2009-01-1312

Mechanical Hybrid System Comprising a Flywheel and CVT for Motorsport and Mainstream Automotive Applications

Douglas Cross
Flybrid Systems LLP

Chris Brockbank
Torotrak (Development) Ltd.

ABSTRACT

Hybrid drivetrain systems focusing on Kinetic Energy Recovery Systems (KERS) will be introduced in Formula 1 for the 2009 season with the clear intent of directing technical developments in motorsport that will have an impact to the key issue of fuel efficiency in road cars.

The 2009 season specification defines a system that can recover, store and reapply 400kJ of energy per lap at a maximum rate of 60kW. 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 has been defined.

Flybrid Systems LLP have developed a mechanical KERS utilising a high speed carbon filament flywheel and a Torotrak full-toroidal traction drive Continuously Variable Transmission for use both within F1 and motorsport but also for mainstream automotive applications.

This paper describes the Formula 1 system and the development of road car systems covering the energy storage requirements, system efficiencies, energy savings and hence performance improvements.

INTRODUCTION

For the 2009 racing season, the FIA (Federation Internationale L'Automobile) have authorized hybrid drivetrains for Formula 1 racing with the clear objective of using the engineering resources of the Formula 1 community to develop hybrid technology for use not only in motorsport but also mainstream automotive applications. To this end, the specification of the hybrid systems has been kept to a minimum – in particular, the type of hybrid system has purposefully not been specified. This open specification has succeeded in its objective and has led to the study and development of various alternatives to the prevalent electrical hybrids.

With a focus on safety, the FIA have specified a limit on both the power rating of the hybrid system at 60kW and the quantity of energy transfer per lap at 400kJ. Although at first this appears a relatively small amount of power and energy with respect to the energy available in a vehicle slowing from over 200mph / 320kph at over 5'g', it is entirely appropriate when one considers the weight of the F1 car (~600kg) and the power already available (in excess of 550kW). Regarding the mainstream automotive sector, the 60kW / 400kJ figures readily transfer providing significant benefits when applied to road cars. In addition, the system can only recover, store and reapply vehicle kinetic energy – energy that would otherwise have been wasted under braking; i.e. the hybrid system cannot be 'charged' by the engine directly. This requirement has led to the designation of 'KERS' or Kinetic Energy Recovery System.

The system requirements for a hybrid for motorsport are very similar to a mainstream automotive applications namely :-

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

SAE Customer Service: Tel: 877-606-7323 (inside USA and Canada)
Tel: 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
SAE Web Address: http://www.sae.org

9-2009-01-1312

Printed in USA

- rapid recovery of energy
- high efficiency, energy density & power transfer
- cost-effective
- small package
- low weight and
- minimal degradation in performance over use

Given the 'open playing field' regarding system specification, the engineers reviewed all the potential hybrid systems architectures from the chemical battery / electric motor systems as currently used in Series Production by Toyota, Honda and Ford (amongst others) to the pneumatic or hydraulic high pressure storage systems that have been developed to flywheel based mechanical hybrid systems. Given the system requirements stated above, it became clear that the system which best met the specification was the flywheel based mechanical hybrid system – all of the other systems have major issues with either weight, efficiency, degradation and / or cost.

Application of a rotating mass or flywheel as an energy storage device is a particularly well developed technology being successfully utilised in multiple commercial applications including Uninterrupted Power Supply (UPS) systems for hospitals, military, NASA, IT / data centre, financial and air transport market sectors.

One leading UPS company state over 53 million customer "runtime-hours" achieved on UPS around the world with a 20-year useful life with no degradation in performance [1].

Integration of a flywheel into an energy recovery and reapplication device is a fairly well documented development; Torotrak's origins lie in Leyland Vehicles which developed and reported to the SAE and UK IMechE a flywheel hybrid Bus in conjunction with British Petroleum (BP) in 1985 [2], [3].

In addition, flywheel battery and hybrid developments have been reported to the SAE [4], [5], [6].

To date, although application of flywheel based systems to the mainstream automotive sector has not been achieved, both development and low volume systems have previously been developed by the Technical University of Eindhoven [7], and it is possible to ride on a flywheel powered tram from Stourbridge junction in England [8].

Therefore Flybrid Systems LLP, a company comprising former Formula 1 engineers, have developed a flywheel based mechanical hybrid system for use in motorsport and mainstream automotive applications.

On examining flywheel energy storage it was clear that for a sensible package space and weight, it was necessary to store energy by means of high speed, rather than high J value hence Flybrid Systems have chosen to develop high speed, relatively low inertia flywheels, with significant energy density. Flybrid flywheels are typically filament wound carbon fibre rims pressed over steel hubs.

To control and transfer energy to and from the flywheel, Flybrid Systems investigated numerous CVT options such as push-belt, hydrostatic, full electric, etc., which are all possible, but chose a Torotrak full-toroidal traction drive variable transmission unit for the Formula 1 application because of its high power density, torque based control system and easy scalability to different power levels.

Torotrak is a Research & Development company specialising in development of full-toroidal traction drive transmission technology for multiple applications ranging from low-power ancillary drive units through to multi-regime transmissions suitable for passenger cars, SUVs, buses, trucks and off-highway vehicles.

Although Torotrak's full-toroidal traction drive technology is normally associated with high torque automotive applications, first commercial launch of the technology has occurred in the USA in the Outdoor Power Equipment (OPE) market for domestic and commercial Ride-on Lawnmowers and garden tractors

Previously, Torotrak have demonstrated 20% fuel economy benefit from the full-toroidal traction drive technology in a twin regime 'Geared Neutral' Infinitely Variable Transmission (IVT) arrangement in a fleet of V8 powered Sport Utility Vehicles (SUVs) [9].

In addition, the disc and roller durability [10] and traction fluid developments [11] have been reported.

BACKGROUND

FLYWHEEL BASED MECHANICAL HYBRID

A kinetic energy recovery system requires two basic elements namely :-

1. a method of storing and recovering energy from the driveline
2. an energy storage medium

The well documented electrical hybrid systems utilise chemical batteries as the storage medium and electric motor / generator systems as the energy transfer and control media.

In contrast, the mechanical hybrid utilises a rotating mass (or flywheel) as the energy storage device and a variable drive transmission to control and transfer the energy to and from the driveline.

