Full-Toroidal Variable Drive Transmission Systems in Mechanical Hybrid Systems – From Formula 1 to Road Vehicles

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1.   Introduction

As reported at the 2008 CTI Transmission Symposium in Southfield, Formula 1 is introducing hybrid drivetrain technologies for the 2009 race season.

In order to promote technical development into all potential hybrid solutions, the specification of the hybrid system has purposefully been kept open and simple; all that has been specified is that a defined amount of energy (400kJ) at a defined maximum rate (60kW) can be recovered and reapplied each lap. The clear intent is to direct motorsport developments to impact the key issue of fuel efficiency in mainstream on-road vehicles.

The outcome is a fresh investigation into hybrid architectures resulting in technical developments to achieve highly efficient, lightweight, compact hybrid drivetrain systems whilst providing the exhilaration a Formula 1 devotee craves via a "Push to Pass" boost system.

Torotrak is participating in the development of a mechanical Kinetic Energy Recovery System (KERS) which utilises the full-toroidal traction drive variator connected to a high speed flywheel. Following the FIA's (Federation Internationale L'Automobile – Formula 1's organising body) purpose of Formula 1 developing technology in racing for application in mainstream vehicles, the system has been developed from the racing design to a hybrid system suitable to volume production in mainstream automotive applications.

The paper describes the key elements of the Formula 1 KERS and discusses its extension to passenger cars and bus applications.

2.   Formula 1 Mechanical KERS

The Formula 1 KERS for the 2009 season is allowed to recover, store and reapply 400 kJ of energy per lap to and from the vehicle at a maximum rate of 60 kW. Although a relatively low power and energy recovery requirement given the quantity of energy dissipated by a Formula 1 car under braking, when one recognises that the existing ~550 kW engine remains unchanged, the safety implications of limiting an additional power boost are clear.

In addition, 60 kW is a significant quantity of power for a hybrid system to deliver to a road vehicle. Depending upon the automotive application, the energy storage quantity may be maintained at the 400kJ or increased.

The 400 kJ / 60 kW specification will remain for at least the 2010 Formula 1 season with discussions regarding downsizing the engine and running a higher specification KERS (e.g. circa 200 kW) ongoing for future seasons.

A Formula 1 car has similar requirements for a hybrid system as a road car – both vehicles require a rapid recovery of energy from the vehicle inertia, high efficiency in the transfer of the energy to and from the storage medium, high efficiency of the storage medium itself and delivered with high energy density in a small package with low weight.

As described at this conference last year, a mechanical storage medium of a flywheel connected via a variable drive to the vehicle driveline has advantages in weight, package, cost, performance degradation and overall efficiency to the incumbent battery / electric motor systems currently applied to road vehicles

To deliver a functional system to the F1 community, a partnership of three companies was generated comprising Flybrid Systems (an independent, innovative engineering company comprising Engineers from F1 who are developing mechanical hybrid technology including the flywheel), Xtrac (a specialist transmission supplier to the motorsport, aerospace and automotive sectors) and Torotrak as the CVT technology supplier.

The mechanical KERS comprises the Flybrid Systems' flywheel and the Xtrac sourced, Torotrak variable drive unit is shown below :-
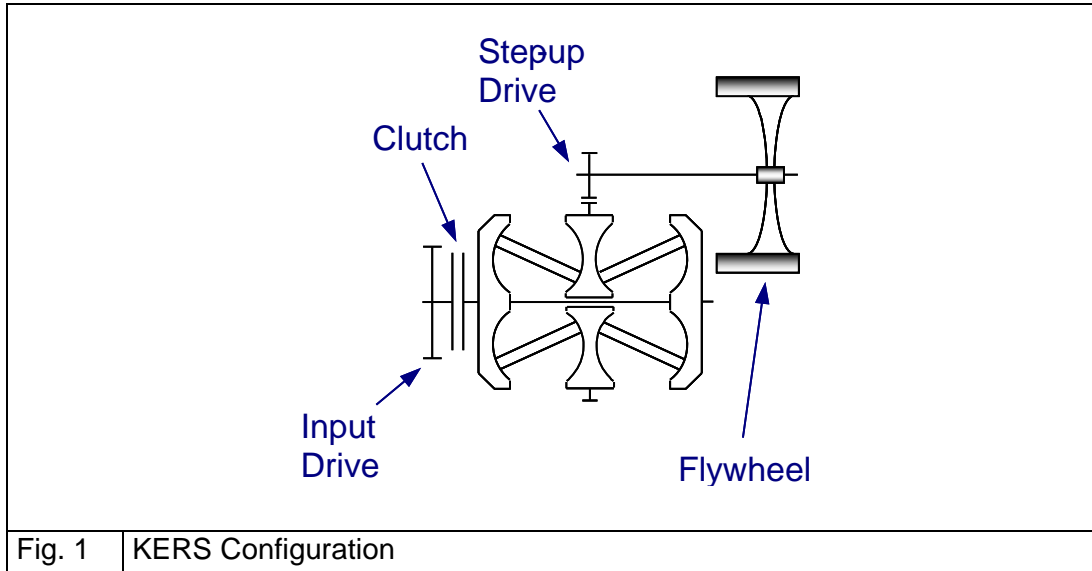
| Fig. 1 | KERS Configuration |

