

Hybrid Assessment Part 2

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1 Introduction

1.1 Task

In this report I will be discussing the design of a series hybrid version of an off-road buggy using a previously generated drive-cycle. The series-hybrid vehicle will consist of a power-plant internal combustion engine (ICE), generator, energy storage, controller, motor and any transmission if needed. Figure 1 shows the arrangement of the design. There are two primary benefits of converting the off-road buggy into a series hybrid design: The capability to run the power-plant internal combustion engine at its most efficient point and the capability to recover energy from the system which would otherwise be wasted, such as the kinetic energy lost as heat due to braking prior to corners and the potential energy lost whilst descending hills. In order to perform this investigation it is first necessary to determine if these gains are significant enough to warrant investigation. The company has requested that the ICE must sustain sufficient power to supply mean power to the wheels. Once the design of a hybrid has been specified a short discussion on the power-plant, generator, storage system and motors will be included before a specification is designed.

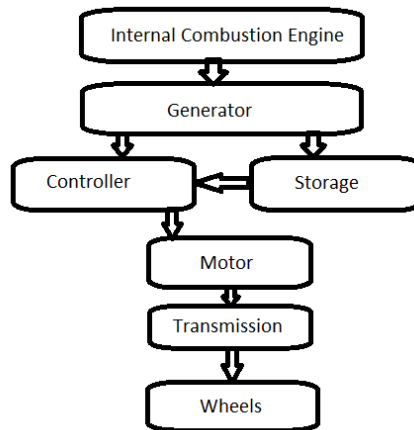


Figure 1: Diagram showing the hybrid setup.

1.2 Hybrid Benefit Analysis

In order to perform an initial investigation the buggy has been considered to be using its existing ICE as a power-plant and that the efficiencies will remain the same. This will not be accurate as there will be additional losses in transmitting energy across the system however it will provide ball-park figures on possible gains to be made. I have calculated the mean and median power, the peak power, the total energy storage required, the energy used per lap and used these to values to calculate recoverable energy the fuel consumption per lap. These are available in the below table.

Mean Power (kW)	12.5
Median Power (kW)	14.1
Peak Power (kW)	16.4
Storage Required (kJ)	51.576
Energy Used Per Lap (MJ)	1.58
Max Recoverable Energy (MJ)	0.26
Fuel Consumption (g)	215.2

With these parameters it can be calculated that the buggy could save 27.9% of its fuel per lap by introducing a hybrid system, additionally 15% of the energy per lap is recoverable which could reduce running costs further. With

the ICE producing mean power the buggy only operates at surplus during corners, which makes a significant portion of the track design. Overall, this data shows that it is worthwhile to investigate a hybrid version of the buggy.

2 Components

In this section I will discuss the components of the series-hybrid system, this section will discuss the components in the following order: power-plant, motor/generator and controller, and storage system.

2.1 Power-Plant

The power-plant of the hybrid system will consist of an internal combustion engine, the cheapest option for a power-plant will be to continue to use the current engine of the buggy, and as the calculations in Table 1.2 show, there are significant fuel savings to be made in doing this. However, this engine is larger and more powerful than necessary and as such will affect the overall performance of the vehicle. An additional benefit of using the current engine is that the mechanics will already be familiar with the engine, reducing the training required to maintain the vehicles. There are however alternatives that would result in lower fuel consumption overall, such as a purpose built ICE to act as a generator. A rotary engine is another suitable alternative given its small size, low weight as using it at a lower, steady RPM resolves some of its inefficiency issues.

2.2 Motor/Generator and controller

In this section I will consider three types of motors brushed DC motors, brushless DC motors and SRM drives. The motor of the system must be capable of holding varying RPMs and torques, and be under a lot of stress. The generator only needs to run at a single consistent RPM which reduces overall stresses of the system, given the generator is not going to be exposed and will be in close contact with the engine it is likely to be under some heat without sufficient cooling.

Brushed DC motors are the oldest electric motors on the market and generally consist of external permanent magnets as stators and an armature containing rotating electromagnet as a rotor. When current is applied to the electromagnet the rotor rotates to align the two magnets, when they are fully aligned the commutator switches the direction of the current, changing the poles of the electromagnet and causing the rotation process to repeat. This is a mechanical process wherein the commutator is in contact with the rotor via "brushes" which cannot be lubricated due to the electric charge travelling across them. This motor has the benefit of being particularly easy to control, especially when only used in one direction, such as in use as a generator. The major downside of a brushed DC motor is the wear caused by continuous use, requiring maintenance, with many larger DC motors having replaceable rotors. The use of permanent magnets in this motors construction does however mean it can suffer at high temperatures if not cooled properly as the magnetic domains will be destabilised at high temperature.

Brushless DC motors operate on the same system of magnetic attraction and repulsion as brushed DC motors, however their construction differs from that of a brushed DC motor. The brushless DC motor's construction is of permanent magnets attached to the rotor and windings on the stator. As opposed to a brushed motor's mechanical design the switching of the magnetic field is electronically controlled, requiring an electronic active control system. This reduces wear, adding longevity to the motor, but increases the cost of the system. The brushless motor is also quieter due to lack of brush arcing and generally has a higher efficiency. This motor also uses permanent magnets, which means when used in high temperature environments or without sufficient cooling the permanent magnets can lose their magnetic field. There are two types of brushless DC motors, surface permanent magnet (SPM) and interior permanent magnet (IPM), the SPM motor has a rotor with its permanent magnets being placed on the surface of a core, the IPM however has its permanent magnets placed internally. The difference in this setup means that the IPM motor is able to take advantage of reluctance torque in addition to magnetic torque, whereas SPM motors are entirely reliant on magnetic torque, the rotor of an IPM motor is also more robust as the permanent magnet is held in place by the material of the rotor, a factor which limits the drive speed of an SPM.