Kinetic energy recovery systems (KERS) store energy under vehicle braking and return it under acceleration. This is different from traditional hybrids in that stop start functionality is not a prime goal of the system. KERS work very well in conjunction with engine mounted Stop/Start systems, or can themselves be engine mounted and used for stop start functionality. The energy flow in a mechanical hybrid system is from the initial kinetic energy of the vehicle, through a series of rotating shafts and gears, and ends up as kinetic energy in a rotating flywheel. This method of storage obviates the need to transform energy from one type to another. For example, electrical KERS systems must take the vehicle kinetic energy, convert this to electricity using an electric motor, transform the electricity from one voltage to another and finally transform electricity to chemical potential energy in a battery. To return energy to the wheels for acceleration each of these processes must be reversed. Each transformation brings its own losses and the overall efficiency is poor compared to mechanical storage.

The transfer of vehicle kinetic energy to flywheel kinetic energy can be seen as a momentum exchange. Energy is drawn from the vehicle and supplied to the flywheel. In doing this, the speed of the vehicle reduces, (effectively this is braking), whilst the speed of the flywheel increases. At the start of braking, the vehicle has a high speed and the flywheel a low speed, giving a certain gear ratio between them. At the end of braking, the vehicle has a low speed, and the flywheel a high speed, so the ratio of speeds has changed. Examination of the energy transfer shows that the ratio between vehicle speed and flywheel speed necessarily changes continuously during the energy transfer event. See Figure 1.

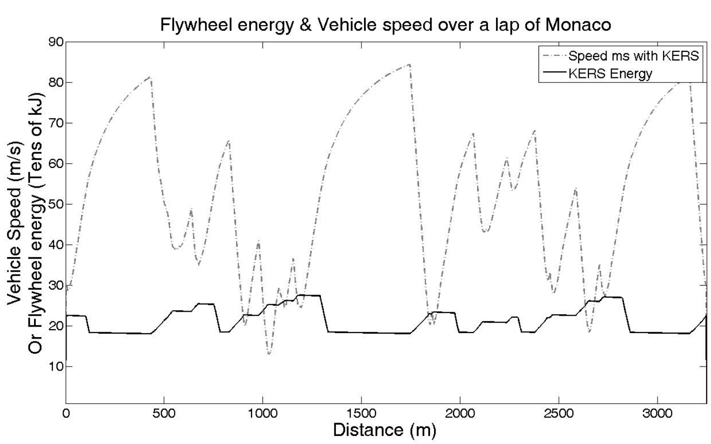

Figure 1: Vehicle Speed versus Flywheel Speed during a lap of Monaco.

To cope with the continuous change of ratio between Flywheel and road-wheels, a continuously variable transmission (CVT) is used. The energy transfer is caused by 'pushing' or 'pulling' on the CVT ratio: i.e. if the ratio flywheel speed / road-wheel is a known value, then forcing a higher ratio will tend to cause the flywheel to speed up, and thus the road-wheels to slow down, resulting in a transfer of kinetic energy. The same is true in reverse, so forcing a lower ratio will cause the flywheel speed to reduce and road-wheel speed to increase, so an energy transfer takes place which accelerates the vehicle.

The rotational or kinetic energy of the flywheel can be calculated using Equation 1 :-

$$E = \tfrac{1}{2} J \omega^2$$

where :-

E = Kinetic Energy(Joules)

J = Moment of Inertia of the rotating mass (kgm^2)

ω= Angular Velocity (rad/sec)

Rather than employ a solid flywheel, a filament wound carbon composite flywheel is utilised whose moment of inertia is defined in Equation 2 :-

$$J = \tfrac{1}{2} m \left(r_1^2 + r_2^2\right)$$

where :-

m = mass of the flywheel

r1 = outer radius of the flywheel

r2 = inner radius of the flywheel

The flywheel is connected to the vehicle by a Continuously Variable Transmission (CVT), and control of energy storage or recovery is managed by an electro hydraulic control system. A clutch allows disengagement of the device when not in use.

Figure 2 describes the system schematically :-

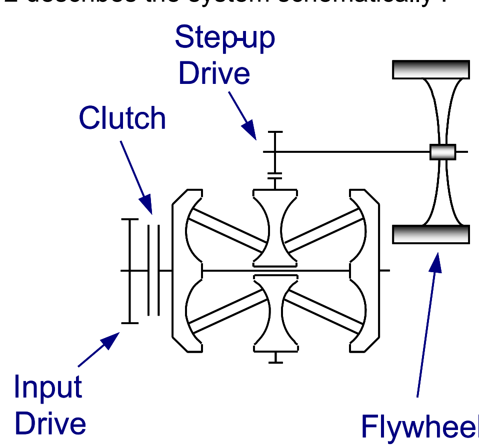

Figure 2: Schematic of Flywheel Hybrid System

THE FILAMENT WOUND CARBON FIBRE FLYWHEEL

Equation 1 shows that the energy in the flywheel is proportional to a single multiple of rotational inertia (hence mass and diameter) and the square of the speed in radians per second. In order to reduce mass and package size, it is possible to use high-speed low inertia flywheels to store as much energy as low speed high inertia flywheels. It is particularly mass efficient to do so because of the squared relationship of speed to energy.

Hence the Flybrid Systems KERS uses a light weight composite flywheel rotating at high speed. The flywheel comprises a carbon fibre filament wound rim surrounding a steel hub. At tip speeds greater than the speed of sound in air, the action of the flywheel rim against air will cause friction, and hence efficiency losses, as well as heating the carbon rim, potentially above its glass transition temperature. To optimise efficiency, the flywheel runs in a vacuum and is enclosed within a housing that provides containment in the event of failure.

Figure 3: Filament Wound Carbon Fibre Flywheel

The key enabling technology for allowing direct drive of such flywheels is a fully hermetic vacuum seal. This has been invented and patented by Flybrid Systems LLP.

