Formula 1 Mechanical Hybrid Applied to Mainstream Automotive

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Abstract:

Hybrid drive train technology focussing on Kinetic Energy Recovery Systems (KERS) will be introduced for the 2009 Formula 1 (F1) race season, with the clear intent of directing motorsport developments to impact the key issue of fuel efficiency in road cars.

The 2009 season specifications define a system that can recover, store and reapply 400 kJ of vehicle kinetic energy per lap at a maximum rate of 60 kW. In order to encourage technical innovation, the system type (electrical, mechanical or hydraulic), its weight and control strategy have been left undefined.

Torotrak are participating in the development of a mechanical KERS utilising a full-toroidal traction drive variator connected to a high speed flywheel. Although optimised against F1 competition, the system concept is capable of volume production in mainstream automotive applications.

The paper will describe the key elements of the F1 KERS and discuss its extension to volume passenger cars. The influence of energy capacity, limiting power transfer and control strategy upon fuel economy and vehicle performance will be examined using validated modelling techniques.

1. Introduction

Hybrid powertrains, which recover and reuse kinetic energy traditionally wasted via braking with the target of reducing fuel consumption and emissions, are universally viewed as an essential solution to the road transport sector. The majority of hybrid systems both in series production and under development are based upon electrical architectures with a variety of designs and storage media. However, converting mechanical energy to electrical energy and then to chemical energy and vice versa produces rather poor system efficiencies. In addition, the storage media, power electronics and motor / generators produce a complex powertrain with corresponding impacts on system cost, weight and package.

However, as alternative solutions have not been available, Engineers have focussed their efforts upon developing the electrical systems to improve both the physical as well as the commercial aspects.

An alternative to the electric hybrid powertrain is a mechanical hybrid system. A mechanical hybrid powertrain utilises a rotating flywheel as the energy storage device and a variable drive to transfer the energy to and from the vehicle driveline.

Flywheel mechanical hybrid systems offer advantages of higher efficiencies due to the removal of the energy conversions together with a significantly less complex system providing considerable weight, package and cost benefits over electrical systems.

Flywheel mechanical hybrids are not new and have been previously developed by a number of companies (Torotrak developed a flywheel hybrid powertrain in a Bus application in the mid 1980’s). However, concerns existed regarding the safe containment of the flywheel energy inhibited development and mainstream application. The FIA initiative has successfully kick-started technical developments in this area resulting in engineering solutions to the previously viewed issues so providing the opportunity to investigate the benefits of mechanical hybrid powertrain in modern mainstream automotive applications.

2. Formula 1 Hybrid Development

In July 2006, the Federation Internationale L’Automobile (FIA) announced draft regulations for the recovery and reuse of energy on F1 cars – in essence, promoting hybrid systems for application in F1 racing.

The FIA announcement was a culmination of discussions regarding the focus, direction and cost of technical development in F1 and the lack of relevance of these developments to mainstream automobile applications – particularly the continued focus on engine design to increase the maximum engine speed beyond the current level of 19,000 rpm level. The FIA firmly believe that motorsport, and F1 in particular, should provide excellent entertainment whilst promoting technology relevant to society by directing technical developments targeted at the key issue of fuel efficiency in road cars.

The Kinetic Energy Recovery System (KERS) was subsequently confirmed for introduction during the 2009 F1 season, specifying a system that can recover, store and reapply 400 kJ of energy per lap to and from the vehicle at a maximum rate of 60 kW. In order to promote technical development, neither the type of system (be it electrical, mechanical, hydraulic, etc), the weight of the system nor the strategy for reapplication of the recovered energy have been defined. However, one suggestion is that the hybrid system should provide a “Push to Pass” boost system providing 60 kW of boost for 6.67 seconds per lap (= 400 kJ) with the obvious impact on overtaking potential.

The 400 kJ / 60 kW specification can be viewed as a surprisingly low power and energy recovery requirement given the kinetic energy dissipated by an F1 car under braking. However, when one recognises that the existing engine remains unchanged (delivering well in excess of 550 kW in a vehicle weighing circa 600 kg), then the safety implications of an additional power boost of greater than 60 kW are clear.

