

BSc Motorsport Engineering- University of Wales Trinity Saint David- Swansea

A Theoretical Installation of KERS to an MCR Race Car

Final Dissertation Report

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Abstract

This report primarily looks into the relevance of hybridisation for racing cars and the effect it has on the motorsport industry. The project investigates the relevance of installing a Kinetic Energy Recovery System to an MCR Race car and is discussed in detail; this is to understand why the project needs to be conducted. The concept of how Kinetic Energy Recovery and Regenerative Braking Systems work has been explained, including the specifications of the components which make up the system. The efficiencies of KERS which is 66% have been discussed with the aid of research. Research has been conducted where graphs were found to show the performance characteristics of the energy storage systems, as well as this, further research discovered the efficiencies of the storage systems. The ZyteK ERS system is discussed and evaluated to investigate the suitability of the installation on the MCR. All relevant data has been collated, as well as calculations, this is expressed in the report. The performance gains when the MCR is converted into a hybrid vehicle is discussed and illustrated through two forms of simulation.

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1.0 Introduction

Hybridisation of racing cars is becoming more popular in modern times, this is mainly due to the increase of carbon dioxide (Co₂) emissions into the atmosphere, which is widely accepted as one of the main causes of climate change. The Earth's atmosphere immediately prior to the industrial revolution contained around 280 parts per million of carbon dioxide, however once fossil fuels started being used as a widespread energy source (both domestic and industrial) the amount of Co₂ in the atmosphere began to rise. In the 1950's it had attained a new level of 315 parts per million, when measured again in 2007 the figure had risen to 380, increasing annually by an average of two parts per million (McKibben, 2007). Subsequently there has been considerable political pressure to reduce emissions in motorsport, consequently there are huge economic and ethical reasons for the governing bodies of motorsport to make the sport more eco-friendly, this was expressed largely in a Race-car Engineering article about the Motorsport carbon footprint (Race-Car Engineering, 2012). Formula One and endurance racing (Le Mans etc.) have become substantially more environmentally friendly in recent years with the use of Kinetic Energy Recovery and in 2014 Formula One became even more efficient utilising the relatively new concept of Waste Heat Energy Recovery. Another advantage of the hybridisation in motorsport vehicles is the increased performance. Although high end motorsport and some road vehicles have had hybrid technology, it is yet to be designed for any club level motorsport.

In a Limited power championship or a championship (where the size of engine or relative power) determines the class, it is imperative that any possible performance gain is maximised, although it is important to check the relevant regulations of the championship in which the vehicle is competing in to ensure that any system is compliant. The 2014 SRCC SPORTS 2000 DURATEC Championship regulations state that the power output of the

engine should not exceed 185Bhp, but doesn't state that the use of different power sources to aid the drivetrain is prohibited (SRCC, 2014).

The First aim of this project is to critically assess the potential performance gains of an MCR Race car when added with KERS Technology. Data from a standard MCR will be collated, and with the aid of calculations and simulations data will be reverse engineered to establish any performance potential.

The Second aim of the project is to analyse various storage devices which could be used with a Kinetic Energy Recovery System. An evaluation will consider the harvesting and deployment capabilities of these devices, factors such a weight, size and cost will also be considered.

2.0 Project Relevance and Reasoning

Since 2009 Formula One and other areas of motorsport have been asked by the governing body of the sport to incorporate Kinetic Energy Recovery Systems to work alongside the Internal Combustion Engine (I.C.E). A regenerative braking system was used in Formula One to regain the energy that would be converted into heat losses in friction braking but, instead convert it into potential useable energy. The Formula One 2009 technical regulations state that the vehicles can only store 300Kj on board before leaving the pit garage and that the maximum power in and out must not exceed 60Kw. The technical regulations also state that the maximum energy released over a one lap period cannot exceed 400kj; the conversion of power is approximately 80BHP for 6.6 seconds a lap (FIA, 2009). This figure can be clarified by using the calculations expressed below.

$$KW \frac{Kj}{Time} = \frac{400}{6.6} = 60.6$$

(Zammit, 1987)

$$P(BHP) = \frac{P(KW)}{0.745699872} = \frac{60.6}{0.745699872} = 81.26 \text{ BHP}$$

(Zammit, 1987)

These regulations are in place to make the sport fair due to it being a developing technology in 2009. There has been development on road vehicles and other areas of motorsport with KERS but it's only on high end motorsport and new cars.

As well as Formula One, Le Mans uses hybrid technology to reduce Co2 levels and Pollution. The Le Mans technical regulations state that there is no limit of the release power from the energy recovery. However, depending on which system is used, limits the amount of fuel flow rate per lap and on board fuel capacity (Le Mans, 2014).

In *Fig 2.0.1*, illustrates to what extent teams wish to harvest and deploy energy. The energy harvested determines the fuel allowance per lap for the vehicles. It shows that if 8MJ is harvested and deployed over a single lap, the fuel flow limit per lap will be 4.42 litres. However if a team only desired to harvest and deploy only 2MJ per lap, the fuel limit increases to 4.8 litres. This allows teams the option to develop prototypes with various hybrid capabilities depending on their research goals. The fuel saved per lap can be as high as 32% in a diesel hybrid. This percentage of fuel saving per lap over a 24 hour race, amounts to less fuel used thus meaning less time lost in pit stops (Elias, et al., 2015).

		Private teams only	All teams			
	2011 cars	2014 cars	2014 cars			
	2011	non hybrids	hybrids			
Energy ERS – Hybrid (size of hybrid system)	0 MJ	0 MJ	2 MJ	4 MJ	6 MJ	8 MJ
Car's weight	900 kg	830 kg	850 kg			
Fuel allocation per lap	Not limited / Estimation 6,13L/lap	4,95 L/lap	4,8 L/lap	4,65 L/lap	4,50 L/lap	4,42 L/lap
Fuel consumption reduction		19%	22%	24%	27%	28%
Fuel tank	75 L	64,4 L	64,4 L			
Diesel allocation L/lap	Not limited / Estimation 5,26L/lap	3,99 L/lap	3,93 L/lap	3,81 L/lap	3,68 L/lap	3,56 L/lap
Fuel consumption reduction		24%	25%	28%	30%	32%
Diesel fuel tank	60L	53,3 L	53,3 L			

Figure 2.0.1 LM P1 Synthesis Table (FIA WEC, 2014)

There is little evidence for KERS technology being installed on a club level racing car or in the lower formulas of racing series. Due to the large gain in performance proven by the Formula One figures and in Le Mans shown in *fig 2.0.1*, it seems that Kinetic Energy Recovery technology should be brought in to lower levels of racing. This is because there could be potential to gain greater BHP levels per lap, in a vehicle which only produces 185BHP at the wheels. The development from this project could inspire club level racing to reduce engine sizes and converting to hybrid technology this could possibly reduce the costs of the internal combustion engines for a racing season and save fuel costs in low level motorsport series.

3.0 MCR Race Car

The MCR race car is designed and manufactured by a company in Wales, the company utilises the latest technology and high quality components to create these vehicles. The MCR is a racing car which fits into the sports prototype category; it is built for speed and endurance. The MCR is a very robust vehicle and is designed to be easily serviced and maintained, even by a novice mechanic. The production company can fit the MCR with various options of engine and transmission types to comply with the regulations of a variety of championships. The MCR owned by the University of Wales Trinity Saint David is fitted with a 2.0 Litre Duratec Engine with a power output of 185Bhp (MCR Race Cars, n.d.) (SRCC, 2014).

Table 3.0.1 MCR Specifications (MCR Race Cars, n.d.) (Dowden, 2015)

Wheel base	2590mm
Length	4470mm
Width	1720mm
Front Track	1500mm
Rear Track	1445mm
Rolling Resistance	0.278m
Mass	561Kg
Mu	1
Front Wheel	6"x13"
Rear Wheel	8"x13"
Centre of Gravity Height (m)	0.4
Weight Split	40/60

The above table shows the vehicle specs for the MCR, the majority of these figures will be used in various calculations both manually and in a spreadsheet.

4.0 Theory of Kinetic Energy Recovery

Kinetic Energy Recover Systems (KERS) and regenerative braking mean different things but are linked to one another. KERS is a term used to recover any form of wasted kinetic energy into a usable energy and regenerative braking is a system that can be used to convert wasted energy into usable energy. Regenerative braking recovers energy that would usually be wasted in friction braking. The energy is recovered by a motor/generator unit (MGU) which can act as a generator under braking and as a propulsion electric motor during acceleration (Siddartha & rasad, 2013). The energy recovered can be stored using batteries, flywheels, capacitors and hydraulic energy, each of these having pro and cons which make them desirable depending upon the requirements of the particular race car. There are currently no regulations governing how much energy can be recovered from the MCR and how long the energy boost can be deployed for, the gains may not be as large as Formula One and Le Mans but the energy boost time could be significantly greater. The efficiency of regenerative braking has been predicted in an SAE Paper written by Gino Sovran to be around the figure of 66%, meaning not all of the waste energy can be converting into useable energy (Sovran, 2011), this is due to KERS only using the rear brakes to harvest for safety reasons. In *fig 4.0.1* below, the harvesting and deployment of Kinetic Energy Recovery is illustrated in a diagram.

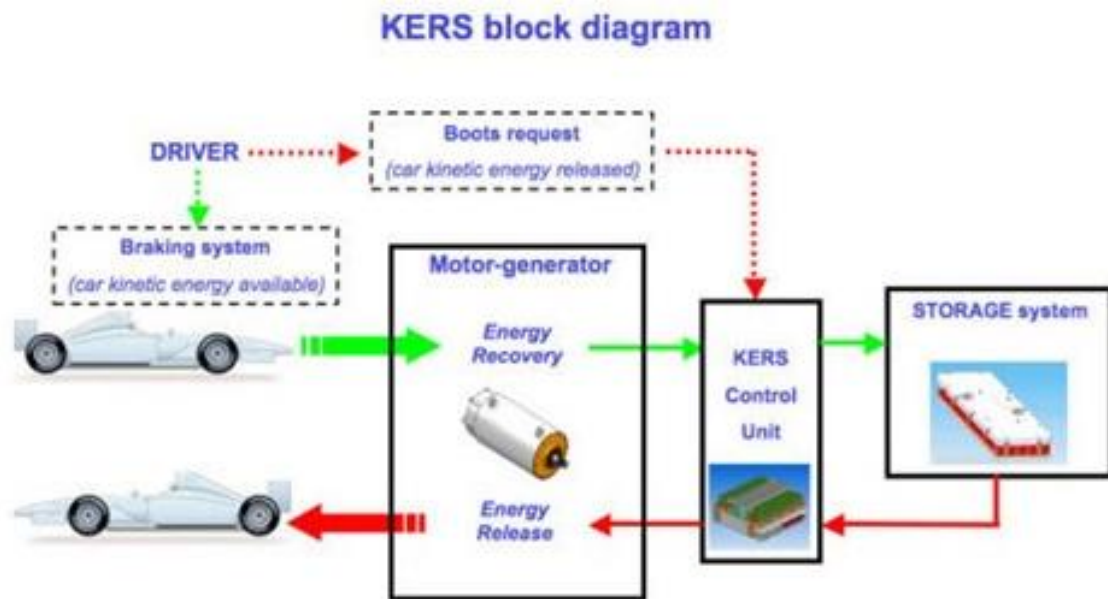


Figure 4.0.1 KERS System Diagram (Model Space, n.d.)

