates forward, the variator reaches its minimum ratio. As this point, with the low regime clutch engaged, there is no relative speed across the high regime clutch and therefore the high regime clutch can be engaged synchronously. The low regime clutch can then be released and the entire ratio spread of the variator is used a second time in high regime and the epicyclic gear set is bypassed.

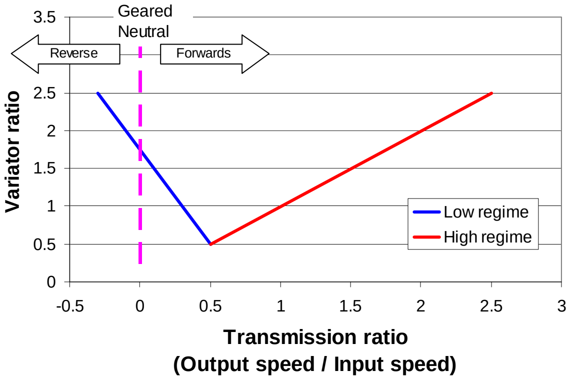

Figure 7: Variator ratio vs Transmission ratio

IVT arrangements are not limited to two regimes; multiple regime IVT's 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.

4. Commercial Vehicle Applications

A prototype 2-Regime IVT has been applied to a European Midi-Bus (an Optare Solo provided by the Optare Group) with a gross weight of 11,300kg. This is a popular class of vehicle in Europe, typically accommodating about 30 passengers. The Solo has a four-cylinder diesel engine and a 5-speed automatic transmission.

The IVT transmission is a two-regime shunt incorporating a full-toroidal traction drive variator. This transmission is not optimized for the test vehicle having been designed for, and previously installed in, a Ford Expedition SUV. A minor change to the transmission output gear ratio accommodates the change from SUV gross train weight to the Midi-Bus gross weight.

Figure 8: The Optare Solo European Midi-Bus.

The UK has a well established test cycle for urban buses known as the Millbrook London Transport Bus Cycle (MLTB) which is an intensive stop start cycle replicating a demanding urban bus route (Figure 9).

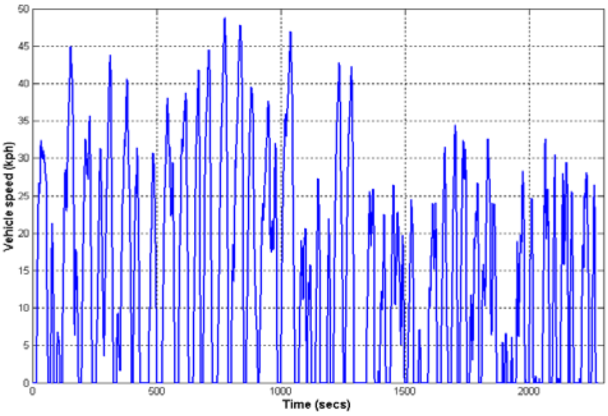

Figure 9: MLTB test cycle.

The test cycle totals 9km, comprising of 6.5km of “medium” speed operation followed by 2.5km of “low” speed operation, taking 38 minutes to complete.

Testing was undertaken at the internationally recognized Millbrook proving grounds in the UK.

5. Engine Control Line for Optimum Fuel Economy

The IVT is able to decouple the engine speed from the vehicle wheel speed whilst accurately defining the load demand placed upon the engine. This enables the engine to be controlled at its optimum operating condition to maximize fuel efficiency.

For the test vehicle this concept is demonstrated in Figure 10. The engine specific fuel map is represented, and the desired operating control line is shown. This control line aims to run the engine at minimum specific fuel consumption for any required power output. For clarity, the lines of constant power have been removed. The desired OCL identifies the minimum specific fuel use for each engine power.