THE FULL-TOROIDAL VARIATOR

The operating principle of the Torotrak full-toroidal traction drive Variator is described in Figure 4. The flywheel is connected to the input discs (1) and power is transmitted via the rollers (2) to the output discs (3). When the rotational velocities of the input and/or output discs change, the rollers automatically alter their inclination in order to adjust to the new operating conditions (4). Power transmission is achieved by traction, i.e. by shearing an extremely thin, elasto-hydrodynamic fluid film (traction fluid [11]) and not through metal-to-metal friction. Hence the name 'traction drive', which is defined in [12] as: “a power transmission device which utilizes hardened, metallic, rolling bodies for transmission of power through an elasto-hydrodynamic fluid film”.

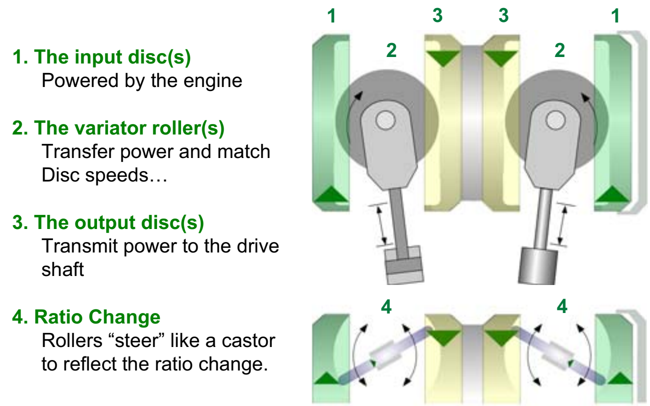

Figure 4: Full-toroidal Variator schematic

The Torotrak Variator is torque controlled in that the required system torque is set by applying hydraulic pressure to the pistons of the Variator and the Variator follows the ratio automatically [10].

Figure 5 explains this approach using a simplified single roller model in high regime. Applying a reaction force F to the roller causes a reaction torque (T_a and T_b) 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. The application of a castor angle to the roller carriages (Figure 6) enables the rollers to ‘steer’ to a new angle of inclination (ratio). This happens automatically – only the Variator disc speeds and reaction force are defined externally. In the Torotrak design, reaction force is applied hydraulically to individual roller carriage pistons.

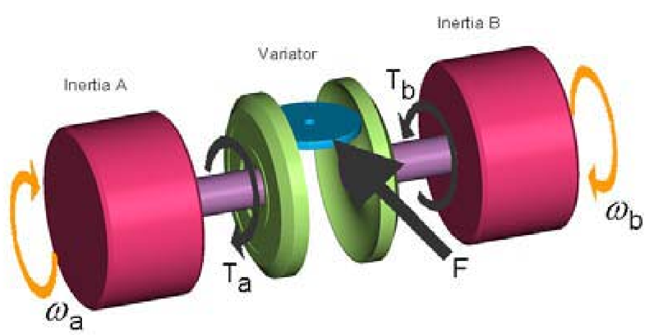

Figure 5: Principle of Torque Control

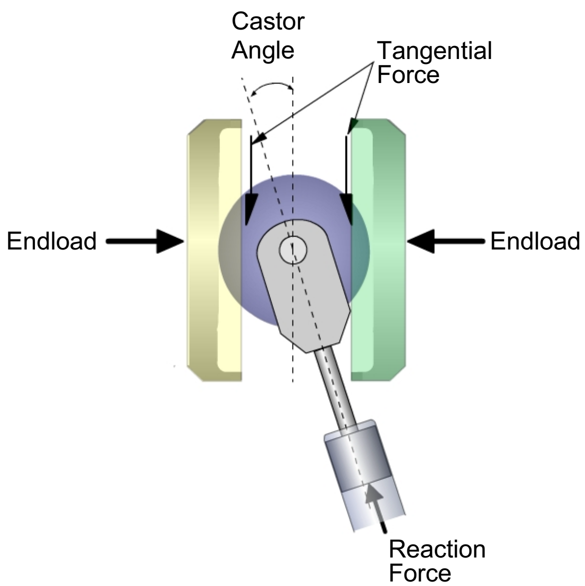

Figure 6: Variator Force Balance

FORMULA 1 KERS

The specification for the Flybrid Systems' Formula 1 KERS was finalised, and the system parameters are provided in Table 1 :-

Power	60kW
Energy Transfer	400kJ per lap
System Weight	25kg
Flywheel weight	5kg
CVT weight	5kg
Flywheel Diameter	200mm
Flywheel Length	100mm
Efficiency	> 70% round trip
Flywheel inertia	0.026kgm^2
Dynamic response	50ms
Flywheel max speed	64,500rpm
Vacuum pump	not required on the car
Hermetic vacuum seal	sealed when stationary and throughout the operating range

Table 1: Flybrid Systems Formula 1 KERS Specification

With the application of the high rotational speed of the flywheel, the mass has been significantly reduced from previous arrangements to only 5kg. The resulting system is delivered in a compact, power dense 25kg package.

The complete hardware for the flywheel based mechanical hybrid system is shown in Figure 7.

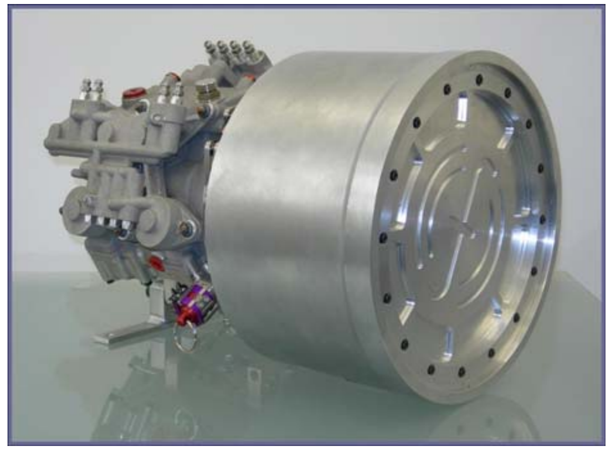

Figure 7: Flybrid Systems Mechanical Hybrid

KERS TEST PROGRAMME

With safety particularly in mind, Flybrid Systems LLP determined a test programme to ensure the following :-

- structural safety of the components
- flywheel containment in a crash or failure situation
- system response time
- system efficiency

The Flybrid Systems KERS has been designed from the outset as a safe system. Flybrid are extremely safety conscious, as a single flywheel failure has the potential to destroy the market for mechanical KERS systems. The base flywheel design provides protection from overspeed, loss of vacuum, shock loading, etc. and has been proven to Formula 1 standards for containment in the event of a failure (e.g. bearing or support failure) or from a crash. A 24'g' frontal impact test has been successfully completed at the end of which the flywheel was still spinning on its bearings at full speed. Full speed failure of the bearing system has also been proven after a bearing failure occurred at over 64,000rpm, with the flywheel being safely arrested using a Flybrid Systems LLP patented containment system.