Reproduced courtesy of Flybrid Systems LLC

| Fig. 2 | F1 KERS – CVT and Flywheel |

The Flybrid Systems' Formula 1 flywheel comprises a carbon fibre filament wound rim surrounding a steel hub. Weighing in at circa 5kg with a diameter of 200mm and a length of 100mm, the flywheel spins at high speeds with an operating range of 64,500 rpm to 32,250 rpm. Operating in air would result in friction between the flywheel rim and the air causing both an efficiency losses and heating the carbon rim, potentially above its glass transition temperature. Therefore, the flywheel therefore runs in a vacuum and is enclosed within a housing that provides containment in the event of failure.

Total system weight for the flywheel, housing gear drives and CVT is less than 25kg.
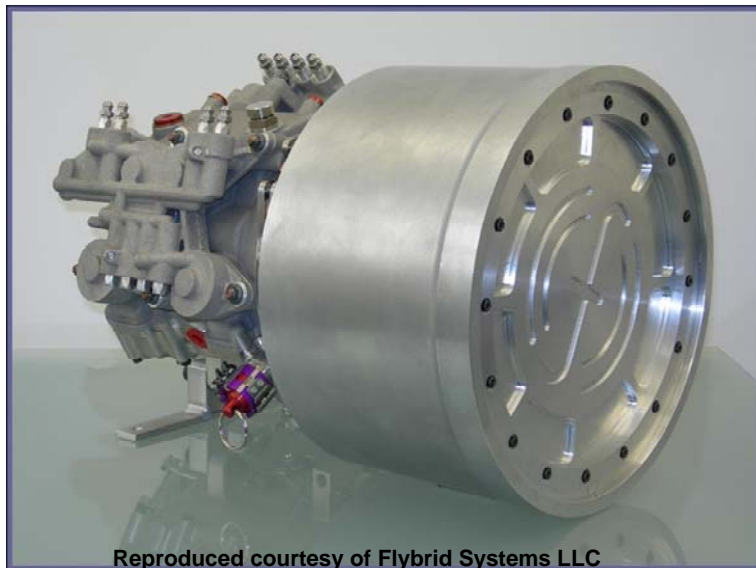
Fig. 3	: Formula 1 Mechanical KERS

3. KERS Transmission System

As the Torotrak variable drive system is torque controlled, the Variator transfers the energy to and from the flywheel irrespective of the speeds of the driveline of the flywheel. The familiar twin cavity "compact lever" roller control design of Torotrak's full-toroidal Variator is utilised producing a compact variable drive system.

The calculation process for defining the Torotrak Variator specification was described last year with contact stresses, temperatures and efficiencies compared together with the package requirements to determine the following specification :-

- Ratio spread = 6
- Twin cavity, 3 disc / 6 roller design
- Roller diameter ~ 55mm
- Disc diameter ~ 103mm
- Compactness ratio = 1.18
- Lever roller control design
- Disc and roller weight ~2.7 kg
- CVT weight ~5 kg

| Fig. 4 | Compact Lever Variator |

4. Road Car Applications

Flywheel energy storage systems for passenger vehicles are not a new concept – a number of systems have previously been developed with examples including a system by the Technical University of Eindhoven and another by Torotrak with Leyland Trucks which demonstrated a flywheel kinetic energy storage system in a bus in the 1980's. It is also possible to ride on a flywheel powered tram from Stourbridge Junction in England. Flywheel based systems are not without their areas requiring focus – most notably the containment of the rotating mass and the method of control and transmission of the energy to and from the flywheel – which have inhibited development and mainstream application. The FIA initiative has successfully 'kick-started' technical developments in these areas resulting in technical solutions to the previously viewed issues.

System efficiency is a key area where the mechanical hybrid system excels over the electric hybrid. Battery based electric hybrid systems require a number of energy conversions each with corresponding efficiency losses (e.g. mechanical to electrical energy, AC to DC, DC electrical energy to chemical energy in a battery). On reapplication of the energy to the driveline, the energy conversions are repeated. The result is a circa 31% to 34% round trip efficiency.

The mechanical hybrid system stores the recovered energy mechanically in a rotating flywheel hence eliminating the various energy conversions and providing a far more efficient

system. Measured round trip efficiencies for the mechanical system exceed 70% – twice as efficient as an electric system.

