Simulation of the fuel consumption benefits of various transmission arrangements and control strategies within a flywheel based mechanical hybrid system

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Abstract

Flywheel based mechanical hybrid technology is being developed for both motorsport and mainstream automotive applications. One particular road car application project, part funded by the UK Government Technology Strategy Board, is being led by Jaguar Land Rover, managed by Prodrive and using advanced technology from Flybrid Systems, Ford, Ricardo, Torotrak and Xtrac. During the two year programme, the group will develop the new technology and build a demonstrator vehicle equipped with the system.

The mechanical system recovers kinetic energy from the vehicle during braking to a high speed rotating flywheel via a variable drive system. When compared to an electric motor / battery arrangement, the mechanical hybrid system offers benefits in cost, weight, package, efficiency and ultimately vehicle fuel consumption.

As part of the development and optimisation process in order to specify the road car system, all aspects of the mechanical hybrid system are under investigation by the group. Alongside the required quantity of energy storage and the rates of energy recovery and reapplication, a number of different physical architectures for the system are being analysed.

The Torotrak full-toroidal traction drive has been assigned as the variable drive element of the mechanical hybrid system. Multiple configuration options are available including direct drive, epicyclic shunted, range extended CVT and epicyclic shunted IVT arrangements.

In addition, the flywheel and variable drive system can be connected to the powertrain in a variety of different locations, from the engine through the powertrain to the wheels.

This paper describes the simulation of the mechanical hybrid system with particular focus on the impact on the fuel consumption benefit, over multiple drive cycles, of the variable drive configuration, the location of the variable drive & flywheel system and the control strategy options.

1. Introduction

Hybrid powertrains, which recover and reuse kinetic energy traditionally wasted via braking in order to reduce 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.

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

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

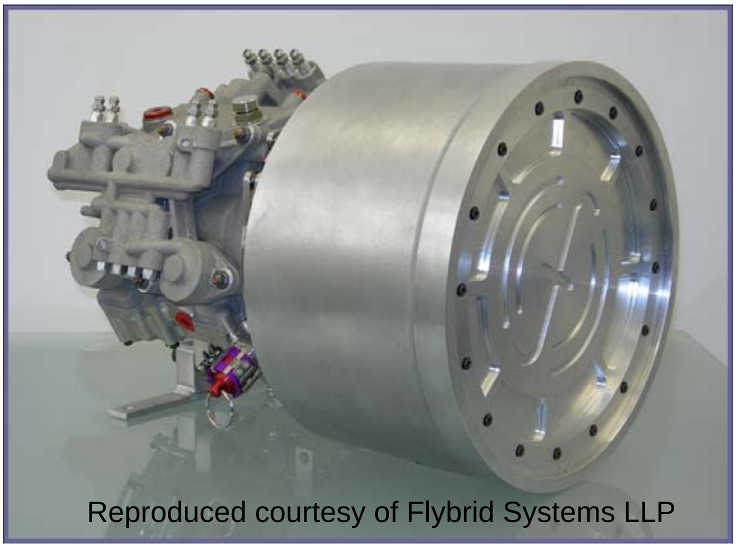
Such a flywheel based mechanical hybrid system has been developed by Flybrid Systems for use in both motorsport (with Formula 1 as the initial target) and mainstream automotive applications and was described at this conference last year [1].

2. F1 Mechanical KERS System Specification

The mechanical KERS for the F1 application has been previously described [1] and consists 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 of circa 64,000 rpm, and hence operates in a vacuum.

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.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Picture 1: Flybrid Systems' Formula 1 Mechanical KERS Introduction

3. Flywheel Hybrid System for Premium Vehicles Project (FHSPV)

The Flybrid Systems F1-based flywheel hybrid system is now being researched for applications in road cars by a group of leading British companies.

The project, part funded by the UK Government Technology Strategy Board (TSB), is being led by Jaguar Land Rover and managed by Prodrive with advanced technology from Flybrid Systems, Ford, Ricardo, Torotrak & Xtrac. During the two year programme, the group will develop the new technology and build a demonstrator vehicle equipped with the system.

The targets for the new system are to have a round trip efficiency of 70%, with a fuel economy improvement over the NEDC (New European Drive Cycle) of 20% when integrated with complementary powertrain technologies as described in this paper. One of the key advantages is that improvements in real world fuel economy are also expected to be in line with that over this legislative cycle. This has remained a challenge for conventional full electric hybrids.

As part of the conceptual design phase, a fuel economy simulation study has been conducted to aid selection of the most appropriate location for and configuration of variable drive. The vehicle used for the simulation is a production vehicle with the standard 3.0l diesel engine and automatic transmission.