With the safety aspects satisfied, before being combined on an engine driven test rig, the flywheel and CVT were individually tested to optimise the component efficiencies and the Flybrid developed control system.

The entire system was then dynamically rig tested with a V8 engine simulating the inertia of a Formula 1 vehicle and supplying the necessary power and energy – see Figure 8.

Figure 8: Dynamic Testing of the KERS

From the testing, two key items were determined namely a system response time of ~50ms was achieved (required by Formula One regulations) and system efficiency was measured at 86% one way (Storing energy to the flywheel) and 74% round-trip.

Hence, the flywheel based mechanical hybrid system has been realised, delivers high power density and system efficiency in a small package. The next step was to develop the system for automotive applications.

CYCLE EFFICIENCY MODELLING

The formula one system from Flybrid was rated at 60kW, and 400kJ of storage. These parameters transfer well to road vehicles, where the mass is usually much higher than a formula one car, whilst the top speed is typically much lower.

The benefit of a hybrid system is highly duty cycle dependent. In order to quantify the benefits of a Flybrid – mechanical hybrid, the US-FTP75 cycle was chosen. This is a standard duty cycle, used for regulating fuel economy measurement in the USA. This cycle is reasonably aggressive and so represents real world driving much better than the New European Drive Cycle (NEDC).

In Figure 9, we can see the speed Vs time trace of the US-FTP75 cycle. This is the cycle which will be used to determine the energy saving benefits of KERS.

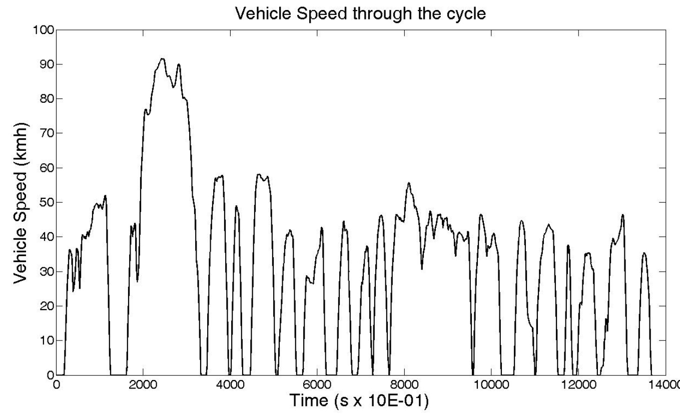

Figure 9: US-FTP75 cycle

The vehicle parameters used for simulation can be found in Appendix I. This vehicle speed can be converted into kinetic energy of the vehicle given the mass data found in Appendix I.

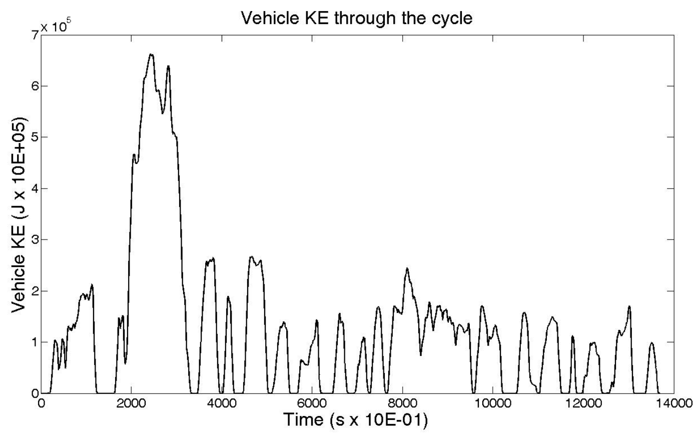

Figure 10: Vehicle Kinetic Energy over the FTP75 cycle

As expected, the kinetic energy profile is very similar to the speed Vs time profile.

To accelerate the vehicle, the energy required is the change in kinetic energy, plus the energy used to overcome losses such as aero drag, and rolling resistance of the tyres. Figure 11 is a graph of the change in energy with time through the cycle.

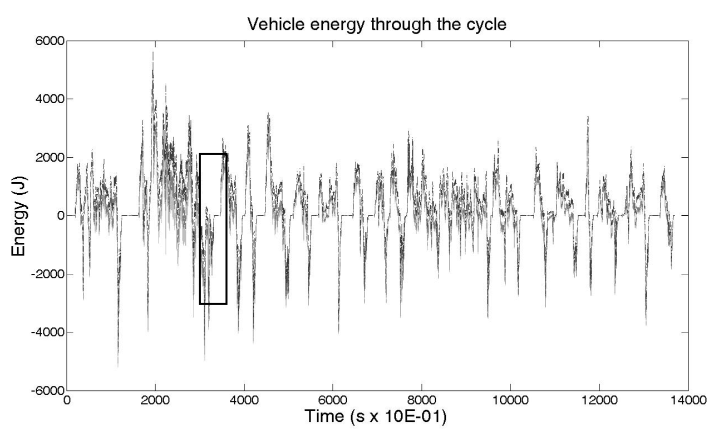

Figure 11: Change in Energy through the Cycle

Expanding a portion of Figure 11, it can be seen in Figure 12 that that the energy required to propel the vehicle along the velocity profile can be positive (acceleration) or negative (braking). Also, the total energy required to accelerate is ∆KE plus losses, but the energy available for recovery under braking is ∆KE minus losses.