Discussions regarding downsizing the engine and running a higher specification KERS of circa 200 kW are under way for the future and KERS is also being considered for other areas of motorsport including Le Mans for the 2009 season and potentially DTM for 2010.

3. Formula 1 KERS System Requirements

A Formula 1 car has similar requirements from 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

Delivered with high energy density in a small package with low weight.

However, one area that differs from hybrid road cars is the magnitude of the change in the “State of Charge” of the storage medium on a race car. Whereas road cars may strive to maintain a battery state of charge at 90 or even 95% to maximise battery life, a race car will charge and discharge the storage medium as much as possible due to the nature of racing. This can have a dramatic impact on the performance of battery based hybrids with potentially significant degradation of the operational efficiency of the storage medium over the race.

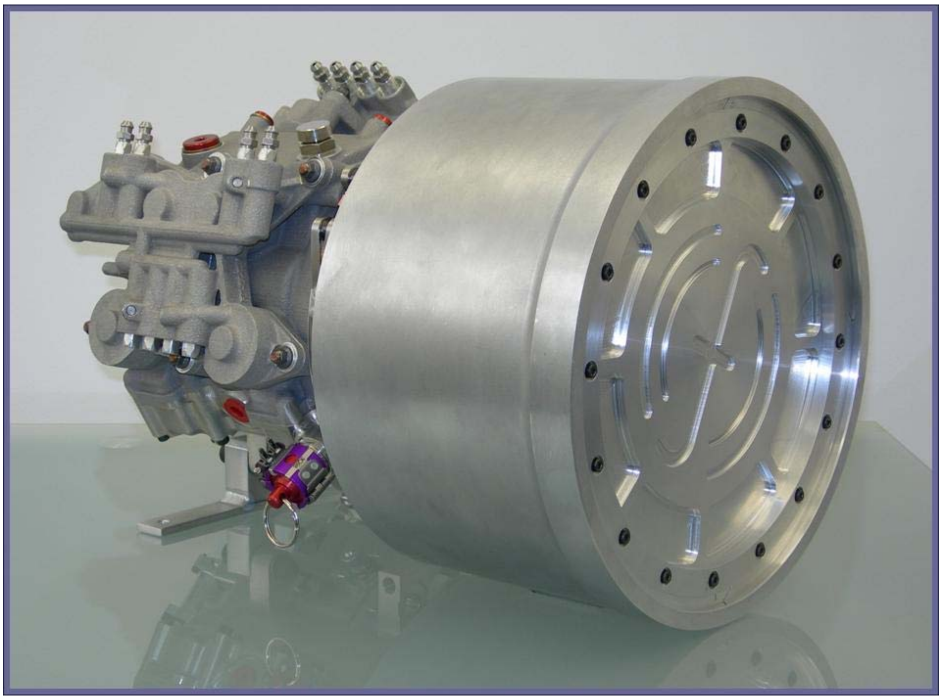
After reviewing the various alternative systems, including the prevalent battery / electric motor systems currently applied to road vehicles, the preferred solution to the request for hybrid drive for a number of F1 teams is a flywheel connected via a variable drive to the vehicle driveline. All of the other alternative solutions, from electrical to high pressure storage systems, suffered with issues of weight, package, cost, performance degradation and overall efficiency.

4. F1 Mechanical KERS System Specification

The mechanical KERS for the F1 application has been previously described [1] and consist of a high-speed flywheel comprising a carbon filament wrapped round a steel hub (developed by Flybrid Systems LLC) and a Torotrak full-toroidal traction drive CVT (produced by Xtrac Ltd). Weighing in at circa 5kg, with a diameter of 200mm and a length of 100mm, the flywheel spins at high speeds with an operating speed range of 32,250 rpm to 64,500 rpm, and hence operates in a very low vacuum of 1 X 10-7 bar. Sealing is of course critical to maintain the vacuum and Flybrid Systems have developed and patented a hermetic seal – a key to success for the flywheel design.