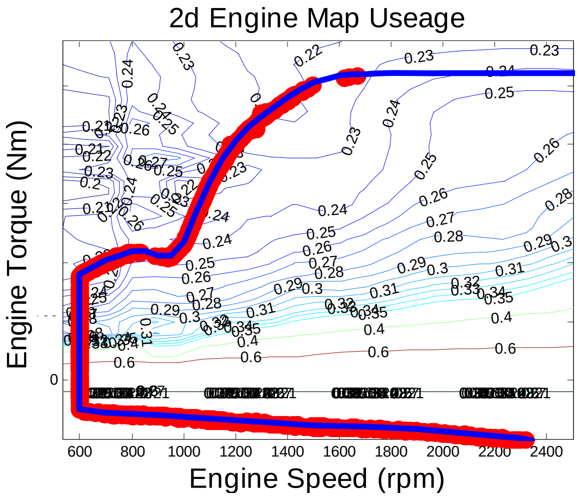

Figure 10: Engine Fuel Map with IVT Control Line.

Note also the extension of the desired operating control line into the negative engine torque quadrant. This makes it possible to utilise the engine as a power sink to actively decelerate the vehicle on overrun conditions. As the engine speed is decoupled from the wheel speed by the IVT, the engine is capable of emulating the function of the electrical retarder usually fitted to this vehicle.

The IVT tightly constrains the engine to operate on the desired operating control line. By contrast an automatic transmission defines the engine operating conditions as a function of the fixed gear ratios and its torque converter characteristics. For the vehicle test cycle, the engine operating conditions are shown in Figure 11 superimposed upon the engine fuel map. The IVT operating control line is repeated for comparison.

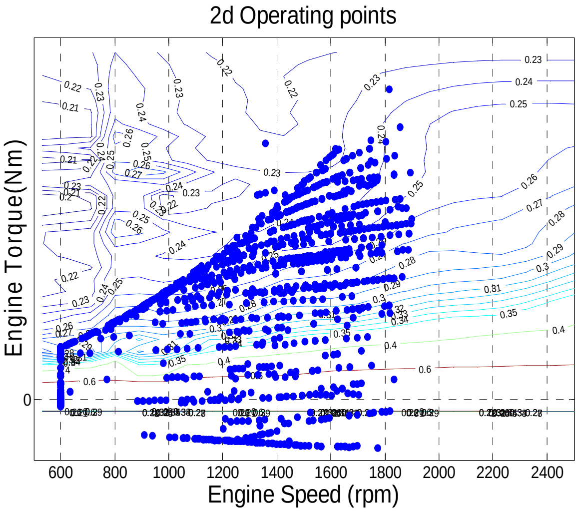

Figure 11: Engine fuel map and 5AT operating points.

6. Test Results

The Bus was fuel economy tested with both the standard fit 5AT and the prototype IVT with the IVT delivering a 19% fuel economy improvement over the standard driveline

As predicted, the fuel economy benefits are delivered by the IVT's ability to accurately control the engine speed and load and hence adhere to the ideal OCL. During the test cycles the engine operating conditions were measured. This data is compared with the simulation predictions in Figure 12.

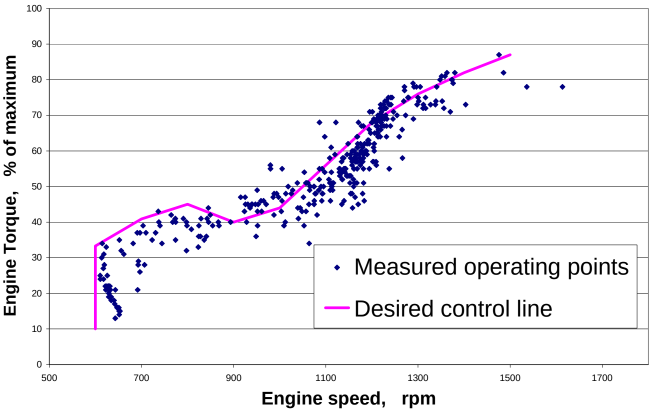

Figure 12: IVT engine operating point during cycle test.

The measured engine operating conditions show good, but not perfect, correlation with the desired ideal operating line. A fully integrated driveline controller and more detailed knowledge of the engine map will produce more accurate control of the engine and hence improve fuel economy further.

