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Fuel Economy benefits of a high torque Infinitely Variable Transmission for Commercial Vehicles.

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ABSTRACT

Replacing a conventional automatic transmission with a high torque capacity, full-toroidal traction drive Infinitely Variable Transmission (IVT), delivers fuel economy benefits approaching those achieved by hybrid drivelines when a suitable balance between battery life and fuel economy is implemented, but with minimal additional on-cost, weight and complexity. These benefits are achieved by optimizing the engine operating conditions, eliminating the torque converter and removing torque interruptions during the gearshifts.

Recent application of a non-optimal IVT to an Optare Solo bus (an 11,300kg European Midi-Bus) produced fuel savings of 19% over the standard Allison 5-speed automatic transmission. These measurements were independently performed by the internationally recognized Millbrook Proving Ground, UK. The precise control of the engine operating condition was demonstrated and this, in conjunction with the ability to decouple engine speed from wheel speed provides new opportunities to engine designers.

This paper describes the operation of the IVT and the fuel economy benefits achieved in an Optare Solo European Midi-Bus application. Extending the IVT to satisfy larger commercial vehicles by creating a modular family of transmissions is discussed, together with the future hybridization potential of the IVT

INTRODUCTION

An Infinitely Variable Transmission (IVT) is able to decouple the engine speed from the vehicle wheel speed while accurately defining the load demand placed upon the engine. These features enable the engine to be controlled at its optimum operating condition to maximize fuel efficiency and minimize emissions.

The single step of replacing a conventional Allison 5-speed automatic transmission in an Optare Solo 11,300kg European Midi-Bus with an un-optimized IVT produces a fuel saving of 19%, measured independently by the internationally recognized Millbrook Proving Ground, UK.

Fully exploiting the features of an IVT offers significant further benefits above the headline fuel efficiency gains. Engine designers are offered a new freedom to consider optimized combustion cycles or to optimize engine output characteristics, free from any constraints imposed by a fixed ratio transmission. Vehicle designers can implement downsized engines or hybrid power sources, with the potential to delete retarder braking systems. Drivers benefit from exceptional drivability while passengers experience a supremely smooth ride.

REASON FOR THE STUDY

The increasing price of fuel and ever more demanding emission regulations are causing many vehicle manufacturers to consider hybrid drivelines. This is especially true for vehicles operating in urban environments. Hybrid drivelines often add considerably to the vehicle cost and also increase vehicle weight and complexity. Increased servicing requirements and a long payback period are also unattractive features in a marketplace with no government subsidy for hybrid vehicles. There is also a compromise to be found between the vehicle fuel efficiency gains and the service life of the batteries for diesel/electric hybrid architectures. An acceptable battery service life significantly reduces the headline fuel efficiency claims of most diesel/electric hybrid drivelines.

It is believed that simply replacing an automatic transmission with an IVT will provide a very significant percentage of hybrid fuel efficiency gains with minimal increase in vehicle cost or weight. Once an IVT is established in the vehicle driveline it offers many future upgrade paths.

THE TEST VEHICLE

The test vehicle is an Optare Solo European Midi-Bus with a gross weight of 11,300kg, provided by the Optare Group. This is a very popular class of vehicle in Europe, typically accommodating up to 60 passengers (37 seated and 23 standing). The test vehicle has a four-cylinder diesel engine and either an Allison 5-speed automatic transmission, or a Torotrak full-toroidal IVT, mounted longitudinally behind the drive axle at the rear of the bus.

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 1. The Optare Solo European Midi-Bus.

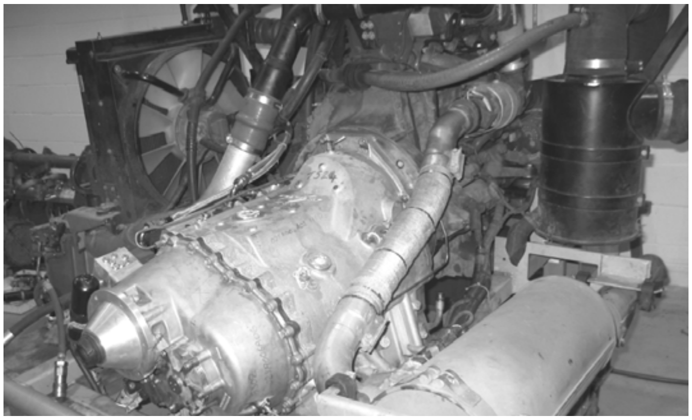

Figure 2. IVT mounted to engine.