The first stage in developing a mechanical hybrid specification for mainstream automotive applications is to predict the potential fuel consumption reduction for a target application. A number of criteria (including the quantity of energy storage, the power transfer rate, ratio range of the system, etc) can then be optimised to determine the maximum benefit to the vehicle.

To simulate the benefit of the mechanical hybrid powertrain, a generic 2000 kg D / E class base vehicle specification was created comprising a ~200 kW / 400 Nm engine with a 7 speed DCT. Simulation of this vehicle over the NEDC and FTP 75 drive cycles provided the baseline for the comparison.

Regarding the flywheel operating speeds, either the F1 high speed / low mass and inertia flywheel (operating from 32,250 to 64,500 rpm) or a lower speed / higher mass and inertia flywheel can be utilised. The final specification of a flywheel for a mechanical hybrid system will depend upon a number of factors including overall package space, energy storage requirements, weight, vacuum requirements and containment system specification. However, for the sake of this study, an operating speed range slower than the F1 system but higher than previous flywheels has been assumed; namely 12,000 to 24,000 rpm. The 400 kJ of useable energy has been maintained resulting, for this study, in a flywheel with an inertia of 0.169 kgm².

Regarding the variable drive system, the F1 KERS full-toroidal variator of a 55 mm roller diameter with a ratio spread of 6:1 has been used. Although capable of higher powers over the ratio range (e.g. circa 110 kW at 1:1), the F1 power limit of 60 kW has also been assumed.

However, whereas the Variator in the F1 application can be used as a simple CVT with the ratio spread of 2 on the flywheel and 3 on the vehicle speed, for mainstream automotive applications the ratio spread requires extension. Assuming an operating range of the engine of 6 (1000 to 6000 rpm) and a flywheel ratio of 2, a total ratio spread of 12 is required. This is achieved by incorporating the variator into a mechanical shunt with a simple epicyclic gearset of basic ratio of 4.7 with :-

- The Sun gear is connected to the engine and variator input

- The Annulus is connected to the variator output

- The Planet Carrier is connected to the flywheel drive.

Driving the variator at engine speed (through a disconnect / start clutch) and matching the operating range of the flywheel to the engine, a step up gearing arrangement of 13.1 has been assumed comprising a two stage gear trains both with a ratio of 3.63:1.

| Fig. 5 | Assumed Driveline Layout |
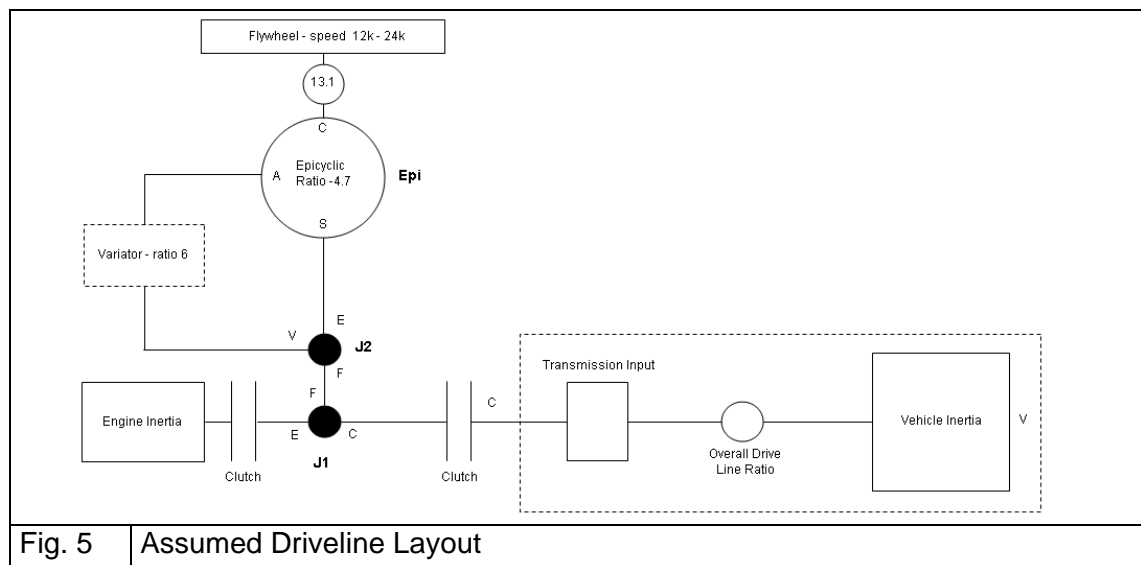
5. Road Car Simulation Results

The first item to note regarding the NEDC cycle is that the relatively low vehicle speeds and gentle accelerations and decelerations together with considerable time spent with the vehicle stationary and the engine at idle speed. Even though the engine delivers little power during these phases, it absorbs considerable energy overcoming its inherent motoring losses.