Safety is of course a primary concern, therefore the flywheel is enclosed in a metal housing that has already been successfully performance and crash tested.

Total system weight for the flywheel, housing gear drives and CVT is less than 25kg. As the system is active in discrete events for the F1 application, the system is connected into the driveline via a clutch.



Picture 1: Formula 1 Mechanical KERS

5. Comparison of Hybrid Systems for Road Car Applications

The advantages of a mechanical hybrid system over an electric hybrid system as identified in the Formula 1 application also apply to road car applications – namely efficiency, package, cost and lack of performance degradation.

Starting with efficiency, to store recovered energy a battery based electric hybrid system requires a number of conversions with corresponding efficiency losses:-

Mechanical energy into electrical energy (29%),

May undertake an AC to DC conversion (9%),

Electrical energy to chemical energy (10% +0.003% per minute).

To reapply the energy to the driveline, the above energy conversions are repeated. The result is a circa 31% to 34% round trip efficiency.

The mechanical hybrid system stores the energy mechanically in a rotating flywheel so eliminating the various energy conversions and providing a far more efficient system. Losses for the mechanical system can be summarised as:-

Gear mesh loss (1.5% per gear pair)

CVT loss (8%)

Parasitic losses (e.g. oil pumps – depending upon application 500W to 1 kW)

Flywheel storage losses (2% per minute).

Hence the flywheel system has measured overall round trip efficiencies of >70% – twice as efficient as an electric system.

The clear disadvantage of the mechanical system is the difference in storage losses when compared to a battery system – if medium to long term storage of energy is required a battery system is the preferred route. However, for stop-start driving in automotive applications, the 2% loss per minute has low impact.

The further advantage of eliminating the various energy conversions, together with the high energy density of the flywheel energy storage medium and the full-toroidal variable drive system, is a significant reduction in the system components and the corresponding packaging, weight and cost reductions.

Overall, comparing an assumed hybrid system, the mechanical hybrid provides twice the efficiency of an electric hybrid with half the weight, half the volume and an estimated quarter of the system costs.

6. Mainstream Automotive Applications

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 D / E class base vehicle specification was created comprising:-

2000kg vehicle weight

~200kW / 400Nm engine

7 speed Dual Clutch Transmission.

Simulation of this vehicle over the NEDC and FTP 75 drive cycles provided the baseline for the comparison.

For the mechanical hybrid the flywheel operating speeds, ratio spread and inertia require definition, as does the variable drive arrangement. Starting with the flywheel operating ratio, as the energy storage capacity of a flywheel varies as the square of speed, reducing the speed of the flywheel by 50% provides 75% of the available energy. Hence the operating ratio spread of 2 for the flywheel has been carried over from the F1 application.

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 400kJ 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, a full-toroidal variator of a size (55mm roller diameter) and ratio spread (6:1) as used in the F1 KERS has been assumed as a starting point. Hence, although capable of higher powers over the ratio range (e.g. circa 110kW at 1:1), the F1 power limit of 60kW has also been assumed.