THE TEST CYCLE

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

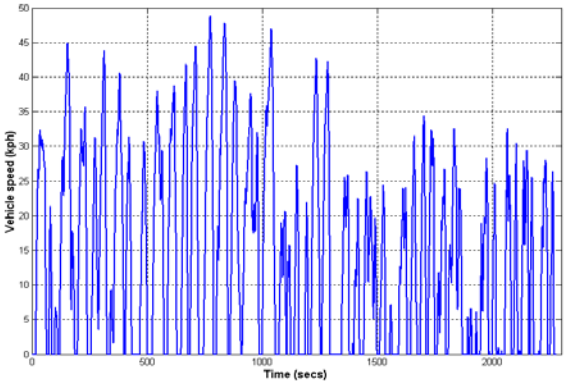

Figure 3. Millbrook London Transport Bus test cycle.

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 on a fully certified chassis dynamometer at the internationally recognized Millbrook Proving Ground in the UK.

PRINCIPALS OF IVT OPERATION

In order to understand how the fuel economy gains accrue and to outline the opportunities available to vehicle powertrain designers, the operating principals of the IVT are first described.

FULL TOROIDAL TRACTION DRIVE VARIATOR

The heart of the IVT is the well-proven Torotrak full-toroidal traction drive variator. The performance and durability of this variator are excellent; it is well researched and well understood having been proven both on rig test [1] and in a variety of vehicle applications.

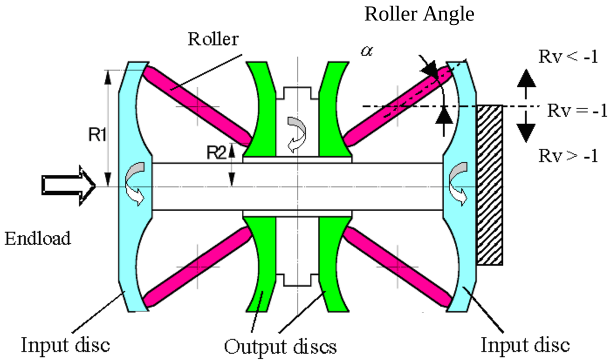

Figure 4. Dual cavity full toroidal variator.

The variator comprises four discs, which create two toroidal cavities. Each toroidal cavity contains three rollers that transmit power from the input discs to the output discs. The speed ratio of the variator is dependent upon the angle, alpha, of the rollers within the toroidal cavities.

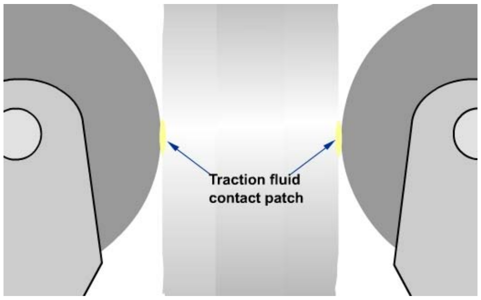

Figure 5. The traction contact patch.

Axial load is applied to the variator to create a contact normal force at the contacts between the rollers and the discs. Power is transmitted from the two input discs through the six rollers to the two output discs by shearing a traction fluid in the twelve elastohydrodynamic contacts between the discs and the rollers. The traction fluid is under pressure, which enables it to transmit force by shear, while also preventing metal-to-metal contact.

SHUNT ARRANGEMENT

The variator discs are always rotating if the engine is rotating, therefore to achieve a useful automotive transmission the variator must be incorporated into a shunt arrangement.

The variator is positioned within an input-coupled mechanical shunt arrangement that provides two regimes of transmission operation. The engine is connected directly, via judicious choice of gear ratios, to both the variator input and to one branch of an epicyclic gear set. No starting device or torque converter is required. The variator output is connected to a second branch of the epicyclic gear set and to the transmission output, via a clutch. The third branch of the epicyclic is also connected to the transmission output via a second clutch.

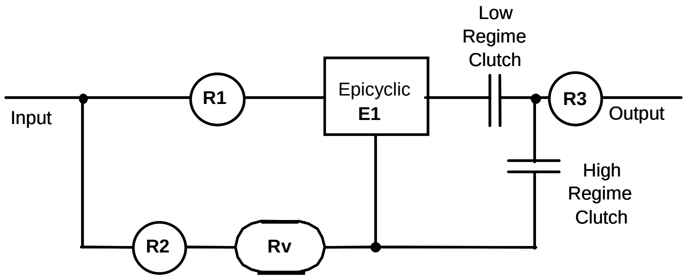

Figure 6. Typical 2-regime IVT shunt arrangement.