Figure 6 compares the energy dissipated by the engine overcoming its internal losses (Motoring) with the energy dissipated by the vehicle completing the NEDC cycle (Vehicle Drive). The first data pair (Engine Only) shows the energy balance for a conventional non-hybrid driveline. The low performance requirement of the vehicle means that 60% (9 MJ) of the total energy expended (15 MJ) is dissipated by the engines internal losses. The second data pair show the energy saved by the addition of regenerative braking (0.64 MJ) derived from the flywheel and the effect of switching the engine off when not required i.e. when the

flywheel is charging or discharging. Addition of the flywheel enables the marked reduction in the energy dissipated by the engine (3.5 MJ) resulting in a saving of 20 %.
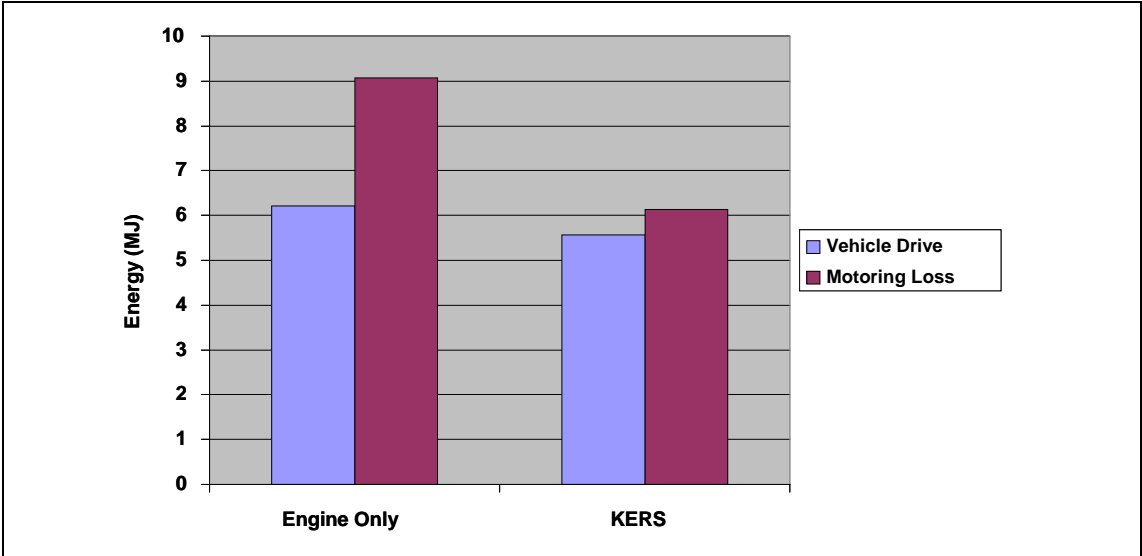

| Fig. 6 | NEDC – Energy Comparison With & Without The Flywheel Hybrid System |

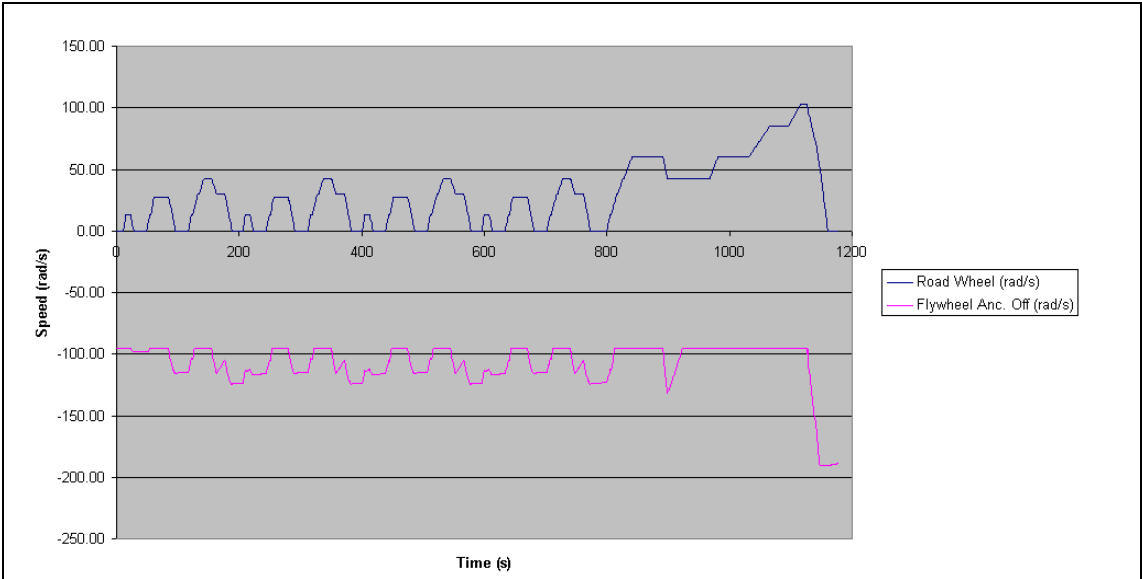Figure 7 plots the vehicle and resulting flywheel speed profiles for the NEDC cycle.

| Fig. 7 | Flywheel Speed Over the NEDC Cycle |

When converted from energy saving to fuel saving, a 30.2% fuel economy improvement results.