5.0 Data Collection

The data has been collected from a MCR Race Car after completing a series of laps and tests around the Pembrey Race Circuit. This data is used to gain further information regarding the vehicles capabilities. The data demonstrates the velocity of the vehicle when completing a lap of Pembrey Race Circuit, as well as a coast down test.

A coast down test is used to calculate the resistance to motion, this is completed by driving the MCR in a straight line in the highest gear at maximum speed and then coasting down in neutral to a complete stop, assuming the wind resistance and gradient does not vary, it should be able to be used to calculate the resistance to motion and the deceleration rate of the car. The information from the tests completed will be further analysed using the Pi Toolbox software.

The data is recorded using a Pi Data Logger which is installed on the MCR; this logs the data at a rate of 100Hz. The rate of the data being logged is efficient enough in terms of receiving accurate data without major interference to cause inaccuracies.

6.0 Data Analysis Methods

The Data from the MCR Racing Car that has been collected needs to be evaluated. This is analysed using the Pi Toolbox software and a Microsoft Excel spreadsheet, complete with equations. Due to the limitations of the system not all aspects of information needed to complete the project aims are available, the data that has been collected therefore will be reversed engineered, using standard equations in order to complete the task.

The data which includes a flying lap of the Pembrey circuit and a coast down test needs to be correctly analysed, in order that the tractive force, resistance to motion, acceleration, deceleration caused by resistance, Static, dynamic and total torque and power, braking energy, wheel lock limit and the potential energy recovery are calculated from these areas of data.

When the data is being analysed using the Pi toolbox software, interference on the data may cause inaccuracies. This is why a filter is used on the data, especially if irregular spike patterns appear on the waveforms. The filter allows an average line to be taken throughout the waveform, although it must be noted that if the filter is set at an incorrect speed parts of significant data could be overlooked.

As well as using the above methods for data analysis, simulation software created by the company Optimum G called Optimum Lap will be used. The software was created by the company to simplify vehicle dynamic simulations but still gain reasonably accurate and useful results within minutes. The Optimum Lap software has a process of which vehicles

can be designed by the user, as well as pre-modelled vehicles. The vehicles created by each Optimum Lap user can be exported onto a database to allow other users the use of them. Track designs can be created from logged vehicle data imported into the software or by using actual track coordinates. As well as designing tracks, previous circuits created by other users can be downloaded from the Optimum Lap database. The simulation section of the software assumes the vehicle is a point mass model,(meaning no weight transfer and transient effects are taken into account), however it is claimed by the Optimum G website that simulated results correlate with logged data results to within 5-10%. the analysis section of the software can be utilised once a simulation is complete. The graphing tool in this section allows for comparisons of tracks and vehicles on a global scale, as well as this it can highlight subtle changes made to a vehicle in various forms of graphs and data. The simulated and analysed data can be exported from Optimum Lap into other software packages such as MATLAB and Excel (Optimum G, 2016).

Shown below in *fig 6.0.1* are screenshots of the various analysis graphs which can be used within the Optimum Lap software. These graphs are just a few of 60 output channels which can be used to display various results.

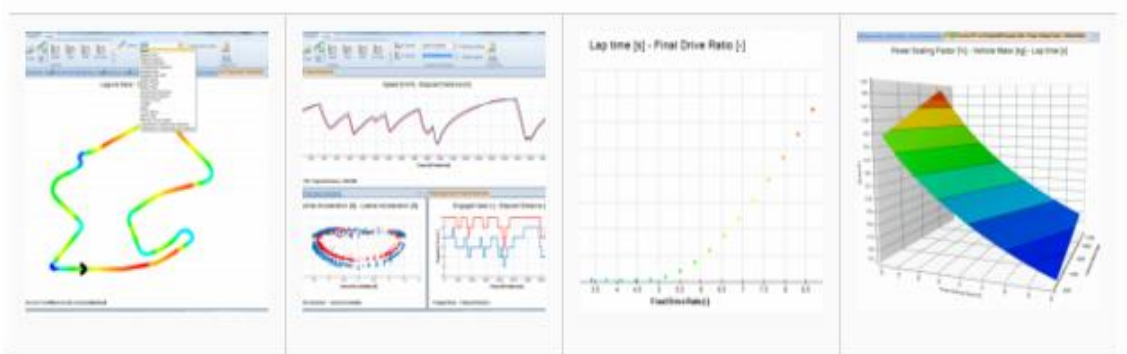


Figure 6.0.1 Optimum Lap Analysis Graphs (Optimum G, 2016)

6.1 Calculations

The set of data received from the MCR Race Car doesn't have all the sufficient values and sections to easily calculate the potential recoverable energy from the vehicle. A set of data from one lap including time and velocity can be used to reverse engineer sections of data and subsequently produce plausibly accurate simulations.

An SAE paper written by Doug Cross suggests several equations that could be used to calculate the various values and figures needed, the other calculations needed to complete the data spreadsheet were found in an engineering science book written by S.J. Zammit (Zammit, 1987).

$$\text{Rolling Resistance} = \text{Mass} \times 9.81 \times \text{Coefficient of rolling friction (Cr)}$$

$$\text{Drag Force} = \frac{1}{2} \times \text{Air density} \times Cd \times \text{Frontal Area} \times \text{Velocity}^2$$

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

$$\text{Time} = \frac{\text{Distance}}{\text{Velocity}}$$

$$\text{Power (Static)} = \text{Resistance to Motion} \times \text{Velocity}$$

$$\text{Power (Dynamic)} = \text{Mass} \times \text{Accel} \times \text{Velocity} \times \text{Time}$$

$$\text{Power (Total)} = \text{Power (Static)} + \text{Power (Dynamic)}$$

$$\text{Acceleration} = \frac{\text{Final Velocity} - \text{Initial Velocity}}{\text{Time}}$$

$$\text{Torque (Static)} = \text{Resistance to Motion} \times \text{Rolling Radius}$$

$$\text{Torque (Dynamic)} = \frac{\text{Power (Dynamic)} \times \text{Rolling Radius}}{\text{Velocity}}$$

$$\text{Torque (Total)} = \text{Torque (Static)} + \text{Torque (Dynamic)}$$

$$\text{Kinetic Energy} = \frac{1}{2} \times \text{Mass} \times \text{Velocity}^2$$

To calculate the acceleration at the contact patch due to the engine, the equation below would be used.

$$\text{Engine Acceleration Force} = \frac{\text{Engine Power}}{\text{Vehicle Velocity}}$$

$$\text{Acceleration Force} = \text{Engine Acceleration Force} - \text{Aero Drag} - \text{Rolling Resistance}$$

To calculate the engine acceleration force with the potential KERS values included, it would be done using the calculation below.

$$\text{Engine Acceleration Force with KERS} = \frac{\text{Engine Power} + \text{KERS Power}}{\text{Vehicle Velocity}}$$

(Cross, 2008)

6.2 Pembrey Lap Data

A Velocity-Time graph is a great way to illustrate a vehicles speed around a circuit. The in *fig 6.2.1* below a velocity-time graph is displayed; the graph shows the velocity of the standard MCR during an entire lap of Pembrey race circuit. The speed trace on the graph is used as a baseline figure when comparing for any performance gains achieved by adding KERS to the MCR race car. The graph is plotted with velocity in m/s along the Y-Axis and time measured in seconds along the X-Axis.

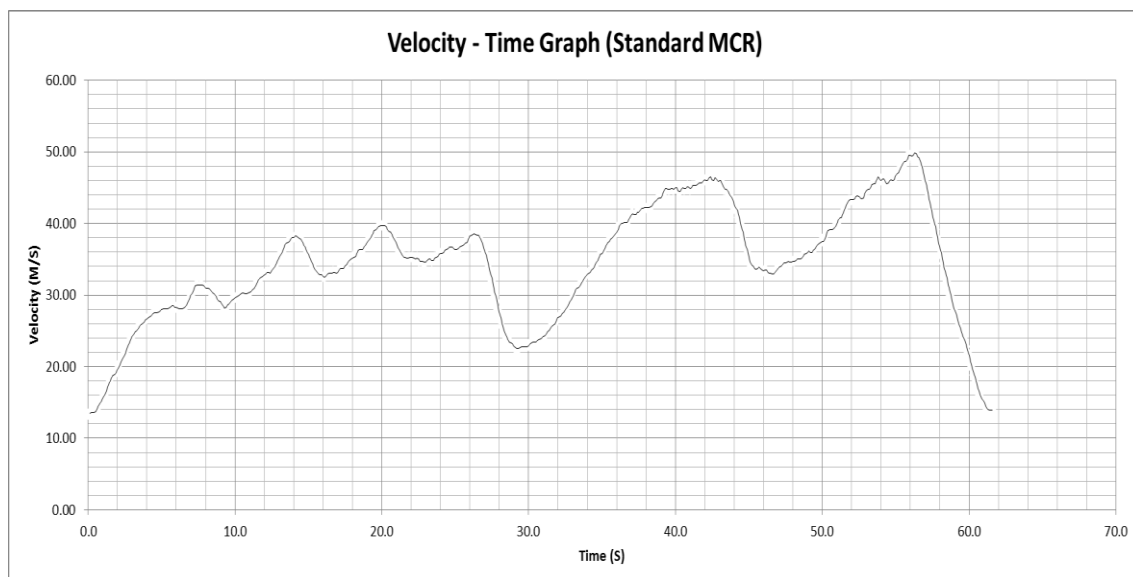


Figure 6.2.1 MCR Velocity - Time around Pembrey Lap (Tudor, 2015)

A Velocity-Distance graph illustrates a vehicles speed around a circuit but plotted against distance instead of time. The in *fig 6.2.2* below a velocity-distance graph is displayed; the graph shows the speed of the standard MCR during an entire lap of Pembrey race circuit. The speed trace on the graph is used as a baseline figure when comparing for any performance gains achieved by adding KERS to the MCR race car, the graph will add a different aspect of speed advantage or disadvantage. The graph is plotted with velocity in m/s along the Y-Axis and distance in metres along the X-Axis.