Fuel economy improvements cannot be achieved at the expense of vehicle performance and measured data demonstrates that the test vehicle has comparable (if not slightly improved) performance when fitted with the IVT – see Figure 13.

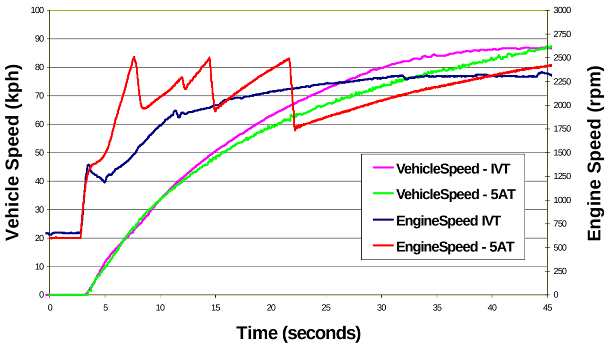

Figure 13: Measured vehicle performance

7. Extending IVT to larger vehicles

The 2-Regime IVT as applied to the Midi Bus is well suited to the application. For higher power, torque and tractive effort Commercial Vehicle applications, either the size (i.e. Variator roller diameter) of the 2-Regime design can increase or a 3- or 4-Regime design can be utilised.

Although the addition of an further regime can appear, at first, a strange addition of complexity, there are key benefits namely an increase in tractive effort and a powersplit architecture providing both efficiency and durability benefits. Hence, for a given application and duty cycle, a 3-Regime IVT can be more efficient, smaller and lighter than an equivalent 2-Regime.

Figures 14, 15 and 16 below consider both a 2- and 3-Regime IVT design for a single Commercial Vehicle application and compare the efficiency, Variator reaction torque and Variator power for each arrangement.