When considering the USA FTP 75 cycle, a similar result is achieved but due to the higher speed nature with more stop-start events, more energy and hence fuel is saved resulting in over 40 % benefit compared to the based vehicle.

| Fig. 8 | FTP 75 – Energy Comparison With & Without The Flywheel Hybrid System |

| Fig. 9 | Flywheel Speed Over the FTP75 Cycle |
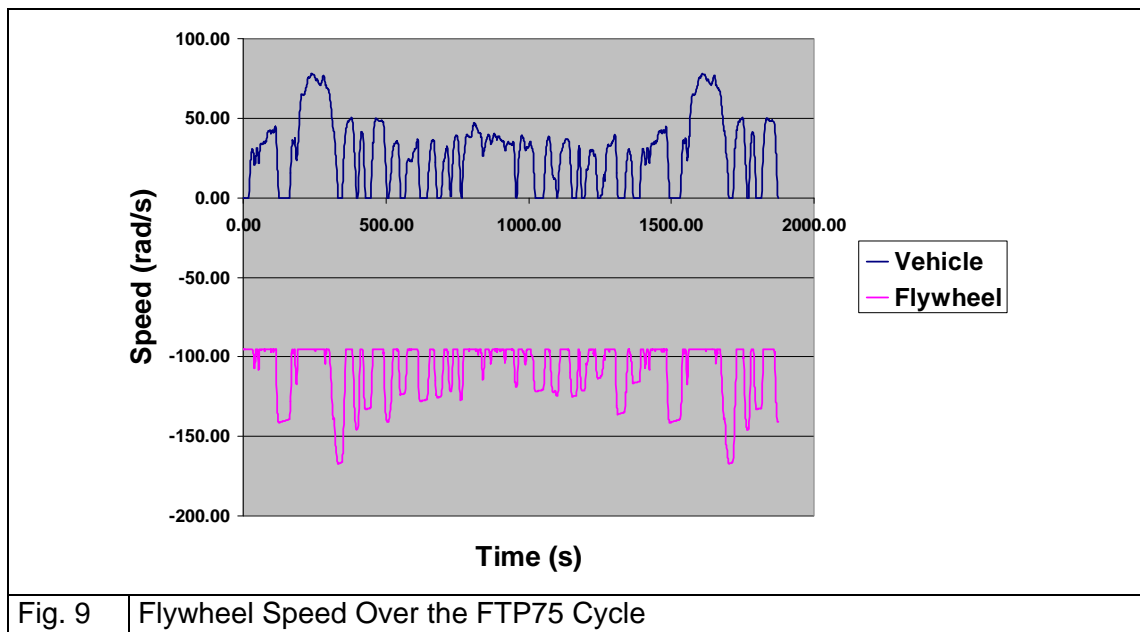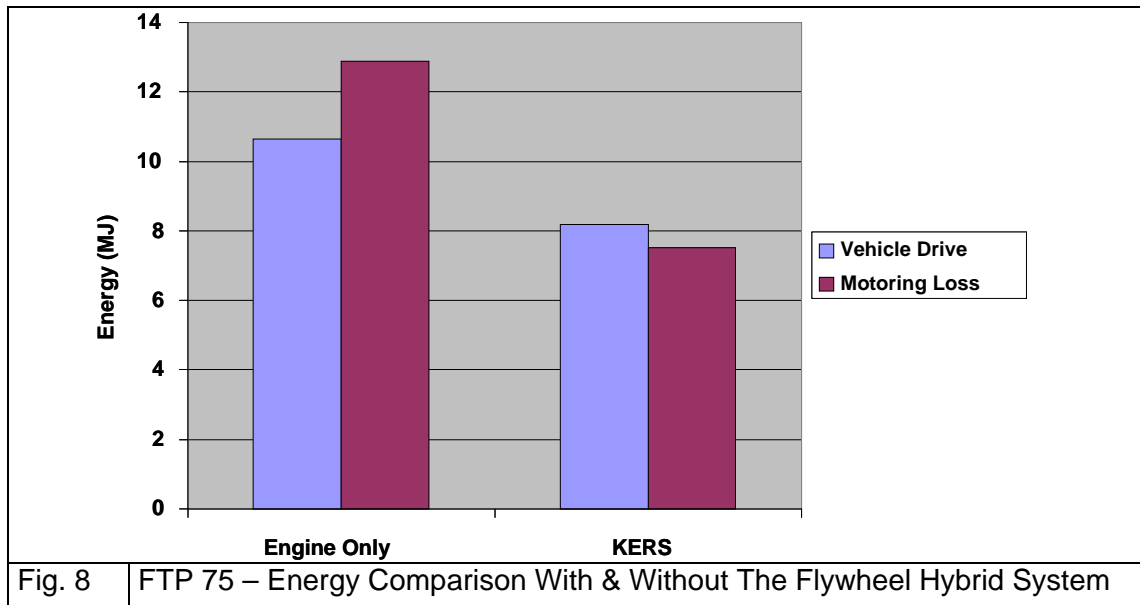
As discussed, the fuel economy is realised by saving energy by 'engine off' operation. The obvious downside of this is a situation common to all 'engine off' hybrid systems i.e. lack of engine driven ancillaries such as air conditioning or power steering. A particularly interesting point of the mechanical hybrid system is that the flywheel could be used to supply energy to these systems during the 'engine off' period. The fuel economy benefit is, of course, impacted but the ability to have fuel economy with full ancillary system functionality is a significant advantage of the mechanical system over other designs.