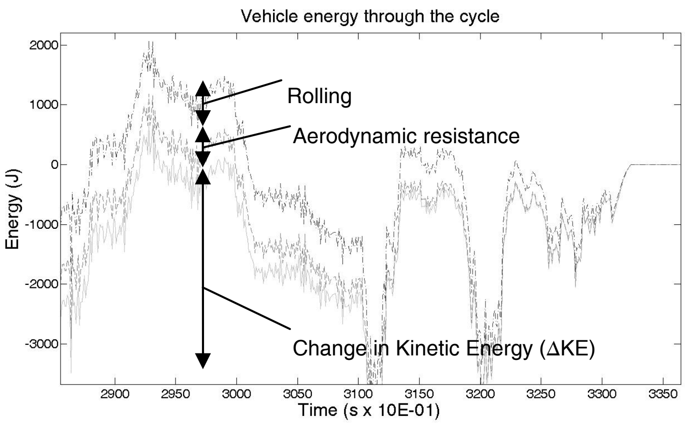

Figure 12: Energy Required to Propel the Vehicle

Figure 13 highlights the recoverable energy through the cycle.

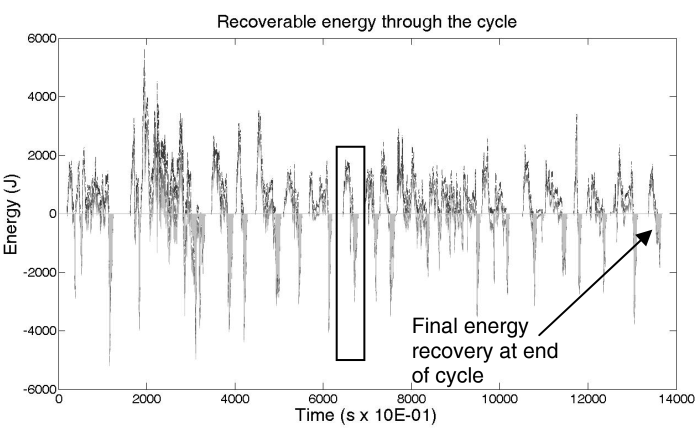

Figure 13: Recoverable Energy through the Cycle

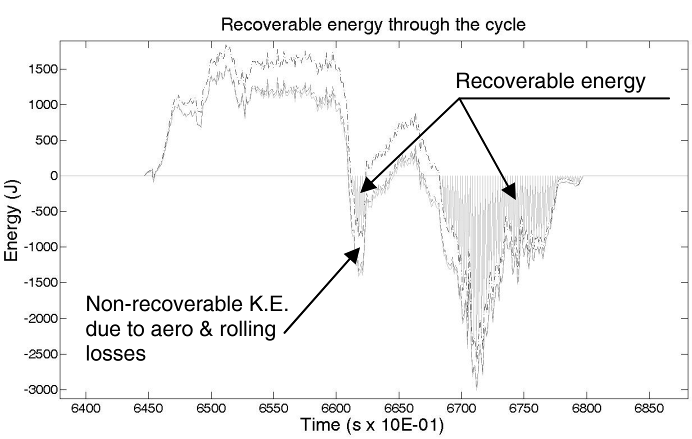

Figure 14 : Recoverable Energy - Expanded

Taking the sum of all of the positive energy in the cycle as the energy required to accelerate the vehicle, or maintain its velocity, and the sum of the shaded areas as the total recoverable energy under braking, we find that the sums are as follows :-

- Energy required for acceleration / maintaining velocity = 8.54MJ
- Energy available for recovery under braking = 2.59MJ

So, if we use the recovered energy to propel the vehicle the energy saving would be :-

- Energy saving = (2.59MJ / 8.54MJ) * 100 = 30.3%

However, we note that the energy recovered under braking is only useful if we can use it to re-accelerate the vehicle. Thus, the energy from the last braking manoeuvre, which brings the vehicle to a halt, can be stored but not used as the cycle has ended. See Figure 13.

The energy from the final braking phase is stored in the flywheel. This means that under this drive-cycle, we will start with zero flywheel energy and end it with a fully charged flywheel, i.e. Not a zero to zero state of charge.

A better method of assessing the benefits of hybrids is to consider a zero to zero state of charge across a cycle. This can be achieved by pre-charging the flywheel hybrid to the same state as it ends the cycle in. In this revised cycle, the energy stored under the final braking phase is considered as useful recoverable energy.

This also prevents a strategy of highly charging the flywheel and running it down through the cycle so that the state of charge at the end is lower than the state of charge at the start, hence using much less fuel.

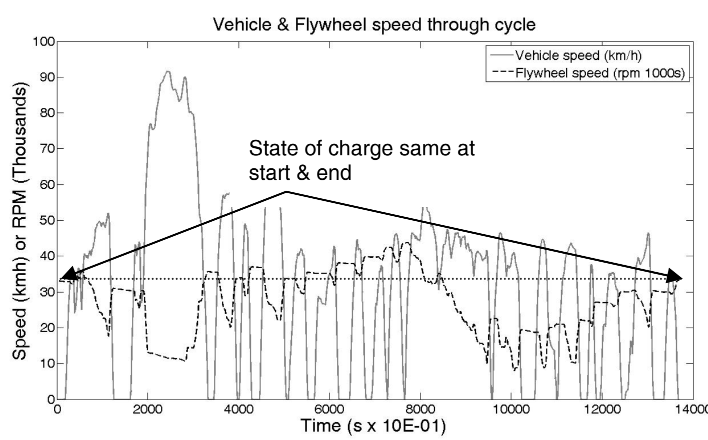

Figure 15 shows vehicle speed in km/h and flywheel speed in thousands of rpm versus time. It can be clearly seen that considering a US-FTP75 cycle with pre-charged flywheel, the flywheel has the same rpm at the start and end of the cycle, hence the stored energy is the same at the start and end of the cycle.

It should be noted that each time the vehicle decelerates, the flywheel speed increases, as energy is stored. Under acceleration, the flywheel speed decreases as it transfers energy back to the vehicle. At constant non-zero velocity the flywheel is powering the vehicle and so flywheel speed decreases. When the vehicle is stationary, the flywheel speed decreases with its own losses.

Using this strategy, we have already determined that the total amount of recoverable energy is 2.59MJ, and that this represents 30.3% of the energy required to propel the vehicle through the cycle.

Of course, this assumes that 100% of the energy can be stored and that 100% of this energy can be returned to the wheels without loss. Also, during the period that the vehicle is being powered by the recovered energy, the engine will still be turning, even if it is not required to provide power to the wheels.