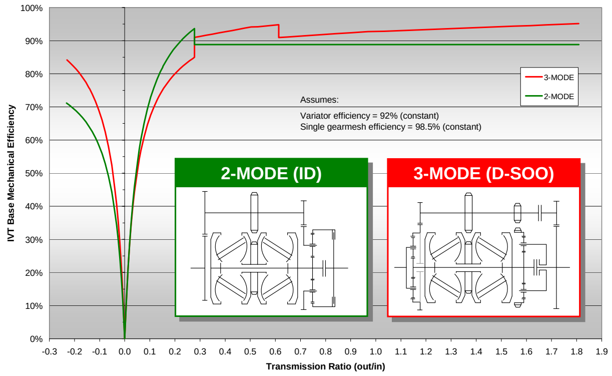

Figure 14: Efficiency Comparison
2-Regime v 3-Regime IVT

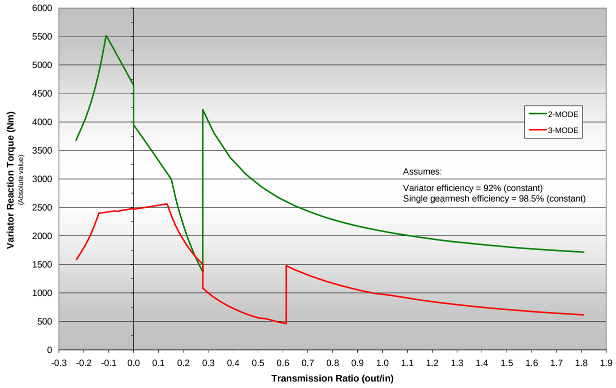

Figure 15: Variator Reaction Torque Comparison
2-Regime vs 3-Regime IVT

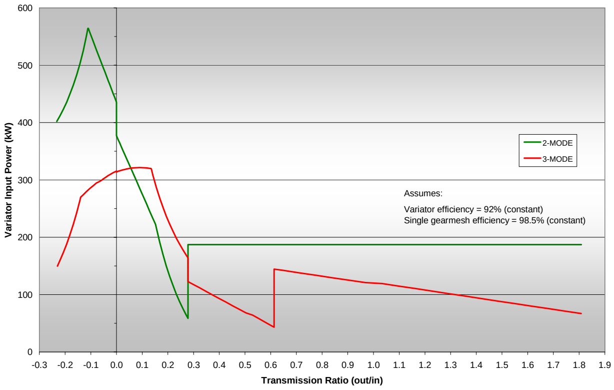

Figure 16: Variator Power Comparison
2-Regime vs 3-Regime IVT

It is clear that the powersplit feature of a 3-Regime IVT significantly reduces the Variator workload (reaction torque and power) resulting in higher transmission efficiencies.

Applying a typical CV duty cycle and comparing the life fraction consumed on the Variator components (figure 17) provides a clear indication of the benefit. Defining a ‘safety factor’ of 2 on durability (i.e. only allowing 50% life fraction consumption), in the application considered, either a 140mm Variator roller diameter 2-Regime IVT or a smaller, more efficient 120mm 3-Regime IVT would be suitable

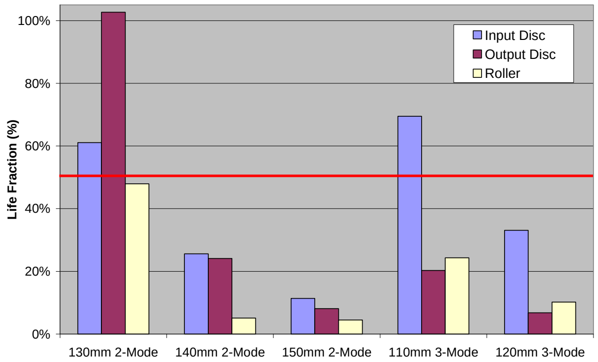

Figure 17: Variator Power Comparison
2-Mode vs 3-Mode IVT

A typical 2-Regime IVT arrangement for Commercial Vehicle is provided in Figure 18 with a corresponding specification. Figure 19 provides a typical 3- Regime (Patent Applied) IVT arrangement.

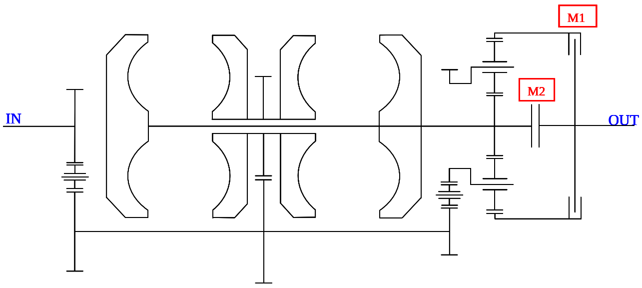

Figure 18: Typical 2-Regime Commercial Vehicle IVT

Typical Input Power	160 kW
Typical Input Torque	850 Nm
Typical Output Torque	5500 Nm
Transmission Ratio	-3.76 to +0.55
Typical Final Drive	6.0 : 1
Typical Tractive Effort	50 kN
Typical Overdrive Ratio	77 kph/1000rpm

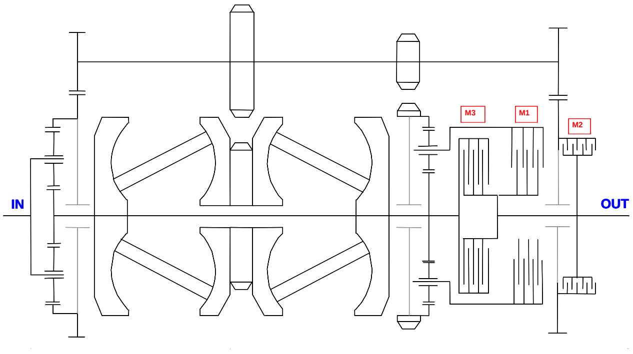

Figure 19: Typical 3-Regime Commercial Vehicle IVT

Typical Input Power	330 kW
Typical Input Torque	2300 Nm
Typical Output Torque	8400 Nm
Transmission Ratio	-4.83 to +0.35
Typical Final Drive	5.3 : 1
Typical Tractive Effort	80 kN
Typical Overdrive Ratio	108 kph/1000rpm

8. 4-Regime IVT Architecture

Extending the range of an IVT further by incorporating a 4th regime allows application of IVT to the largest on- and off-highway vehicles.