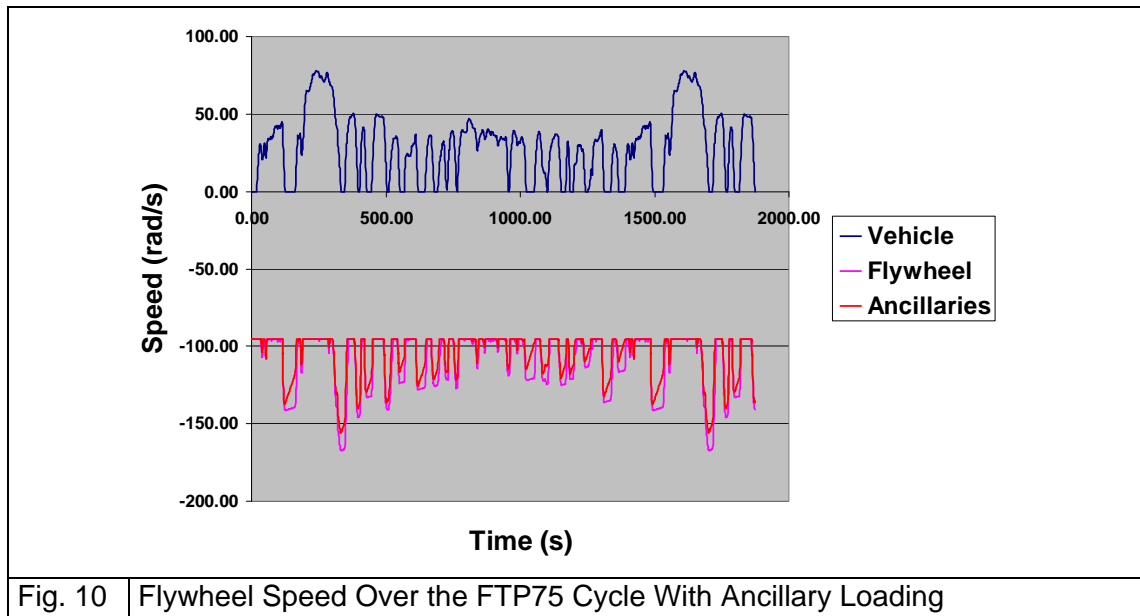Figure 10 describes the impact on the flywheel speed of also running typical ancillary loads.

| Fig. 10 | Flywheel Speed Over the FTP75 Cycle With Ancillary Loading |

The table below summarises the simulation results for both cycles with and without the ancillary loading.

Cycle	ENERGY		FUEL ECONOMY	
	Flywheel & Engine	With Ancillaries	Flywheel & Engine	With Ancillaries
NEDC	20.3%	9.9%	30.2%	16.2%
FTP75	30.6%	18.2%	42.7%	27.4%

6.   Bus Application

In many ways the city bus represents the best possible application for the KERS principal. High mass, relatively low rolling resistance and consistent stop start operation provide the greatest regenerative braking potential.

The model used for the road car analysis has been applied to a 'generic' 8500 kg 30 seat city bus driven by a 110 kW diesel engine through a five speed automatic transmission using a torque convertor as the engine coupling. The flywheel speed range has been retained at 12,000 rpm to 24,000 rpm but the flywheel inertia has been increased to 0.323 kgm^2 to enable storage of the kinetic energy of the bus when deceleration from 48 kph (30 mph). Flywheel power capacity has been assumed to replicate the engine allowing full vehicle

performance when powered by the flywheel. In fact the simulation shows a maximum stored energy equivalent to 75 % of this value implying only a 600 kJ capacity (50 % higher than the F1 unit) to be adequate.