Switched Reluctance Motors (SRM drives) do not use any permanent magnet and instead consist of a rotor made from a magnetic material and the stators have windings to create a magnetic field, this uses the reluctance force to rotate the rotor, moving the direction of the field with a controller. The SRM has a low cost construction however it requires power electronic and rotor positioning sensors. The SRM motors also have high fault tolerance, capability to have high speed and high torque operation.

Permanent Magnetic Synchronous Motors (PMSM) are AC motors which use permanent magnets and have a sinusoidal back-EMF waveform. The PMSM is a cross between a brushless DC motor and an induction motor, much like a brushless DC motor it has permanent magnets on the rotor and windings on the stator however windings and stator structure are designed to produce a sinusoidal waveform like an induction motor. Whilst the motor works well in high speed, high efficiency processes it requires a controller capable of vector control techniques. PMSM systems are commonly used for steam turbines, gas turbines, reciprocating engines and hydro turbines as generator to generate electricity.

2.3 Storage system

The storage system of the vehicle has to be able to store sufficient energy for the maximum energy deficit as well as be able to output sufficient power for the maximum power output, the storage methods I will be looking at are lead-acid batteries, lithium-ion batteries, capacitors and flywheels.

The lead-acid battery is the traditional car battery, making them cheap to setup however they have a lower energy density and a high power density. Additionally, the lead-acid battery has a low lifetime of around 200 cycles, making it useless for this use, given at least one cycle will be performed per lap.

The lithium-ion battery is a long favourite of manufacturers given its high energy and power density however it cannot be overcharged and requires complex battery management technologies. The lithium-ion battery has about 10x the lifecycle of a lead acid battery, meaning less replacements, reducing overall running costs despite the more expensive initial setup.

Capacitors/ultracapacitors are characterised by a significantly higher specific power with a much lower specific energy than batteries. This means ultracapacitors are great for short burst of high power however they lack the capacity to support long term discharge. In order to not lose energy from inefficiency the ultracapacitor must be kept in its high voltage region, above 60% of its rated voltage.

Flywheels are a simple technology that stores energy as kinetic energy, the speed the flywheel spins at. Flywheels for modern hybrid electric vehicle use tend to be small and made of composite materials, allowing them to spin at extremely high RPMs, an electric machine is used to store and take energy from the system. Generally, in order to reduce frictional losses the flywheel housing is kept at close to vacuum conditions which adds cost to the initial setup however the energy density of a flywheel is generally high, dependent on the strength of the material used and has an extremely long lifecycle, unlikely to ever need replacing.

3 The setup

The setup for the hybrid vehicle I will be looking at will use the engine currently on the vehicle, as this reduces overall cost. A flywheel system, due to the longevity of the system and the low storage requirements 90kJ for the whole run. Additionally, the flywheel is easily capable of producing power to support the vehicle during moments of peak power (3.9kW). For the generator I will use a PMSM due its high efficiency and its capable to perform at high speed, this is important as the generator will be constantly in use. The motors for the wheels themselves will be mounted at the rear wheels in order to reduce losses from a transmission. I will be using PMSM motors for this due its high performance capabilities at high and low speeds and the absence of torque ripple, improving its efficiency.

Component	Cost	Mass	Details
ICE	£0	N/A	Current ICE of the vehicle, producing 12.5kW of power continuously
Flywheel	£848	6	Storage:200kJ, Output 4kW, Efficiency:90%
Drive Motor	£1258	26	Output 11kW
Generator Motor	£589	15	Operates continuously at single RPM
Controller	£438.45	4	Translates controls from driver to drive motors
Total	£1972	51	

The flywheel storage system used is not an actual product, its cost has been generated using values from [?], [?], [?].

In order to maximise the fun of the lap the controller will simulate the gearing of the original buggy, this increases user participation and allows the users to display greater skill and thus feel greater achievement. This has the added benefit of being able to use the previous calculated drive cycle, with the mass and efficiency of the system modified to account for the changes in the buggy's drive-train.

4 Analysis of Hybrid System

The primary areas of interest in the analysis is the total cost, the total fuel savings and value of these fuel savings. This will then allow for calculating the time until the parts have paid for themselves. The components selected to build the hybrid buggy all have particularly long lifetimes and require little maintenance and as such part failure will not be considered in this analysis. The previous ICE only system consumes 215g of fuel per lap, the modified hybrid cycle consumes 157g over the cycle, this correlates to a 26.9% fuel savings, even with significantly worse efficiency losses across the power-train. The total cost of the system is £1972 and if installation is all performed in house this can further reduce costs. The total fuel savings per lap is 58g, which correlates to 0.075l, fuel currently costs 163.28p/l so the company saves 11.83p per lap. It would take 16669 laps to recover the cost of the parts, at a rate of 50 laps a day it would take 333 days to recoup the cost. Given the wear rate of the components this is well within their lifecycle, and they would continue to operate far beyond this point. Thus it would be a worthwhile investment for the company to create hybrid versions of their buggy.

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