The epicyclic gear set acts to combine the engine speed and the variator output speed to produce the epicyclic output speed. The epicyclic output speed is passed via the Low Regime Clutch to the transmission output and hence to the vehicle wheels. The variator output speed is a function of the variator ratio, and for a particular variator ratio the epicyclic sums its input speeds to produce zero output speed. With the low regime clutch engaged, this condition is referred to as “Geared Neutral”, or infinite reduction. The engine, transmission input and variator are rotating, but the transmission output is stationary. Increasing the variator ratio causes the epicyclic output to rotate backwards, hence the vehicle moves off in reverse; and decreasing the variator ratio causes the epicyclic output to rotate forwards, hence the vehicle moves off forwards. The vehicle launch is exceptionally smooth and shuttling between forward and reverse is easily accomplished by changing the variator ratio, without the need to engage or disengage gears or clutches.

When the variator reaches its minimum ratio, with the low regime clutch engaged, there is no relative speed across the high regime clutch. 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, gear R1 and the epicyclic gear set being bypassed in high regime.

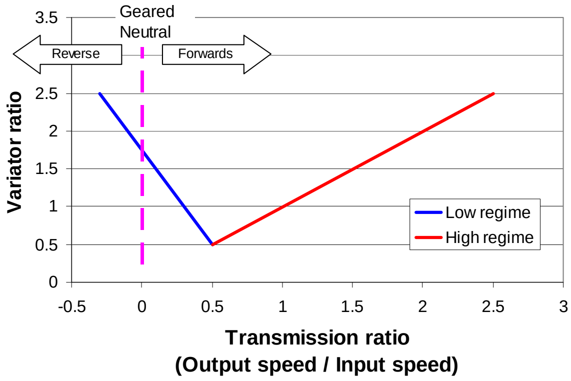

Figure 7. Variator ratio vs Transmission ratio

The change from low regime to high regime occurs at synchronous speed and can be regarded as a power-shift between regimes. The driveline suffers no discontinuities in torque or power delivery to the wheels during the regime change.

TRANSMISSION TORQUE CONTROL

Accurately controlling transmission ratio is difficult. Hence the chosen control strategy for the variator and IVT is that of torque control.

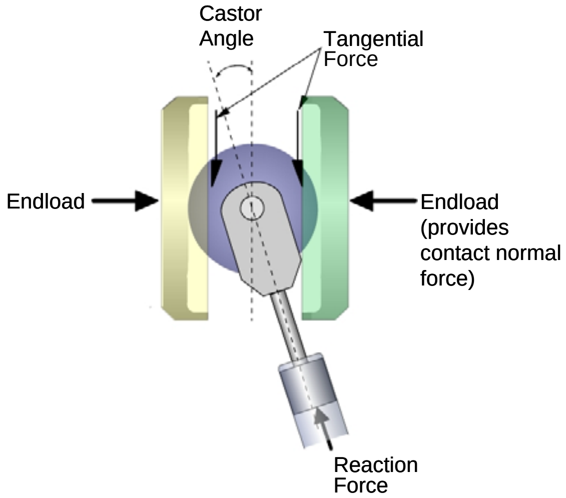

Figure 8. Roller force balance.

The reaction force applied to the rollers creates a tangential force at the contact between the roller and the discs. This tangential force is in turn reacted by the discs at a radius defined by the roller angle within the toroidal cavity. Hence the reaction force applied to the roller is directly proportional to the torque on the input and output discs. Applying the roller reaction force hydraulically results in the variator torque reaction, hence input and output torques being directly proportional to the system control pressure.

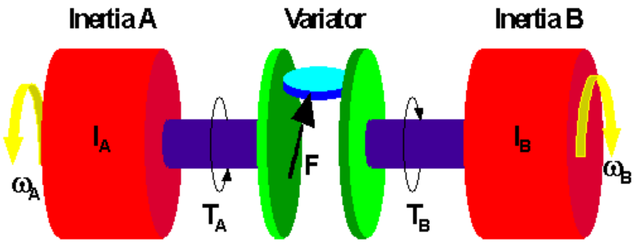

Figure 9. Torque control system balance.

