

University of Wales Trinity Saint David

School of Engineering

A THEORETICAL INVESTIGATION: THE EFFECT OF APPLYING KERS TO A SPORTS 2000 RACE CAR

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Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David
(UWTSD, 2017)

M SPORT > ENG

(M Sport Eng, 2016)



(MoTeC, 2019)



(BPS, 2019)

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: _____

Date: 30/04/2020

Abstract

This project investigates the effect of applying KERS to UWTSD's MCR Sports 2000 race car around the Silverstone International track. Various experiments, calculations and discussions were carried out including coast down tests and wheel lock limit calculations to assist in the production of a simulated KERS lap. The data was then analysed, and it was found that energy could be recovered four times throughout the track and deployed three times accumulating to 9.76 seconds. Having the KERS implemented caused the lap time to be 1.82 seconds quicker which is a 2.7% decrease in the lap time.

Factors such as the car measurements, governing body and championship regulations, component specifications and safety influenced the investigation throughout. The calculated KERS lap was only carried out in Excel and not in the Base Performance Simulator due to the interruptions of the Covid-19 Pandemic.

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Key Terms

KERS	Kinetic Energy Recovery Systems
UWTSD	University of Wales Trinity Saint David
M Sport ENG	UWTSD's race team
SRCC	Sports 2000 Racing Car Club
ERS	Energy Recovery System
WEC	World Endurance Championship
LMP1-H	Le Mans Prototype 1 – Hybrid
BTCC	British Touring Car Championship
WRC	World Rally Championship
NASCAR	National Association of Stock Car Auto Racing
Li-Ion	Lithium-Ion Battery
MUK	Motorsport UK
MGU	Motor Generator Unit
MGU-K	Motor Generator Unit – Kinetic
RMS	Rinehart Motion System
ISO	International Organisation for Standardisation
CFD	Computational Fluid Dynamics
BPS	Base Performance Simulator
CAD	Computer-Aided Design

Abbreviations for Equations

v	Velocity
t	Time
Cd	Coefficient of Drag
A	Frontal Area of the Car
ρ	Air Density
a	Acceleration
μ	Coefficient of Friction (adhesion)
P	Power
RR	Rolling Resistance
u	Initial Velocity
Δt	Change in Time
S	Distance
ω	Angular Velocity
π	Mathematical value of Pi
R	Rolling Radius

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1 Introduction

This project investigates how a Kinetic Energy Recovery Systems, KERS, can affect the performance of a race car. This report documents the whole project from the initial research phase through to the analysis of the results. Hybridisation is the future of motorsport and KERS is the leading form of mild hybridisation in the industry (Shilpa, 2018). KERS collects some of the wasted energy from braking to generate power. This project is only a theoretical investigation as the budget of the race team and the championship's regulations do not currently allow for this to be physically tested. Hence, this investigation is conducted through analysing real-life data and a simulation model. This project was interrupted by the pandemic outbreak of Covid-19 and therefore part of the simulation model was not able to be used by the author to finalise their results.

1.1 Aims and Objective

The objective of this project is to investigate how the application of a KERS can affect a Sports 2000 Race Car, specifically the UWTSD MCR Race Car.

There are three aims to this project. The first is to conduct significant, in-depth research to promote a thorough understanding of how KERS functions. The second is to calculate and simulate the application of a KERS and compare the data. The third aim is to critically analyse the effect a KERS can have on the lap times, both in simulation and calculations, and whether it is reasonable to be implemented for the Sports 2000 championship.

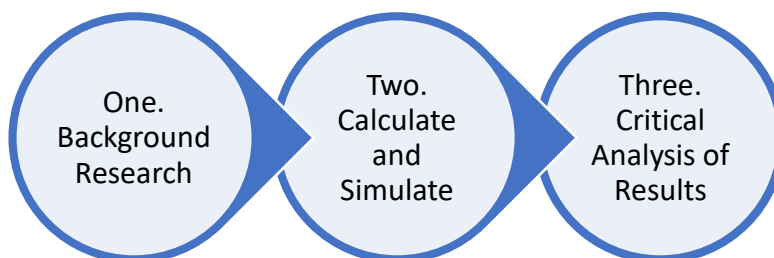


Figure 1-1 Aims of the report

1.2 Case Study

To ensure a thorough investigation was carried out, some initial parameters were set. Firstly, the car being investigated was chosen to be the UWTSD MCR Race Car due to the ease of access to the physical car and both track and simulation data.



Figure 1-2 The UWTSD MCR Race Car (M Sport Eng, 2016)

As this car was chosen, the championship being investigated was The SRCC Sports 2000 Duratec Championship. This championship consists of open cockpit, two-seater, rear-engine 'sports prototype' cars using 2000cc Duratec engines (SRCC, 2019). The cars compete on race circuits around the UK and sometimes Europe if the competitor enters the endurance championship. For the purpose of this investigation, the endurance championship isn't being considered as there is no track data available from the car.

The track that the data was collected on was decided as the Silverstone International Circuit as this has the longest amount of regenerative braking sections.

1.3 Timing Plan

This project followed a timing plan which was continuously updated throughout the project, see Figure 1-3.

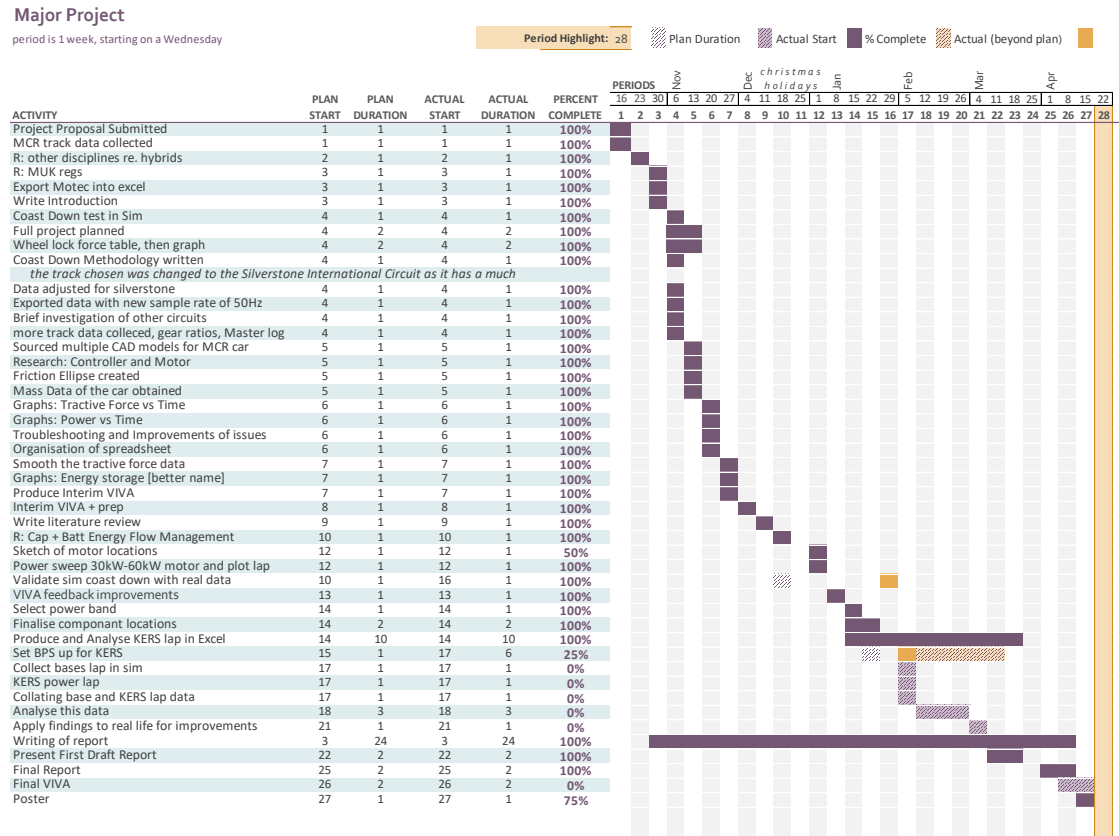


Figure 1-3 Full Project Gantt Chart

There were four main milestones in this project. The first was the production of graphs to analyse the track data, as this allowed the ability to assess the possible use of a KERS. The second was the VIVA presentation as this provided opportunity to reflect on all the research and data analysis up to the Christmas break. The third is the completion of the simulated KERS lap in Microsoft Excel as this quantified the benefit of applying KERS to the MCR. The final milestone is the dissertation because it allows the project to be summarised and evaluated as a whole.

Certain activities were not completed within the timing plan due to the pandemic impact, documented in Section 6.

Some activities took longer than expected such as setting up the BPS to run KERS. This activity was one which was not completed due to the pandemic outbreak but took longer than planned due to the extensive work which was required to understand and interpret the simulators programming.

2 Literature Review

There are a few areas of background research required to be able to fully investigate the effect Kinetic Energy Recovery Systems can have. The first place to begin this research is with the theory and relevance of KERS. The rest of the research consisted of investigating the key components which make up the system.

2.1 Theory of KERS

A KERS is a system which recovers waste energy, such as thermal, under braking and stores it in to be used under propulsion (Mercedes AMG F1, 2019). In batteries this energy is stored as chemical, in flywheels it is kinetic. This is known also regenerative braking in the automotive industry; however, it is referred to as KERS, or ERS, in the motorsport industry. The application is also different between the two industries, where motorsport often use the motor as a power increase on top of the engine power whereas the automotive industry uses the power as a replacement or reduction in engine power. The purpose of implementing this type of system in the automotive industry is to make the vehicles more efficient and reduce fuel usage, whereas in motorsport its aim is to increase the power of the vehicle thus making it go faster (Holt, 2012).

Figure 2-1 depicts the entire system is in a simple diagram.

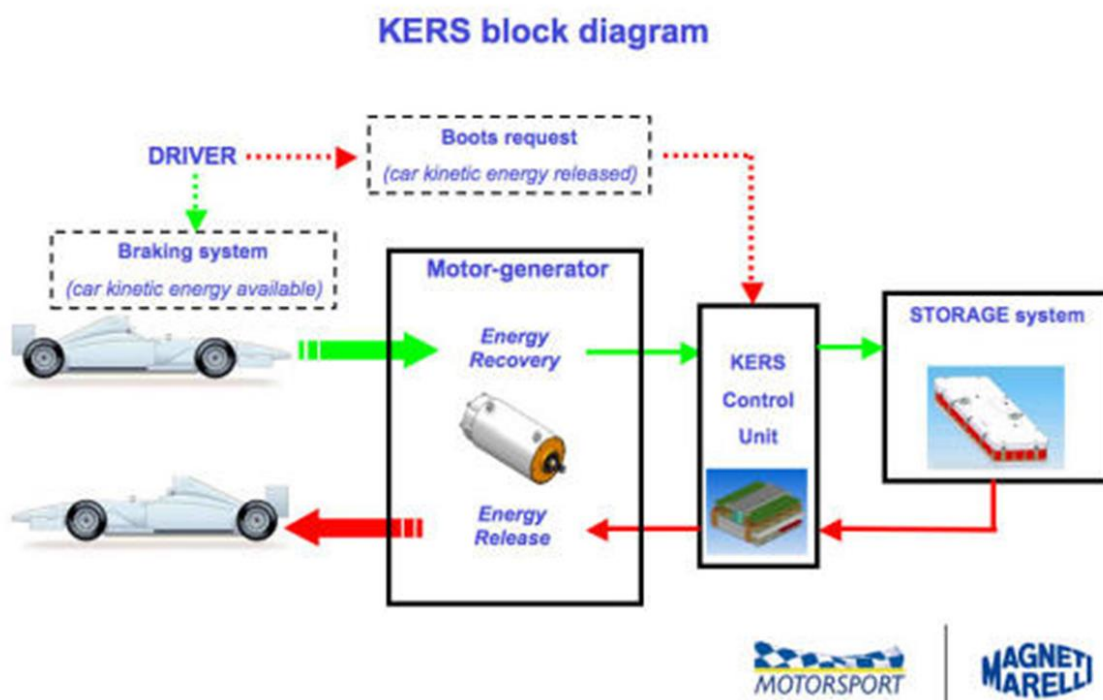


Figure 2-1 KERS block diagram (Magneti Marelli, 2010)

When the system is in use, its job is influenced by the driver who has control of two options: to brake or to boost. Under braking the Motor Generator Unit, MGU, recovers energy by acting as a generator and assisting the friction brakes. The control unit dictates how much energy is recovered and transfers as much as the storage system can absorb (X-Engineer, 2019). The energy then remains in the storage system until the driver requests for more power through a 'boost' button on the steering wheel. The signal is sent to the control system which requests energy from the energy store and delivers it to the MGU (Collins, 2013). The MGU then acts as a motor and releases kinetic energy into the powertrain to increase the power of the car.

The two main types of regenerative braking are series and parallel. They behave differently and are each beneficial in different applications. Series brakes are often used in automotive as they are more efficient in normal driving conditions and give the driver a normal pedal feel. For motorsport however, parallel braking can sometimes be used as it is much cheaper. Since cars are often braking at high or maximum braking force the systems are equally efficient due to the MGU acting at its maximum power. At high braking force, the poor pedal feel does not occur due to the generator being at its maximum force as well as the friction breaks.