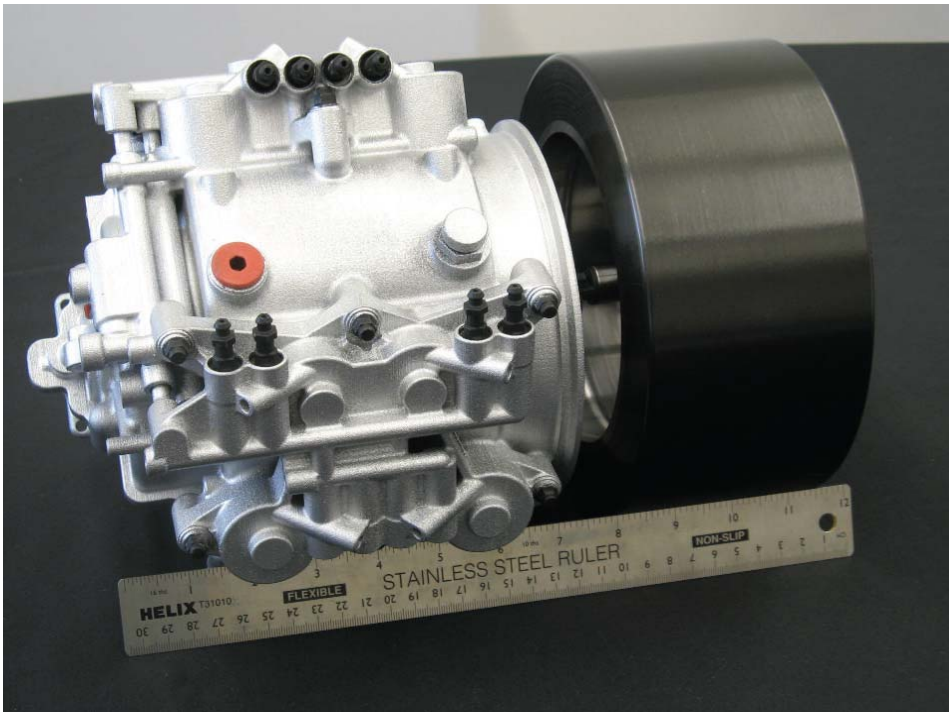


Figure 2 – KERS full-toroidal traction drive technology CVT and flywheel

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 where :-

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.

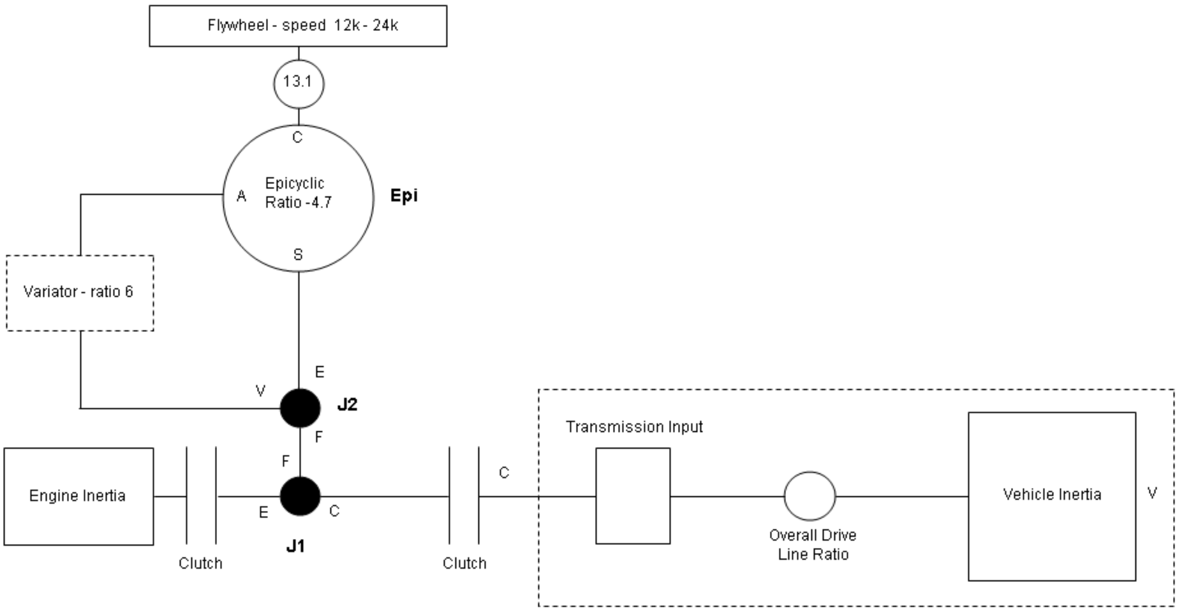


Figure 3 - Assumed driveline layout.