Consider the driveline as inertias (engine side inertia A and vehicle side inertia B) and simplify the transmission and variator to a single roller between two discs. Applying a reaction force F to the roller hydraulically creates reaction torques (T_A and T_B) at the variator discs and consequently an acceleration of the two inertias. This will change the speed of the engine and/or vehicle inertia resulting in a change of variator ratio. The application of a castor angle (Fig. 8) to the roller carriages generates a self-steering force that causes the rollers to automatically adjust to the correct ratio. The key advantages of the torque controlled IVT, compared to ratio controlled devices, are its dynamic responsiveness and that geared neutral becomes a safe and realistic option.

ENGINE CONTROL LINE FOR OPTIMUM FUEL ECONOMY

An Infinitely Variable Transmission (IVT) is able to decouple the engine speed from the vehicle wheel speed while accurately defining the load demand placed upon the engine. These features enable 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. If lines of constant power were also plotted on this figure they would run in curves from top and left to bottom and right, moving from left to right with increasing power. The desired operating control line identifies the minimum specific fuel use for each engine power.

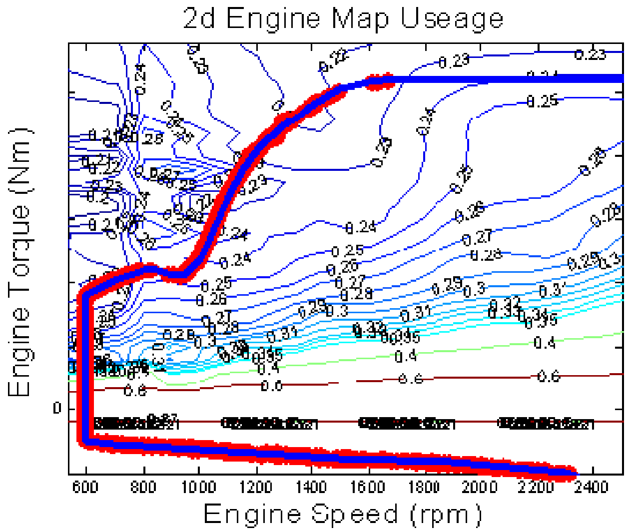

Figure 10. Engine fuel map and IVT operating control line.

Note also the extension of the desired operating control line into the negative engine torque quadrant. This makes it possible to utilize the engine as a power sink to actively decelerate the vehicle on overrun conditions. Because the engine speed is decoupled from the wheel speed by the IVT transmission the engine is capable of emulating the function of the electrical retarder usually fitted to this vehicle [2].

Prior to committing to the test hardware, the Midi-Bus was exercised over the test cycle in the virtual world. This was achieved using well validated in-house simulation tools running in the MatLab® and Simulink® environments.

The IVT tightly constrains the engine to operate on the desired operating control line. By contrast the 5-speed 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 shown in figure 3, the simulated engine operating conditions are shown in figure 11 superimposed upon the engine fuel map. The IVT operating control line is repeated for comparison.

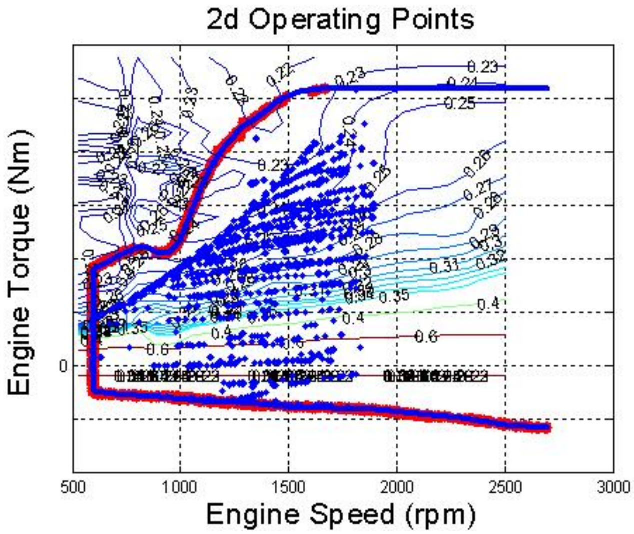

Figure 11. Engine fuel map and 5AT operating points.

To compare the engine operating conditions over the chosen test cycle more clearly, the engine fuel map is deleted and an additional time axis is added in figure 11. There is a large amount of time spent with the vehicle stationary to allow passengers to embark or disembark. However there is a clear distinction between the single operating line for the IVT and the broad scatter of operating points for the 5-speed automatic transmission.