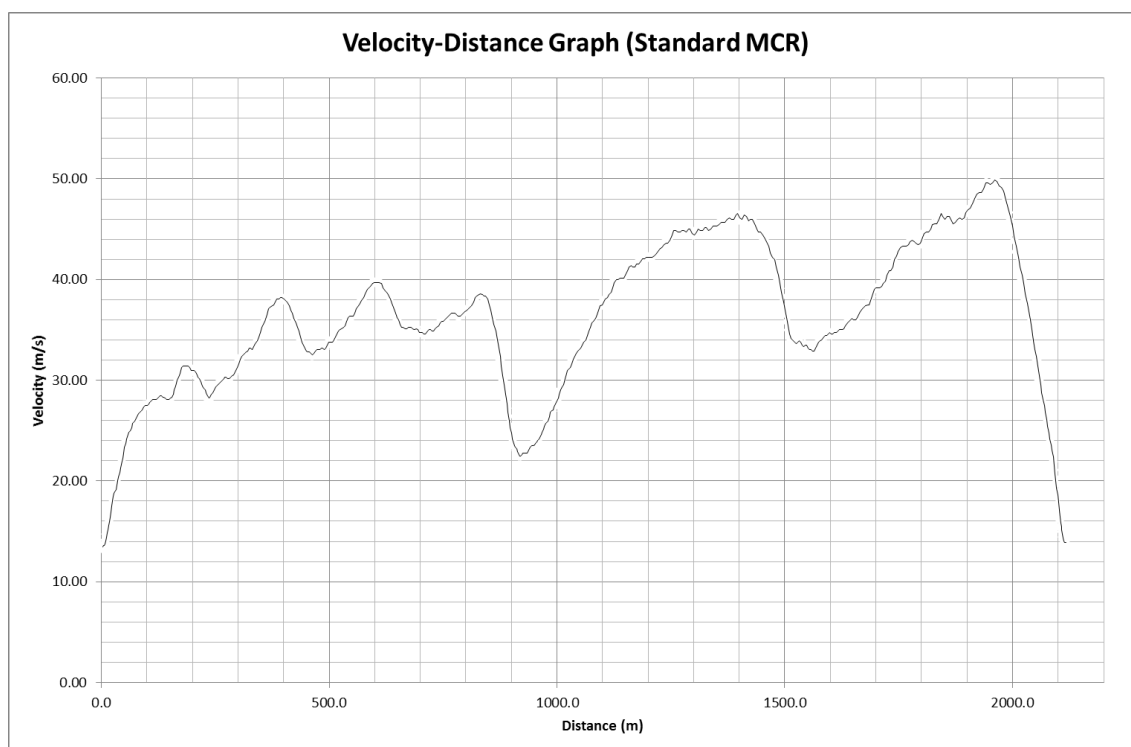


Figure 6.2.2 MCR Velocity – Distance around Pembrey Lap (Tudor, 2015)

The Acceleration of the MCR is calculated via the data spreadsheet, the results from this calculated data show the acceleration and deceleration of the MCR throughout an entire

lap of Pembrey race circuit. The results are then formatted into a graph, this allows for any anomalies or spikes in data to be discovered, if these are causing an issue, these inaccuracies can be addressed. Shown below in *fig 6.2.3* is an acceleration graph of the MCR, it illustrates the maximum acceleration and deceleration. The largest deceleration point for the MCR is 56 seconds into the lap; this is caused by the driver braking into the Pembrey hairpin. The Deceleration of the vehicle is $11.11M/S^2$, knowing that $1M/S^2 = 0.101972g$ (Zammit, 1987), the deceleration of the vehicle can be calculated into 1.13g. This figure is used in the wheel lock limit equations when determining the level of weight transfer into the hairpin.

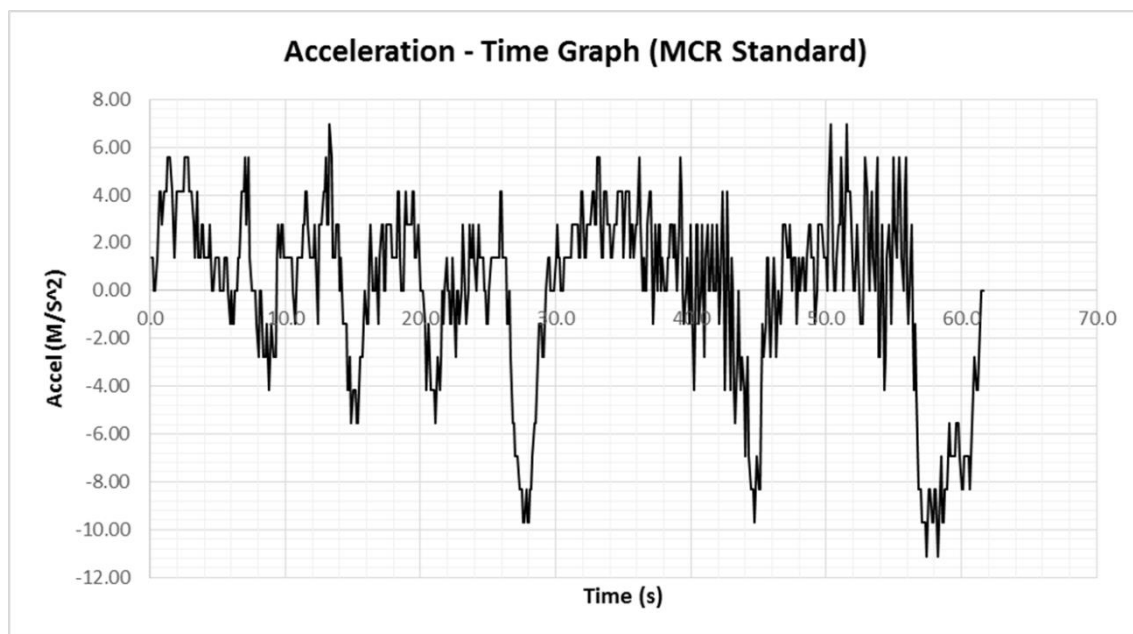


Figure 6.2.3 MCR Acceleration – Time around Pembrey Lap (Tudor, 2015)

The total power of the MCR throughout an entire lap of Pembrey has been determined, by calculating the dynamic and static power of the MCR around Pembrey, creating a power total. In *fig 6.2.3* below a total power data trace is shown, this illustrates the power of the standard MCR.

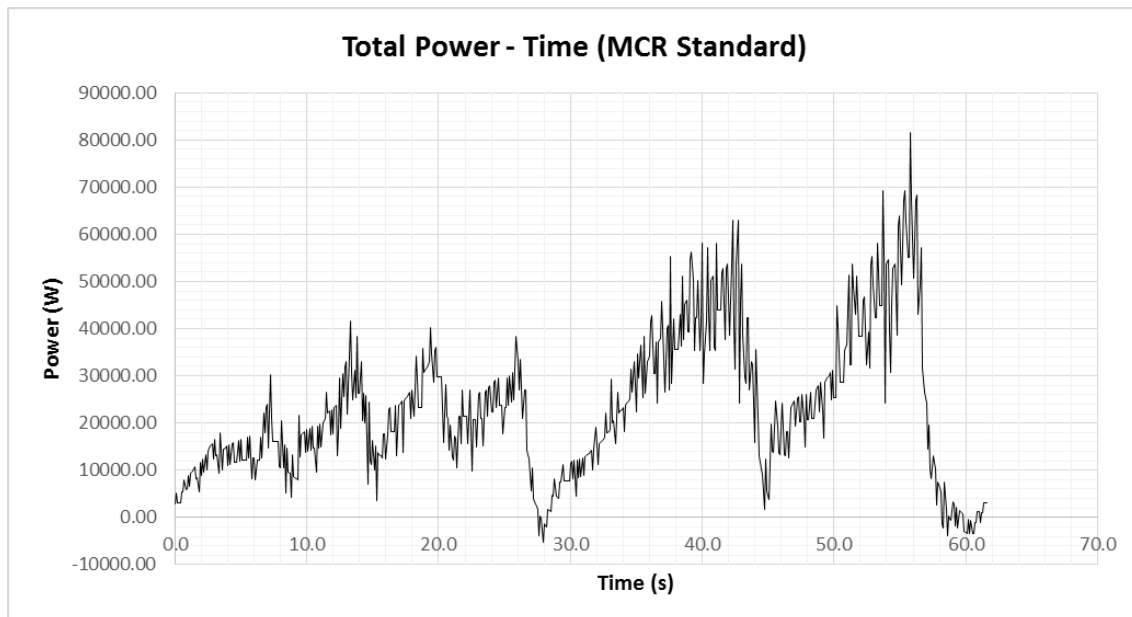


Figure 6.2.4 MCR Total Power around Pembrey Lap (Tudor, 2015)

6.3 Coast Down Testing

A coast down test is a frequently used test in the Automotive and Motorsport industry. The test is conducted by a travelling at a predetermined speed with the engine ungear. The speed and time is recorded via a data logger until the vehicle comes to a rest.

The main objective of conducting a coast down test is to evaluate the resistive forces acting on the vehicle at various speeds (Preda, et al., 2010). The forces which are acting on the vehicle is aerodynamic drag (Higher Speeds) and rolling resistance (Lower Speeds). When conducting a coast down test in the open and windspeed and gradient varies, the test would then have to be completed in both directions, this helps eliminate any variables.

The coast down testing on the MCR was conducted at Pembrey race circuit, one vital feature that makes Pembrey circuit an ideal place to host a coast down test is that there is very little gradient changes. The test began with the vehicle travelling at approximately 30m/s, the vehicle is taken out of gear and allowed to coast to a stop. The velocity – time graph below *fig 6.3.1* demonstrates the rate of which the vehicle is slowed. The trend line

illustrates the initial decrease in velocity due to aero and rolling resistive forces, however the decreasing speed steadies due to the reduction of aerodynamic forces acting on the vehicle.

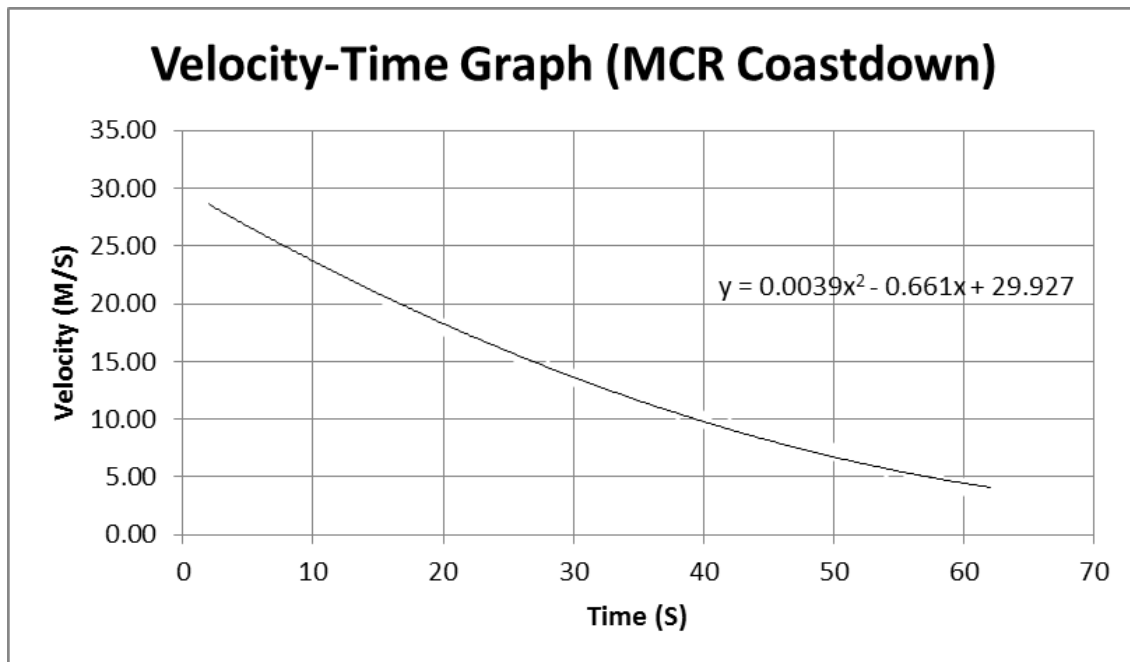


Figure 6.3.1 Velocity – Time Graph Coast down (Tudor, 2015)

The forces acting on the vehicle from the coast down test are inputted into a graph see *fig 6.3.2*, the graph shows the various forces at different vehicle velocities throughout the coast down test. A trend line is displayed on the graph, this trend also determines an equation, and this is the equation used in the data spreadsheet to calculate the resistance to motion.