2.2 Relevance of KERS

The SRCC championship currently has no reference to hybrid or electric integration into their championship, but there are hybrid and electric examples in other motorsport championships. The WEC championship has a fully hybrid class of cars; the LMP1-H (FIA, 2019). There is also a fully electrified circuit racing championship, Formula E.

Other championships are now planning on moving to hybrid by 2022 including BTCC (2018), WRC (Evans, 2019), NASCAR (2019) and IndyCar (2019). The introduction of hybrids in IndyCar has changed the championship considerably. The power output has increased from a maximum of 700 horsepower to be in line with the Formula 1 power of 900 horsepower (O'Kane, 2019). But this is just one example of the introduction of hybrids increasing power and therefore lap times. WRC are taking a different approach and using the hybridisation to travel between stages and through cities on full-electric mode to reduce noise and air pollution (Evans, 2019).

Electrification is not just the responsibility of the championship organisers but also the manufacturers. Volkswagen has committed to making their racing division all-electric by 2025, stating they will drop all "factory-backed commitments" to race cars with combustion engines

(Volkswagen Motorsport, 2019). This comes as no surprise after their success having broken four motorsport records with their first all-electric motorsport car, the ID.R (Wilkinson, 2019). The ID.R broke the track record for the fastest car at Pikes Peak, the Tianmen Shan Pass and at Goodwood where it was unbeaten since 1999 (Wilkinson, 2019). As well as these, the ID.R holds the fastest electric lap around Nürburgring track (Wilkinson, 2019).

Despite this success in the motorsport world, Volkswagen is not committing the same goals for their road-going vehicles at this moment in time. However, this is the direction the company is looking to go down in the future. Another reason that encourages the hybridisation of vehicles is how environmentally conscious people are becoming. The United Kingdom has become the first major economy to pass a zero-emissions law as of 2050 (Gov.uk, 2019). This will mean that all cars will need to be electrified, whether that is hybrid or fully electric. KERS, also known as regenerative braking in the automotive industry, is an easy and accessible method for manufacturers to produce hybrid vehicles.

2.3 Energy Storage

The current energy storage system for electric and hybrid cars is through Lithium-Ion batteries, Li-Ion. First, Lead Acid batteries were considered, but their discharge time was too slow (Battery University, 2017). Originally, battery technology was not able to charge and discharge at a high enough rate but with the recent developments in hybrid batteries, Li-Ions are able to and therefore meet the needs of the motorsport industry (Zaheer, 2019).

Another form of energy storage is a supercapacitor, also known as an ultracapacitor. These work similarly to a standard capacitor by storing energy via a static charge. The benefit of a supercapacitor is it can discharge and charge at rapid speeds, much quicker than Li-Ion batteries which can take between 10 and 60 mins to charge compared to the 10 seconds for a supercapacitor (Battery University, 2019). Also, supercapacitors can discharge completely unlike batteries and have a much longer cycle and service life. The specific power of supercapacitors can also be 10 times larger than that of a Li-Ion battery (Battery University, 2019). However, the specific energy of a supercapacitor is much less than a Li-Ion battery by approximately 10 to 50 times, as well as being unable to hold their charge for long periods like batteries. (Battery University, 2019)

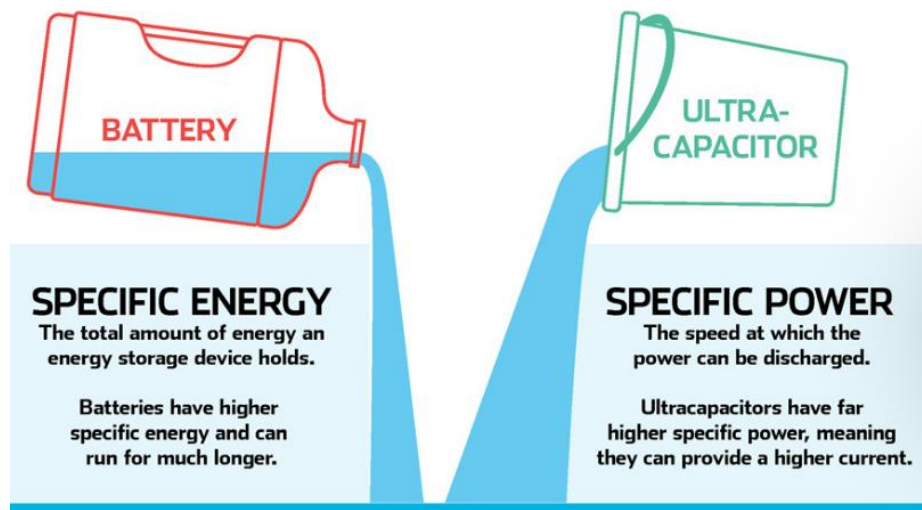


Figure 2-2 Comparison of batteries and ultracapacitors (Skeleton Tech, 2016)

Another factor is the costs associated. Supercapacitors are a lot more expensive per kilowatt-hour than most Li-Ion batteries due to the ability to discharge instantly (Battery University, 2019). Supercapacitors can be found in high-end cars that have regenerative braking, such as the Lamborghini Sian which is claimed to be faster by ten percent when accelerating to 130km/h with this system (Slovick, 2019).

An alternative type of capacitor is a Lithium-Ion Capacitor Cell, this is a hybrid between a Li-Ion battery and a supercapacitor. It is made up of a pre-doped carbon anode as the negative electrode and an activated carbon positive electrode (JSR Micro, 2017).

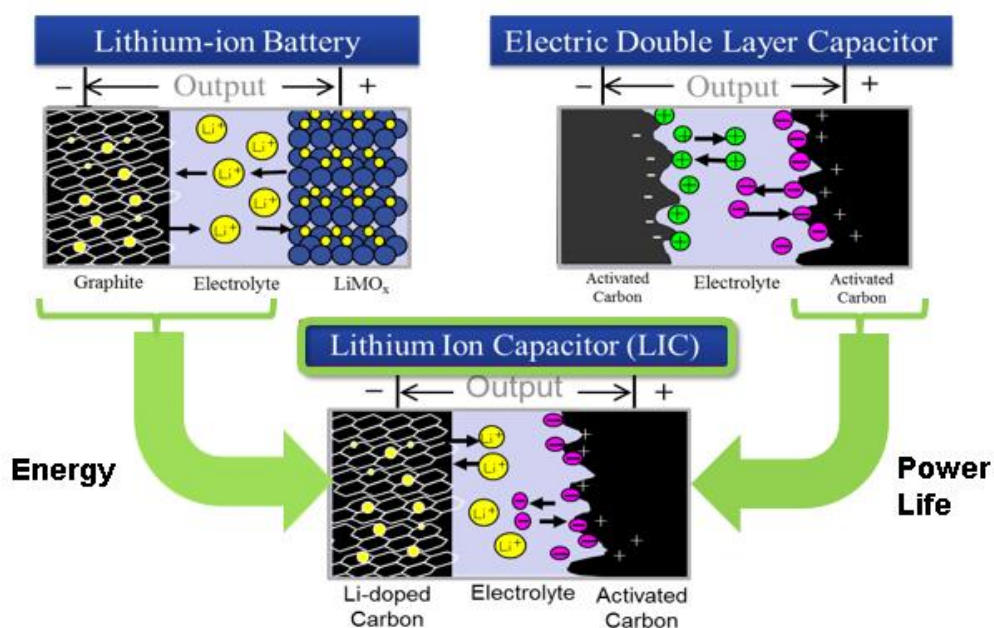


Figure 2-3 Li-Ion Capacitor (JSR Micro, 2017)

This concept allows both the benefits of the high specific power of a supercapacitor as well as the high specific energy of Li-Ion battery. The only issue with this type of energy storage is they are not easily available and are also very expensive.

Another way of having the benefits of both supercapacitors and Li-Ion batteries is to have a combination of both wired into a self-contained energy storage system. Systems like this are used in some formula one teams (Scarborough, 2012). These systems work in different ways depending on their application and the budget available. Generally, for regenerative braking, the supercapacitor absorbs the energy under braking and trickle feeds the energy into the battery. After the braking finishes, the supercapacitor ensures it is at full charge using energy from the battery if needed, so it is ready to deploy the power when required by the driver.

Another form of energy storage which was used in early hybrids was flywheels. They have high charge and discharge rates like supercapacitors but due to their packaging ability and the fact they are rotating at extremely high speeds, not many companies or race teams will use these any more, especially with the advances in battery technology over the last few years.

There are many energy storage options for the motorsport industry, and this project, but the main options that will be considered are Li-Ion batteries, supercapacitors, and a combination of the two. If a small amount of energy needs storing, then a supercapacitor can be used. Unfortunately, Motorsport UK, or MUK, the governing body of four-wheeled motorsport in the UK, does not currently allow supercapacitors as a form of energy storage in hybrid or electric vehicles (Ratley, 2020). This means a Li-Ion battery that can charge and discharge at high enough rates will be required. This will be decided once the rest of the system, such as motor has been considered.

2.4 Motors

There are many different motor companies which have produced motors for both the motorsport and the automotive industry. Zytec (2019) is one company who have been supplying hybrid systems for motorsport since the late 1990s. They offer complete battery and motor as a conversion package (Zytec, 2019). However this set-up is quite old, its motors specific power is average in its performance at just 5.9kw/kg, but it does have a peak power of 50kW. McLaren also offers a motor for hybrid cars and, like the Zytec, it is a radial permanent magnet Motor Generator Unit, MGU. It has a peak power of 120kW and a specific power of 4.6kw/kg (McLaren, 2019). This size motor would be too powerful for the MCR as

the power at the wheel is only 113.5kW, see Appendix A Appendix A - MCR Dynamometer Graph.

Another style of motor is an axial flux MGU which is produced by both YASA and EMRAX. The axial flux is a recent design of motor which functions slightly differently to the radial flux motor, see Figure 2-4.

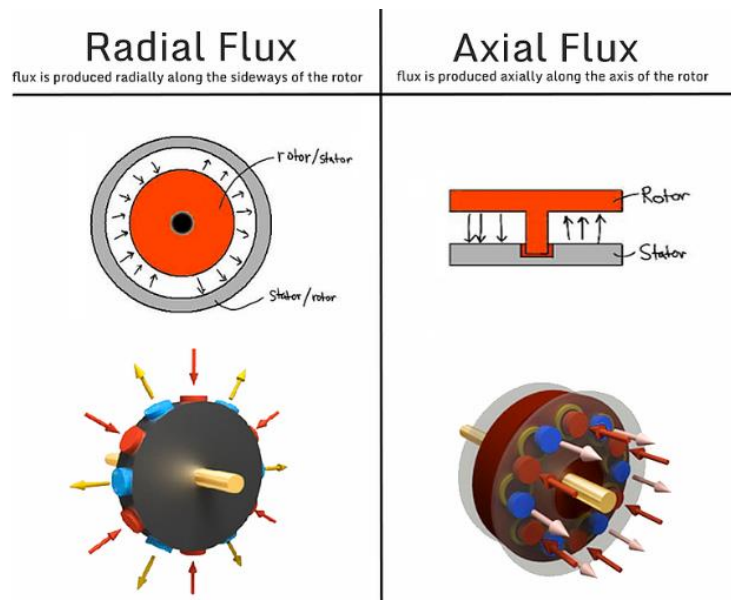


Figure 2-4 Comparison between Radial Flux and Axial Flux motors (Moreels, 2017)

The benefit of the axial flux design is that they usually have higher torque density due to having a bigger distance between the magnetic field interaction and the motor axis. Also, the axial motors are more efficient due to the flux paths being shorter so a reduction in magnetic losses (Moreels, 2017).

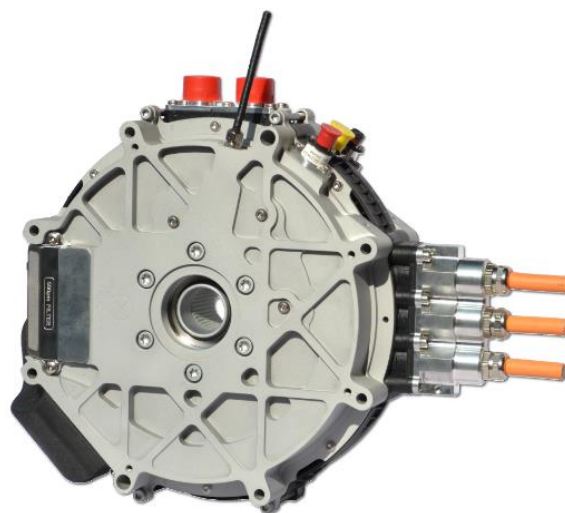


Figure 2-5 An Axial Flux Motor by YASA (2018)

The YASA motor is claimed to be the smallest and lightest in its class with a specific power of 6.7kw/kg, but once again this motor is much too powerful for the MCR at 160kW (YASA, 2018). Even though it does not need to use all the power and can be tuned for lower powers, as low as 20kW, it still has a large mass of over 24kg (YASA, 2018). As it is an axial flux motor, the shape is different to the previous models and so offers better packaging space as it is a circle with a diameter of 305mm and is only 80.4mm thick (YASA, 2018). YASA has produced a custom motor for Ferrari's first hybrid production car, SF90 Stradale, producing an extremely large 14kW/kg power density (Business Wire, 2019).