4. Flywheel Hybrid – Variable Drive Hardware Options

The available variable drive layout and location options for a specific vehicle will be constrained by packaging, particularly if fitted as an additional device on a current production vehicle. The Flywheel Hybrid System (FHS) must also have no detrimental impact on crumple zones. If the system is incorporated into the initial vehicle or driveline design there will be significantly greater flexibility. The TSB project is considering fuel economy, vehicle performance and functional benefits. This study concentrates on the fuel economy impact.

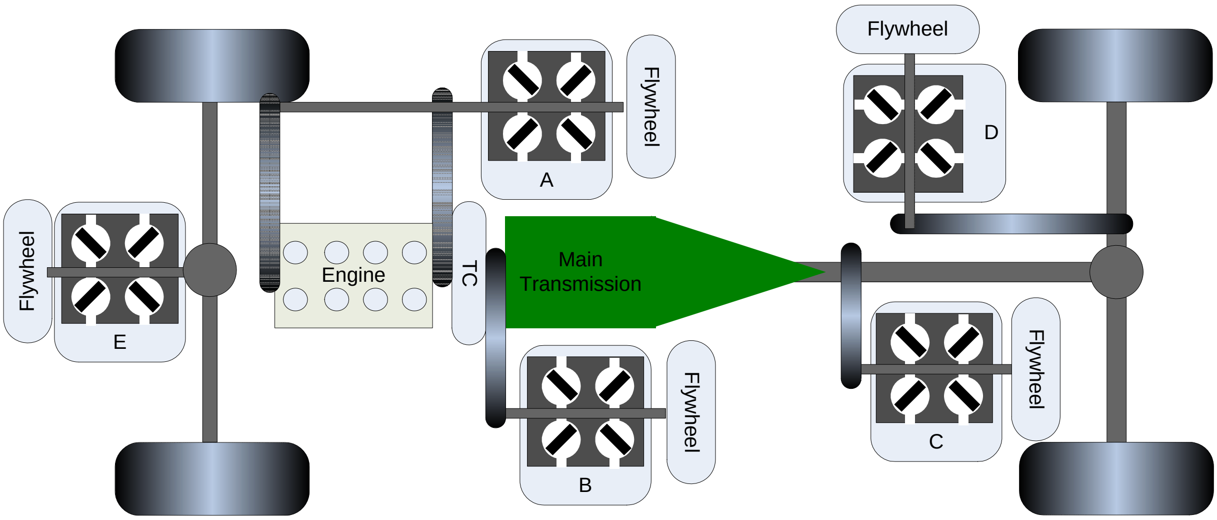


Fig. 1: Potential locations for Flywheel Hybrid System

Figure 1 shows the possible points for connecting a FHS to a longitudinal rear wheel drive powertrain. Location A represents connections on the engine side of the torque converter. If the FHS is mounted on the front of the engine, flywheel propulsion without the engine rotating is clearly not possible. If the FHS is mounted behind the engine, and separated by an additional clutch, this can be achieved. Location B represents a connection to the transmission input shaft, downstream of the torque converter. C refers to a generic connection onto the propshaft, which may be at the back of the transmission or at the final drive. D represents a connection to individual drive-shafts, and will require a pair of variable transmissions and potentially, though not necessarily, a pair of flywheels. The final option E represents a connection to the previously undriven front axle.

In addition five variable drive transmission layouts have been considered:

1. CVT:

   A direct drive CVT with all power passing directly through the variator, similar to the F1 KERS system. This provides a ratio spread of 6.

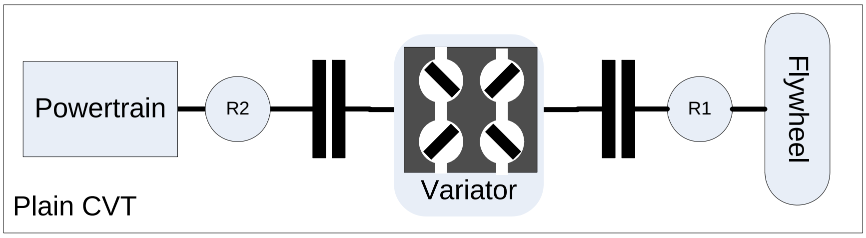


Fig. 2: Direct drive CVT layout

2. Extended CVT (EXT CVT)

   A direct drive CVT plus a two speed gearbox with a ratio difference of 5, giving an overall ratio spread of 30 (6x5).