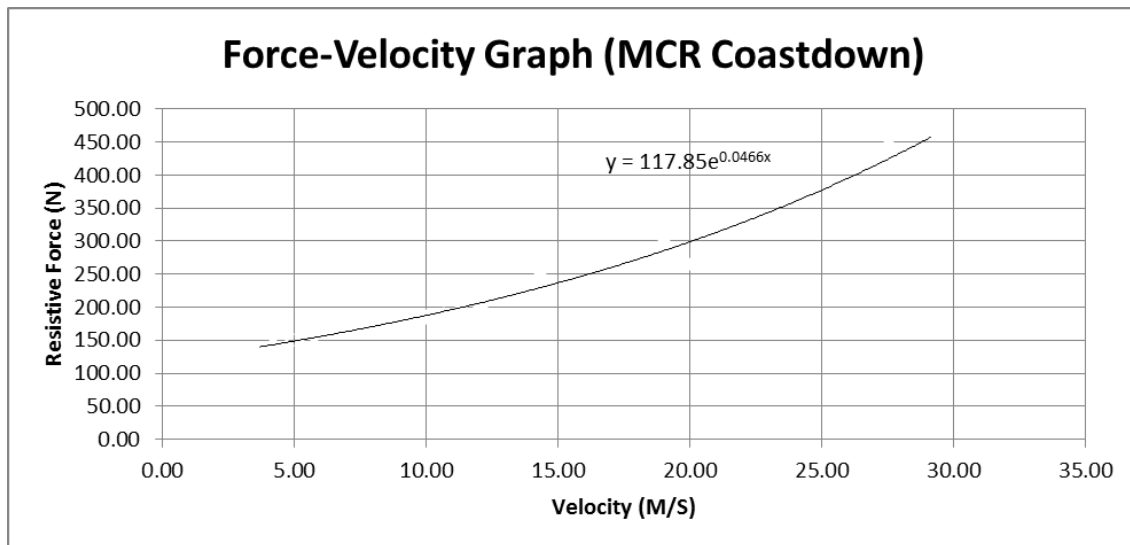


Figure 6.3.2 Force – Velocity Graph (Tudor, 2015)

6.4 Wheel Lock Limit

The surface of a race circuit and a vehicle tyre are connected due to there being an adhesion coefficient. The grip level comes from heat being transmitted into the tyre making it softer and grip better, this is due to the tyre surface being able to mould into the grooves of the track surface. When a large amount of acceleration or braking force is applied to the tyre, it can exceed the grip coefficient level causing the wheel to spin or lock depending on the force (Wright, 2005). The Adhesive capability between a tyre and the road surface will be a big limitation to how much energy the MCR can harvest (Ehsani, et al., 2009).

When under braking a vehicle preparing for an approaching corner, weight transfer occurs. This type of transfer in weight is known as forward weight transfer, this essentially means that the rear of the vehicle gets lighter as the weight shifts towards the front of the vehicle. Due to the rear of the vehicle having less weight, the rear wheels are more likely to lock and potentially create the vehicle to spin, this is the reason almost all cars are fitted with smaller rear brakes (Driving Fast, n.d.). Shown below in *fig 6.4.1* is a basic illustration of forward weight transfer due to braking.

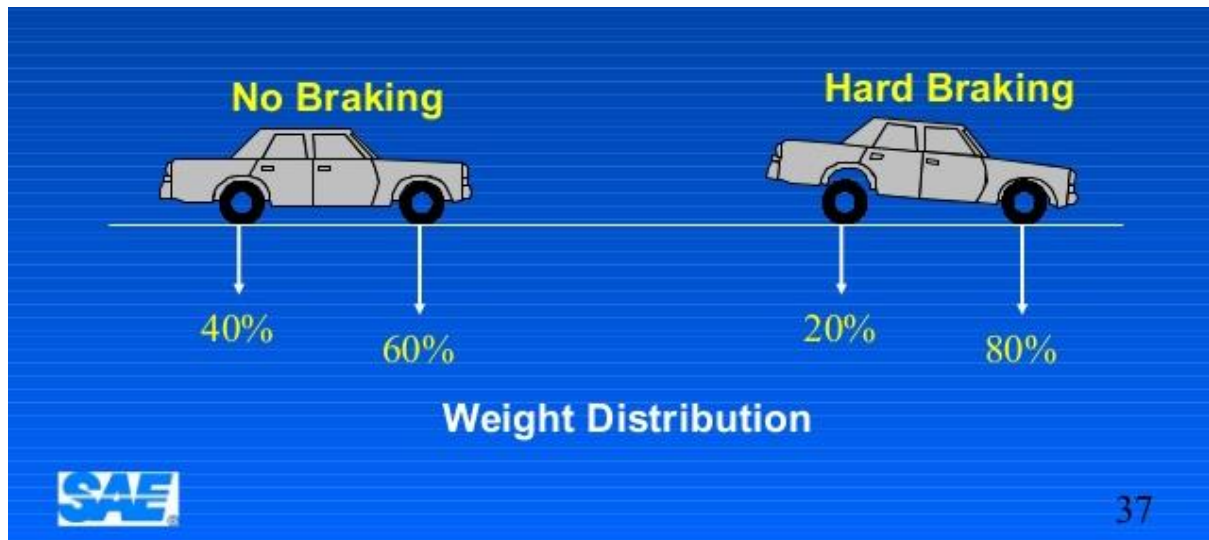


Figure 6.4.1 Braking Weight Transfer (Slide Share, n.d.)

When harvesting Kinetic Energy from the rear brakes, the Motor Generator Unit (MGU) acts as a large percentage of rear braking system. The MGU resists the rotation of the rear axle thus removing a majority of the rear brake energy and converting it into reusable kinetic energy. The MGU system always resists the same amount of axle rotation, meaning that if the coefficient of friction between the tyre and road surface is reduced, the rear wheels can lock. This has been seen in various forms of Motorsport which utilises KERS, especially Formula One. The amount potential energy which can be harvested is limited by the wheel lock. The equations below are used to determine the wheel lock limit of the MCR.

$$\text{Weight Transfer} = \frac{\text{Vehicle Mass} \times \text{CofG}}{\text{Wheel Base}}$$

$$\text{Dynamic Axel Mass} = \text{Rear Static Mass} - \text{Weight Transfer}$$

$$\text{Wheel lock Limit} = \text{Dynamic Axle Mass} \times \text{Acceleration due to Gravity} \times \mu$$

$$\text{Torque} = \text{Rolling Radius} \times \text{Wheel Lock Force}$$

$$\text{Power (Wheel Lock Limit)} = \text{Wheel Lock Force} \times \text{Lowest Vehicle Velocity}$$

(Engineering Inspiration , 2014) (Tech and Talk, 2015)

6.5 Harvesting Period

Kinetic Energy harvesting period is when the vehicle is braking in preparation for a corner, this period ends when the brake pressure is released and the driver adds a steering input to turn the vehicle.

Throughout an entire lap of Pembrey in the MCR, there are a total of 6 potential kinetic energy harvesting phases, with the largest collecting period being the hairpin corner. These are discovered by using the vehicle data from the MCR, the brake pressure, Velocity and steering input are all used to determine these factors. The MCR under braking around the Pembrey lap for a total of 11.4 seconds, this in turn means that the total harvesting period is also 11.4 seconds.

6.6 Optimum G- Optimum Lap

The Optimum Lap software created by Optimum G, allows a vehicle to be created or modified to then produce a predicted lap time simulation. The software uses relatively simple key factors to allow the user to create a vehicle. The majority of these parameters used to create an MCR simulation is shown below (Optimum G, 2016).

- Vehicle Type (Prototype Car)
- Vehicle Mass
- Driven Type (2WD)
- Drag Coefficient
- Downforce Coefficient
- MCR Frontal Area
- Air Density
- Tyre Radius
- Rolling Resistance
- Engine Speed (RPM)
- Engine Torque (N/m)
- Gear Ratio
- Final Drive Ratio
- Power Factor

- Grip Factor
- Aero Factor

The majority of the above parameters had been calculated at the initial stage of data collection and assigned into the data spreadsheet, other parameters were calculated at a later date. The gear ratios for the MCR were designed using a MCR gear spreadsheet supplied by UWTSD lecturer Timothy Tudor (Tudor, 2015), this spreadsheet helped immensely during this stage of the project.

Final Drive Ratio	3.1			
Rolling Radius	0.269999			
		Teeth	Teeth	Ratio
Gear Ratios	1	14	36	2.571429
	2	15	30	2
	3	17	28	1.647059
	4	18	25	1.388889
	5	21	26	1.238095
Max RPM	7300			
Min RPM	4500			

Figure 6.6.1 MCR Gear Ratio Spreadsheet (Tudor, 2015)

The above *fig 6.6.1* is a screenshot of the MCR gear ratio spreadsheet, it shows the final drive ratio and the ratio of each gear, this data is essential when creating a vehicle in Optimum Lap.

7.0 Component Sizing

It is important to investigate components that can be used for the Kinetic Energy Recovery System; this will help discover various advantages and disadvantages of each, (especially storage systems), the reason for this is that each of them have different performance features, sizes and working characteristics. Researching these correctly will

determine the energy storage system, motor generator unit and inverter selected for use on the MCR, this research will aid the completion of aim two. The operating characteristics and efficiencies of these components determine the speed at which the reusable energy can be harvested, stored and deployed over a lap.

7.1 Motor Generator Units (MGU)

A Motor Generator Unit (MGU) is a device which can operate in two opposite modes. The MGU works by deploying energy via a motor, the same motor can then change the electrical flow and become a generator unit during the harvesting period. As a generator unit, it consumes mechanical energy to produce electrical energy. Whereas the motor unit consumes electrical energy to produce mechanical energy (Gable & Gable, 2014).

MGU's are typically one of two types, either dc (Direct Current) or ac (Alternating Current). The symbol ac or dc indicates the type of electrical energy the MGU consumes and generates. An Alternating Current changes direction as the electricity flows through a circuit, a direct current however only travels in a single direction (Herman, 2011). *Fig 7.1.1* shows the visual difference between a Direct Current and an Alternating Current.