EMRAX MGUs have a smaller specific power than YASA but they do offer smaller motors as well. Their smallest motor is the 188 model which has a dry weight of only 7kg, whilst being able to offer peak power of 52kW and having a continuous power of up to 35kW (EMRAX, 2019).

The power of the MGU also must be considered. Within Formula 1, a motor power of 60kW was used when they started to allow hybrids, this has now increased to 120kW (Collins, 2013). This change occurred due to the entire powertrain changing in 2014. The engines went from 2400cc to 1600cc and the fuel usage to complete a Grand Prix was reduced by 35% (Collins, 2013). For the cars to be able to complete the race they needed another form of energy and this came in the form of an increased MGU-K and an introduction of a motor-generator that recovers and uses power at the turbo. Whereas BTCC has announced their motor will have a peak power of 30kW (BTCC, 2019). For the Sports 2000 championship, a power increase of 30kW would be enough to allow for competitive racing. It would result in a 26% increase, from 113.5kW, in power when the motor is used neglecting any inefficiencies in the system.

Depending on packaging space either the ZyteK or EMRAX would be suitable for the MCR. The other types of motors available are either too large, in size and mass, or too powerful for the car.

2.5 System Controllers

There are various companies which offer controllers including UniTek, Sevcon and RMS, all offering similar functions. They can measure wheel rotation speed and calculate how much rotational force is available under braking to generate back into the energy store. The controller also controls the flow of the electricity between the MGU and the energy store. The controllers also offer the ability to switch between friction brakes and the generator to have series braking. However, due to the car only carrying out hard braking, this is not needed as

the car will always be exerting high braking percentage so having smooth braking at low efforts is not needed.

As well as controlling the energy recovery, it also controls when the motor can release energy. For example, it could be programmed only to allow the motor to release energy when the throttle position is at least 90% depressed. This would allow for maximum benefit from the energy recovery system as well as ensuring it cannot be accidentally deployed when the cars not accelerating. The controller can also control lights in the instrument panel to show when the system is live and when it is turned off. There are various safety factors they offer as well, such as high voltage safety interlock circuit.

The Sevcon Gen5 controller is one which is suitable for the application in this project due to its small size and versatility. It meets the safety criteria set out in the hybrid automotive ISO tests for both functional and electrical safety (Sevcon, 2016). Overall, the decision on the controller will depend on what motor and energy store is used and its compatibility to both components.

3 Work Carried Out

This section covers all the experiments, calculations and discussions needed to produce a simulated KERS lap for the car.

3.1 Data Collection

To begin with, all the necessary data that is available for the MCR was collected. The first type of data that was collected was the real-life track data, this was from the 2019 championship. It was recorded at multiple tracks and included testing, qualifying and race data. For this project, only the data from a single lap of a chosen track needs to be investigated. However, to calculate the wheel lock power, data from all rounds is required to find values such as the minimum velocity and the largest braking section. Understanding this section would allow an appropriate battery to be selected that could handle the most energy the car would be able to recover, without wasting mass, space and money on having a device more powerful than needed. This data was collected through data loggers that were connected to the car, which can be viewed in MoTeC. To compare and calculate a simulated KERS lap this data was exported into Microsoft Excel, see Appendix B, with a sample rate of 50Hz. 50Hz gives data for every 50th of a second meaning it is a big enough sample rate to allow for in-depth analysis and understanding but not too large to make processing time consuming or lead to failure.

Some key pieces of data were required at the start of the project. These included the mass, the coefficient of drag and the car power data. The mass was collected from the 2019 championship logbook. This is a spreadsheet which contains the suspension set up and the mass of the car as well as everything about each round, from gear ratios and tyre pressures to drivers' comments and the weather. This extra data gave a deeper understanding of the conditions on the day for the lap that would be selected. Alongside the logbook was the gear calculator which gave all the gear and final ratios as well as what they are for each round of the championship. The power of the car was collected from the dynamometer print out of the car, which allowed for the power at both the engine and wheels to be collected. The coefficient of drag was collected in a few ways to allow for comparison. The first was from a third-party study carried out on the aerodynamic profile of the car using Computational Fluid Dynamics software. Another piece of data that was acquired was real-life data from when the car was sent to MIRA's wind tunnel. This data gave information such as drag and lift forces and coefficients as well as axle loads under wind speeds of approximately 35m/s.

Some data was not available at the start of the project including the actual real-life coast down data which would allow the actual resistive values to be calculated. However, later in this

project this data became available. This data consisted of the car doing three laps where the car was taken up to a set velocity and then left to decelerate with no brakes and the clutch being depressed on each straight. This was beneficial as it allowed for more than just the aerodynamic resistive force to be calculated. It gave the actual resistive force, including mechanical and rolling resistive forces, at certain velocities. This would allow for an equation to be produced to show the relationship between resistive force and velocity.

Except for the MoTeC data, all the data that was collected was inputted into one Master Spreadsheet ready for the chosen laps data to be exported into it. This was done so that all the relevant information throughout this project would be in the same location to make calculations and data sourcing easier.

Some data was not attainable such as how much brake and throttle were applied throughout the lap. This data would have helped with finding the key energy harvesting locations. When analysing a lap, it would show clear locations where brakes were applied and whether they are fully applied. The throttle position would help when simulating the KERS lap, as the motor could then be used when at least a certain percentage of the throttle is applied such as over 90%. However, other available pieces of data will need to be looked at and compared to make assumptions when the brake and throttle pedal are applied at high pressures. Another piece of data that would have been useful to be collected would be a coast down test where the car came to a complete stop. This would allow for a more accurate assumption of the rolling resistive force as well as a more accurate resistive equation.

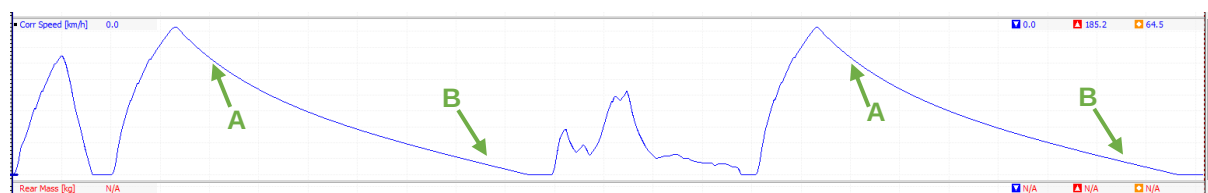
Once this data was collected a decision was made on the track. Originally Brands Hatch was selected however after a basic analysis of each round, taking into account the maximum braking times and cumulative braking time, the Silverstone International track was selected. This is because it had both the longest braking section as well as the largest cumulative time, so this track was then selected. In the main spreadsheet, the data and calculations that were specific to track date were recalculated.

3.2 Coast Down Test

A coast down test was carried to calculate the rolling resistive force and aerodynamic force on the MCR car. The test is carried out as the resistive force for the car at all velocities needs to be known to assist in the calculation of the KERS lap. This is because not all the decelerating force is available to be recovered under braking as some force is lost through rolling, aerodynamic and mechanical resistance. Also, to calculate the acceleration, the resistive forces are required.

3.2.1 Simulation Methodology

To carry out a simulated coast down test the UWTSD's Base Performance Simulator, BPS, was used. This has an accurate model of the car being investigated as well as the tracks from the championship. The coast down test was carried out on a track called the Skidpan as it has a long strip of track that has no gradient that would affect the results. The car was driven to the start of the test strip and stopped. The car was then accelerated up to fourth gear and held on the limiter for a moment before the clutch was disengaged and the car rolled to a complete stop with no driver interference. Once the car came to a stop it was turned around and the test was repeated in the opposite direction. Repeating the same test in the opposite direction is common practice when carrying out physical tests to account for environmental conditions, such as wind, however in the simulator these conditions were not affecting the test. The reason the test was repeated was to allow for an average to be taken from the runs.



Graph 3-1 – Coast Down in BPS: Velocity vs Time

Graph 3-1 shows the velocity plotted against time. At point A both aerodynamic drag and rolling resistance are affecting the rate of deceleration whereas at point B only rolling resistance is assumed to be affecting it. For the purpose of these calculations, the rolling resistance is assumed to be constant at all velocities to allow for an approximated calculation of the coefficient of drag, even though this is not true. This is due to the rolling resistance increasing very slightly with velocity, however the increase is quite insignificant when it comes to these calculations. At point A and B the deceleration was calculated over an approximately one-second interval. These decelerations were then multiplied by the mass of the car to give the deceleration force at both sections, Equation 3-1.

$$F_{drag} = m \frac{v_2 - v_1}{t_2 - t_1}$$

Equation 3-1 Coast Down drag force

The deceleration force at point B is taken to be the rolling resistive force. Using Equation 3-2 The Coefficient of Drag, C_d , was calculated. Where F_{dragA} and F_{dragB} are the drag forces at points A and B respectively. ρ is the air density, v_m is the average velocity at point A, and A is the frontal area of the vehicle. The reason the result is left as C_dA and not C_d is because only one car is being investigated so the area is a constant to the calculations.

$$CdA = \frac{2(F_{dragA} - F_{dragB})}{\rho v_m^2}$$

Equation 3-2 The Coefficient of Drag

The values for the coefficient of drag, CdA , and the rolling resistive forces can be seen in Table 3-1. The average values for the coefficient of drag and rolling resistance were calculated and inputted into the main sheet in the Excel workbook.

Table 3-1 Resistive Values

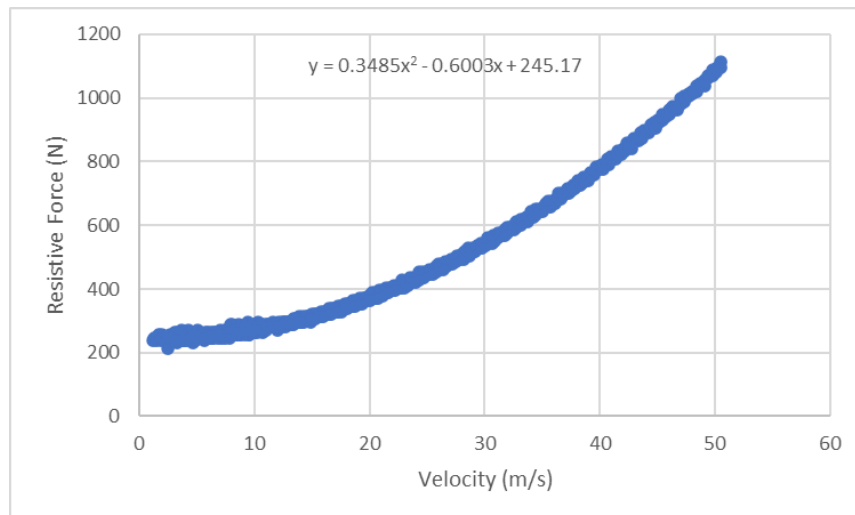
	CdA	Rolling Resistance Force
Test One	0.57237	281.42
Test Two	0.58788	265.553
Average	0.58012	273.486

To get an improved estimation, a maths channel was created in MoTeC to calculate the resistive force, see Equation 3-3.

$$F_{resistive} = -ma$$

Equation 3-3 Coast Down Resistive Force

The data was then exported into Excel where the resistive force was plotted against velocity as a scatter plot and a trendline was added, see Graph 3-2.



Graph 3-2 Simulation Coast Down: Resistive Force vs Velocity

The equation of the trendline was added to the graph and this equation for resistive force shows the relationship between both rolling and aerodynamic resistive force and their effect on the car at different velocities. This equation would help compare and correlate the resistive values to the real coast down test data.

3.2.2 Physical Methodology

The coast down data, that was collected during testing at the Pembrey track, was used to calculate a real resistive force equation. The calculation of the resistive force was the first part of data interpretation. This was carried out using Equation 3-3 in a MoTeC maths channel, see Figure 3-1. This was carried out with the acceleration being filtered due to the recorded values fluctuating.