Finally, the flywheel based hybrid uses a CVT transmission, which has a maximum and a minimum ratio hence the storage of energy is limited by clutch capacity when the CVT is not within its ratio limits.

ENHANCED SIMULATION

To more accurately simulate the energy savings, the following boundary conditions have been employed:

CVT Ratio:

- When the ratio of flywheel speed to vehicle speed exceeds the capacity of the CVT one of two clutches is slipped. Torque is still transferred, but at a lower efficiency due to clutch slip.

- If the CVT ratio is too low (Moving vehicle, stationary flywheel), the output clutch is slipped. This disengages the drive between vehicle transmission and CVT

- If the CVT ratio is too high (Stationary vehicle, rotating flywheel), the input clutch is slipped. This disengages the drive between flywheel and CVT

Results are presented in energy values instead of fuel consumption, as this method is independent of engine type, efficiencies between transmission and engine – such as torque converter slip – and manufacturer specific gear selection strategies.

RESULTS

The following results are calculated using the boundary conditions described above and consider a pre-charged cycle, ensuring no net gain or net loss of flywheel energy over the cycle (zero to zero). Calculations were made in 0.1 second time steps throughout the cycle.

The Flybrid power was set to a maximum of 60kW. Two clutches were used, one between the main vehicle transmission and the CVT part of the Flybrid unit. The second clutch was placed between the flywheel and the CVT.

Figure 16 shows how the change of vehicle energy (required / available) and the change of flywheel energy vary with time. Change of vehicle speed with time has also been plotted, so that it is clear if the vehicle is accelerating, decelerating, at constant non-zero speed or stationary.

Note that an increase in vehicle speed requires a positive energy change to the vehicle, but comes as a result of energy leaving the flywheel (negative change). To ease comparison of the differences between energy leaving the flywheel and arriving at the vehicle in Figures 16 and 17, the sign of flywheel energy change has been inverted (negative for positive and vice versa), giving it the same sign as vehicle energy change.

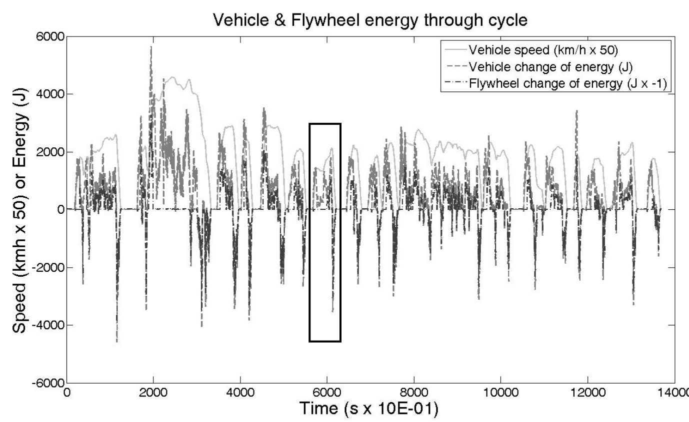

Figure 16 : Flywheel & Energy Change with Time

Figure 17 shows a close-up view of part of the cycle. It can be seen that under acceleration the change in flywheel energy is less than the energy required to accelerate the vehicle. This is due to the discharge strategy of the Flybrid system, i.e. the flywheel must discharge its energy combined with the prime mover, and not instead of the prime mover.

Under deceleration, it can also be seen that the flywheel energy change is less than the available vehicle energy under braking. This is due to efficiencies, as the Flybrid cannot store 100% of the available energy.

When the minimum or maximum ratio is exceeded, it is necessary to transfer energy through a slipping clutch. This is less efficient than when the clutch is not slipping.

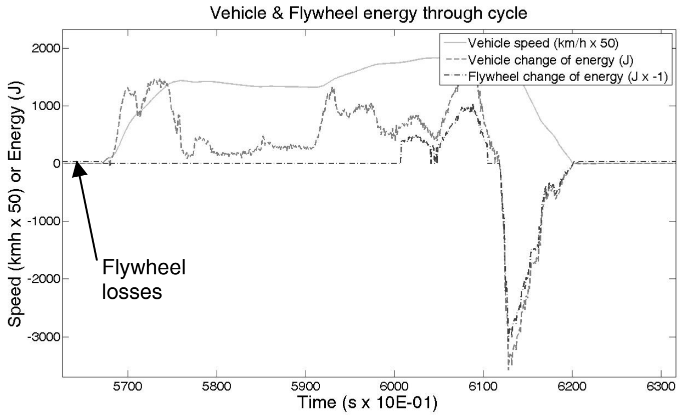

Figure 17 : Flywheel & Energy Changes – Expanded.

When the vehicle is stationary, and the flywheel is rotating, the drive between flywheel and CVT module is disengaged. The flywheel then slows down with bearing and seal friction losses. This is shown in Figure 17, as the flywheel has a change of energy even when the vehicle is stationary.

Given that the vehicle speed and the flywheel speed are known throughout the cycle, we can display the speeds on the CVT input and output discs and examine the working envelope.

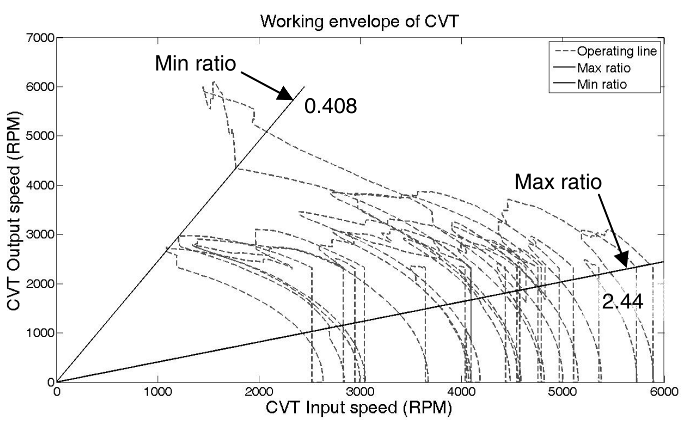

Figure 18 : CVT Ratio Envelope.

Figure 18 shows a graph of CVT input speed versus CVT output speed. The CVT input is connected to the flywheel via the epicyclic gear set. Thus CVT input speed is Flywheel speed divided by the epicyclic ratio.