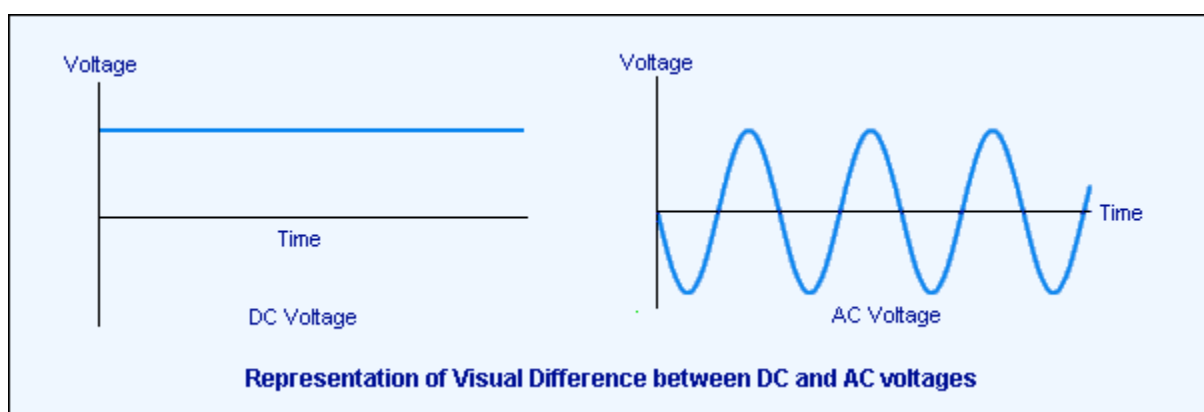


Figure 7.1.1 Visual Difference Between ac and dc Voltages (Kulmar, 2013)

The Motor Generator Unit used in hybrid and large electrical vehicles is typically an ac MGU specification. This evidence was gathered by researching various MGU systems,

Zytek, YASA Motors and McLaren MGU all use an ac formatted system (YASA Motors, n.d.) (Zytek Automotive, n.d.) (McLaren Technologies, n.d.). Due to these companies using the format of system, the decision was taken to investigate ac MGU's in more detail.

A typical ac Motor Generator Unit consists of four main components. These components are a rotor, stator, slip rings that carry the current to and from the rotor, and brushes which are in contact with the slip rings and transfer the current to and from the circuit (Gable & Gable, 2014).

The Generator side of the unit works when the rotor is driven by a mechanical power source (vehicle braking), as the rotor spins, the wire coil surrounding it passes over permanent magnets in the stator and an electric current is created in the wires surrounding the rotor. Due to the loops in the coil passing the North Pole and then the South Pole of the magnets, the electrical current created continuously and rapidly changes direction. Slip rings are individually fitted at each of the two ends of the rotor's wire loop to provide a current path. The brushes have a contact against the slip rings which completes the circuit and allows a current path (Gable & Gable, 2014).

The Motor side of the unit works essentially the same way as the Generator but in reverse. Instead of the rotor spinning to create electricity, the current is fed via a circuit, through the brushes and slip rings to the rotor. The electrical current feeding into the wire coil surrounding the rotor creates an electromagnet. The magnets located in the stator repel the electromagnetic force, resulting in the rotation of the rotor. As long as electrical flow is present, the motor will rotate (Gable & Gable, 2014).

The Suitable ac Motor Generator Units for a hybrid vehicle have a typical efficiency ranging from 93-96% (YASA Motors, n.d.).

7.2 Storage Systems

Flywheel Energy Storage

Flywheel storage systems function by having a rotating mass to act as an energy storage system. Energy is received to and from the driveline to store or deliver energy. When the vehicle is at a high speed, the flywheel, assuming that the energy has been used will be at a low speed. Once the vehicle applies the brakes the energy generators will slow the vehicle (acting as the brakes), the energy is transmitted to the flywheel causing it to rotate, known as a momentum exchange (Kapoor & Parveen, 2013). Once the vehicle is accelerating, depending on the system design power can be deployed exiting the corner thus gaining acceleration quicker.

The storage capabilities of a flywheel are dependent on the maximum rotational velocity, which is limited by material development. The total energy a flywheel can store relies on the flywheel mass and rotational speed. Flywheels are a mechanical form of energy storage, meaning the depth of discharge is 100%.

A Light-Duty flywheel which is suitable for a family vehicle or a medium size racing car has a kWh rating of 0.3-0.5, a delivered energy rating of 1.08-1.80MJ and a peak power of 25-40Kw. These figures have been discussed in a report written by James Hansen and David O’Kain, the topic discussed in the paper is an assessment of flywheel high power energy storage technology of hybrid vehicles (Hansen & O’Kain, 2011).

Battery Energy Storage

Battery energy storage systems range from a traditional lead-acid to Lithium Ion, Lithium Polymer and Nickel Based Batteries. The lead acid battery has been commercially successful for over a century and is still widely used in the automotive industry. The lead-acid battery advantages are that due to mature technology and common materials, the cost of it is relatively low in comparison to other energy storage devices. The disadvantages with

lead-acid batteries are that a poor characteristic is developed when the operating temperature is below -10°C and its energy and power is greatly reduced. The lead-acid battery also is affected by rapid charging; meaning its compatibility for a KERS system wouldn't be favoured due to constant recharging in the braking zones and instant power outputting in the acceleration zones. Nickel and lithium ion based batteries have a greater performance than the Lead-acid battery but can also suffer with rapid charging issues and come at a greater cost (Ehsani, et al., 2004). A lead acid battery is the least energy dense; however the cost per unit is much lower than newer technologies, such as Lithium Ion and Lithium Polymer. A Lead acid battery can discharge to around 50% without causing damage, however optimum discharge levels are around 20%. More than a 20% discharge is referred to as a deep cycle (Massachusetts Institute of Technology, 2008).

The Lithium Ion (Li-Ion) battery is currently being developed and improved by many battery technology companies. It is used in many mobile phones and is a favoured choice for various electric vehicles; the Nissan Leaf uses a Li-Ion battery pack. The efficiency of the Li-Ion Battery is said to range from 80-90% (Sun, 2010).

The Nickel-Metal Hydride (NiMH) battery is another selection choice as an energy storage system, however after conducting further research into this battery type, there is little to no information on the specifications. The efficiency of this battery was however discovered to be at 66% (Sun, 2010).

Super and Ultra Capacitor Energy Storage

Super-Capacitors are an alternative energy storage device which could potentially be selected for a Kinetic Energy Recovery System. A Super-Capacitor works in a way similar to a regular capacitor by having two plates separated by a thin insulator. Although when the plates are fully charged a double layer is formed, this is one of the differences between a

regular capacitor and a super-capacitor. The level of energy storage is greater when compared to that of a regular capacitor. Super-Capacitors only have a voltage level of around 2-3 volts, they can be connected in a series to produce larger amounts of voltage to use with powerful equipment (Woodford, 2015). Due to Super-Capacitors having an almost instant charge and discharge rate, it is a possibility that it could be used as a temporary energy storage device for a regenerative braking system (Frackowiak, 2013).

A Super-Capacitor with a peak power of 50Kw has been stated to have an efficiency rating of up to 97.94% (Zhong, et al., 2006).

Energy Storage System Comparison

A technical report written by Radhika Kapoor and C. Mallika Parveen discusses a comparative study on various KERS technologies. The report explains the various components used to complete a Kinetic Energy Recovery System. It demonstrates using the aid of graphs the cost comparison and efficiency of various storage systems.

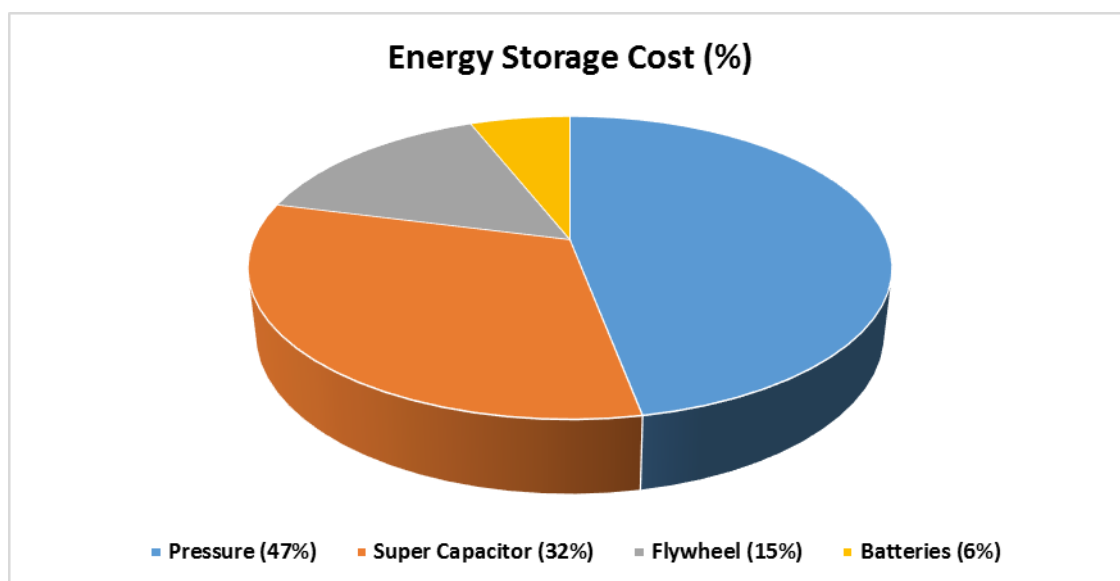


Figure 7.2.1 Energy Storage Cost Comparison (Kapoor & Parveen, 2013)

In *fig 7.2.1* it shows the cost of each storage system, this is calculated by the cost of purchase or manufacturing to the capabilities of the system.

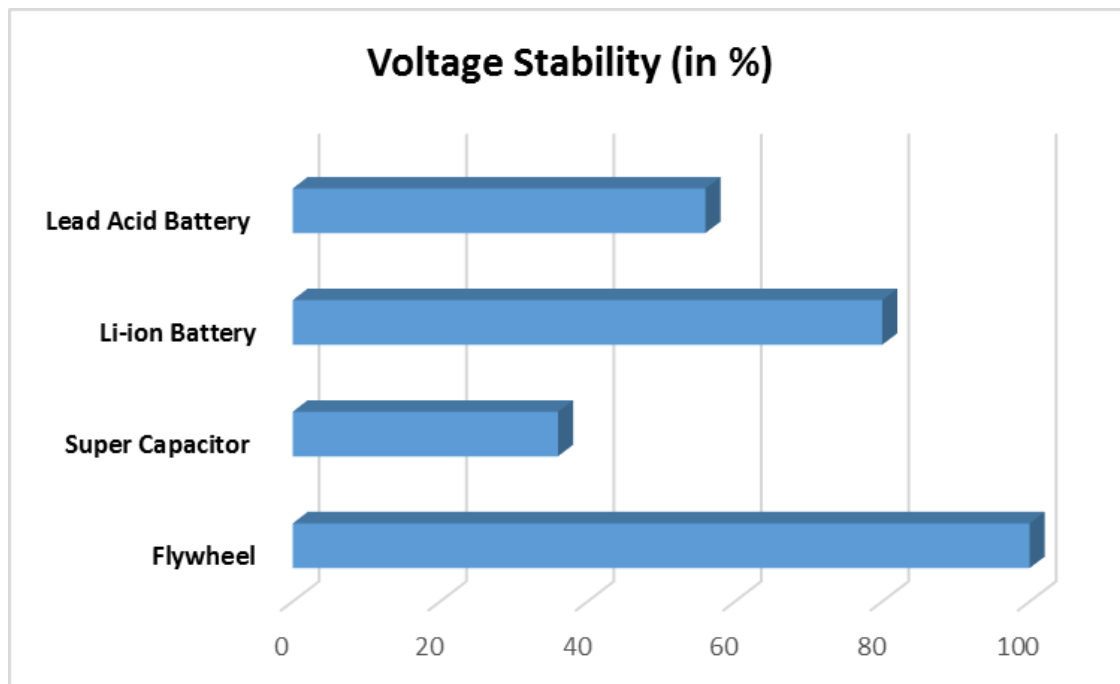


Figure 7.2.2 Energy Storage Voltage Stability (in %) Comparison (Kapoor & Parveen, 2013)

Above in *fig 7.2.2* it is shown how much voltage can be stored compared to the self-discharge rate of being used. This is why the capacitor has a low figure, due to its self-discharge rate.