The relationship between the variator ratio and the overall transmission ratio is a design parameter for multiple regime IVT's and a typical relationship for a 4-Regime IVT being shown in figure 20. This IVT retains all of the features previously described for the 2-and 3-Regime transmissions.

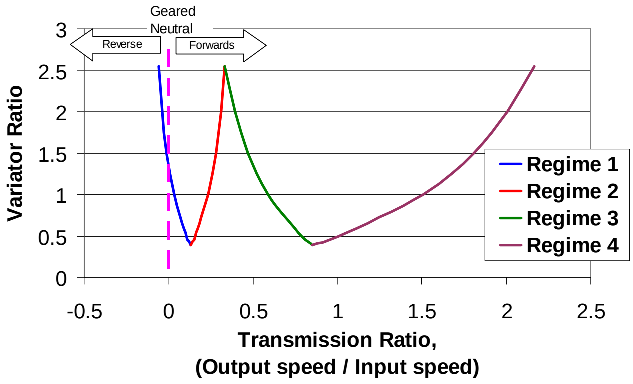

Figure 20: Variator ratio vs transmission ratio.

As with the move to 3 regimes, the power-split architecture of a 4-Regime IVT results in the Variator element experiencing far lower powers than that actually being transmitted by the transmission. The majority of the power is transmitted by mechanical elements. This leads to a large increase in the mechanical efficiency of the transmission, further increasing its attractiveness to the commercial vehicle application (Figure 21).

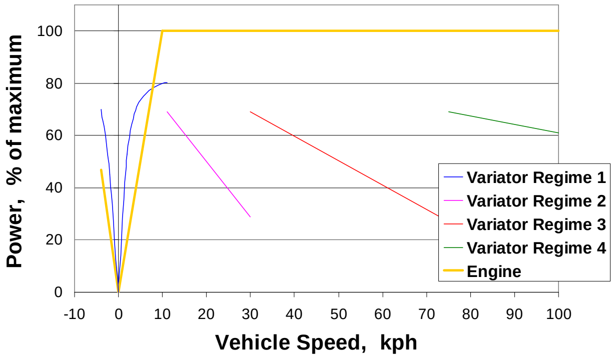

Figure 21: Power-split architecture of multi regime IVT

A 4-Regime architecture is described in figure 22.

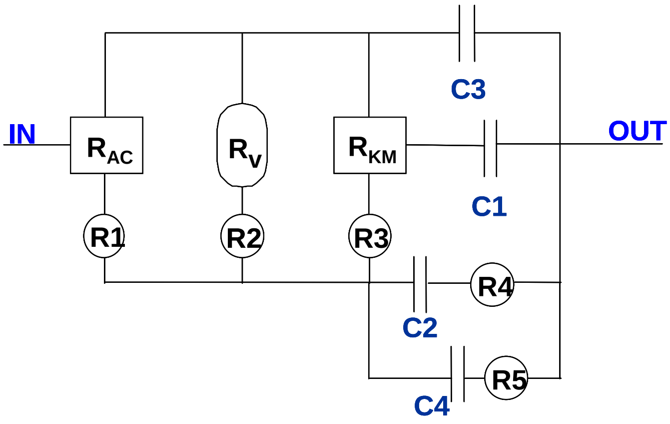

Figure 22: Power-split architecture of a 4-Regime IVT

Of particular interest is the similarity of the 3- and 4-Regime schematics in Figures 19 and 23 – a modular design has been achieved where the 4th regime is provided by the addition of separate module at the rear of the transmission. In this manner, a family of IVTs is easily created with high parts commonality.