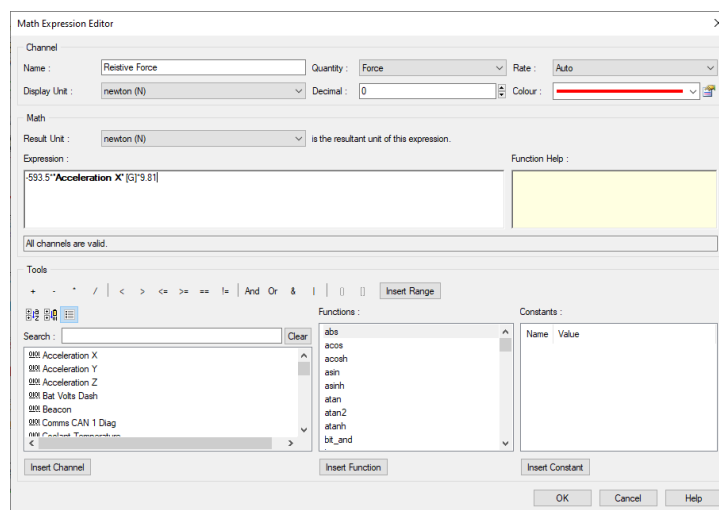
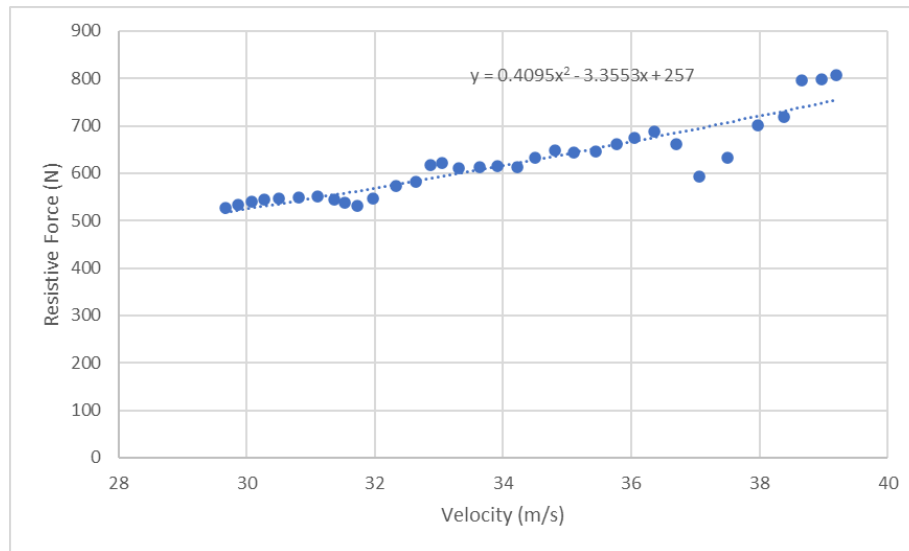


Figure 3-1 Maths Channel of Resistive Force

This data from the MoTeC file was then exported into Excel so the data could be manipulated. The sections where the car was not doing any Coast Down, such as when it was going around the bends and entering and leaving the pit lane were deleted. The resistive force for all the coast down runs were plotted against their corresponding velocities, see Equation 3-3. A trendline was added, and its equation gave a real estimation for the resistive force experienced by the car. This was carried out on all five runs and an average was taken to produce a final equation.



Graph 3-3 Real Coast Down: Resistive Force vs Velocity

Alongside this real data, there is also wind tunnel data of the actual car. This test was carried out at MIRA, where lots of data were collected such as the coefficient of lift and the drag for the car. This test consisted of 17 runs, each of which had a coefficient of drag value calculated by MIRA. These values were calculated assuming the frontal area was one meter squared so in fact the values were the CdA. The average of these 17 runs gave the value 0.639 for the CdA. This value is as expected as it is within 10% of the calculated value in the simulation coast down test. This agreement of the values demonstrates the accuracy of the simulation.

3.2.3 Comparisons

Comparing the Resistive Force of the Calculated, Simulated and Real equations will help with finding the most accurate resistive force equation. This allows them to be plotted on the same graph for comparison.

To find the Calculated Resistive Force, Equation 3-4 was used, where the rolling resistive value was taken from the simulation test. The CdA value used was the average of the MIRA, simulator and CFD values. This produced Equation 3-5.

$$F_{Resistive} = \frac{1}{2} \rho C_d A v^2 + RR$$

Equation 3-4 Resistive Force

$$y = \frac{1}{2} 1.223 \times 0.59x^2 + 273.49$$

Equation 3-5 Calculated Resistive Force

The Simulated Resistive Force, Equation 3-6, comes from the trend line on graph Graph 3-2 in section 3.2.1.

$$y = 0.3485x^2 - 0.6003x + 245.49$$

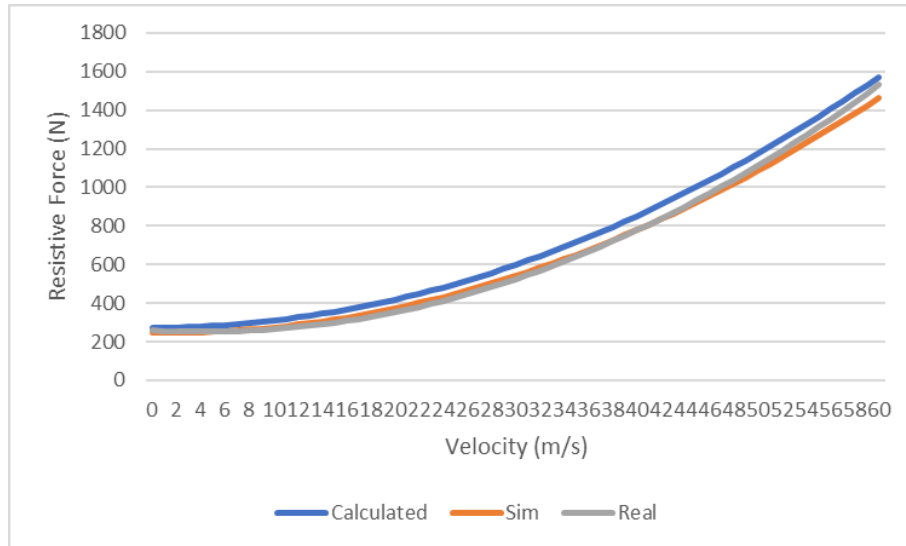
Equation 3-6 Simulated Resistive Force

The Real Resistive Force, Equation 3-7, comes from the trend line on graph Graph 3-3 in section 3.2.2.

$$y = 0.4095x^2 - 3.3553x + 257.00$$

Equation 3-7 Real Resistive Force

These three equations were plotted on the same graph, see Graph 3-4, so they could be compared.



Graph 3-4 Resistive Force Comparisons: Resistive vs Velocity

All three equations produced similar results. This triangulation of results displays accurate and validated result which will provide an accurate calculation for the resistive force for KERS lap. The calculated resistive force is slightly larger than the other two lines. This could be due to the MIRA CdA value being larger at 0.639 whereas the simulated and CFD values were 0.561 and 0.580, causing the average CdA to increase. The real coast down resistive force displayed slightly larger values than the simulated force. This was expected as the real data includes all the mechanical resistance, whereas the simulated does not. This indicates that the real coast down test would be deemed the most accurate so this equation can be used in the calculation of resistive force for the calculated KERS lap.

3.3 Wheel Lock Limit

The wheel lock limit is the point at which the tyres exceed the adhesion limit and the wheel ceases rotation (Wright, 2005). This point is important because energy is harvested from the rear wheel which has less vertical force under hard braking. This means at low velocities if the Motor Generator Unit, or MGU, is trying to harvest more power than the tyres can handle, whilst retaining grip, then this will cause the rear wheels to lock and the car could spin. To prevent this from happening, calculations were carried out to assess the maximum amount of harvesting power at the lowest velocities in both wet and dry track conditions. This limit is a large factor in the amount of harvesting of energy that can be carried out on a vehicle.

The wheel lock limit force is calculated using the load on the rear tyres in Newtons then multiplied by the coefficient of adhesion, see Equation 3-8. The load on the rear tyres under braking was taken from the MoTeC data. This data contained the values for the corner load at any point, taking into consideration the weight transfer. The coefficient of adhesion for the MCR under dry conditions was 1.4 and during wet conditions was 0.8.

$$F_{wheel\ lock\ limit} = (Static\ Load_{rear} - Weight\ Transfer) \mu$$

Equation 3-8 Wheel lock limit force

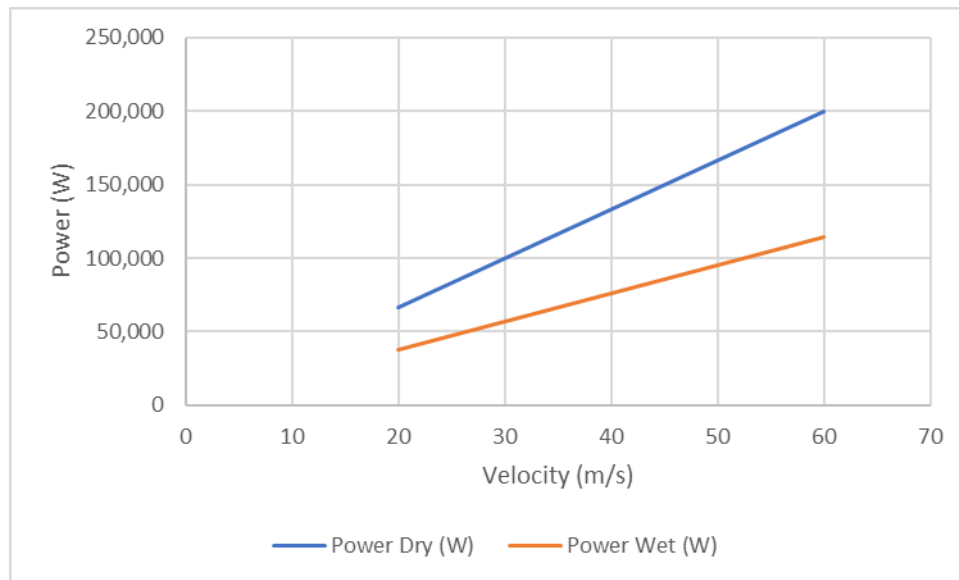
The wheel lock limit power could be calculated from the force at a variety of velocities using Equation 3-9.

$$P = F_{wheel\ lock\ limit} v$$

Equation 3-9 Wheel lock limit power

The calculation for wheel lock power was carried out from 60 m/s to the minimum velocity recorded across the championship, 19 m/s. This minimum velocity will be a significant factor in the decision of the power of the MGU for this project.

Graph 3-5 shows the available power that can be harvested at certain velocities in both dry and wet conditions. The maximum available power to be harvested at the minimum velocity is 67kW in the dry and 38kW in the wet. This means in dry conditions, assuming the efficiency of the MGU is about 95%, an MGU of up to 70kW could be used in the championship without causing the wheels to lock under normal conditions. In wet condition, an MGU of up to 40kW could be used.



Graph 3-5 Wheel Lock Limit: Power vs Velocity

This result means that if an MGU of over 40kW is selected then the system will have to be recalibrated to harvest less power than this on the tracks with the low velocities during wet conditions. However, if an MGU of less power is selected then the weather conditions will not be a concern as the wheels should never lock under normal racing conditions, caused by the motor.

3.4 Motor Power Investigation

To decide on a power for the MGU a small-scale investigation took place. The investigation compared how motors ranging from 30kW up to 60kW affected the time to complete one straight on the Silverstone track. The reason 60kW was the maximum motor chosen was that anything larger would cause wheel lock issues under braking. The section of track being investigated, see in Figure 3-2, took 4.64 seconds for the standard car to complete. See **Error! Reference source not found.** for the full track. The maximum amount of energy that could have been recovered from the previous braking section was 2.4 seconds, so this is the amount of energy used for this investigation.

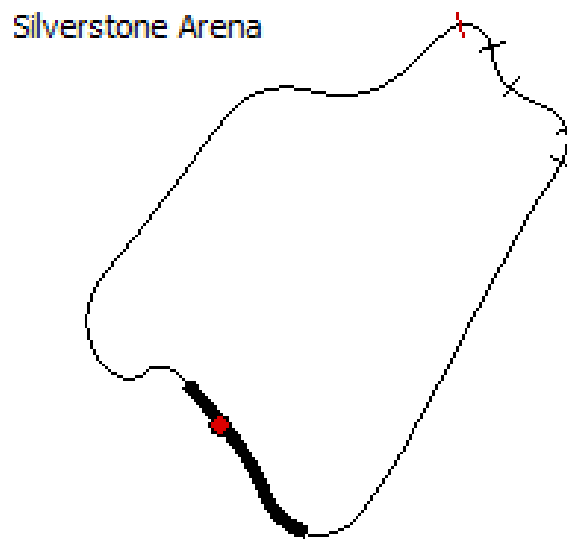


Figure 3-2 The used section of the Silverstone International Track (See Appendix B for the full track)

The data in MoTeC needed some calculations to be carried out before it was exported into excel. First, the recorded GPS speed was converted from kilometres per hour into meters per second using a maths channel, see Figure 3-3. This displayed a new channel called velocity.

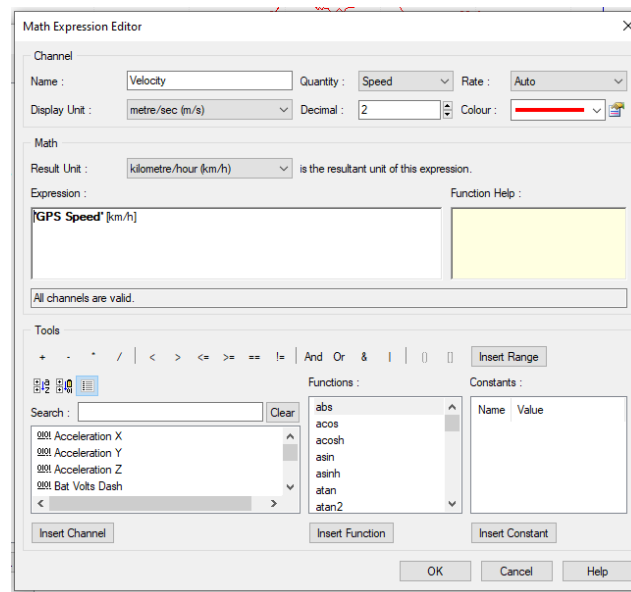


Figure 3-3 Maths Channel of Velocity Conversion

Another Maths channel was produced to display the power at the wheels. This was the sum of the dynamic power and the power to overcome resistance to motion, see Equation 3-10.

$$P = \left[ma + \left(RR + \frac{1}{2} \rho C_d A v^2 \right) \right] v$$

Equation 3-10 Power

This Maths channel, see Figure 3-4, used the velocity maths channel, Figure 3-3, in its calculation and displayed the results in kW.