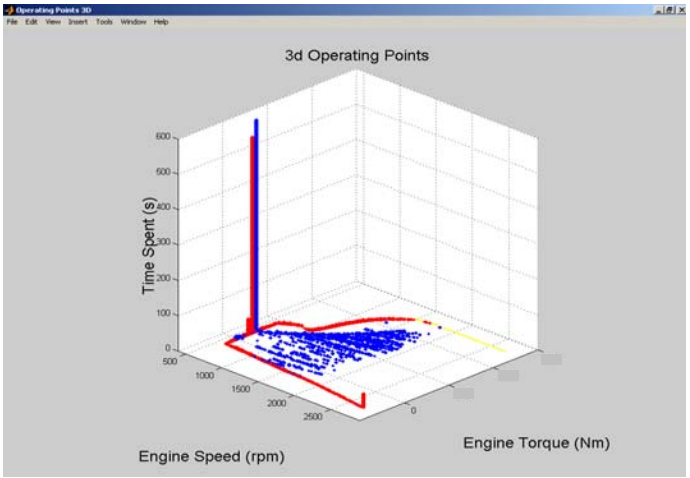

Figure 12. Simulated engine operating conditions for IVT and 5AT on the Milbrook London Transport Bus test cycle.

VEHICLE CONTROL STRATEGY

Extending the transmission torque control strategy to the complete vehicle allows the driver to become part of the vehicle control strategy. Consider the driver's accelerator pedal to define the wheel torque requirement. For a given vehicle speed this wheel torque equates to a wheel power, hence the transmission output power. In turn the transmission output power defines the required engine power, and via the engine operating control line, an engine speed requirement.

The transmission is able to control the torque load applied to the engine and thereby vary the engine speed, in conjunction with the engine control strategy. In effect a torque balance is created between the engine output torque and the transmission loading torque. Disturbing this balance causes the engine speed to change, and the transmission ratio changes as a consequence to suit the new condition. By virtue of controlling the driveline torque rather than the transmission ratio the engine will always operate exactly on its chosen control line or surface.

The driver acts as the control strategy feedback loop. Should the driver desire the vehicle to accelerate then more wheel torque is demanded by depressing the accelerator pedal. Once the desired vehicle speed is achieved the driver will naturally back-off the accelerator pedal thereby reducing the wheel torque demand. Driveline torque is the controlled variable and at all times the engine is kept on its optimum control line, with the transmission ratio following the torque requirements.

The result of this driveline control strategy is an extremely easy vehicle to drive that offers a very smooth ride for the passengers, while delivering best possible fuel economy.

TEST RESULTS

FUEL ECONOMY

The test work was performed by the independent and internationally recognized vehicle test facilities at Millbrook Proving Ground in the UK, observing their standard test procedures on a fully certified chassis dynamometer.

The EURO 3 emissions compliant engine was completely standard with no modifications made to either the engine or the exhaust system. The transmission controller communicated with the engine via the standard J1939 bus link, requesting either an engine torque or an engine speed.

With the standard engine and exhaust, the test vehicle delivered a 19% fuel economy improvement when the 5-

speed automatic transmission was replaced with the IVT.

ENGINE CONTROL

The Fuel economy benefits accrue from the IVT's ability to accurately control the engine load and adhere to an ideal operating control line. During the test cycles the engine operating conditions were measured. This data is compared with the simulation predictions in figure 13.

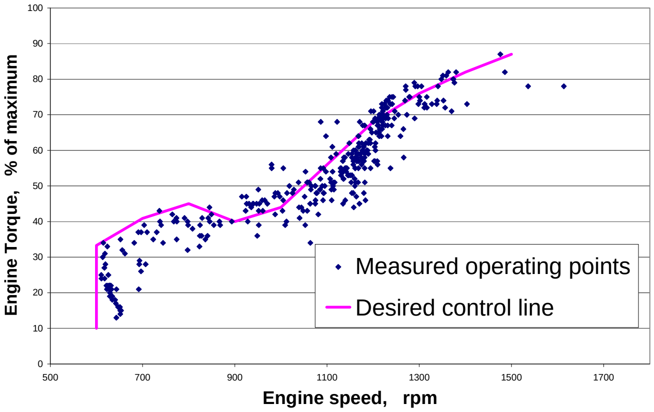

Figure 13. IVT engine operating point during cycle test.