7. Simulation Results

For the simulation study, two cycles have been considered namely the NEDC and the FTP 75. The first item to note is the difference between the two cycles. The NEDC has relatively low vehicle speeds over the cycle with gentle accelerations and decelerations and 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 4 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 required of the vehicle means that 60% (9MJ) of the total energy expended (15MJ) is dissipated by the engines internal losses. The second data pair show the energy saved by the addition of regenerative braking (0.64MJ) derived from the flywheel. The engine is run over the complete cycle and so its internal losses are unchanged. The last data pair shows the effect of switching the engine off when not required i.e. when the flywheel is charging or discharging. Although it does not contribute directly to the energy saved (3.5MJ) the flywheel enables the marked reduction in the energy dissipated by the engines internal losses, hence a net saving of 20%. To put this into context, 9MJ dissipated over the cycle (1180 s) is equivalent to an average power loss of 7.6 Kw or the assumed engine loss at 1200 rpm.

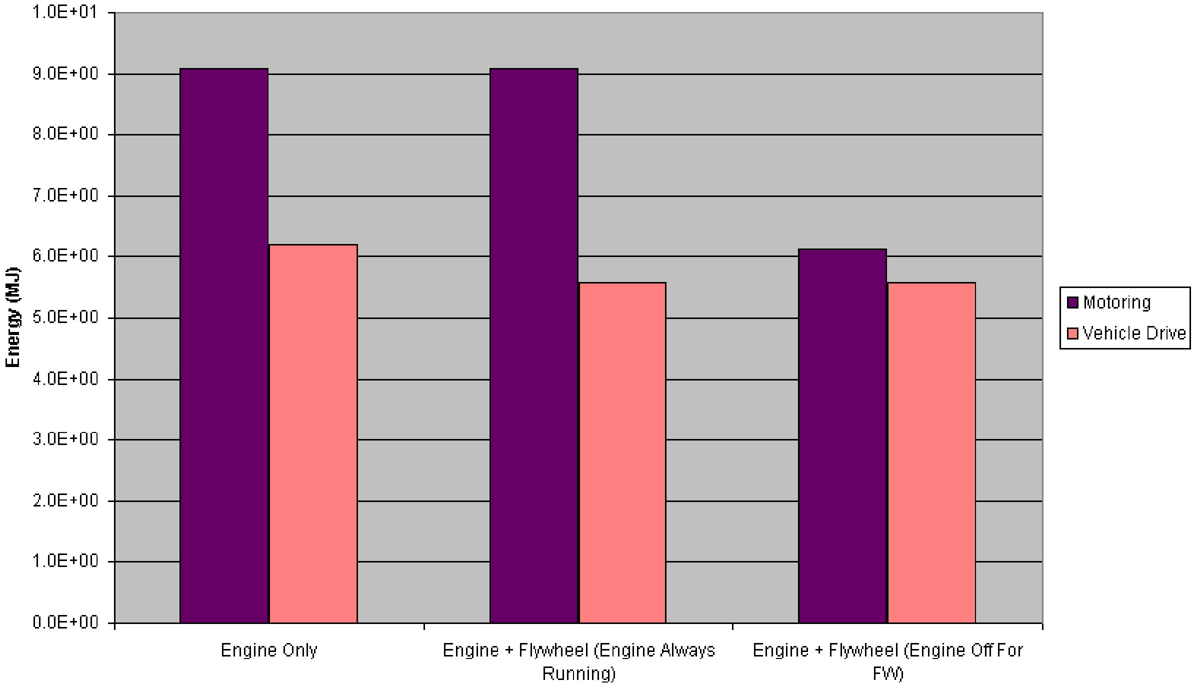


Figure 4 – NEDC – Energy Supplied By Engine

The same analysis applied to the Metro element of the FTP75 cycle illustrates the effect of a more aggressive speed profile – Figure 5. The greater energy dissipated by the vehicle provides more opportunity for energy savings from regenerative braking.(7%). But again the majority of the available savings (30%) is derived from limiting engine use.