The paper written by Radhika Kapoor and C. Mallika Parveen will aid the comparison of the various storage systems.

A Light-Duty flywheel which is suitable for a family vehicle or a medium size racing car has a kWh rating of 0.3-0.5, a delivered energy rating of 1.08-1.80MJ and a peak power of 25-40Kw. These figures have been discussed in a report written by James Hansen and David O’Kain, the topic discussed in the paper is an assessment of flywheel high power energy storage technology of hybrid vehicles (Hansen & O’Kain, 2011). These figures can be compared against that of Li-Ion and NiMH, the Li-Ion Battery efficiency is said to range

from 80-90% (Sun, 2010), the efficiency of a an NiMH battery is only around 66% (Sun, 2010). A Super-Capacitor with a peak power of 50Kw has been stated to have an efficiency rating of up to 97.94% (Zhong, et al., 2006).

The price comparison of the energy storage devices in *fig 7.2.1* shows that to most expensive system is Supercapacitor's at a figure of 32%. The graph then shows flywheel storage to be the second most expensive at 15% and the finally battery technology being the cheapest at only 6%. However since flywheel energy storage has issues with being material limited, it would be expected that flywheel would be the most expensive.

7.3 Inverter and Converter Units

An Inverter Converter Unit is a component used in hybrid and electrical vehicle to manage and control the electric drive systems. An Inverter Converter Unit typically has a charge controller, the unit supplies current to the energy storage system during the regenerative braking recharge phase. As well as this the unit provides electricity to the MGU to aid vehicle propulsion. Hybrid vehicles typically use low voltage dc batteries to reduce the physical size and mass, but also use high voltage and efficient ac MGU's. The Inverter Converter Unit manages how these diverse currents and voltages work together (Gable & Gable, 2014).

An ac motor controller inputs ac current and converts it into three phase waveform. The waveform frequency (Hz) controls the speed of the ac motor. Pulsating voltage being sent through a motor is how dc brushless motor controller works; this in turn creates a magnetic force on the motor creating torque (Hills, 2005). The Inverter and Converter Units being manufactured currently, usually send signals and controls via an integrated CAN system (Zytek Automotive, n.d.) (Electric Motorsport , n.d.).

7.4 Zytec

Zytek Automotive is a company which specialises in various electronic technologies, but the main area Zytek Automotive which is of interest for this project is the Energy Recovery System (ERS). Zytek Automotive have been a supplier of hybrid systems for Motorsport applications since the late 1990's. The company have gained knowledge since the return of Kinetic Energy Recovery into Formula One. Zytek Automotive have developed a Kinetic Energy Recovery System (KERS), for the use is a wide variety of Motorsport racing series (Zytek Automotive, n.d.).

The image below in *fig 7.4.1* shows the Kinetic Energy Recovery System designed by Zytek Automotive. It shows the Internal Combustion Engine (I.C.E), the gearbox, the MGU, Battery and the Inverter Converter Unit. The MGU locates into the gearbox housing; this is made possible by either modifying one half of the gearbox casing or having a company manufacture a new casing. The Battery and Inverter Converter Unit can be packaged anywhere on the MCR with minimal modifications to the vehicle. A possible location for the Battery and Inverter Converter Unit could be in the passenger part of the MCR, this would then create the potential of a more even weight distribution.

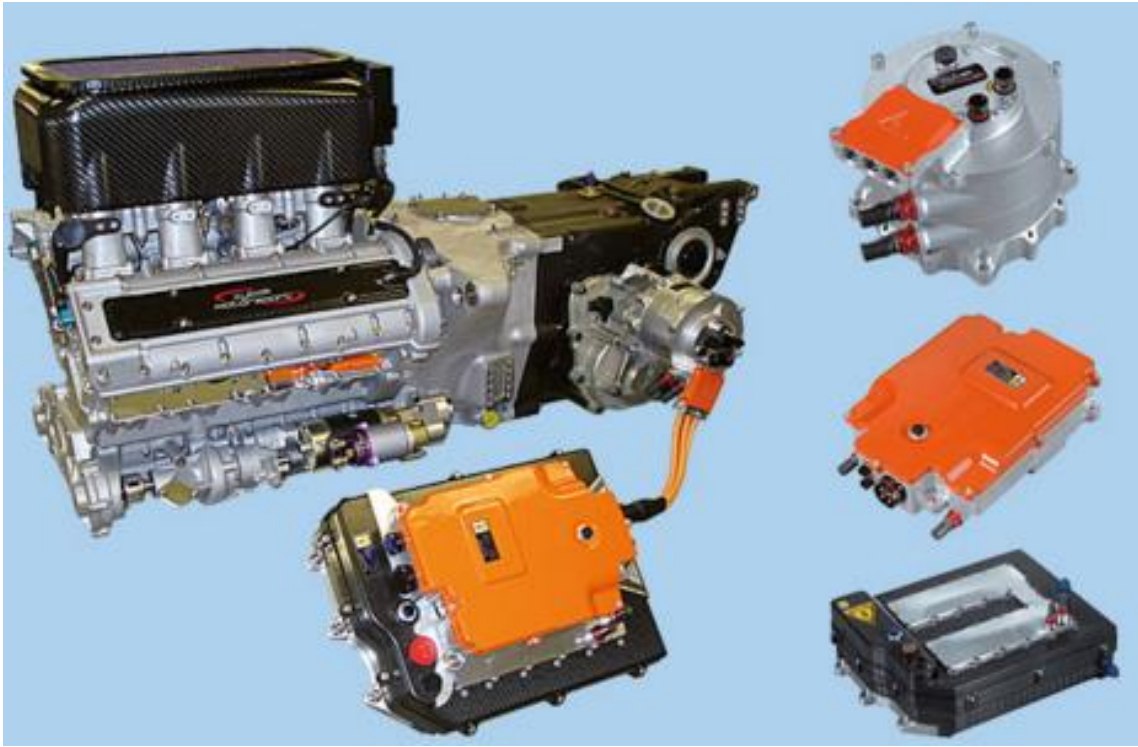


Figure 7.4.1 Zytek KERS system (Zytek Automotive, n.d.)

Table 7.4.2 Zytek Inverter Specification (Zytek Automotive, n.d.)

Inverter	
Type	IGBT 3-phase bridge
Voltage range	180 – 340V DC
Weight	5.8kgs
Vehicle communications	Single CAN 2.0b
Safety	Supports HVIL and active discharge

Table 7.4.3 Zytec Motor Specifications (Zytec Automotive, n.d.)

Motor	
Type	AC permanent magnet synchronous machine
Cooling	Water/Glycol
Peak power	50kW
Peak torque	40Nm
Max speed	14,000rpm
Weight	8.5kgs

Table 7.4.4 Zytec Battery Specifications (Zytec Automotive, n.d.)

Battery	
Zytec	Li-Ion
Cooling	Water/Glycol
Capacity	0.88kWh (3.15MJ)
Weight	24kgs
Volume	20 Litres
Peak power	55kW
Voltage range (min, nom, max)	216V, 274V, 302V

The above tables show the specifications for the Zytec Components; however these specifications are missing battery charge and discharge efficiencies and MGU efficiencies. Via research it was discovered the YASA Motors make a similar specification MGU to that of the Zytec and the efficiency rating is 95%. In a paper written by John Sun on Battery Efficiencies, it is stated that Li-Ion Batteries have an efficiency of 80-90% (Sun, 2010), it will be assumed that the Zytec battery has an efficiency of 90%. These losses in efficiency mean

that the amount of energy which can be harvested has to have 15% deducted before calculations and simulations are conducted. The total weight of the ZyteK ERS system is 38.3Kg.

8.0 Results and Analysis

8.1 Wheel Lock Limit

The wheel lock limit for the MCR has been calculated using the data spreadsheet and the previously stated equations in section 6.4. The wheel lock limit has been calculated at various grip levels by using different figures for the coefficient of friction. The formula function on Microsoft Excel has allowed for calculations to be conducted at different vehicle speeds, the speed ranges from the highest velocity braking into the hairpin (largest braking zone) to the lowest velocity. The minimum vehicle velocity is the main speed to consider, this is due to the wheel being most likely to lock at the period, due to the increasing amount of forward weight transfer and the reduction in aerodynamic forces.

In *fig 8.1.1* below shows the wheel lock trends at various velocity and grip levels. The green data trace shows the values of wheel lock when the μ value is 1.3, this value is assuming perfect track and weather conditions. The wheel lock limit at this grip coefficient is 50Kw, this is the limit of how much energy can be harvested when the track is in this condition. The blue data trace shows the values of wheel lock when the μ value is 0.9, this value is an assumption of the coefficient of grip when the track is wet or greasy. The deceleration of the vehicle was altered for the calculations due to a vehicle not being able to decelerate at a figure over 1g when the value for μ is less than one. The wheel lock limit at this grip coefficient is 35Kw, this is the boundary of how much energy can be harvested when the track is in this condition. Finally the red data trace shows a μ value of 0.4, this

value was selected purely as an experiment to discover how the effect of minimal grip coefficient affects the wheel lock limit.

The Assumed track condition for the MCR is the green data trace, meaning that the amount of energy that can be harvested is 50Kw for 11.4 seconds. The efficiency losses from the MGU and Battery has to be considered as well, this mean 15% has to be deducted due to losses, making the energy potential in a lap 42.5Kw for 11.4 seconds. This figure matches the outputs of the Zytec system, for this reason the Zytec ERS system has been selected.

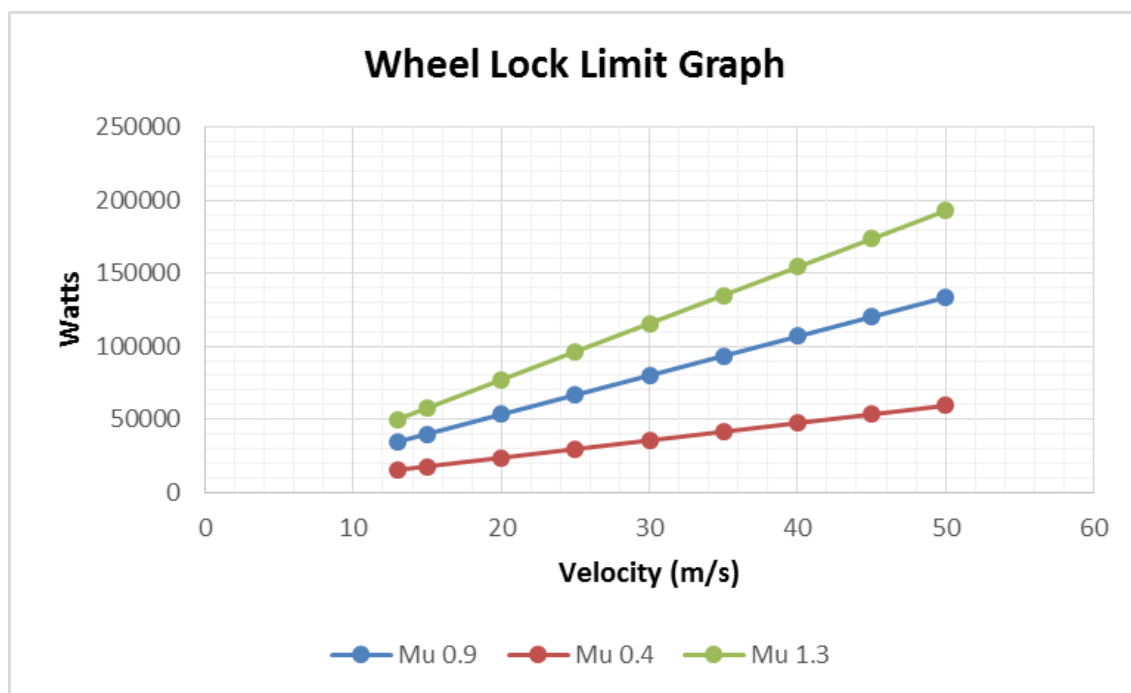


Figure 8.1.1 Various Wheel Lock Limits

8.2 Hybrid Lap

The wheel lock limit in ideal conditions was calculated at 50Kw at 13m/s (lowest braking velocity), taking into account the losses in the hybrid system the hybrid power potential is 42.5Kw. The harvest time of 11.4 seconds means that the deployment time will be 11.4 seconds as well, resulting in an extra 42.5Kw for 11.4 seconds a lap.