The reduced speed range of the diesel engine (500rpm to 2500rpm) provides the opportunity to reduce the overall ratio spread of the Variator shunt to 9:1 with a consequent reduction in the recirculating power to 1.07 of the transmitted power (hence improving system efficiency).

The system torques have been reduced by increasing the Variator speed with a 3:1 drive ratio on the shunt input which allows the flywheel drive ratio to be reduced to 7:1. In this configuration the operating torque reaction seen by the Variator lies between 300 Nm and 500 Nm requiring a 75 mm roller diameter Variator.

The most significant difference between the bus study and the road car study is the presence of the torque convertor. Typical bus operation does not apply the lockup clutch until third gear. The resulting degradation in driveline efficiency would effectively prevent flywheel charge in the first two gears. However the flywheel acts as a constant power source at any transmission input speed. Fluid coupling torque multiplication is not therefore required. The transmission shift schedule is therefore modified to lock the convertor when possible and when operating on the flywheel at all conditions other than launch in first gear.

Given the power capacity of the flywheel and the inherent torque control of the Variator, this will neither reduce vehicle performance nor degrade driveline smoothness.

As for the road car application, it is essential to reduce parasitic fuel consumption by moderating engine operation while the flywheel drives. However the ancillary load for a large passenger vehicle is likely to be significant and must include a pneumatic load for brakes and suspension as well as air conditioning or heating. Engine drive of the ancillary load has therefore been assumed at all times. Flywheel operation will therefore disconnect the engine from the driveline but keep it operating at or near idle speed.

8. Bus Application Results

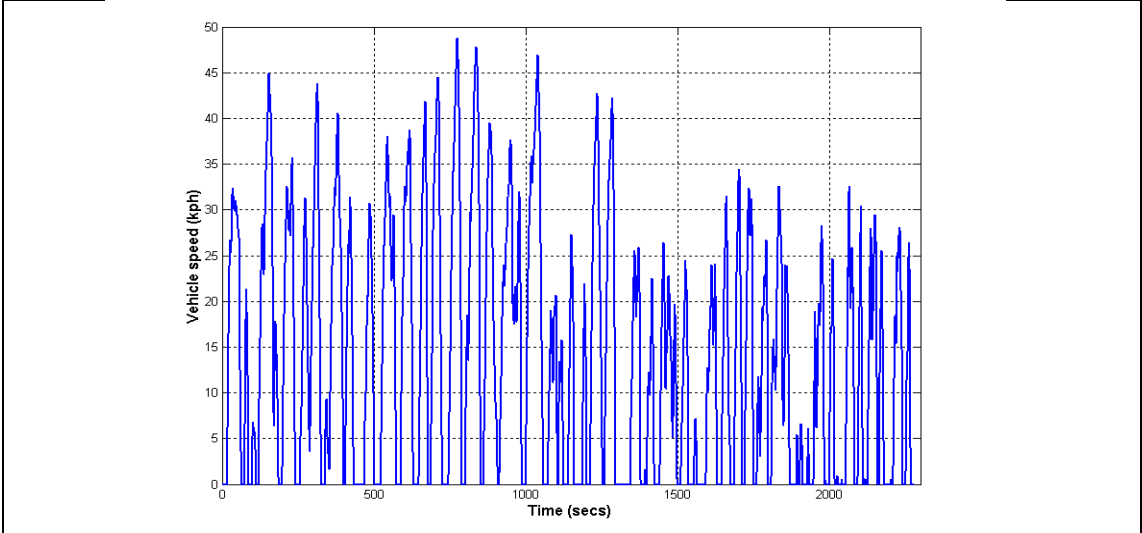The simulation has used the official UK 'MLTB '59' bus drive cycle