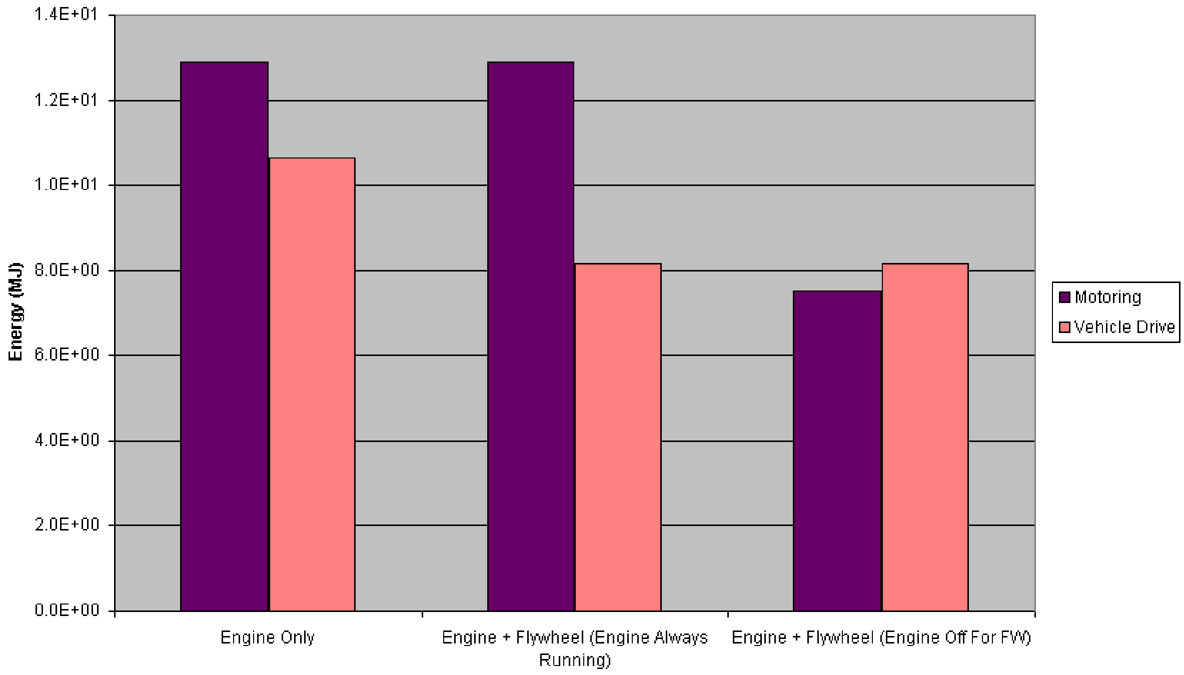


Figure 5 – FTP75 – Energy Supplied By Engine

Figure 6 plots the vehicle and resulting flywheel speed profiles for the NEDC cycle. It shows the relatively low energy levels stored by the flywheel contrasted against the high proportion of time available for engine off operation.