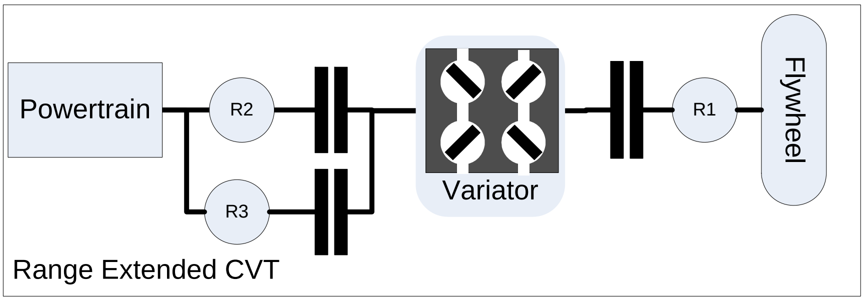


Fig. 3: Direct drive CVT with range extender gearbox

3. IVT:

   Placing the variator within an input coupled shunt, with the flywheel defined as the input, to provide a geared neutral condition.

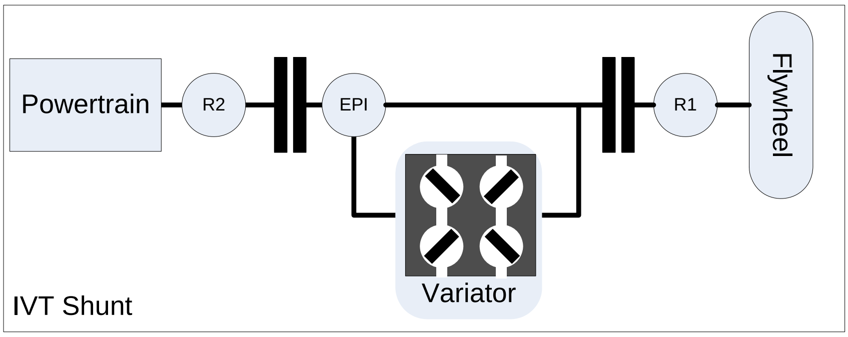


Fig. 4: IVT shunt

4. Increased Efficiency Shunt (Inc. Eff Shunt)

   An output coupled shunt providing increased efficiency through a power-split. Ratio spread is reduced to 4. An output coupled shunt was chosen to provide best efficiency at low flywheel speeds; an input coupled shunt will provide best efficiency at high flywheel speeds.

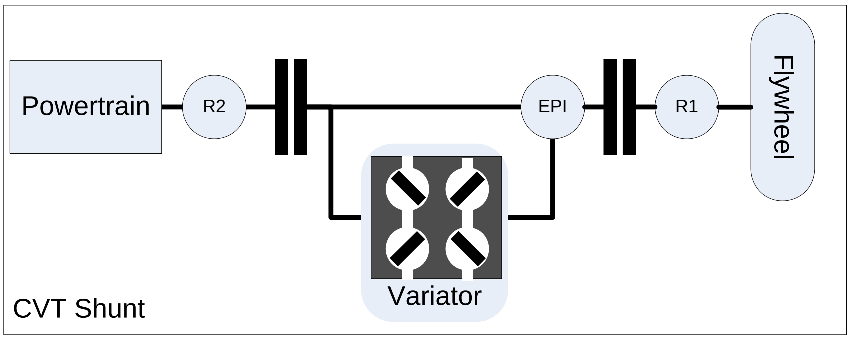


Fig. 5: Output coupled CVT shunt

5. Increased Ratio Shunt (Inc. Ratio Shunt)

   An output coupled shunt (as option 4 above but using a different epicyclic ratio) to provide an increased ratio spread of 15. Efficiency is reduced due to power recirculation. The output coupled arrangement was chosen for the reasons covered in option 4.

Each of these arrangements has a clutch on either side of the variable ratio element, with a gear ratio at each end to step down from the high flywheel speeds to the lower driveline speeds. The clutch on the flywheel side enables the flywheel to be disconnected from the rest of the drivetrain, minimising coastdown losses whilst the system is not used. For the purposes of this analysis this clutch is assumed locked at all times. The clutch on the output side is required to open when the ratio between flywheel and vehicle speeds moves outside the transmission ratio limits. It can also be allowed to slip in order to transmit torque whilst outside of the ratio limits.

5. Modelling

The inverse fuel economy model within the Torotrak System Design Tool (SDT) was used as a basis for these simulations. Modifications were made to enable additional flywheel hybrid system models to provide additional torque at different points within the drivetrain. With these in place the SDT model was validated over the NEDC drive cycle against JLR supplied results, providing good correlation to the base vehicle.