| Fig. 11 | MTLB 159 Bus Cycle |

The energy comparison plot shows that, unlike the road car application, the engine motoring loss of 15 MJ is significantly less than the energy supplied to the vehicle (26.5 MJ). Hence the energy saving due to energy recovery is significant at 36%.
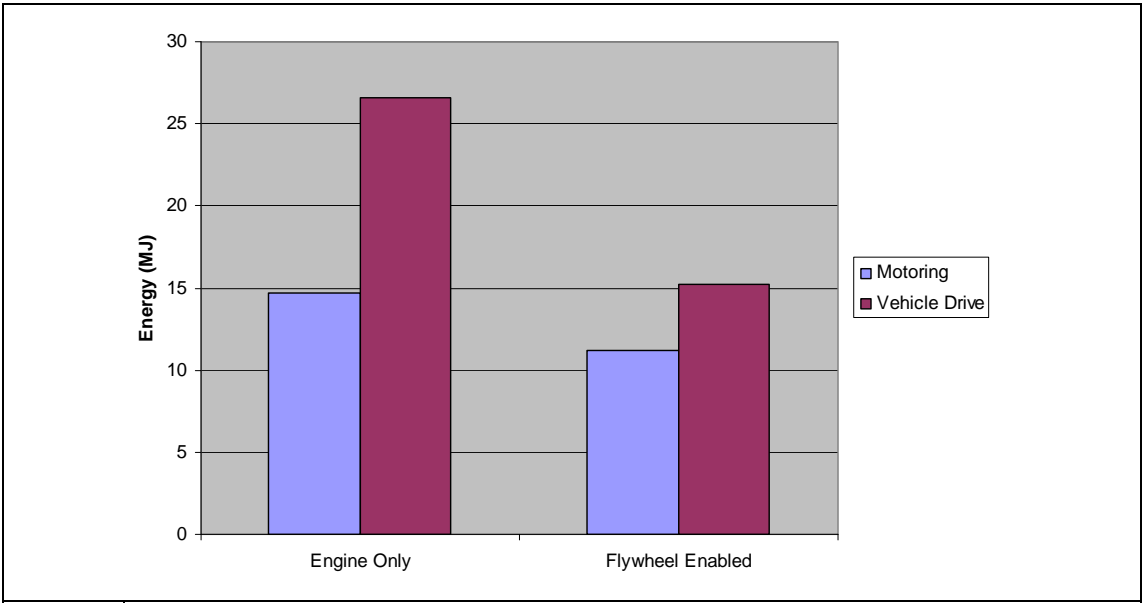

| Fig. 12 | MLTB 159 Energy Comparison With & Without The Flywheel Hybrid System |

Overall the 36% energy saving delivered by the KERS unit equates to a 34% fuel saving in the 8,500kg diesel engined bus application.
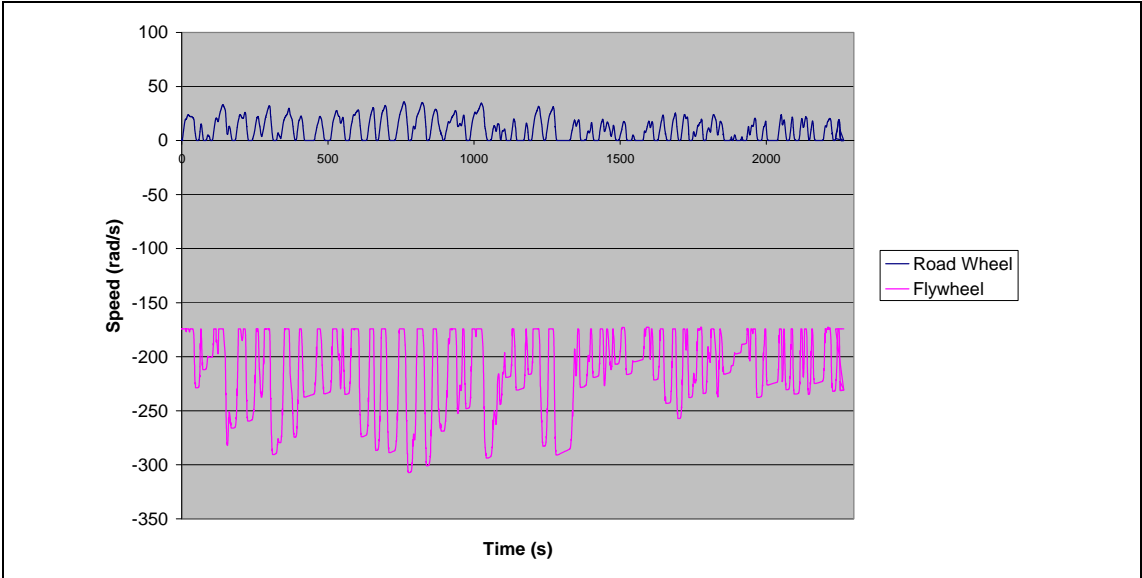

| Fig. 13 | Flywheel Speed Over the MLTB 159 Cycle |

9.   Summary

A mechanical hybrid has been realised providing 400 kJ at 60 kW for introduction in the 2009 Formula 1 race season. The system comprises a mechanical flywheel as the storage medium and a Torotrak full-toroidal traction drive system as the transmission.

The transmission is based upon Torotrak's standard automotive specification of materials and traction fluids and utilises a 5 kg, 55 mm roller diameter variator.

Mechanical hybrid systems for road car and bus applications are being developed as the energy, fuel economy and performance benefits, as well as the cost, weight and package advantages, of the mechanical hybrid are clear.

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