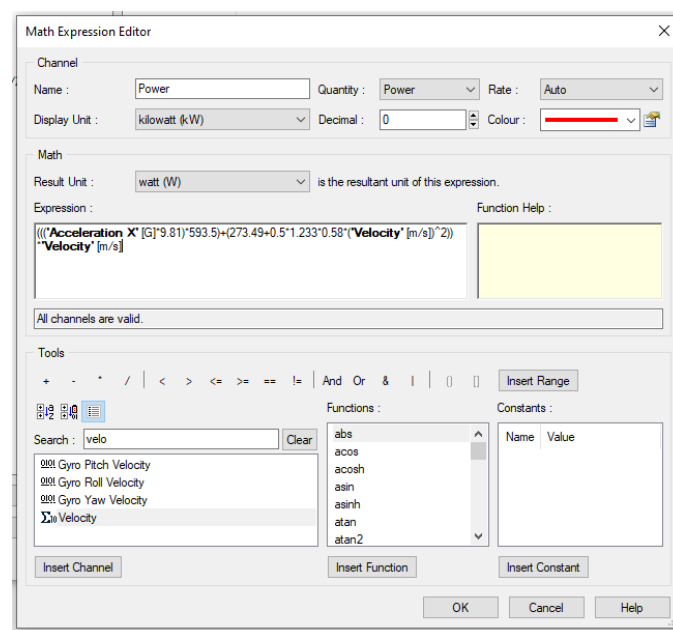
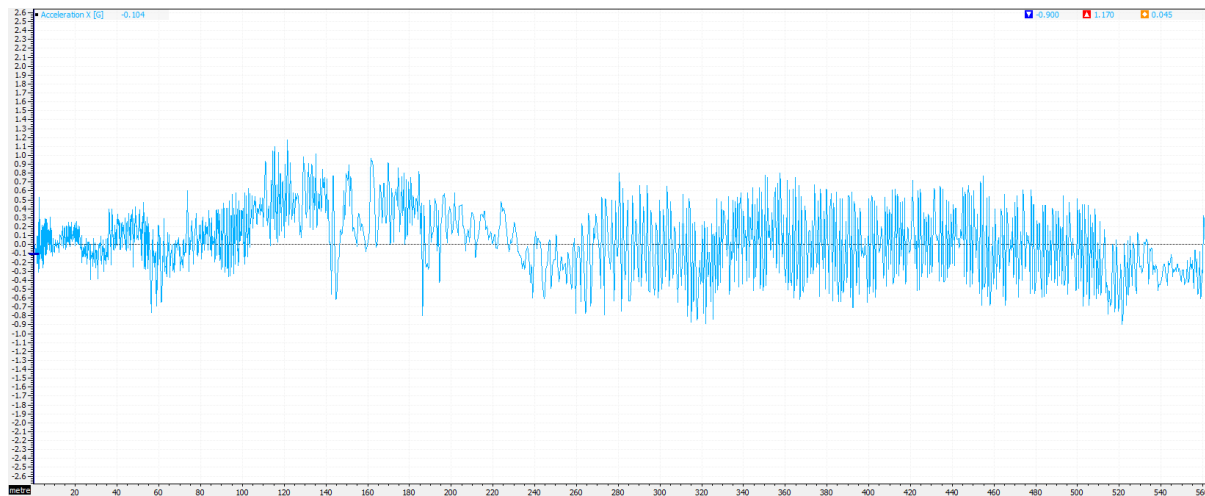


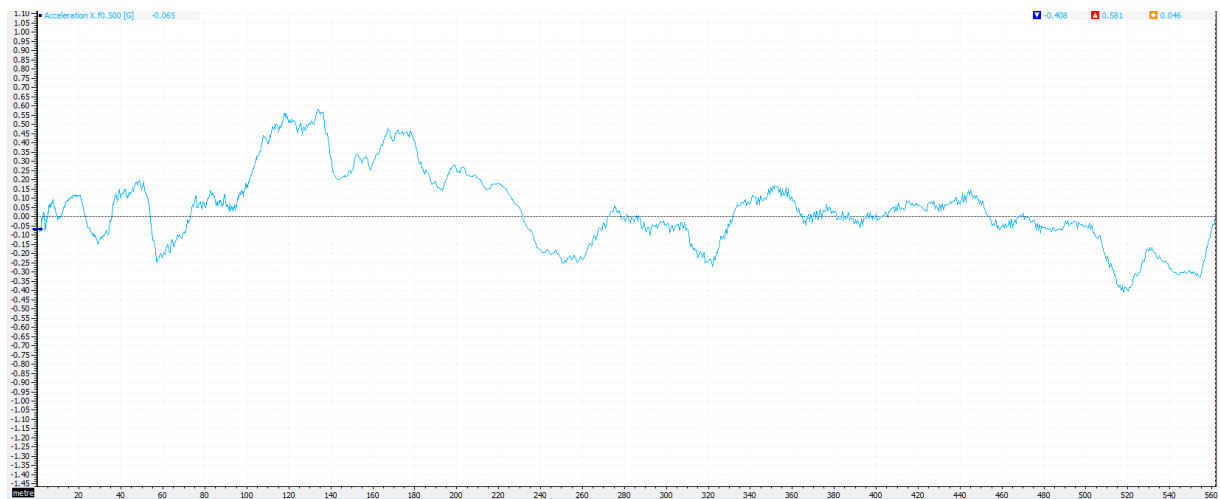
Figure 3-4 Maths Channel of Power

The final step before exporting was to improve the recorded acceleration values. Unfortunately, the data appeared to fluctuate a lot, this is due to the sensitivity of the data logger, see Graph 3-6. However, it did show the correct values by its trend. This means the data can be manipulated to give more accurate results.



Graph 3-6 Maths Channel of Acceleration: Unfiltered

The acceleration maths channel was filtered at a rate of two hertz to remove all the vibration of the data and an improved graph was formed, Graph 3-7.



Graph 3-7 Maths Channel of Acceleration: Filtered

The data for the section being investigated was exported as a CSV file, with a sample rate of 25 hertz, so the data could be manipulated. To calculate the KERS section times eight new columns of data were added, see Table 3-2..

Table 3-2 Power Comparison Calculation Table Titles

New Power	Aero Force	Resistive Force	Acceleration	Dynamic Force	Total Force	New Velocity	New Distance
kW	N	N	m/s/s	N	N	m/s	m
98.79824762	665.2772311	938.763453	2.825802237	1677.113628	2615.877081	43.38888889	1378
99.55244566	667.8400945	941.3263164	2.818664092	1672.877138	2614.203455	43.41666667	1380

The first two columns of data were copied across from the exported values to be the starting values for the KERS section. The following equations were used to populate the remaining values for the section.

The resistive force was calculated using the CdA and RR value from the simulated coast down test, as the real coast down data was not available at this point.

$$F_{Resistive} = RR + \frac{1}{2} \rho C_d A v^2$$

Equation 3-11 Resistive Force

The power was the power at the wheel and when the KERS was activated it was increased by the value specified for each power of the motor.

$$F_{Total} = \frac{P_{Total}}{v}$$

Equation 3-12 Total Force

$$F_{Dynamic} = F_{Total} - F_{Resistive}$$

Equation 3-13 Dynamic Force

$$a = \frac{F_{Dynamic}}{m}$$

Equation 3-14 Acceleration

The new velocity was calculated using Equation 3-15, where u is the previous velocity, a the acceleration and Δt is the difference in time, which was 0.04 seconds as the data was 25 hertz.

$$v = u + a\Delta t$$

Equation 3-15 New Velocity

The distance was calculated to be able to identify when the car needed to brake as well as knowing when the car finished the section.

$$S = S_{previous} + \frac{1}{2}(u + v)\Delta t$$

Equation 3-16 New Distance

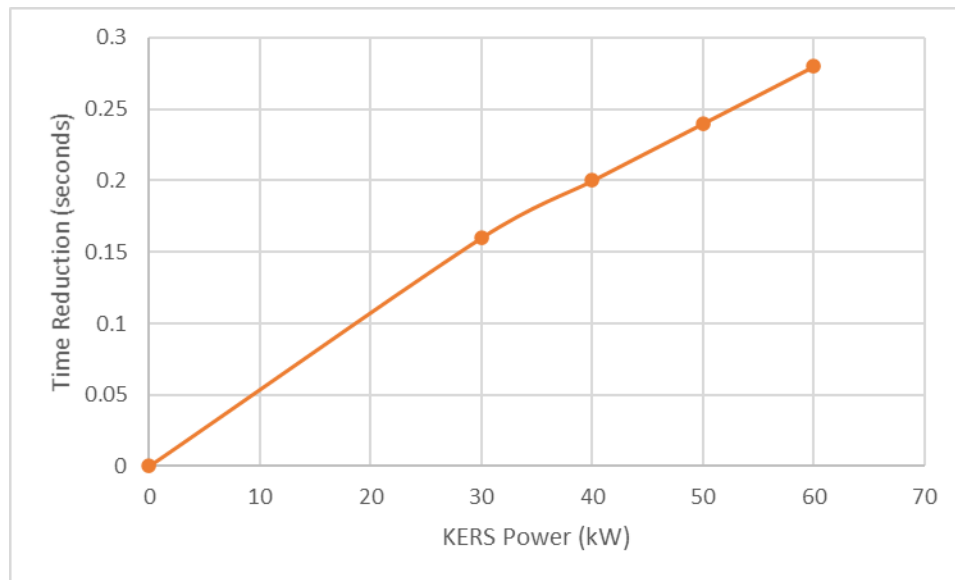
Due to the car travelling faster with KERS it had to brake at an earlier point on the track to ensure it would be able to slow down enough for the bend. This meant that the car had to slow to the same velocity as the non-KERS lap when it began to brake at maximum deceleration. This resulted in the velocity braking for the corner and going around the corner being the same for both the standard and the KERS lap.

This was repeated for 30kW, 40kW, 50kW and 60kW motors. The total system was assumed to have an efficiency of 89.4% for this investigation. This meant for 1 second worth of energy recovery through a 30kW motor gave 1 second worth of power at 26.83kW. Table 3-3 shows the section times for each power motor as well as their motor value after efficiency and the percentage time quicker.

Table 3-3 Motor Efficiencies

kW	kW (eff)	Time (s)	Quicker (s)	Quicker (%)
0	0	4.64	0	
30	26.83	4.48	0.16	3.448275862
40	35.7689455	4.44	0.2	4.310344828
50	44.7111819	4.4	0.24	5.172413793
60	53.6534183	4.36	0.28	6.034482759

When the time reduction and the KERS power are compared in Graph 3-8 a linear relationship is observed, as expected.



Graph 3-8 Power Comparisons: Time Reduction vs KERS power

However, even though 60kW is twice the power of the 30kW motor it did not reduce the time by twice as much. This is because the KERS power is only used for a limited time, not the entire acceleration. From this result, the 30kW motor displays a large enough time reduction to allow for quicker lap times and a more spectacle race whilst retaining the low power levels of the championship.

3.5 Packaging and Final Components

Before deciding on the final packaging location of the system, possible locations need to be considered so that the final components can be selected.

3.5.1 Considerations

Things that will affect the location of the components include the component size and safety regulations. Another limiting factor is the specification of the components. The motor is the major component to focus on first. The motor could mount within in the gearbox on either the input shaft or output shaft and it could also mount on the final drive or even the hub. Another possibility which could be considered is to follow in Mitsubishi's lead, mounting the motor directly on the crankshaft (Mitsubishi Electric, 2017). Mounting directly on the shaft, and not via a belt system, will increase efficiency so improve both power output and generation (Mitsubishi Electric, 2017). The limiting factor of this decision is the available space to mount the motor as well as the motor specification of how fast it can rotate. If the motor is mounted in the gearbox input shaft or crankshaft of the engine, then the motor will need to be able to rotate up to 7000RPM, see Appendix A. Whereas if it were mounted on the wheel, the maximum rotational velocity would be approximately 2240RPM, at 139mph. This value comes from Equation 3-17, where v is the velocity in meters per second and R is the rolling radius in meters, which is 0.265m.

$$\omega_{RPM} = \frac{60v}{2\pi R}$$

Equation 3-17 Angular Wheel Velocity

The most limiting factor in component location is the safety regulations. A recent document released by Motorsport UK contains proposed guidance and regulations for hybrid and electric cars competing in motorsport (Ratley, 2020). All the following values discussed are referenced from here. These regulations would have a large influence in the production of hybrid Sports 2000 championship regulations, if one were to ever be produced. The regulations state that only a single motor can be used, and the motor cannot be mounted as a hub or wheel motor. This means a single motor must be mounted on either the crankshaft, final drive or within the gearbox. The Energy Storage System, or ES, has numerous requirements it needs to meet. It cannot be a supercapacitor or flywheel but must be a single battery pack. For the MCR, it must be installed inside the engine or passenger compartment. The battery must be housed within an enclosure that meets a rating of IP65 or higher as well as be in a safety barrier meeting UL94-V0 standards. If the system is deemed a high voltage system, larger than 60V DC or 30V AC, then the cables and connectors must meet approved standards.