The vertical axis of the graph in figure 13 is the percentage of engine torque available. This metric is plotted because it was easily derived from the J1939 bus data available from the engine management system. The desired engine operating control line is superimposed upon this axis set. The measured engine operating conditions show good correlation with the desired ideal operating line. This demonstrates the ability of the IVT torque control strategy to precisely define the engine operating condition. A fully integrated driveline controller and more detailed knowledge of the engine map would show even more accurate control of the engine.

The engine operating condition was also measured for the test cycles with the 5-speed automatic transmission, the results shown in figure 14.

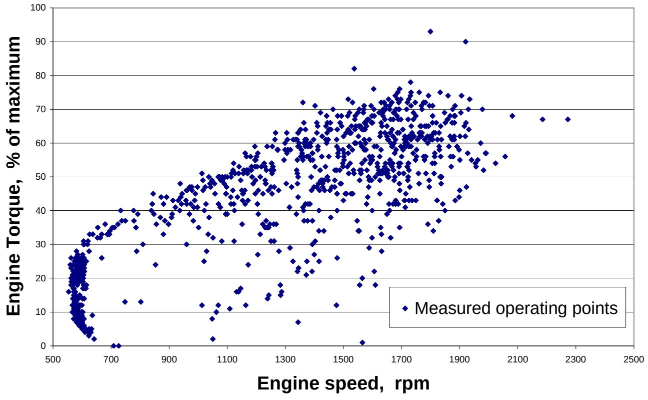

Figure 14. 5AT engine operating point during cycle test.

Once again the measured values show good correlation with those predicted by simulation. In this case the broad scatter of operating conditions is exactly as expected because of the limitations imposed by the fixed transmission ratios.

EMISSIONS

The reduction in fuel consumption is mirrored by corresponding reductions in $C0_2$ and HC emission. However a small increase in NOx and PM is observed together with an increase in CO. This is most likely a result of not finding the ideal balance between fuel economy gain and emission reduction due to having imperfect knowledge of the engine emission map. The NOx increase is not unexpected when a diesel engine is operated at relatively high load at low speeds. While an increase in emitted NOx is a concern there is a high degree of confidence that current engine after-treatment systems can deal satisfactorily with the NOx emissions.

The absence of conventional gearshifts with the IVT clearly removes any emission spikes created by the standard 5-speed automatic transmission during shift events. This helps to minimize any increases in total emissions.

RETARDER

An IVT is insensitive to the direction of power flow. Hence it is possible to maximize the engine's potential as a power sink during vehicle deceleration. Exploiting the engine's overrun torque capability enables the transmission to mimic the function of the electric retarder fitted between the automatic transmission and propshaft on the base vehicle. Previously the subject of a theoretical study [2], initial test results indicate that the IVT does have the potential to delete the electrical retarder from the test vehicle.

VEHICLE PERFORMANCE

Measured data shows that the test vehicle has better performance when fitted with the IVT, compared with the 5-speed automatic.

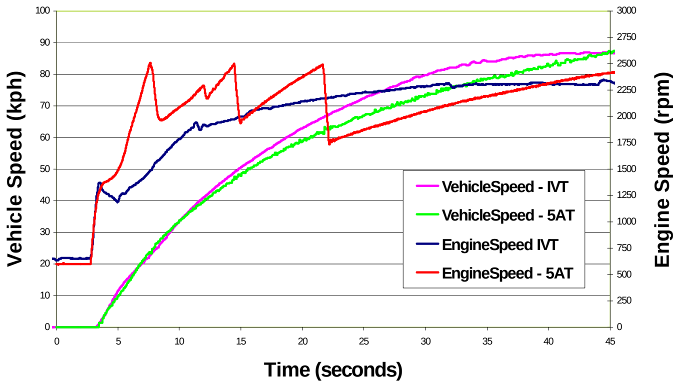

Figure 15. Measured vehicle performance, IVT and 5AT

This improved performance is achieved with a more steady, and lower, engine speed; thus enhancing the passenger experience. Unlike the 5-speed automatic, the IVT does not experience the step changes due to ratio shifts.

DRIVELINE OPTIMISATION

The reported fuel economy benefit has been achieved with a significantly non-optimal driveline. The test program was an initial investigation to demonstrate the real fuel economy benefit potential of simply substituting a conventional 5-speed automatic with an IVT. The IVT itself is a pre-prototype unit originally designed for a gasoline engined Ford expedition SUV. The transmission is therefore clearly less than ideal for a commercial vehicle. The IVT is also a development unit, hence it is rather less efficient than a production transmission would be due to the compromises incorporated in the transmission architecture to enable rapid changes in sub systems during the development process. Of specific note is the trade-off between development flexibility of the hydraulic control system and the hydraulic system efficiency. The variator in the IVT also lacks the latest developments, which increase its efficiency by optimizing the traction performance.