The CVT output is connected to the vehicle transmission at the transmission output shaft, and so is a direct function of vehicle speed. Also shown in Figure 18 are the limits of CVT ratio.

It is clear from Figure 18 that the Flybrid system spends a reasonable proportion of the cycle outside of the CVT ratio limits, i.e. below the minimum ratio of 0.408, and above the maximum ratio of 2.44. This means that the clutches are used quite often during the cycle.

Note also that the vertical lines coming from the bottom of the figure represent an increase in vehicle speed, with little or no energy being supplied by the flywheel. This is due to the Flybrid operation strategy which deploys the flywheel energy only after a certain speed is reached.

Figure 19 shows what happens to the total of 3.56MJ of kinetic energy that are available for storage when the vehicle is decelerating.

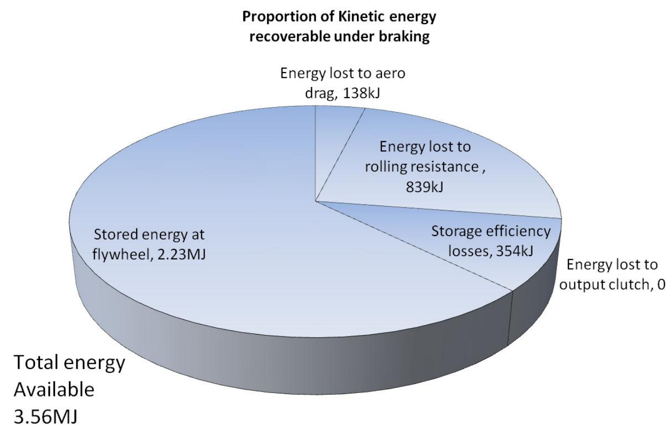

Figure 19 : Proportion of Energy Recovered (J)

We can see that some energy is lost to aero and rolling resistance, and is therefore not recoverable. Of the remaining 2.58MJ of recoverable energy, some is lost when the clutch is slipping and some is lost due to the inefficiency of the Flybrid system. A grand total of 2.23MJ make it through to the flywheel over the course of the US-FTP75 cycle.

In Figure 20, we can see what happens to this stored energy under discharge conditions.

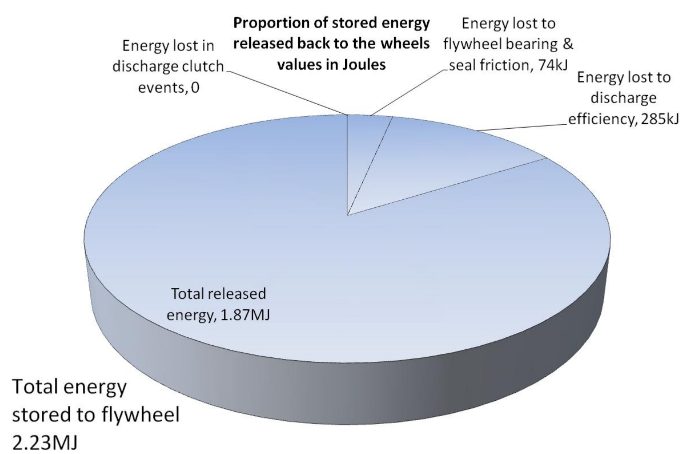

Figure 20 : Proportion of Energy Reapplied (J)

Some of the energy is lost in flywheel bearing and seal friction when the flywheel is spinning but not powering the vehicle. No energy is lost in the input clutch, as it always has enough clutch capacity to transmit the power required, hence there is no slip.

Some energy is lost in discharge efficiency of the Flybrid system. A total of 1.87MJ is released back to the vehicle.

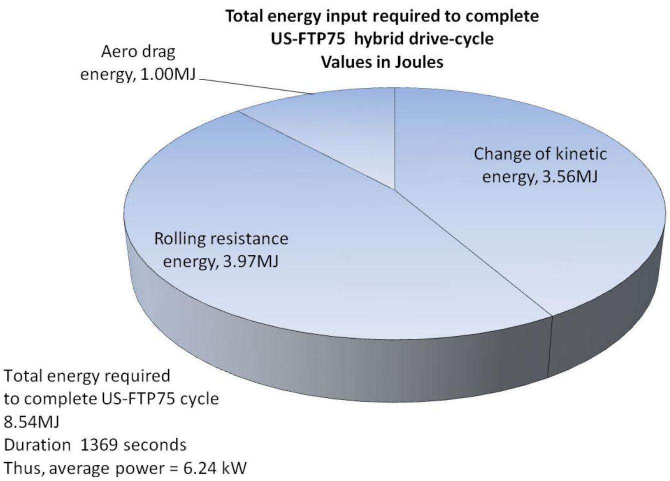

Figure 21 : Total Energy Required for the FTP75 (J)

Figure 21 shows how much energy is required to complete the US-FTP75 cycle. We can see that under acceleration we must provide enough energy to make the change in kinetic energy of the vehicle. Also, the aero losses and rolling resistance losses are working against us through the cycle, so we must provide enough energy to overcome these losses. The total amount of energy required to complete the cycle is 8.54MJ.

The test duration is 1,369 seconds, so the average power required to complete the test is 8.54MJ / 1,369s = 6.24 kW.

Of the 8.54MJ required to complete the cycle, the flywheel is able to supply 1.87 MJ which equates to 21.9%.

These results are dependent on the strategy used for storage and recovery of energy. When flywheel energy is reapplied to the car in order to accelerate it, it can be either used in place of engine power or combined with it. Thus the proportion of flywheel power used to accelerate the vehicle can vary from zero (hybrid switched off) through 50% (half hybrid, half main vehicle engine) to 100% (vehicle engine is switched off).

Also, the speed at which the hybrid begins to return energy can be varied. There is an advantage to returning kinetic energy when the vehicle is accelerating. In this operating condition the engine will normally use acceleration enrichment of the fuel map and so burn disproportionately more fuel. The peaks of fuel usage come when accelerating but also vary with speed. For example, more kinetic energy is required to accelerate the vehicle from 29km/h to 30km/h than is needed to accelerate from 28km/h to 29km/h, because kinetic energy varies with the square of speed. Thus, returning kinetic energy to the vehicle at low speed will save little fuel, since little was being used.