The regulations also state that the battery management system must be housed within the battery pack enclosure. The energy recovery system must be able to be isolated by at least two independent systems, one being manually operated and another being an automatic system controlled by the management system. There are other safety specifications that each component must meet but these do not affect the location of components, they just require the components to meet specific standards and pass specific tests. The car must also be fitted with two safety indicators if it is a high voltage system. These indicators are a safety light, see

Table 3-4, and a white light which indicates charging, see Table 3-5. These would be mounted on the top of the roll cage of the MCR.

Table 3-4 Energy Storage Status Light (Ratley, 2020)

Light Status	RESS Status
Green	Safe
Red	Danger (system defect)

Table 3-5 Vehicle System Status Light (Ratley, 2020)

Light Status	Vehicle Status
Off	HV system de-energised
White always on	HV system energised – vehicle ready to move
White flashing	Charging

As discussed in section 3.2, KERS have already been introduced into Formula 1, Formula E, WEC and now proposed in BTCC. Within these championships, there is a vast range in the power of the MGU's from 30kW in BTCC (2019) to 300kW in the WEC (FIA, 2019). Even Formula E, the fully electric championship, has a smaller motor than WEC at 250kW (FIA, 2020). Another regulation these championships must meet is the amount of energy released per lap. WEC is allowed 8MJ/Lap which is double Formula 1 limit of 4MJ/Lap (FIA, 2019) (FIA, 2020). Whereas the BTCC is only allowed to release 0.45MJ/Lap, the equivalent of 15 seconds of usage (BTCC, 2019). This is similar to how Formula 1 started as in 2009 the regulation stated a maximum of 0.4MJ/Lap (FIA, 2009). The complete mass of the BTCC system is approximately 65kg which is 10kg less than previously used ballast mass (BTCC,

2019). The proposed layout for the BTCC hybrid system, see Figure 3-5, has the MGU located within the gearbox housing. The modification to the gearbox is claimed to only need seven new components, one being the main case, however no major modification needs to be carried out and mounting location should not change (BTCC, 2019). This makes it an easy modification to make to the car, where the main issue for competitors is the financial cost. The location of the cooling system and battery pack is shown in Figure 3-6. This shows that modifications will also need to be made to accommodate the KERS cooling system. As these are not major modifications, they suit the needs of the teams and the championship.

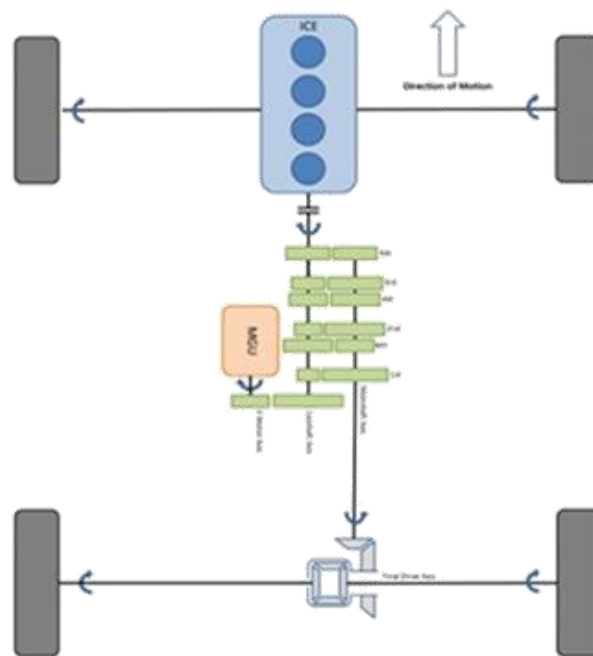


Figure 3-5 BTCC's Motor Installation (BTCC, 2019)

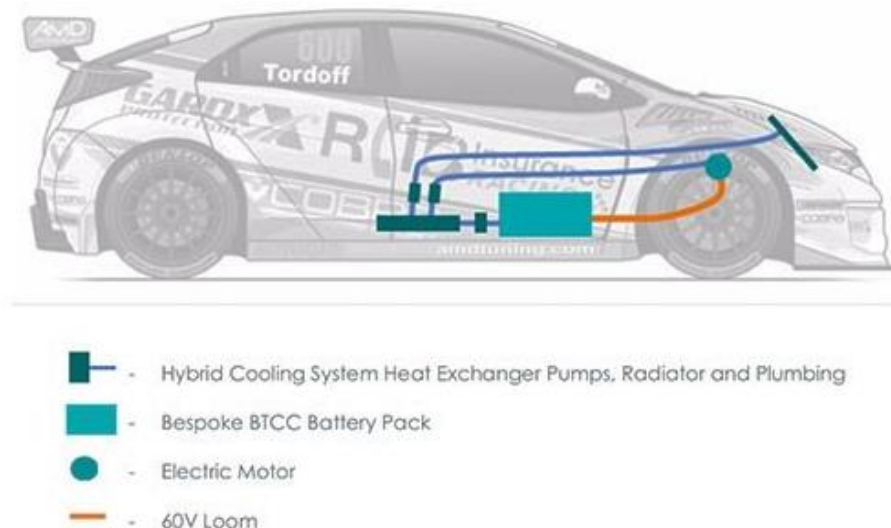


Figure 3-6 BTCC's Hybrid Layout (BTCC, 2019)

3.5.2 Final Components

The power selected for this project is 30kW MGU, as decided in power comparison. This is going to be produced by the EMRAX 188 motor, see Figure 3-7. The dimensions of the motor are 77mm thick and a diameter of 188mm (EMRAX, 2017). these dimensions can be seen in Appendix D.



Figure 3-7 The EMRAX 188 Motor (EMRAX, 2019)

This motor is small in size and has a mass of just 7kg and efficiency of 95% (EMRAX, 2019). Due to the low power, small size, and ability to rotate up to 8000RPM it will be mounted on the crankshaft, at the front of the engine. This means no expensive gearbox modifications are required. Modifications will, however, need to be made to accommodate the motor's mounting plate and a splined shaft will have to connect the end of the crank to the motor. To make space for the motor on the front of the engine the rear subframe may require 1-inch spacers to shift the engine and drivetrain back so the motor does not touch the bulkhead. The EMRAX (2019) motors have a list of compatible controllers and from this list, the controller selected for this project is the Sevcon Gen5, as seen in Figure 3-8. This controller is 98% efficient and has a mass of 6.8kg and is only 285mm by 394mm in size with a thickness of 90mm (Sevcon, 2016). See Appendix E for the engineering drawing. This means that the controller will have minimal effect on the mass distribution of the car. It will also comfortably fit within the passenger compartment of the car.



Figure 3-8 The Sevcon Gen 5 controller (Sevcon, 2016)

The battery will be housed inside an appropriate container located alongside the control system in the passenger compartment. The battery that has been selected is a modified MAHLE mild hybrid battery, see Figure 3-9.



Figure 3-9 MAHLE's hybrid battery (MAHLE, 2019)

This battery is capable of a peak power of 30kW, an efficiency of 99% and has a capacity of 0.5kWh (MAHLE, 2019). The amount of energy recoverable in one lap at 30kW for 15 seconds, considering 100% efficiency of the system, is 0.125kWh which is far less than the batteries capacity (MAHLE, 2019). It has a high cycle life of over 20,000 cycles before the capacity falls below 80% of its initial value, which makes it suitable for the application of an energy recovery system.

The cooling system for the KERS will consist of a combined cooling system. This is where it uses both air and a liquid mixture of water and glycol to keep the components cool. This cooling system will be plumbed into the component using MUK approved pipes and coolant.

The radiator for this system will mount on the left side of the car in the air scoop, see Figure 3-10. This is the opposite side to where the engine's radiator is currently mounted so it will get enough airflow to be able to function appropriately.



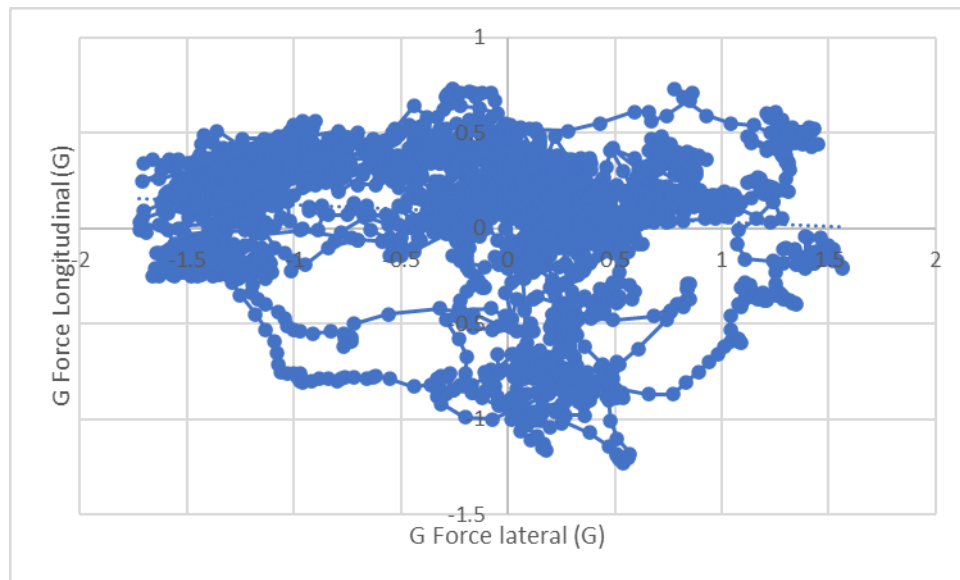
Figure 3-10 proposed KERS radiator location (M Sport Eng, 2016)

The complete mass of the system is 28kg. This value is exceedingly small for a hybrid system; however, it is only a small powered system. This is an increase in mass of 4.7%, so does not drastically affect the mass of the car. Most of the mass is towards the centre of the car which means the front to back mass distribution will not be affected so the handling of the car will not be compromised. Also, by adding the system it will increase the mass on the passenger side slightly so that will cause the left to right distribution to get closer to a 50% split.

3.6 Calculated KERS Lap

To carry out an investigation on an entire lap the MoTeC data, including the maths channels created in section 3.4, was exported at a sample rate of 50hertz. This data could then be used to plot graphs to identify locations for energy regeneration and deployment.

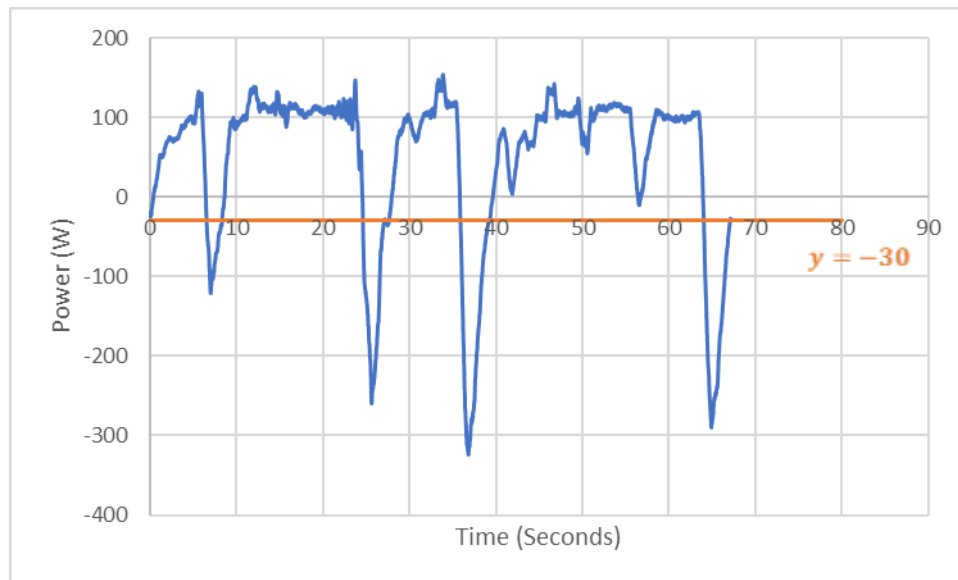
The first graph produced was a friction ellipse to identify areas of grip limitations, Graph 3-9. This graph is plotted with the x-axis being the side to side G force and the y-axis being forwards and backwards G force.



Graph 3-9 Friction Ellipse

For the standardised friction ellipse where the lateral and longitudinal forces are on the opposite axis. See Appendix F. This graph shows that currently the car is not traction limited under acceleration but just power limited. This means it is likely all the power of the motor can be applied as the car begin to accelerate without causing wheel spin.

A graph was produced to show how the power of the vehicle changed throughout an entire lap of the track, Graph 3-10. This graph showed where the power could be recovered and where it could be best deployed. Since the power of 30kW was selected, at sections where the power is less than -30kW the car could recover. This meant the area below the line where $y = -30$, depicted with an orange line, and above the curve was the amount of energy harvestable on each bend. This shows that there are four areas where energy is harvestable under braking.