For fuel economy prediction locations D and E will be little different to C and therefore were not simulated. Whilst there may be some differences in gear efficiencies for final solutions, these will be of significantly lower impact than the other variables being considered.

It has been assumed that the system is fully integrated with the service brakes, using the service brakes only when the FHS is unable to provide sufficient braking. For the light duty of the fuel economy test cycles considered, tyre traction is well within limits and therefore significant braking energy can be recovered. Driving the front wheels from location E may allow greater energy recovery during aggressive / real world braking.

Plant models for each variable drive arrangement were generated and gear ratios chosen to keep the flywheel within the transmission ratio limits as much as possible over the NEDC cycle. Consequently this may not provide the optimum ratio range for other drive cycles, particularly higher speed sections. Locations A and B share ratios, as the speed range of the engine and transmission input are similar. Location C requires a different set of ratios.

6. Control Options

Given the wide variety of hardware options, the control decisions over when to charge and discharge were kept simple. When the powertrain and brakes are required to remove kinetic energy from the vehicle, the flywheel will always be charged provided the flywheel is below its maximum flywheel speed and within variator ratio and power limits. The clutch on the driveline side of the variable transmission is allowed to slip if the flywheel speed is too low to lock the clutch. This enables both initial charging of the flywheel and top up during operation.

Similarly the flywheel will be discharged whenever possible. This is restricted by the minimum flywheel operating speed and the variator ratio and power limits. The demanded output torque is required to cover both the wheel torque demand and other losses in the driveline. If the engine remains connected this loss includes engine friction and ancillaries, therefore allowing fuel cut.

The benefits of this simple control strategy are twofold; it maintains consistency between different architectures without specific calibration and also maintains maximum storage capacity in the flywheel prior to any braking event. Modifying the flywheel discharge timing for a specific system may improve fuel economy.

In addition to flywheel charge and discharge a decision must be made on whether the engine is on or off. Several variations of this were simulated. The first, and simplest, is to keep the engine running at all times. If operating under flywheel propulsion and the FHS is mounted at location B or C, the torque converter is locked to allow the engine to be driven by the FHS. The second option is to enable engine idle stop. If the FHS is mounted at A this functionality may be provided by the FHS; in all other cases an electric engine start is assumed. The final option is to allow the engine stop/start to occur whilst the vehicle is moving, therefore eliminating engine frictional losses during braking and FHS propulsion. It has been shown in previous studies that these contribute a significant proportion of energy requirements [1].

The target for this research was to generate comparative results of the potential gains. This enabled certain assumptions and simplifications to be made to speed up simulation development and run time :-

- The warm engine fuel map was used throughout. This will affect absolute fuel consumption but should affect different layouts similarly.
- For simplicity and consistency between different engine starting devices no energy is required to restart the engine. Clearly these engine starts will require some energy input, which will have an effect on FE, dependant on their frequency.
- The transmission shift and torque converter lockup strategy have been retained from the baseline test. The only override is to lock the torque converter when the engine is in fuel cut and being driven by the FHS from location B or C. Keeping this the same provides consistency between hardware options and ensures vehicle performance has not been compromised. A mechanical hybrid, however, has the ability to provide rapid, high power, response to transient torque demands. This could enable a more aggressive lockup and up-shift strategy, which will be investigated later in the FHSPV project. Modifying the main transmission ratio may also benefit locations A and B by keeping the FHS within ratio limits.

Parasitic losses in the additional components are an important consideration for all hybrid systems as they may increase fuel consumption whilst the hybrid system is inactive. Typically these will be from pumps and electric machines, and frictional losses in gears and bearings. For this mechanical system the main consideration is the pump for the variator and clutch control hydraulics. To provide a single consistent and practical solution for all layouts, an electric pump was assumed. Whilst the mechanical-electrical-mechanical conversion is less efficient than a direct drive pump it ensures pressure is available whatever the shaft speeds. The engine load from the alternator was increased proportionally to represent the increase in current. A high load was applied whenever the FHS was active and a reduced lubrication load was applied at all other times. Requirements from time-steps where the engine was shut down were redistributed amongst time-steps where the engine was active at the end of the simulation. Other alternator loads were not redistributed.

7. Simulation Results

The simulations were arranged to evaluate the effects of three factors; control strategy, location, and variable drive layout. Figure 6 shows the impact of three engine control options.