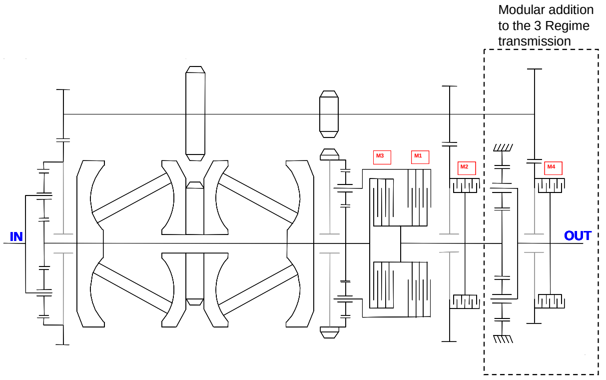

Figure 23: Typical 4-Regime Commercial Vehicle IVT

Typical Input Power	330 kW
Typical Input Torque	2300 Nm
Typical Output Torque	20,600 Nm
Transmission Ratio	-16.33 to +0.462
Typical Final Drive	3.0 : 1
Typical Tractive Effort	115 kN
Typical Overdrive Ratio	140 kph/1000rpm

Therefore, the same variator module can be utilised in the 2-, 3- and 4-Regime transmission

Hence, a family of IVT architectures results as descried in Figure 24 :-

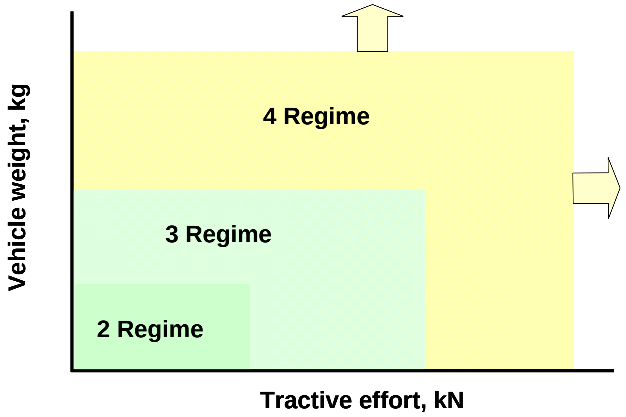

Figure 24: Extending the range of IVT

9. Hybrid Compatibility

This paper set out to demonstrate the ability of an IVT to provide fuel economy benefits to Commercial Vehicles. Once an IVT is established in a vehicle drivetrain its unique abilities readily enable migration to a hybrid driveline. The IVT is insensitive to the power source and therefore any combination of power / torque / energy source can be incorporated into the driveline. The IVT is insensitive to the direction of power flow, so is equally able to deliver power into any energy storage system.

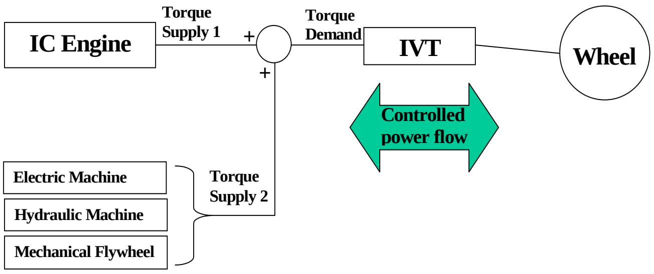

Figure 25: Incorporating IVT into a hybrid driveline.

10. Conclusion

Application of a prototype 2-Regime IVT to an Optare Midi Bus has delivered a measured 19% increase in fuel economy over the standard powertrain via optimisation and precise control of an engine to a desired operating condition.

For higher power, torque or tractive effort applications, 3- and 4-Regime architectures are potentially applicable due to the powersplit architectures employed.

Once IVT is in place in the driveline, electrical or mechanical hybridisation is readily achievable and has been shown (outside of this paper) to provide additional benefits.

11. Acknowledgement

The author acknowledges the contribution of Optare Group regarding the bus development and Phillip Winter, David Burtt of Torotrak (Development) Ltd and our Torotrak colleagues to this work.