

# Fuel Economy Benefits of a Flywheel & CVT Based Mechanical Hybrid for City Bus and Commercial Vehicle Applications

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## ABSTRACT

Hybrid drivetrain systems are becoming increasingly prevalent in Automotive and Commercial Vehicle applications and have also been introduced for the 2009 Formula1 motorsport season. The F1 development has the clear intent of directing technical development in motorsport to impact the key issue of fuel efficiency in mainstream vehicles.

In order to promote all technical developments, the type of system (electrical, mechanical, hydraulic, etc) for the F1 application has not been specified.

A significant outcome of this action is renewed interest and development of mechanical hybrid systems comprising a high speed composite flywheel and a full-toroidal traction drive Continuously Variable Transmission (CVT).

A flywheel based mechanical hybrid has few system components, low system costs, low weight and dispenses with the energy state changes of electrical systems producing a highly efficient and power dense hybrid system.

Due to the system simplicity, the mechanical hybrid delivers a measured 72% 'round trip' efficiency in approximately half the package, half the weight and a quarter of the cost of an electric hybrid system.

Torotrak have assisted in the development of the flywheel based mechanical hybrid applying the Series Production full-toroidal traction drive technology in CVT format for use within motorsport but also as a technology for mainstream vehicle applications

For the mainstream applications, either the high speed / low mass flywheel or a more conventional higher mass / lower speed flywheel can be utilised. The mechanical hybrid system is now being developed for multiple automotive applications including a Government sponsored project with Jaguar Cars Ltd.

Due to the 'stop / start' transient duty cycle, the flywheel based mechanical hybrid system is particularly well suited to City Bus applications and can be extended to larger Commercial Vehicle applications.

This paper describes the flywheel based mechanical hybrid system, the simulation results of applying the flywheel hybrid to a City Bus and the powertrain arrangement for the flywheel hybrid system, energy storage requirements, system efficiencies, energy savings and hence fuel economy 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 lead 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 vehicles.

The system requirements for a hybrid for motorsport are actually very similar to mainstream Automotive and Commercial Vehicle applications namely :

- 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 in Automotive applications 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 previously been reported to the SAE [4], [5], [6].

To date, although application of flywheel based systems to the mainstream automotive and commercial vehicle sectors 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].

To control and transfer energy to and from the flywheel, a Torotrak full-toroidal traction drive variable transmission unit has been chosen for motorsport & automotive applications due to the high power density, torque based control system and simple scalability to different power levels. The flywheel hybrid system for automotive applications has been reported at this year's SAE World Congress [9].

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 has demonstrated 19% fuel economy benefit from the full-toroidal traction drive technology in a bus as a main drive, twin regime 'Geared Neutral' Infinitely Variable Transmission (IVT) arrangement in a mid sized (11 tonne) bus and reported to the SAE [10].

In addition, the disc and roller durability [11].and traction fluid developments [12] have been reported.

## BACKGROUND

### FLYWHEEL BASED MECHANICAL HYBRID

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

1. a method of recovering energy from the driveline
2. a storage medium and
3. a mechanism for reapplying the storage energy back to the vehicle

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

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

Following basic physics, increasing the speed of a flywheel increases its rotational or kinetic energy. Equally, decreasing the speed of the flywheel reduces the energy in the flywheel. Hence the flywheel acts as a mechanical battery – absorbing, storing and releasing energy when required.

Note this can be done at any required power without drastic system size or capability issues.

A significant advantage of the mechanical hybrid system is efficiency; unlike an electric system (with energy lost on each transition between rotational to electrical to chemical and back) there is no change of state of energy.

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

$$E = \frac{1}{2} I \omega^2 \dots \dots \dots (1)$$

where :-

$E = \text{Kinetic Energy}$

$I = \text{Moment of Inertia of the rotating mass}$

$\omega = \text{Angular Velocity}$

Rather than employ a solid flywheel, a carbon filament wrapped composite flywheel can be utilized whose moment of inertia is defined in Equation 2 :

$$I = \frac{1}{2} m (r_1^2 - r_2^2) \dots \dots \dots (2)$$

where :-

$m = \text{mass of the flywheel}$

$r_1 = \text{outer radius of the flywheel}$

$r_2 = \text{inner radius of the flywheel}$

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 and during flywheel start.

Figure 1 describes the system schematically :-

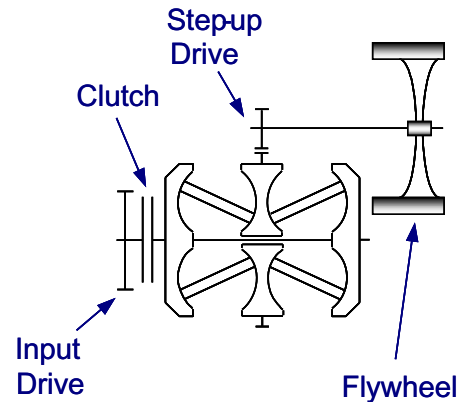


Figure 1: Schematic of Flywheel Hybrid System

## FLYWHEEL STORAGE DEVICES

As the quantity of energy storage in the flywheel is dependant upon the mass / inertia and the speed of the flywheel, either a large, low speed flywheel or a small, high speed flywheel can be used.

With the squared velocity term in Equation 1, increasing the speed of the flywheel becomes far more beneficial from weight and package perspectives than increasing the mass. Energy increases with the square of speed, linearly with inertia.

Hence the flywheel based mechanical hybrid system developed for motorsport and automotive applications by Flybrid Systems LLP uses a light weight composite flywheel rotating at high speed. The flywheel comprises a carbon fibre filament wrapped rim surrounding a metal hub. To optimise efficiency, the flywheel runs in a high vacuum and is enclosed within a housing that provides containment in the event of failure.



Figure 2: Filament Wound Carbon Fibre Flywheel

## THE FULL-TOROIDAL VARIATOR