The EURO 3 emissions compliant engine was completely standard with no modifications made to either the engine or the exhaust system. There is only very limited integration between transmission and engine controllers. Full integration, and a complete knowledge of the engine, would provide enhanced driveline efficiency. Implementing state of the art exhaust after-treatment or EGR technologies would reduce emissions.

The route to an optimized IVT driveline in the Ford Expedition vehicle has been previously described [3]. The principals of driveline optimization apply equally to the Midi-Bus that is the subject of this paper. Hence additional fuel economy benefits of approximately 4% are expected in the future.

IVT BENEFITS TO ENGINE DESIGN

The ability of the IVT torque control strategy to precisely control the engine operating conditions to a user defined envelope or line has been well demonstrated by the test work. This proven control capability, and the ability to decoupling of engine speed from wheel speed, enables engine design to venture into new areas of combustion regimes such as HCCI that are not easily accessed when using fixed ratio transmissions.

The vehicle performance is actually enhanced with the IVT. This demonstrates that a downsized engine can be utilized with an IVT driveline offering further fuel economy benefits.

EXTENDING IVT TO LARGER VEHICLES

The test vehicle is a Midi-Bus tested at 11,300kg with a two regime IVT originally designed for an SUV car. Torotrak have previously built and tested IVTs in heavy-duty vehicles. This experience suggests that an increase in the number of transmission regimes is required as vehicle weight increases. Figure 16 shows the number of regimes required to expand of IVT to larger on-highway commercial vehicles.

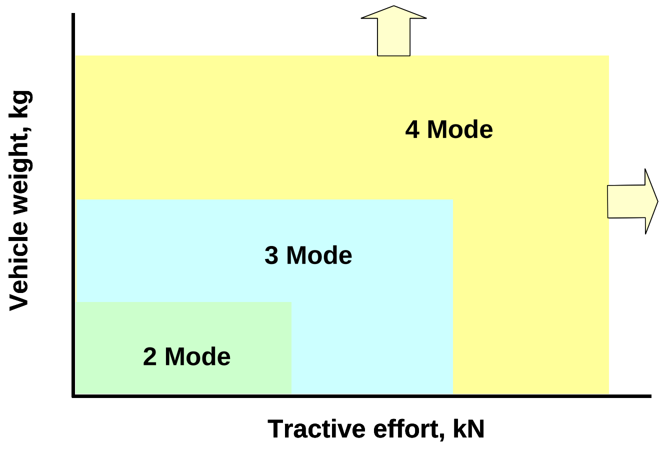

Figure 16. Extending the range of IVT

The relationship between the variator ratio and the overall transmission ratio is a design parameter, a typical relationship for a four regime IVT being shown in figure 17. This IVT retains all of the features previously described for the two regime transmission.

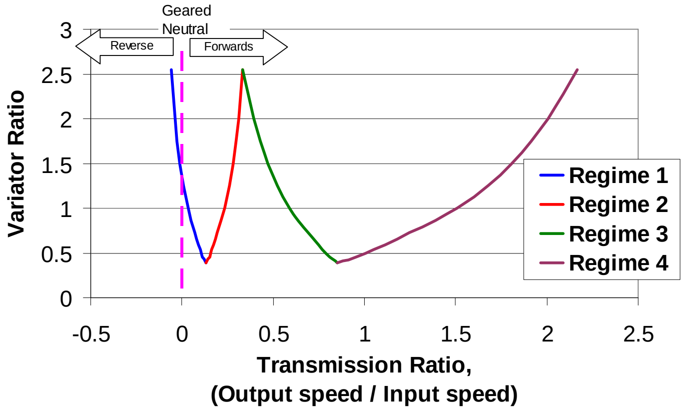

Figure 17. Variator ratio vs transmission ratio.

Increasing the number of transmission regimes above two allows the incorporation of a power-split architecture without significantly increasing transmission complexity. The same variator module can be utilized in the two, three and four regime transmissions. The increase from three to four regimes simply requires a small additional module to be added to the rear of the transmission. In this way a family of IVTs is easily created with high parts commonality.