Graph 3-10 Power vs Time with a line of harvest

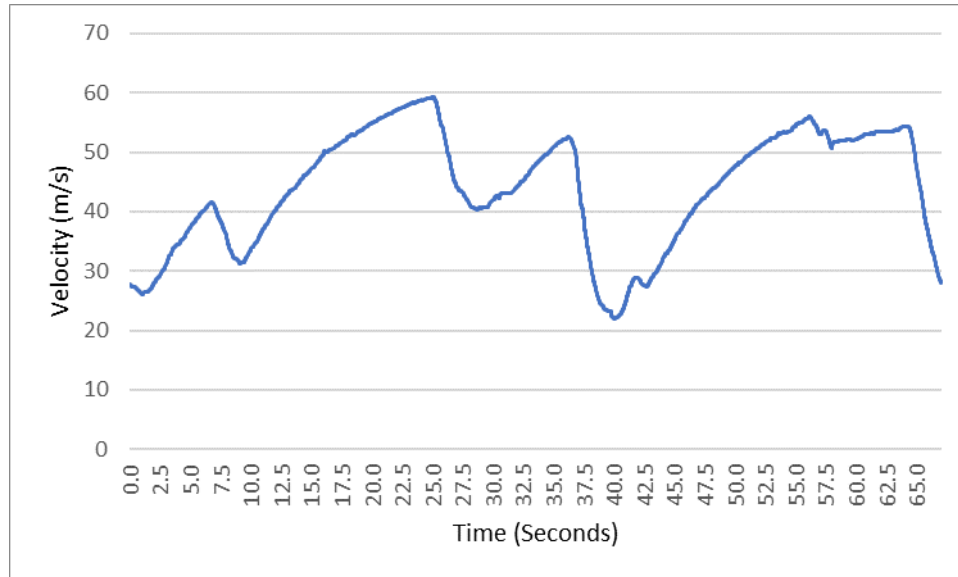
After calculation, this gave a maximum harvest of 9.76 seconds, as clarified in Table 3-7 later in this section.

To be able to compare the benefit of KERS with the standard lap, Graph 3-11 was produced. Once the KERS lap has been calculated, this will allow a visual representation of where the KERS is used and how much faster the car is travelling at each location.



Graph 3-11 Standard Lap: Velocity vs Distance

The velocity was also plotted against time to allow for a comparison of how much faster around the track the car is at any point with a KERS, see Graph 3-12.



Graph 3-12 Standard Lap: Velocity vs Time

A similar table was set up to section 0, see Table 3-6. The equations used in this table were the same as in section 3.4 apart from the equation used for the resistive force which was the real coast down equation. The mass for the system was also considered in the calculation by increasing the car's mass of 593.5kg by the system's mass of 28kg. Also, when the MGU power was used it was calculated to be 26.827kW after the efficiencies of the system, see section 3.5.2 for the efficiency of each component.

Table 3-6 KERS Lap calculations: Formula View

New Power kW	Resistive Force N	Acceleration m/s/s	Force Dynamic N	Force Total N	New Velocity m/s	New Distance m
=AH5	=0.4095*(AP5^2) - 3.3553*AP5 + 257	=AN5/('Car Data'!\$E\$5+'Car Data'!\$C\$32)	=AO5-AL5	=AJ5*1000/AP5	=J5	=B5
=AH6	=0.4095*(AP6^2) - 3.3553*AP6 + 257	=AN6/('Car Data'!\$E\$5+'Car Data'!\$C\$32)	=AO6-AL6	=AJ6*1000/AP6	=J6	=AQ5+0.5*(AP6+AP5)*0.02
=AH7	=0.4095*(AP7^2) - 3.3553*AP7 + 257	=AN7/('Car Data'!\$E\$5+'Car Data'!\$C\$32)	=AO7-AL7	=AJ7*1000/AP7	=AP6+AM6*0.02	=AQ6+0.5*(AP7+AP6)*0.02
=AH8	=0.4095*(AP8^2) - 3.3553*AP8 + 257	=AN8/('Car Data'!\$E\$5+'Car Data'!\$C\$32)	=AO8-AL8	=AJ8*1000/AP8	=AP7+AM7*0.02	=AQ7+0.5*(AP8+AP7)*0.02
=AH9	=0.4095*(AP9^2) - 3.3553*AP9 + 257	=AN9/('Car Data'!\$E\$5+'Car Data'!\$C\$32)	=AO9-AL9	=AJ9*1000/AP9	=AP8+AM8*0.02	=AQ8+0.5*(AP9+AP8)*0.02
=AH10	=0.4095*(AP10^2) - 3.3553*AP10 + 257	=AN10/('Car Data'!\$E\$5+'Car Data'!\$C\$32)	=AO10-AL10	=AJ10*1000/AP10	=AP9+AM9*0.02	=AQ9+0.5*(AP10+AP9)*0.02
=AH11	=0.4095*(AP11^2) - 3.3553*AP11 + 257	=AN11/('Car Data'!\$E\$5+'Car Data'!\$C\$32)	=AO11-AL11	=AJ11*1000/AP11	=AP10+AM10*0.02	=AQ10+0.5*(AP11+AP10)*0.02

The same principle as in section 3.4 was applied where the car would travel at the same velocity during braking and around corners as the standard lap. This simulation used the stored energy as soon as possible after storing it.

The areas of regenerative braking are recorded in Table 3-7.

Table 3-7 Regenerative Braking Zones

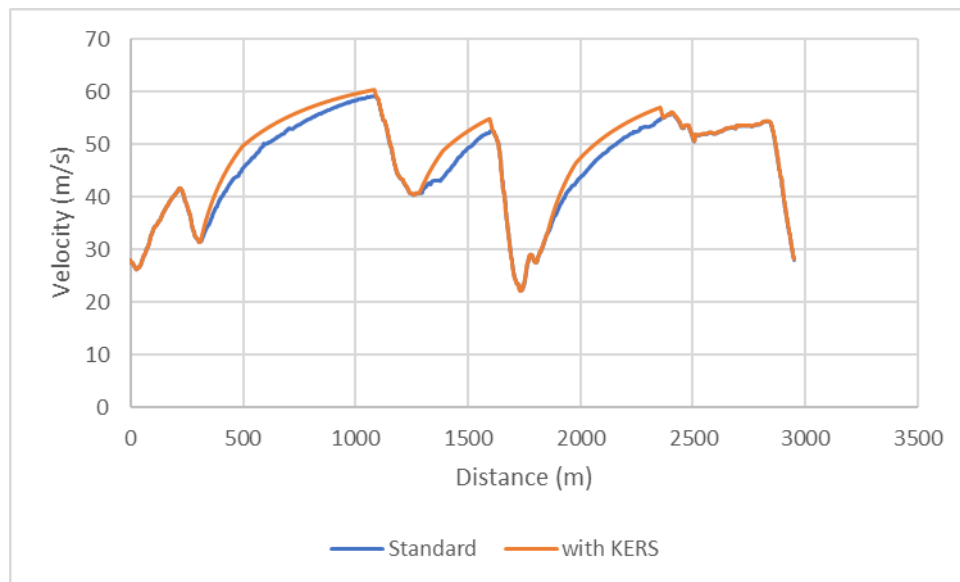
	Accel/Brake	Start Distance (m)	Finish Distance (m)	Total Time (s)	Time Stored (s)
1	Brake	217	276	1.54	4.4
2	Acceleration	313	1013	14.46	0
3	Brake	1063	1187	2.3	2.3
4	Acceleration	1285	1561	6.06	0
5	Brake	1560	1712	3.06	3.06
6	Acceleration	1855	2368	11.1	0
7	Constant Velocity	2368	2503	2.48	0
8	Acceleration	2503	2787	5.4	0
9	Brake	2824	2946	2.86	2.86
Total					12.62

Between the end of section 9 and the start of section 1, the two braking sections, there is a section where the car was not fully accelerating and so KERS cannot be used. The four areas of regenerative braking were used in three sections of power: sections 2, 4 and 6. This can also be seen in the MGU duty cycle in Appendix G.

Once the data was populated for the entire lap, the final improved lap time could be calculated and the velocity around the track could be compared to the original lap.

4 Results

The simulated lap was calculated using three deployments of the MGU. This deployment strategy caused the MCR car to travel around the Silverstone International track 1.82 seconds quicker than a standard lap of 67.06 seconds. This is a 2.7% decrease in lap time even though the car is 28kg heavier. The lap time decrease is a significant amount in racing, but it is what would be expected, as the motor increases the power at the wheels by 24%. Graph 4.1 shows the velocity of the vehicle in relation to its location on the track for both the standard lap, blue line, and the simulated KERS lap, orange.

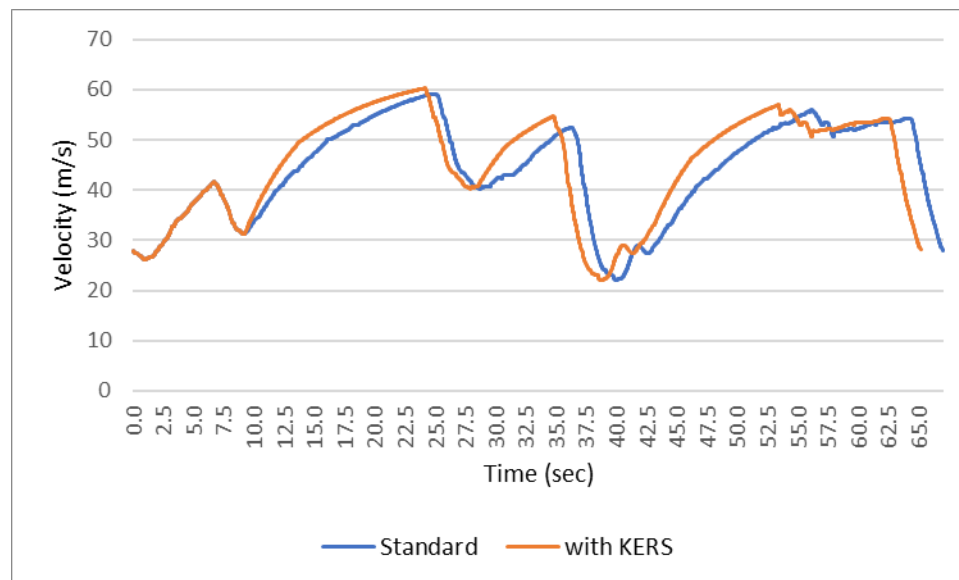


Graph 4-1 Lap Comparison: Velocity vs Distance

The graph is an effective way to validate that all the calculations are correct. The KERS and standard lap have the same velocity under braking and cornering, as well as the sections where the KERS was not deployed. This is what would happen in real life because regardless of how powerful the vehicle is it can only go around each corner and brake at its limit of friction.

The KERS gradients of the acceleration are initially larger due to the increased power, however, once all the power is used and the car is accelerating under only engine power the gradient is less than the standard lap. This happens due to the car travelling at higher velocities thus having a higher resistance to motion therefore a lower acceleration, this would be expected to happen in real life.

Another form of viewing the lap data is shown in Graph 4-2, where the velocity is plotted against time. This shows how much faster the KERS lap is to the standard lap at any point.



Graph 4-2 Lap Comparison: Velocity vs Time

These graphs display what would be expected when a KERS is applied. There are also no anomalies in the data which validates the accuracy of the calculations. The results would look slightly different if, for the KERS lap, the simulated resistive force was used. This would cause the car to be able to accelerate to higher speeds with the MGU engaged, as well as maintaining a slightly faster acceleration at high speeds when the electric motor no longer is engaged.

5 Discussion

There are many ways these results could affect the Sports 2000 championship. If all the cars were fitted with this system, the deployment strategy may not be the same as what was carried out in the above simulation. The drivers could save the energy and deploy it strategically to help overtake another car. Also depending on regulations such as the amount of power allowed to be deployed per lap, a driver could save up a couple of laps worth of energy and deploy it towards the end of the race when other drivers might not have much left in storage. This would also affect qualifying times as a driver could carry out a lot of braking and no power usage in the first couple qualifying laps before deploying as much as possible on one lap to get the best qualifying time.

If hybrid systems were to be used in the championship, it could make for a more entertaining race to watch. This means it could attract a wider audience and larger fan base. This would help keep the championship running for many more years and bring more money into the industry through sponsorships. Also becoming hybrid will allow the championship to carry on whilst society is trying to reduce its carbon footprint (Gov.uk, 2019). The regulations could be set up to reduce fuel usage on track which would encourage teams to make their hybrid systems as efficient as possible as well as reducing the carbon footprint for the championship.

If the championship became hybrid, and a higher-powered motor than 30kW is chosen, the teams would have to consider recalibrating the generator under certain weather conditions to prevent the rear wheel locking. One way the championship could facilitate this would be to allow active brake bias so the driver could reduce rear braking force as well as reducing generator power at low velocities. This would ensure the maximum amount of energy could be recovered without risking wheel lock. The SRCC could consider only changing the Duratec championship to hybrid as this would allow teams who can not afford hybrid systems to continue racing but change engines and enter the pinto championship.