To investigate the potential variability of energy savings with strategy, a sweep of two variables was undertaken. Both proportion of flywheel energy to engine energy and minimum speed for introduction of hybrid power were investigated.

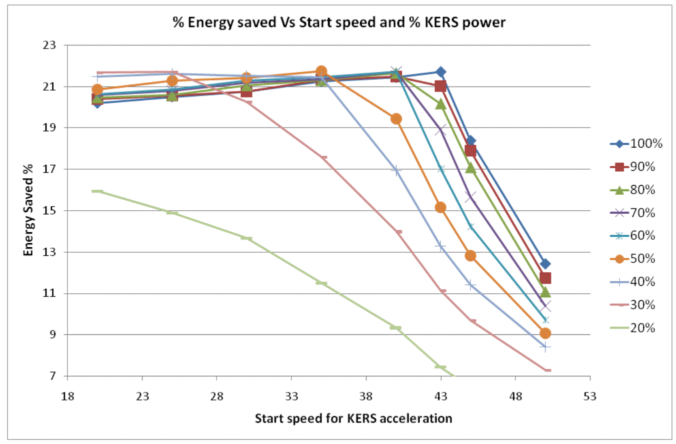

Figure 22: Variation of Energy Saved with Varying Strategy

On the horizontal axis of Figure 22, the start speed for KERS acceleration is shown, whilst on the vertical axis the percentage of energy saving is shown. A number of lines of constant KERS power proportion are shown plotted against these two axes.

With the exception of 20% KERS power, it is clear to see that all KERS power proportions reached a similar peak of energy saving at around 21%. The lowest KERS power proportion at 20% does not achieve significant energy savings as it is often not able to return all of its energy to accelerate the vehicle before the next braking period.

It can also be seen that the peak energy saving occurs at successively higher starting speeds with increasing KERS power proportion. For each KERS power proportion the lower starting speeds are less efficient, then after the peak of efficiency the drop off is quite severe as the energy stored in the flywheel tends not to be fully returned to the vehicle prior to the next braking event.

Good use of energy can be made with a mix of hybrid power greater than 30%, as long as KERS minimum acceleration speed is optimised to match it.

CONCLUSION AND SUMMARY

Kinetic Energy Recovery Systems (KERS) using mechanical flywheel storage have been developed for Formula One applications. The technology is directly transferable to road cars, in terms of both rated power and energy storage.

Safety of the high speed flywheel technology has been proven by crash testing, and performance of the complete system, including rated power and response time, has been measured on a dynamometer.

The key advantages of mechanical flywheel hybrid systems are low weight, high power, high efficiency, but in spite of these key advantages the most attractive quality for road car applications is cost.

A simulation of the mechanical hybrid system has been performed in energy terms for the US-FTP75 cycle. It has been shown that kinetic energy stored during braking and recovered to drive the vehicle can contribute up to 21% of the energy required to drive the complete cycle.

The efficiency is highly sensitive to strategy. A range of strategies have been identified, which give similar peak energy savings.

REFERENCES

[1] http://www.activepower.com/

[2] Medlicott P A C, “Development Of A Lightweight, Low Cost Flywheel Energy Storage System For A Regenerative Braking Application.” The British Petroleum Company plc. 20th Intersociety Energy Conversion Engineering Conference (IECEC), Miami Beach, Florida, August 18-23, 1985. Number P-164-859260

[3] Greenwood C J, “Integration of a commercial vehicle regenerative braking driveline”, Leyland Vehicles, Leyland, Preston, Lancashire. Number C191/86 IMechE 86.

[4] Flynn M M, Zierer J J, Thompson R C, “Performance Testing of a Vehicular Flywheel Energy System.” Advanced Hybrid Vehicle Powertrains 2005, SP-1973, SAE 2005 World Congress, Detroit, USA. Number 2005-01-0809

[5] Barr A, Veshagh A, “Fuel Economy and Performance Comparison of Alternative Mechanical Hybrid Powertrain Configurations”, SAE 2008 World Congress, Detroit, USA. Number 2008-01-0083

[6] Hayes R J, Kajas J P, Thompson R C, Beno J H, “Design and Testing of a Flywheel Battery for a Transit Bus”, SAE 1999 International Congress and Exposition, Detroit, USA. SP-1417, Number 1999-01-1159

[7] http://www.ccm.nl/pdf/FLW-Tech-160204.pdf

[8] http://photo.proaktiva.eu/digest/2008_gyrobus.html

[9] Burke M, Briffet G, Fuller J, Heumann H, Newall J; “Powertrain efficiency optimization of the Torotrak Infinitely Variable Transmission (IVT)”. SAE 2002 World Congress, Detroit, USA. Number 2002-03AC-75

[10] Lee A, Newall J; “Durability of a compact Dual-Cavity Full-Toroidal IVT Variator”. SAE 2004 World Congress, Detroit, USA. Number 2004-10-0353

[11] Newall J, Nicolson D, Lee A, Evans S; “Development and Assessment of Traction Fluids for Use in Toroidal IVT Transmissions“; SAE 2002 World Congress; March 2002; Detroit; Michigan; USA. Number 2002-01-0587

[12] Hewko L. O; “Automotive traction drive CVTs – An overview”; SAE paper 861355; 1986

CONTACT

Doug Cross
Flybrid Systems LLP
Silverstone Technology Park
Silverstone Circuit
Silverstone
Northamptonshire
UK
NN12 8GX
doug.cross@flybridsystems.com

Chris Brockbank
Torotrak (Development) Ltd
1 Aston Way
Leyland
Lancashire
UK
PR26 7UX
chris.brockbank@torotrak.com

APPENDIX I

Mass	~2000kg
Cd – Drag coefficient	0.31
Frontal area	2.28m^2
Cr – Coefficient of rolling resistance	0.02
Gear-train efficiency	83%
Tire width / profile	285mm / 35%
Rolling radius	0.3284m
Flywheel inertia	0.026kgm^2
Flybrid max power	60kW
Flybrid storage capacity	586,000J
Flybrid max CVT ratio (Input/Output)	2.44
Flybrid min CVT ratio (Input/Output)	0.408
Flywheel side losses at full speed	250W
Charge efficiency	86%
Discharge efficiency	86%