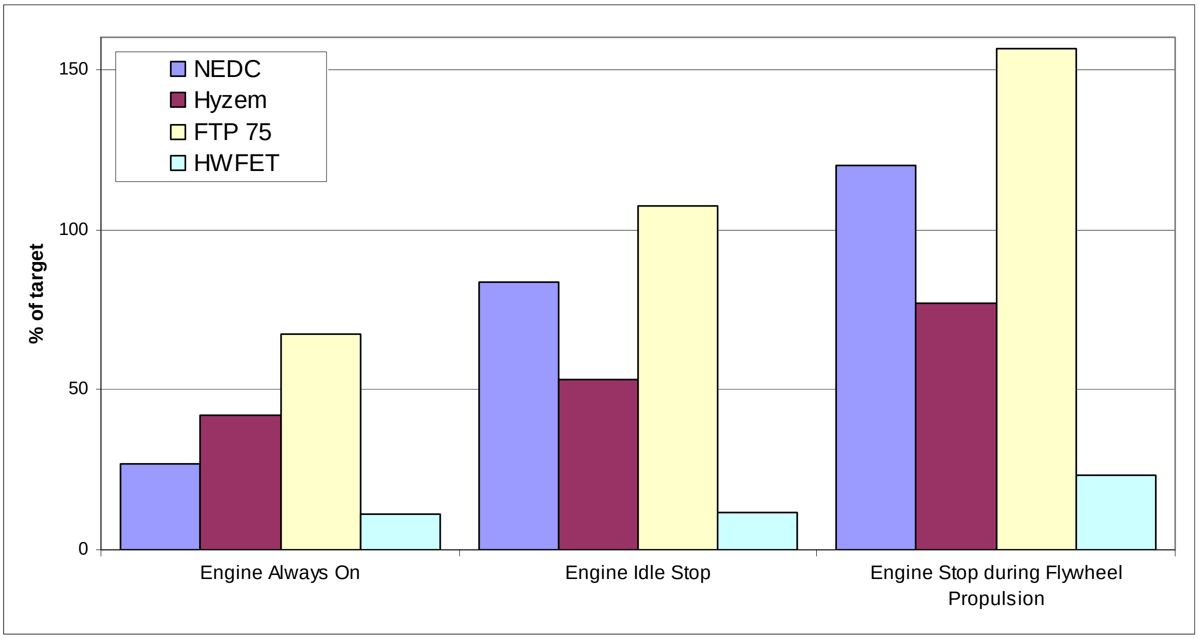
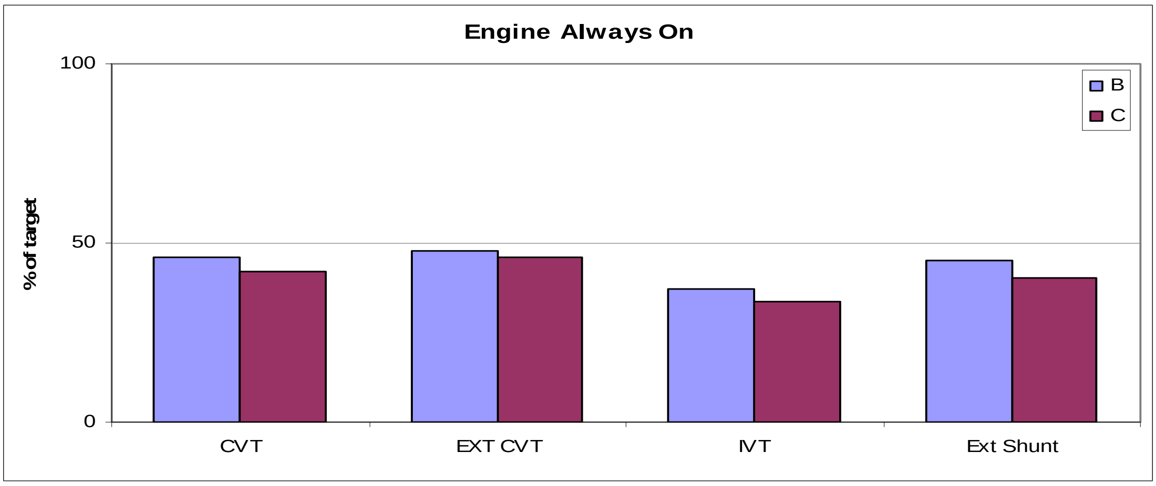


Fig. 6: Fuel economy increase for propshaft mounted CVT

These figures are for a basic CVT (layout 1) mounted at location C, and similar trends occur with all arrangements. The columns to the left show the percentage increase in fuel economy with the most basic charge and discharge strategy. As expected, the benefit varies significantly between drive cycles, with the high efficiency of the mechanical hybrid enabling benefits to be achieved on each cycle, even if the engine remains active at all times.