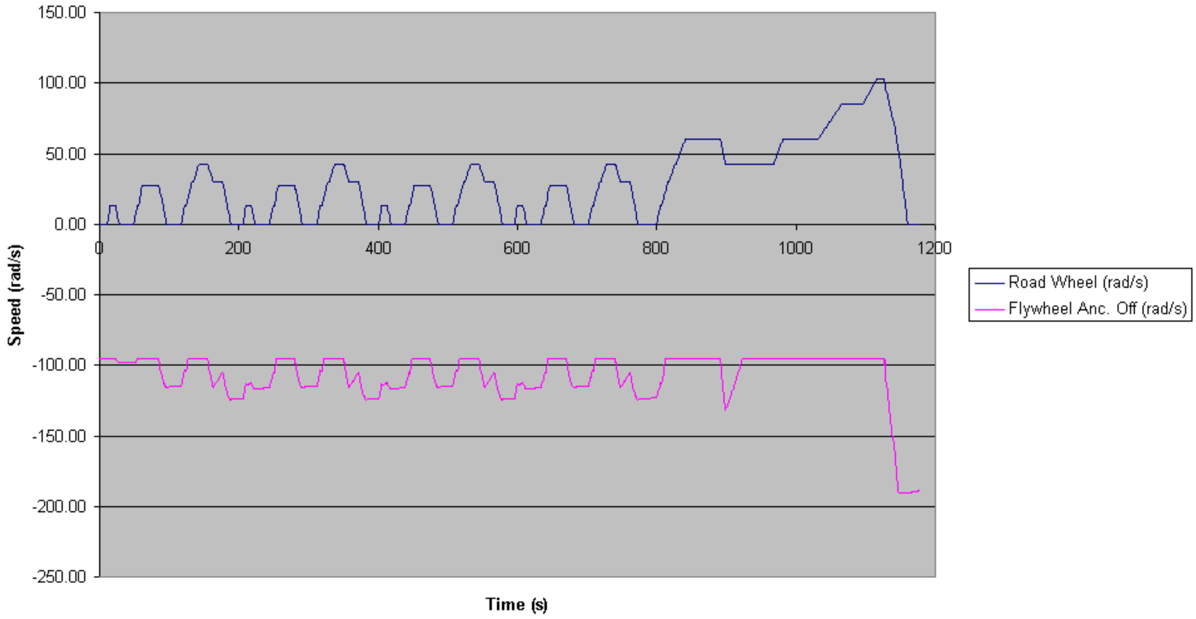


Figure 6 – NEDC Cycle

Heavy reliance upon the reduced usage of the engine requires the flywheel to power at least a proportion of the vehicles ancillary load. Figure 7 shows the assumed power split between air-conditioning and the rest. The 'air-conditioning' typifies the continuous element, the rest is assumed to be run with the engine. Figure 8 shows the Metro element of the FTP75 cycle plotted with the resulting flywheel speeds for ancillaries on and off. Adding the ancillary load caused the energy benefits to reduce from 30% to 18%.