This extra power boost can be calculated with the aid of the data spreadsheet. The standard lap data of the MCR has been used as a vehicle baseline, this data was entered into a different Microsoft Excel work tab, the spreadsheet can be seen in Appendix B. The use of the calculations stated previously in the report are then used to a simulated lap time. The vehicle mass with the ZyteK system is taken into account, however cornering weight transfer could not be investigated.

The deployment of the KERS around the lap also has to be considered, there are various ways in which it can be deployed. The first potential method is to divide the amount deployment time and give the MCR a power boost out of each corner around an entire lap. The second method would be to deploy the entire 42.5Kw in one 11 second burst of power. The final method is to deploy half the power at two acceleration points, the two largest acceleration periods would be selected for this method.

The selected method for KERS deployment is the final one, where the power output is halved and deployed at the two largest acceleration points. The decision was taken to deploy 22.8Kw for an 11 second period at the first acceleration point, and then deploy 22.8Kw for a 10 seconds period. This means not all of the energy in the ZyteK battery will be extracted meaning the deep cycle and depth of discharge is not exceeded (Massachusetts Institute of Technology, 2008).

The graph *Fig 8.2.1* below shows a red Velocity – Time data trace which is the standard lap of the MCR around Pembrey Race Circuit. The green data trace is the MCR lapping Pembrey but with the benefit of Kinetic Energy Recovery. It can be seen that in the initial sections of the lap, that the green data trace is slower, this will be due to the added weight of the KERS. Around the mid-lap period the energy boost is realised at the first acceleration point for 11 seconds, the vehicle then slows for a corner and then accelerates for the final section. The graph shows that the added power of KERS has increased the MCR's lap performance around the Pembrey Circuit, the hybrid lap is 1.5 seconds faster.

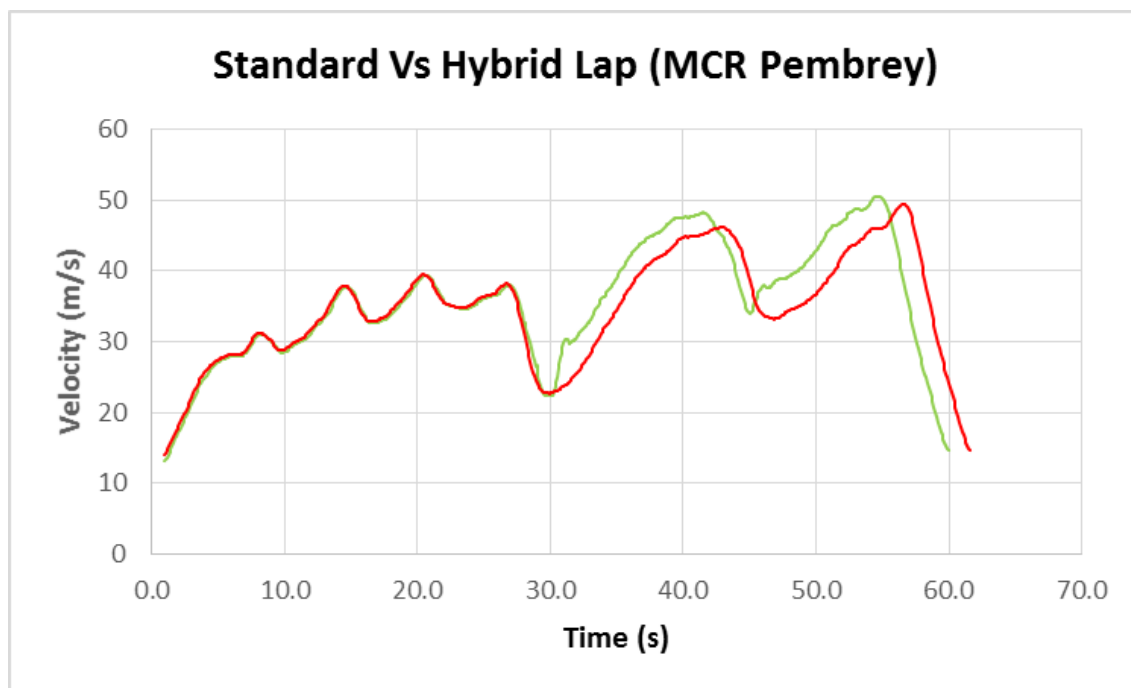


Figure 8.2.1 Standard Vs Hybrid (Velocity – Time)

The graph *Fig 8.2.2* below shows a red Velocity – Distance data trace which is the standard lap of the MCR around Pembrey Race Circuit. The green data trace is the MCR lapping Pembrey but with the benefit of Kinetic Energy Recovery. It can be seen that in the initial sections of the lap, that the green data trace is slower, this will be due to the added

weight of the KERS. Around the mid-lap period the energy boost is realised at the first acceleration point for 11 seconds, the vehicle then slows for a corner and then accelerates for the final section. The graph shows that although the green data trace is faster, due to the added weight and higher velocity, the braking point is sooner than that of the standard car. However this doesn't affect the KERS boost to a massive extent around this circuit.

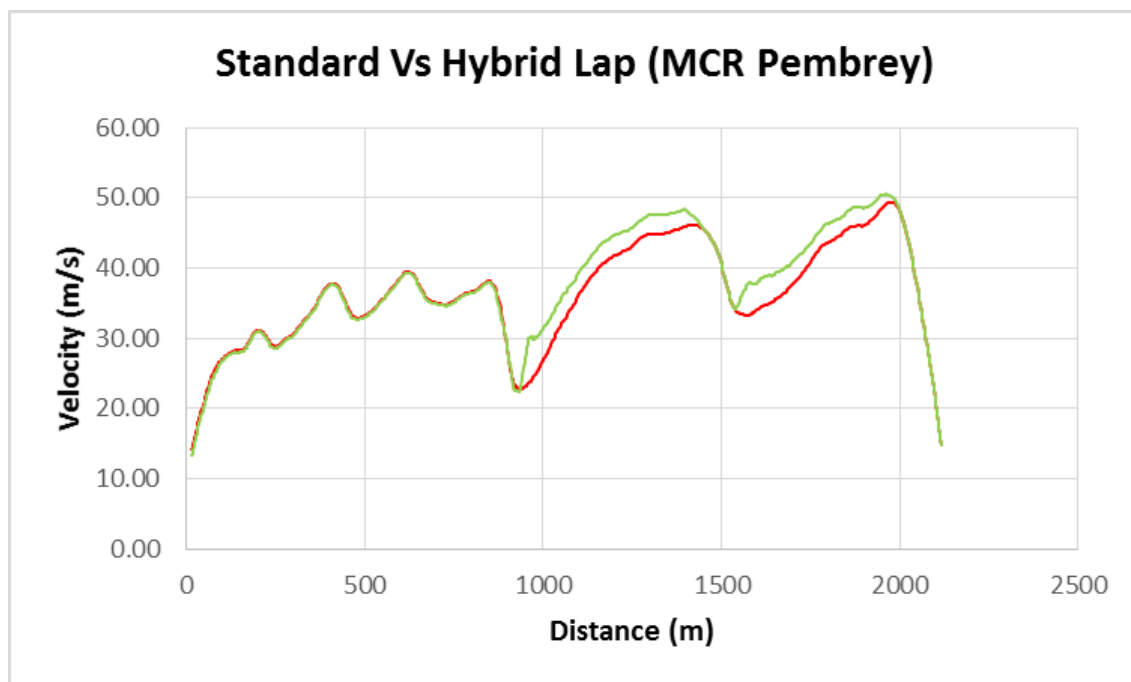


Figure 8.2.2 Standard Vs Hybrid (Velocity – Distance)

8.3 Optimum G Results

The Optimum Lap software created by Optimum G, allows a vehicle to be created or modified to then produce a predicted lap time simulation. The software uses relatively simple key factors to allow the user to create a vehicle (Optimum G, 2016).

The MCR was created in the software using the standard data specification of the car (MCR Race Cars, n.d.), and collected data through various calculations and investigations.

The gear ratio spreadsheet supplied by UWTSD Lecturer Timothy Tudor, was essential in creating the Optimum G MCR (Tudor, 2015). Once the MCR was created a simulation could be conducted, this simulation gave the MCR a predicted lap time of 61.30 Seconds. When compared to the actual lap time of 61.6 Seconds, it displays that at this stage the prediction is very close to live data.

The wheel lock limit in ideal conditions was calculated at 50Kw at 13m/s (lowest braking velocity), taking into account the losses in the hybrid system the hybrid power potential is 42.5Kw. The harvest time of 11.4 seconds means that the deployment time will be 11.4 seconds as well, meaning an extra 42.5Kw for 11.4 seconds a lap.

The MCR with KERS was created by using the previously created MCR as a baseline model and then modify the model to suit. The Optimum Lap software would only allow a power increase over an entire simulated lap. This meant that the vehicle would have a 42.5Kw increase of power for 50.2 seconds of a lap; this would give the MCR unrealistic and useless results in terms of lap time performance. Due to this, the decision was then made to give the MCR a 10kw increase in power for all acceleration points around the Optimum Lap Circuit. Once the modified MCR model was complete with the power modifications a lap could be simulated.

Below in *Fig 8.2.2* shows a Velocity – Distance data graph, this is a comparison of an Optimum G MCR standard lap Vs an Optimum G MCR hybrid lap. The green data trace is of a standard simulated lap of the MCR around Pembrey Race Circuit, the simulation take 61.3 seconds. The black data trace is a simulated lap MCR at Pembrey but with the benefit of Kinetic Energy Recovery. It can be seen that the simulated hybrid MCR is faster at each acceleration section and completes a simulated lap time in 59.48 seconds.