The centre set of columns shows the effect of adding an idle stop facility, producing a significant benefit over the NEDC and FTP75. The Hyzem cycle (derived from real European driving patterns comprising an urban, an extra-urban and a highway cycle) was designed to offer a more representative real world test cycle for hybrid vehicles and has only short periods of idle time. Consequently the idle stop benefits are reduced. The highway cycle has no idle periods, and shows no benefit for an idle stop system. The right hand columns show the effect of combining the two systems to allow engine stop whilst propelling or decelerating the vehicle using the flywheel. On all cycles a significant increase can be seen, which highlights the benefit of fully integrating the FHS with the rest of the drivetrain. It has been previously reported [1] that engine losses form a significant proportion of the energy input required over a drive cycle, a conclusion supported by these findings.

Changing the control strategy will also affect the differences between architectures. Figure 7 shows the relative benefits for architectures B and C for the two extremes of control strategy and four variable drive transmission layouts. If the engine remains on the gains from location B are higher than those from location C for each variable transmission type. If the engine is frequently switched off the gains from location C are higher. It is clear then that the principles of the control strategy, if not the detail, should be decided prior to comparing potential fuel economy gains.



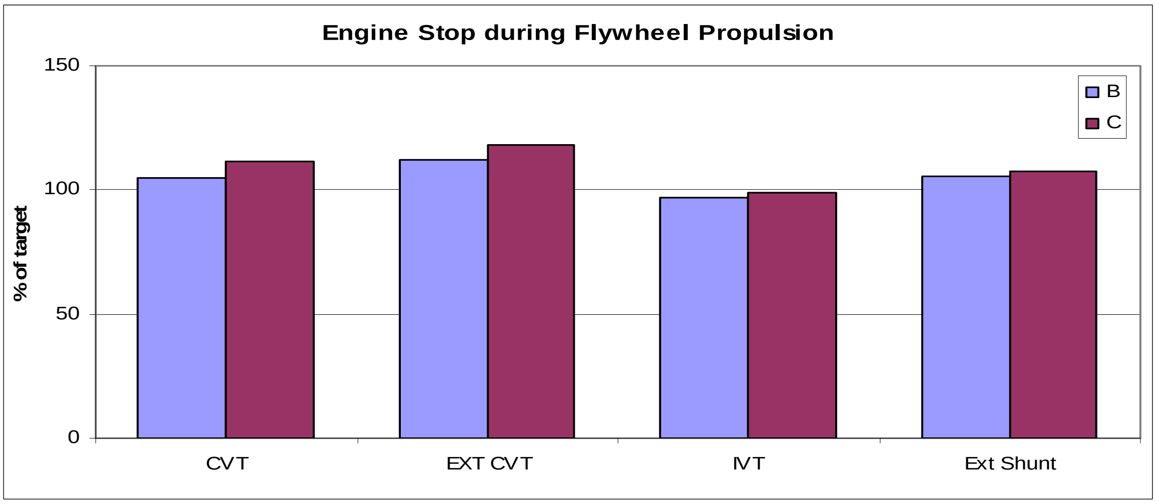
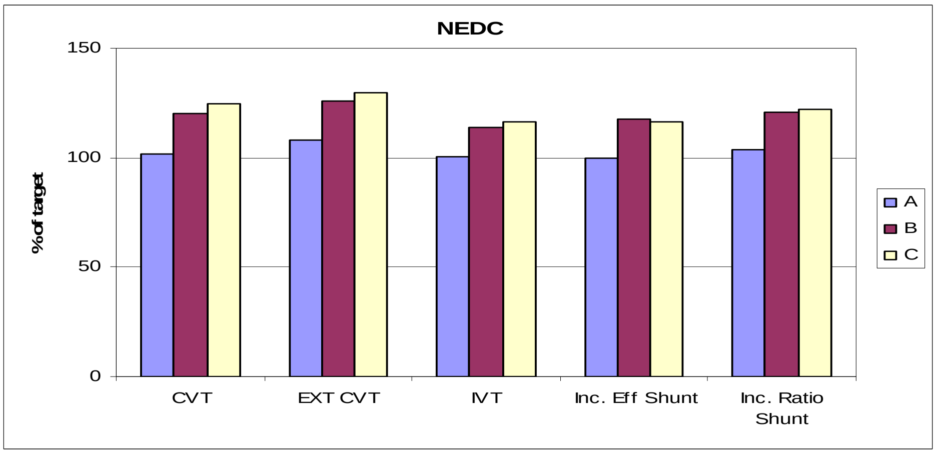
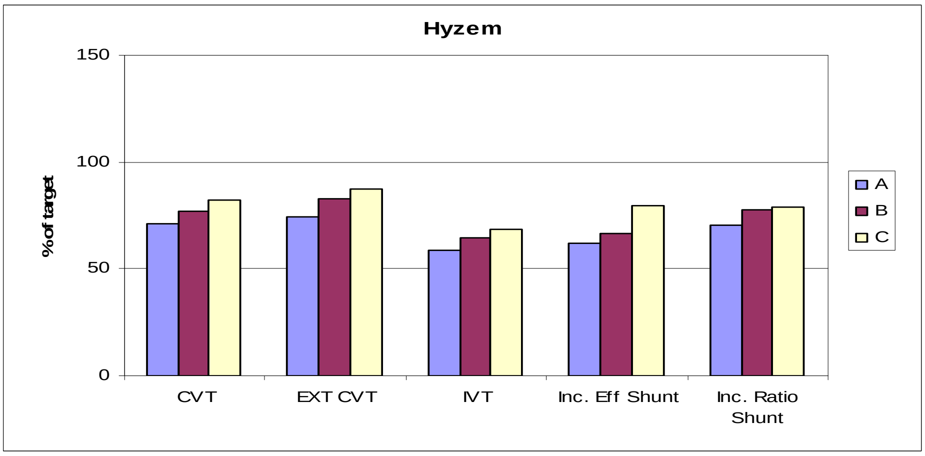