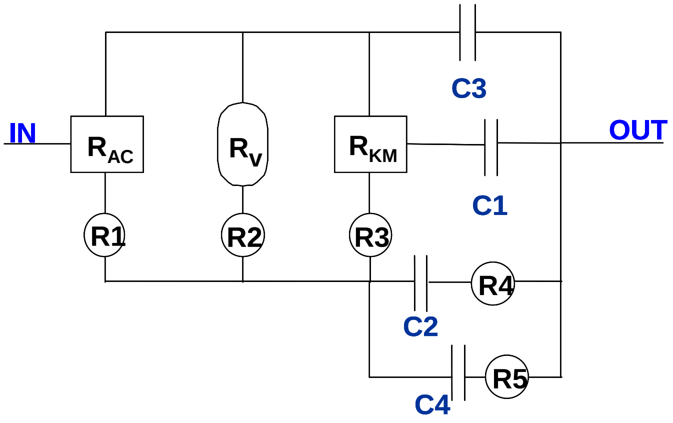

Figure 18. Power-split architecture of multi regime IVT

The power-split architecture 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. The power-split concept is shown in figure 19.

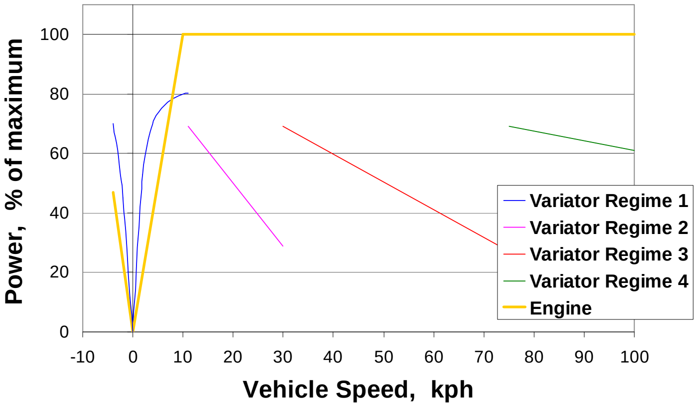

Figure 19. Power-split architecture of multi regime IVT

HYBRID COMPATIBILITY

This paper set out to demonstrate the ability of an IVT to provide fuel economy benefits approaching those achieved by hybrid drivelines in real world operation when a suitable balance between battery life and fuel economy is implemented, but with minimal on-cost and minimal disturbance to the existing powertrain and vehicle architecture.

However, 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. Therefore any combination of power, or torque, producing prime mover, or 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.

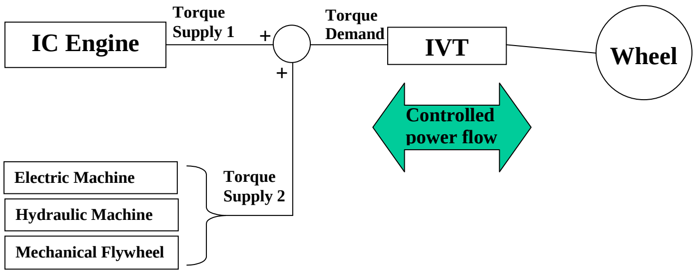

Figure 20. Incorporating IVT into a hybrid driveline.

CONCLUSION

This paper describes the operating principals of an IVT and how fuel economy is derived. Vehicle tests have been conducted with an Optare Solo European Midi-Bus with a gross weight of 11,300kg, provided by the Optare Group comparing the standard Allison 5-speed automatic transmission with a Torotrak IVT. The independently measured results demonstrate the ability of a non-optimized IVT (originally designed for a gasoline SUV car) to deliver a real world fuel economy benefit of 19%, enhanced vehicle performance and precise control of an engine to a desired operating condition.

These proven concepts offer the opportunity to bring new engine technologies to commercial vehicles.

An optimized IVT for a Midi-bus application offers fuel economy benefits approaching those achieved by hybrid drivelines in real world operation, but with minimal on-cost and minimal disturbance to the existing powertrain and vehicle architecture.

REFERENCES

[1]. Adrian P Lee, Jonathan Newall; "*Durability of a compact Dual-Cavity Full Toroidal Variator";* SAE 2004 World Congress; 2004-01-0353

[2]. Matthew Burke, Robert Oaten; *"Midi-Bus Infinitely Variable Transmission Retarder Deletion Study"*; SAE 2005 CommVec; 2005-01-3546

[3]. Matthew Burke, Graham Briffet, John Fuller, Hubert Heumann, Jonathan Newall; *"Powertrain efficiency optimization of the Torotrak Infinitely Variable Transmission (IVT)"*, SAE 2003 World Congress; 2003-01-0971

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