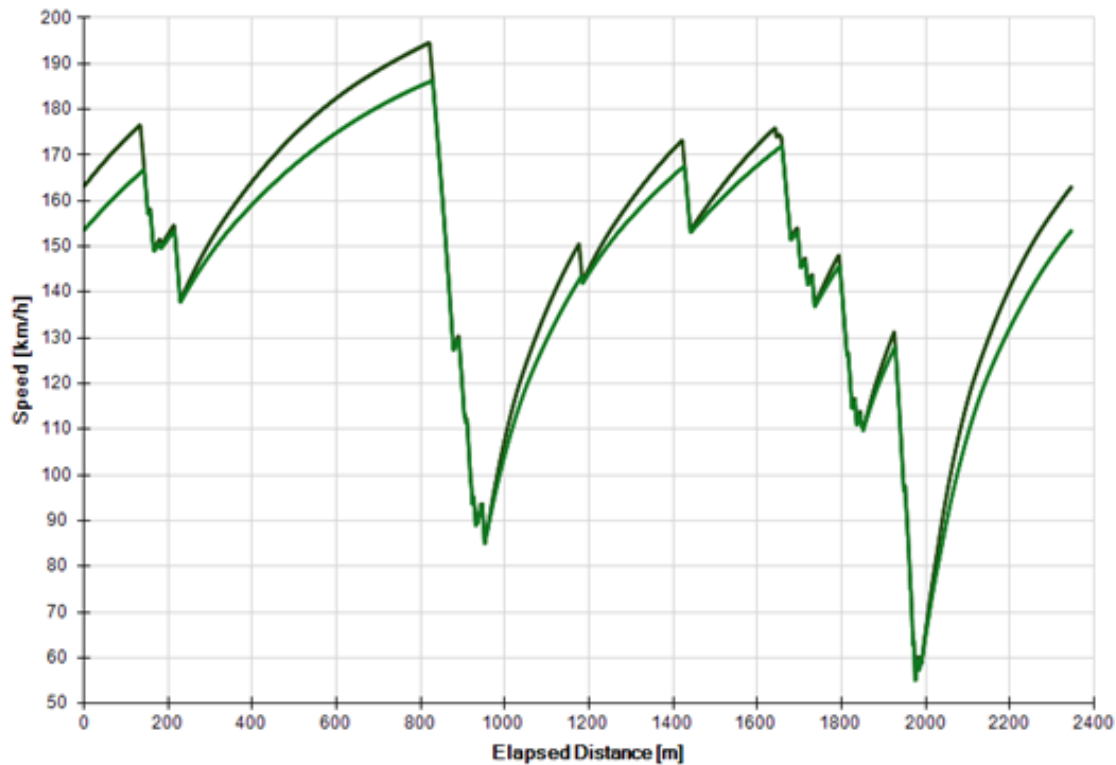


Figure 8.3.1 Optimum Lap- Speed – Distance Graph (Optimum G, 2016)

When trying to create a Speed – Time Graph in the Optimum Lap software, an error report would appear, resulting in this graph display being unattainable. The overall lap times of both the standard and hybrid lap times however would appear, showing the hybrid MCR with performance gains.

9.0 Recommendations and Further Work

When conducting a project, one of the biggest limitations faced is time scale. Time limits how much work can be carried out and limits the amount of investigation doorways which can be accessed. This section of this report will discuss what the author would continue, improve or investigate further given a larger time scale.

A spreadsheet could be created to analyse the mass changes to the MCR when the KERS system is added. This would in turn change the centre of gravity height. The centre of gravity height could then be used to calculate actual cornering weight transfer and see if time would be lost in the corners carrying this extra weight.

Using the mass change spreadsheet discussed in the previous paragraph, the centre of gravity height could again be used to change the mass distribution of the MCR on the UWTSD Base Performance Simulator. Adding the KERS power gain to the simulator would allow for realistic live data results and experimentation with various KERS release periods.

Investigate and design a variable harvest controller, similar to what is used in Formula One. This device would allow the driver to adjust to amount of energy being harvested through the rear axle reducing the chances of wheel lock occurring in poor weather conditions.

Create an accurate Cad model of the MCR. Using the sizes and dimensions of the ZyteK ERS unit (Appendix C), model the components and fit them into the chassis area with minimal modifications and structural changes to the MCR.

The Battery, MGU and Inverter of the ZyteK system creates heat, the recommendation by ZyteK is to reduce the amount of heat by the components with a water system. Research and investigate whether the engine cooling system already installed on the MCR would be able to sufficiently cool the KERS unit, as well as not causing over heating issues with the Internal Combustion Engine.

10.0 Conclusion

After collecting and analysing data using Microsoft Excel and Optimum G – Optimum Lap with various researched calculations, the following conclusions can be drawn.

The wheel lock limit was calculated to at 50Kw, once deducting the battery and MGU inefficiencies of 15% (YASA Motors, n.d.) (Sun, 2010), the total harvest amount was 42.5Kw. This figure was close to what should be expected from a vehicle in this performance category. Formula One (2009) gains 60Kw per lap from kinetic energy harvesting, this figure is a limitation set by the FIA to ensure an equal playing field (FIA, 2009). Taking in account of how much the MCR weighs and the speed, it is around half as much slower. This meant that although the result for the Formula One car is a limited figure, the harvest amount for the MCR would be around half that at 30Kw.

The Excel Data spreadsheet created at the initial stages of the project and continuously used and added to throughout the entirety of the project had proved vital. The spreadsheet has determined the MCR standard data just from time and velocity. The coast down testing to calculate resistive forces was also analysed with it. It was used to determine the harvesting period and the wheel lock limit. The spreadsheet also acted as a fast simulation tool when analysing the performance gains to Kinetic Energy Recovery.

The Optimum G – Optimum Lap software proved to be a more difficult tool to analyse vehicle data. The amount of variables in the software and the lack of ability to specify where the deployment zone are has resulted in questionable results. The results from the software also have to be questioned due to the Optimum G Company stating that the

result accuracy is within 10%, which is a large margin. However as it has been stated, the inaccuracies can be taken into account.

The Theory of converting the UWTSD MCR into a parallel hybrid vehicle has been deemed a success. The hybrid vehicle outperformed the standard MCR in the simulations conducted through Microsoft Excel and the Optimal G – Optimal Lap software. These simulations showed the hybrid MCR to be over a second a lap faster in both formats of tests.

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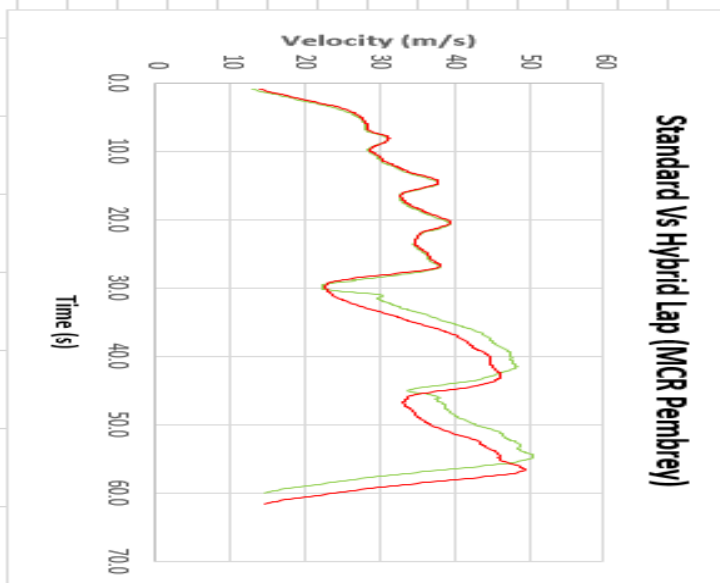
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Appendix A

Date Commencing Weekly	29/09/2014	06/10/2014	13/10/2014	20/10/2014	27/10/2014	03/11/2014	10/11/2014	17/11/2014	24/11/2014	01/12/2014	08/12/2014	15/12/2014	22/12/2014	29/12/2014	05/01/2015	12/01/2015	19/01/2015	26/01/2015	02/02/2015	09/02/2015	16/02/2015	23/02/2015	02/03/2015	09/03/2015	16/03/2015	23/03/2015	30/03/2015	06/04/2015	13/04/2015	20/04/2015	27/04/2015	04/05/2015	11/05/2015	18/05/2015	25/05/2015	
Research																																				
Kinetic Energy Recover and Regenerative Braking																																				
Component Specifications																																				
Relevant Equations																																				
Theory and Previous Projects																																				
Establish Pounds/Sec/Lap Target Potential from Race Teams																																				
Data																																				
Collect MCR Data																																				
Analyse MCR Data																																				
Create Data Analysis Spreadsheet																																				
Define Brake harvesting points																																				
Write up																																				
Project Proposal and Initial Report																																				
Seminar Paper																																				
Seminar Presentation																																				
Project Report																																				
VIVA																																				
Exhibition Paper																																				
Calculations																																				
Input MCR Data Into Spreadsheet																																				
Calculate Resistance to motion, Torque, Power, ect																																				
Calculate Wasted Brake Energy																																				
Calculate Harvest Potential And Amount																																				
Simulations																																				
Simulate The Potential Power increase																																				
Simulate The length of Time For Power Deployment																																				
Simulate a Velocity vs Time Improvement Graph																																				
Pricing																																				
Establish Pounds/Sec/Lap Target																																				
Price KERS Components needed																																				
Review Price of System Vs Pound/Sec/Lap Target																																				
Research																																				
Data																																				
Calculations																																				
Write Up																																				
Simulations																																				
Pricing																																				
Milestones																																				

Appendix B

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Total Distance (m)	Section Distance (m)	Standard Power (W)	Standard Time (s)	Standard Velocity (m/s)	Work (J)	Hybrid Power (W)	KERS Power (W)	Total Hybrid Power (W)	Hybrid time (s)	Hybrid Velocity (m/s)	Hybrid Time Total (s)								
2	1.3	1.3	2924.89	0	13.33	0	2924.89	-300	2624.89	0.000	13.33	0.0								
3	2.7	1.4	5145.79	0.1	13.61	5145.794	5145.79	-300	4845.79	0.106	12.81758	0.1								
4	4.0	1.4	3024.73	0.2	13.61	3024.729	3024.73	-300	2724.73	0.111	12.26113	0.2								
5	5.4	1.4	3024.73	0.3	13.61	3024.729	3024.73	-300	2724.73	0.111	12.26113	0.3								
6	6.7	1.4	3024.73	0.4	13.61	3024.729	3024.73	-300	2724.73	0.111	12.26113	0.4								
7	8.1	1.4	5291.02	0.5	13.89	5291.022	5291.02	-300	4991.02	0.106	13.10139	0.5								
8	9.6	1.4	5438.39	0.6	14.17	5438.394	5438.39	-300	5138.39	0.106	13.38519	0.6								
9	11.0	1.5	8033.93	0.7	14.72	8033.933	8033.93	-300	2924.89	0.100	13.61111	0.7								
10	12.5	1.5	5893.75	0.8	15.00	5893.753	5893.75	-300	2924.89	0.100	13.61111	0.8								
11	14.1	1.5	6050.09	0.9	15.28	6050.088	6050.09	-300	5750.09	0.105	14.52021	0.9								
12	15.6	1.6	8837.19	1	15.83	8837.186	8837.19	-300	8537.19	0.104	15.29583	1.0								
13	17.2	1.6	6533.31	1.1	16.11	6533.312	6533.31	-300	6233.31	0.105	15.37131	1.1								
14	18.9	1.7	9464.96	1.2	16.67	9464.961	9464.96	-300	9164.96	0.103	16.1384	1.2								
15	20.6	1.7	9896.20	1.3	17.22	9896.195	9896.20	-300	9596.20	0.103	16.70014	1.3								



Appendix C