Fig. 7a & 7b: Fuel economy gains (as % of target) over EPA combined cycle

Engine stop-restart systems are available for Automotive applications and are standard equipment on a number of European cars. It is therefore most appropriate to concentrate on this control option when comparing hardware layouts. Some FHS arrangements may also offer engine start whilst the vehicle is moving, via a friction clutch, but with a fixed ratio main transmission induced shock loads on the driveline may be unacceptable. An electric starter will still be required for engine starts when the flywheel is not charged.





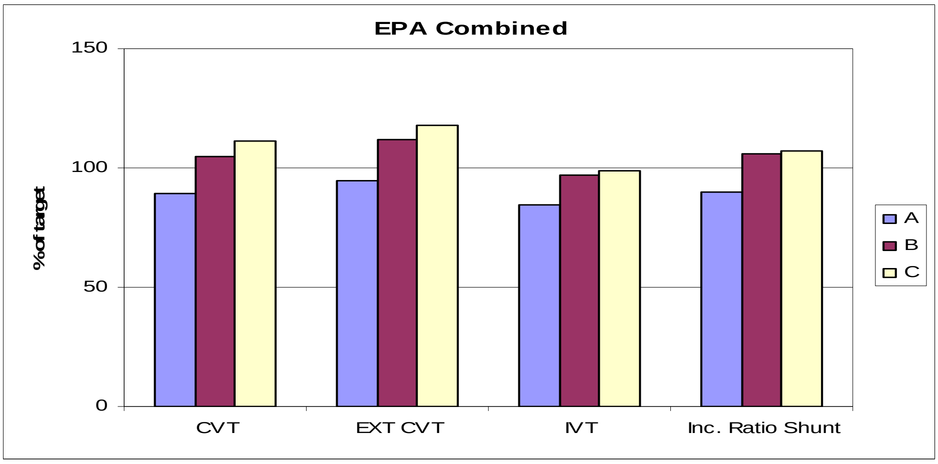


Fig 8: Comparison of % fuel economy benefit versus target for Architectures A, B & C and 4 transmission arrangements with maximum engine shut off over 3 cycles

Figure 8 shows the increase in fuel economy achieved for 12 different hardware variations over the NEDC, Hyzem and the EPA combined cycles (calculated from the EPA city and highway figures to pre 2008 standard).

Comparing architectures A and B, the results from either side of the torque converter, B gives significantly better results than A for the NEDC and EPA combined cycles. This is caused by substantial losses in the torque converter. Over the Hyzem cycle this is substantially reduced as the converter is locked more frequently. Since the engine is shut down whilst the FHS is active, it may be more appropriate to lock the torque converter for A. This increase in efficiency should provide nominally similar results as shown for B.