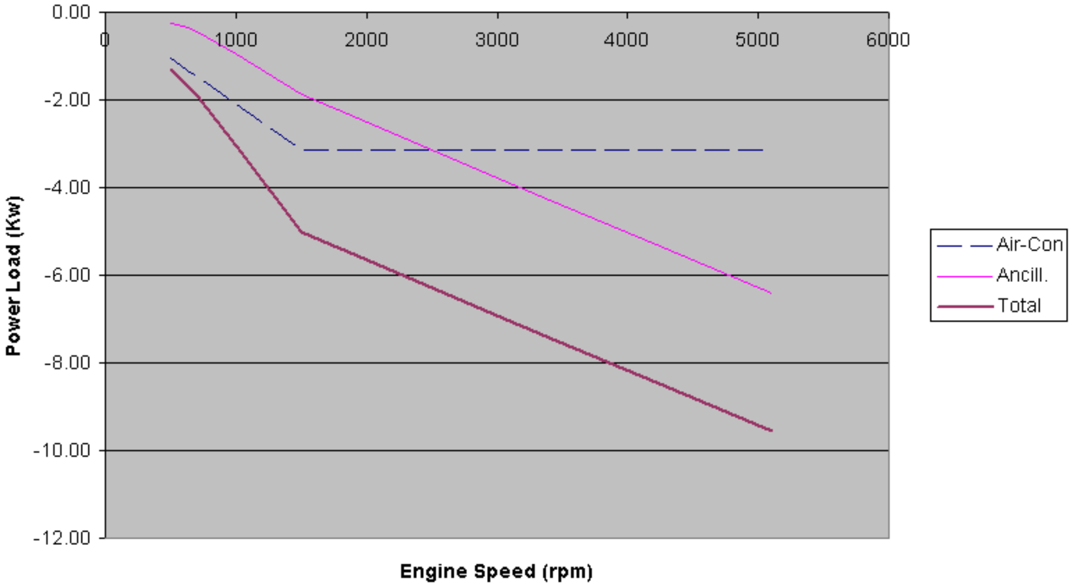


Figure 7 – Ancillary Power Load Split

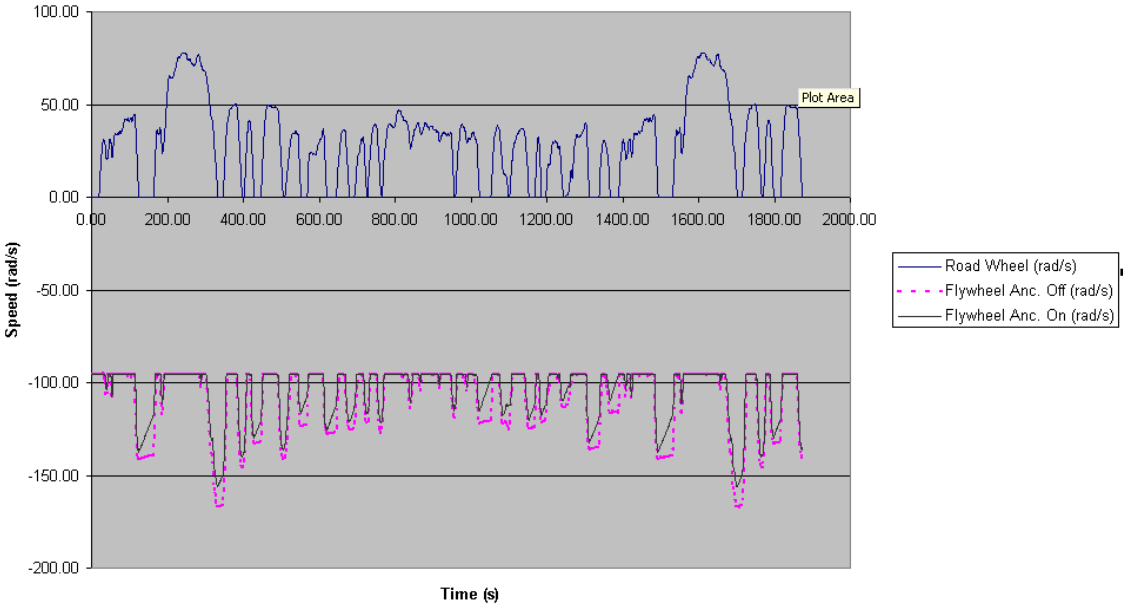


Figure 8 – FTP75 Comparitive Plot – Ancillary Load

Table 1 summarises the simulation results for both cycles. The assumed engine model was associated with a typical fuel map and the equivalent fuel benefits are listed.

	ENERGY			FUEL ECONOMY		
Cycle	Flywheel & Engine	Flywheel or Engine	With Ancillaries	Flywheel & Engine	Flywheel or Engine	With Ancillaries
NEDC	0.3%	20.3%	9.9%	0.4%	30.2%	16.2%
FTP75	7.2%	30.6%	18.2%	7.6%	42.7%	27.4%

Table 1 – Simulation Results Summary

8. Conclusions

The cycle simulations indicate the potential benefits available from a flywheel based hybrid driveline operating under various traffic conditions. Significant regeneration occurs under the stop-start speed profiles found in city and urban environments. Under these conditions between 20% and 40% economy benefits are achievable.

The drive train hybridisation outlined in this paper has resulted from the addition of simple mechanical elements configured as a self contained add on system. The engine, transmission and in fact the majority of drive controls remain unchanged. It has not required the introduction of novel, expensive or untried technologies.

The KERS concept was first conceived as a performance improvement enabling the ‘push to pass’ F1 facility. Given the flywheels high efficiency and power capacity this would equally available for automotive use. The obvious extension is to enable downsizing of the engine providing further improvements due to lower motoring losses. The system could be implemented with two modes – low speed regeneration (economy) and high speed performance improvement.

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 & traction fluids and utilises a 5kg, 55mm roller diameter variator.

Road car applications of the mechanical hybrid are being developed as the energy, fuel economy, efficiency and performance attributes as well as the critical package, weight and cost benefits are clear.

References

[1] Brockbank C : Full Toroidal CVT in a Mechanical Hybrid Configuration, 6th International CTI-Symposium "nnovative Automotive Transmissions", December 2007, Berlin, Germany