Functionally all variable transmission configurations can propel the vehicle from rest with architecture A, whilst only the IVT can do so from B or C. Slipping the FHS clutch at B may enable this for the CVT layouts, although this has not been permitted in these simulations. Specifying a clutch at C with sufficient torque capacity for pull away, without the benefit of the main transmissions torque multiplication, may be difficult. Depending on the ratios chosen the range extended CVT may provide sufficient torque multiplication between the clutch and propshaft, but again this has not been allowed in this simulation. Enabling such functionality in this simulation is unlikely to yield better results, as the engine has been allowed to start and stop frequently without energy consumption. It may however make it easier to achieve these theoretical figures in practice by reducing the number of engine restarts required.

The IVT figures are notably lower than those of the CVT arrangements despite the ability to pull away from rest. If the energy requirement for engine restart was considered this difference will be reduced, depending on the cycle, as the engine start and stop required by the other arrangements for initial pull away will be removed.

Comparing the results for B and C, either side of the main transmission, there is a greater benefit at location C in most cases. When operating with the engine off the main transmission provides an additional loss during both charging and discharging, thereby reducing efficiency. It also provides an improvement in ratio spread, with the change in transmission input speed typically being less than that of the transmission output. As shown in figure 7 this study suggests the efficiency loss is more significant. It should be noted that even with the engine disconnected the transmission ratio has retained its engine based shift strategy. This gear choice could be modified to keep the FHS within ratio limits during braking and avoid slipping the clutch, though the relative benefits of this are as yet untested. It could be reasoned that the base CVT should achieve the figures of the range extended CVT, as the main transmission and range extender are achieving the same end result.

The simulation indicates that the extended range CVT layout provides the greatest benefits over all cycles and architectures. The increase in ratio spread will be of benefit for maintaining consistent driveability and functionality.

The extended ratio shunt provides similar fuel economy benefits to the standard CVT, demonstrating that an increase in ratio spread can compensate for the reduction in mechanical efficiency. Gear ratios in the shunt can be modified to alter the balance between mechanical efficiency and ratio spread, the wide example chosen here is unlikely to be the optimum configuration.

The shunt configured for increased efficiency consistently gave lower benefits than the standard CVT over both the NEDC and Hyzem. Given that it will also compromise functionality, it has not been included in the EPA simulations.

8. Conclusions

The potential benefit of adding a mechanical hybrid system to a standard powertrain is substantial regardless of the configuration with potential benefits shown for a wide range of drive cycles.

Integrating the system with an engine stop-restart system is the key to making the most of the recovered energy, as the net benefit is greater than the sum of the individual benefits. The high power capacity of the FHS enables the engine to be switched off whilst the vehicle is in motion, which dramatically reduces losses in the driveline and enables a significantly higher proportion of the recovered kinetic energy to be returned to the vehicle rather than being dissipated in the engine and ancillaries.

Adopting the start-stop strategy, choosing a location towards the back of the driveline generally offers the best figures in this study. If the power and energy capacity of the FHS are sufficient to propel the vehicle without the engine for a significant proportion of the anticipated drive cycle this will be the most effective option for fuel economy.

If opportunities to shut down the engine are limited architecture A or B could be more appropriate. The torque converter can dissipate a significant amount of energy so If A is chosen it will be necessary to lock the torque converter during FHS operation in order to achieve benefits comparable to B. Architectures A and B also offer the greatest scope for further optimisation through modifying the main transmission ratio.

Use of a CVT provides higher potential fuel economy gains than an IVT arrangement. However overall gains are still significant enough to enable an IVT to be considered if other factors favour an IVT, such as to provide engine start or vehicle launch from the flywheel.

The wide ratio spreads of the range extended and shunted CVT layouts provide the fuel economy benefits of the CVT layout but with reduced clutch slip during flywheel charging. Although the range extended CVT provided the best fuel economy improvement, the impact of the required ratio step change with respect to driveability needs to be understood. Hence the shunted CVT also demonstrates potential for application. It has been shown that a shunt configuration can be pushed to a ratio spread 2.5 times that of the variator without adversely impacting overall fuel economy, despite a reduction in mechanical efficiency.

Therefore, in order to choose the best configuration for a particular project it is proposed that packaging and functional constraints are considered first. The relatively complex mechanical configurations are unlikely to perform radically differently to the more practical options and can be excluded at an early stage. There may also be minimum ratio spread requirements to achieve required functions such as performance enhancement or low speed ZEV mode. The allowable levels of interaction with engine, transmission and brake systems will constrain the basic driveline capabilities and therefore govern the principles of the control strategy. This can then be used to analyse the relative fuel economy for the selected options in more detail.

References

[1] Greenwood, C; Brockbank, C: Formula 1 Mechanical Hybrid Applied to Mainstream Automotive, VDI-Berichte Nr. 2029, Getriebe in Fahrzeugen, June 2008.

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