It is likely that more lower-level motorsport will begin to incorporate hybrid and electric vehicles. This is due to Motorsport UK proposing to release their own regulation specific to electric and hybrid vehicles (Ratley, 2020). A few years ago it would not have been deemed a feasible option but as technology is evolving hybrid systems are becoming cheaper to manufacture as well as being smaller and much lighter.

However, the biggest influence on whether it could happen would be the competitor's opinion. Most competitors are self-funded which means they cannot afford to spend lots of money on the race car, which would occur initially if they became hybrid. Another reason competitor may

not want hybrids in the championship is because the implementation of electronic driver aids changes the driving style drastically. This could cause the more traditional drivers to not want to compete as it means they would have to learn a new racing technique. For competitors who race as a weekend hobby, this could be too much hassle causing them to not enter the championship.

6 Pandemic Impact

Due to the world-wide Covid-19 pandemic, two fundamental areas of this project were not able to be completed. These included acquiring photos of the car for the final location decision and a simulating a lap in the Base Performance Simulator with the car using KERS.

The university shut to all students meaning there was no access to the BPS or the car. A week later the country went on lockdown meaning the university could not open again until further notice, following government guidelines.

6.1 Component Locations

Photos of the car were going to be collected to show where the final component could be located. These photos aid the description and understanding of the space available in these locations as well as supporting the description of the final locations discussed in the Pacakaging and Final Components section 3.5. For example, an image of the front of the engine would aid the description of where the motor can mount, as well as demonstrating why the engine would need to move back a couple of inches.

These location decisions were still made in section 3.5 but photos would have given the reader a much greater understanding.

6.2 Base Performance Simulator

As well as conducting a simulated test in excel, a test was going to be conducted using the universities BPS. This would allow a simulated lap to be completed with and without a KERS. Some work had already begun on this but unfortunately, this was of no use to the project once the pandemic safety laws were enforced.

A copy of the simulation package and its files was sourced to allow an investigation into the engine files to be carried out. This was done as the BPS has a button on the steering wheel which can be pressed to add 'boost', which could simulate an electric motor 'boost'. However, to do this the engine files for the MCR car would need modifying to allow this button to work, as well as providing the correct amount of power. Unfortunately, this editing is not as simple as just putting the power of the motor into the boost line of code but in fact, a value had to be added to make the power a multiple of the current power. This is also calculated for the power at the engine and not at the wheels like calculated in the excel model. This meant that trial and error would take place to analyse the increase in power at the wheels when the button is

pressed. This would be analysed in MoTeC to ensure that the correct formula was entered to provide the 'boost' button to accurately simulate a hybrid lap.

To begin the actual testing, several base laps would take place to allow for the driver to produce consistent non-KERS lap times. The amount of energy that could be harvested could quickly be calculated from this data and then a KERS lap could take place. When this takes place the button would have to be pressed only for the amount of time that is available, so there would need to be a stopwatch used to show the driver how long to hold the button for at each section of use. The KERS lap would have to be repeated several times until consistent lap times were being produced.

Once this test was carried out, different deployment strategies could be applied, such as an entire lap worth of energy used on the longest straight. This could be used to analyse what would be the best way to use the KERS system in the championship.

This data could then be compared to the base laps to see how much quicker the KERS system is and these results could be compared to the excel simulation. It would be expected that the simulation lap times would be quicker due to the resistive force in the simulator being less than real life. However, the difference between the standard laps and hybrid laps should be similar.

These results would allow for correlation of results and an improved estimation for the time reduction of a real-life lap around the Silverstone international track.

7 Conclusion

To summarise, applying KERS to a Sports 2000 race car has a positive effect on the performance if the regulations allow for it.

Firstly, a 30kW MGU was selected once both the wheel lock power and power comparisons were calculated. The power of 30kW may only seem small but it caused the car to reduce its lap time by 1.82 seconds. This time saving demonstrates that the MCR could complete a lap quicker by only using waste energy. This suggests that it would be a benefit to the championship by increasing the power of the cars and making the cars more efficient.

However, a negative impact of applying a kinetic energy recovery system to a Sports 2000 race car is the cost. These systems contain components which are not cheap. It will also cause the car to have multiple modifications. This could be an issue for most competitors as this championship does not require teams to have lots of money. Also, a lot of competitors are self-funded and compete as a part-time hobby. But if the development of hybrid systems continues at its current rate then these systems could become affordable for the average motorsport enthusiast to afford and these systems can end up being common practice within the industry.

8 Further Work

If the opportunity arose, it would be beneficial to finish the original plan for the project of using the Base Performance Simulator to conduct more tests. If more time was available, then the simulation model discussed in the pandemic impact section could be improved to allow a deeper investigation into how the deployment strategy of the system affects lap times.

Another piece of work that would be beneficial to be produced would be a computer-aided design, CAD, model of the car with the hybrid system implemented. This would allow for final locations to be assessed to find out if they are feasible as well as accurately predicting how the mass distribution and centre of gravity of the car would be affected. This model would also help assess the effect of the wheelbase if the rear subframe was moved to allow for the motor. The CAD model could also be used to experiment with new component locations as well as different powered systems. This could be used to see if they would fit and how they would affect the vehicles mass distribution.

A cost analysis could also be carried out on the hybrid system. This would allow a finalised system to be produced that may not be as efficient or as beneficial as the system currently selected but is affordable for the championship.

Finally, this project could be extended to investigate how much other championships or disciplines could benefit from applying KERS to their cars and whether a certain form of motorsport is more suited to this application.

9 References

Battery University, 2017. *What's the best battery?*. [Online]
Available at:
https://batteryuniversity.com/learn/archive/whats_the_best_battery?fbclid=IwAR2OtMKqL9hV1rJfCZ-B5nKnWGQwYIGt-yEpdEFTjge1yiKbzGP9zBJBvXc
[Accessed 3 January 20].

Battery University, 2019. *BU-209, How does a Supercapacitor Work?*. [Online]
Available at:
https://batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor?fbclid=IwAR3Tmyl0vmQtkbT4jN69FHAicbeSV3mK_v3hstt292y20Sp6T0lDXQuPktA
[Accessed 28 December 2019].

BPS, 2019. *Base Performance Simulators*. [Online]
Available at: <https://www.baseperformance.net/>
[Accessed 16 October 2019].

BTCC, 2018. *Hybrid Energy coming to the BTCC*. [Online]
Available at: <http://www.btcc.net/2018/08/01/hybrid-energy-coming-to-the-btcc/>
[Accessed 15 October 2019].

BTCC, 2019. *COSWORTH ELECTRONICS AWARDED BTCC HYBRID SYSTEM CONTRACT: BTCC*. [Online]
Available at: <http://www.btcc.net/2019/07/23/cosworth-electronics-awarded-btcc-hybrid-system-contract/>
[Accessed 15 November 2019].

Business Wire, 2019. *Ferrari Selects YASA Electric Motor for SF90 Stradale, the Company's First Hybrid Production Series Supercar: YASA*. [Online]
Available at: https://www.businesswire.com/news/home/20190530005620/en/Ferrari-Selects-YASA-Electric-Motor-SF90-Stradale/?feedref=JjAwJuNHiystnCoBq_hl-WepL6sRhX6ZA9uIKkLyMC2Ka1ah7uC6RdZY8DBviqXR7fxFuNFTHSunhvli30RIBNXya2izy9YOgHIBiZQk2LO4aHursdTqjq-KNSSWsKUa97ZTKjNldK1
[Accessed 18 December 2019].

Collins, S., 2013. *The Hybrid System and how it works: 2014 F1 explained, The power unit: Articles: Racecar Engineering*. [Online]
Available at: https://www.racecar-engineering.com/articles/f1/2014-f1-the-power-unit-explained/3/?fbclid=IwAR0iUxiXobBiaOnZHqSRaHOvl1qITkK70SuiPumNej6KU_h2azXe7n9DPJI
[Accessed 18 December 2019].

EMRAX, 2017. *Dimensions: EMRAX 118: E-Motors: Home: EMRAX*. [Online]
Available at: <https://emrax.com/e-motors/emrax-188/#1482059435797-eb98587f-6c74>
[Accessed 17 February 2020].

EMRAX, 2019. *EMRAX 188: E-Motors: Home: EMRAX.* [Online]
Available at: <https://emrax.com/e-motors/emrax-188/?fbclid=IwAR2sM-H1iBelhYdPyCKq0CEo3utpzDgrPC0RyBg7a1EjEO3RRYeL1-hq8s8#1482059527961-2c92c2ea-c5c5>
[Accessed 20 December 2019].

EMRAX, 2019. *Recomended Controlllers for EMRAX Motors: Suitable controllers for EMRAX motors: User Manuel for EMRAX motors: Technical Support: Support: Home: EMRAX.* [Online]
Available at: <https://emrax.com/support/technical-support/?fbclid=IwAR0KtE6KHS1FlomwUftCh99LHHgEbSE8xVMW5d0T6YEtTJVfYGEDaj2kR8E>
[Accessed 12 January 2020].

Evans, D., 2019. *Hybrid WRC cars for 2022 announced by the FIA, control tyre returns: Motorsport News..* [Online]
Available at: https://www.autosport.com/wrc/news/144104/hybrid-wrc-cars-for-2022-announced?fbclid=IwAR3DrHtY3FfpWZvct1jsfzCkEXvG0QNQGn_u8qOcMQ_kstcEuvq7oixa0KU
[Accessed 25 October 2019].

FIA, 2009. *2009: Technical Regulations: Formula 1: Regulations: FIA.* [Online]
Available at: https://www.fia.com/regulations?fbclid=IwAR1_VfTEgUDMjxz0sN5xVv_J8FapogJmLwIAA0WjVaMILL_CvuW1Ax7uNnaE
[Accessed 25 October 2019].

FIA, 2019. *2019 Technical Regulations for LMP1 Prototype Hybrid: Technical Regulations: Regulations: FIA.* [Online]
Available at: https://www.fia.com/regulation/category/118?fbclid=IwAR0oR_9LWo7JbOdMZVewYkEX6YJrtOpYBp_sCeGbRMIyLR-AYz-lA1qHoRZU
[Accessed 25 October 2019].

FIA, 2020. *2020-2021: Technical Regulations: FIA Formula E Championship: Regulations: FIA.* [Online]
Available at: <https://www.fia.com/regulation/category/109?fbclid=IwAR2DGUUDWQN7VnawZTX35Fo2d0JYL-DPmCf5JHnyUV5Ra0CkZ1U-elbKaHs>
[Accessed 15 March 2020].

FIA, 2020. *2021: Technical Regulations: Formula 1: Regulations: FIA.* [Online]
Available at: https://www.fia.com/regulation/category/110?fbclid=IwAR2zqp52qaBy1DuucFbVvGKK6_c0nU_P8osoL3FnyF-nm3HFqI61h_Yn4TE
[Accessed 15 March 2020].

Gov.uk, 2019. *UK becomes first major economy to pass net zero emissions law: Climate change and energy: Enviroment: Gov.uk.* [Online]
Available at: <https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero->

emissions-law

[Accessed 16 October 2019].

Holt, S., 2012. *Formula for success - Kers and DRS*. [Online] Available at:

https://www.bbc.co.uk/sport/formula1/20496330?fbclid=IwAR2wXvO85l8JOLtQ8YKrOXnwt_vu6AsFm2rZJenAagpWkkwHZs-2lIC2TKE

[Accessed 23 December 2019].

IndyCar, 2019. *New for IndyCar 2022: single-source hybrid system: News: IndyCar*. [Online] Available at: <https://www.indycar.com/News/2019/08/08-01-INDYCAR-Hybrid> [Accessed 15 October 2019].

[Accessed 15 October 2019].

JSR Micro, 2017. *The concept of Lithium Ion Capacitor: Emerging Technologies: JSR Micro*. [Online] Available at: <https://www.jsrmicro.be/emerging-technologies/lithium-ion-capacitor/concept-lithium-ion-capacitor#>

[Accessed 20 December 2019].

M Sport Eng, 2016. *Our Car: M Sport Eng*. [Online] Available at: http://www.msport-eng.com/?page_id=1665

[Accessed 23 November 2019].

Magneti Marelli, 2010. *KERS (Kinetic Energy Recovery System)*. [Online] Available at: <https://www.magnetimarelli.com/excellence/technological-excellences/kers>

[Accessed 28 November 2019].

MAHLE, 2019. *High Charge Rate 48V Battery Pack: Experience: MAHLE Powertrain*. [Online] Available at: https://www.mahle-powertrain.com/media/mahle-powertrain/experience/48v-battery-pack/48v-battery_screen-all-sites.pdf

[Accessed 17 February 2020].

McLaren, 2019. *E Motor: Products: Applied: McLaren*. [Online] Available at: <https://www.mclaren.com/applied/products/item/e-motor-120kw-130nm/>

[Accessed 20 October 2019].

Mercedes AMG F1, 2019. *EQ Power in F1: A Decade of Hybrid Success: News: Mercedes AMG F1*. [Online]

Available at: <https://www.mercedesamgf1.com/en/news/2019/08/eq-power-in-f1-a-decade-of-hybrid-success/?fbclid=IwAR2Cna0lZLSpkBXmk1U0BPspbtA8PuH3rNdQRbVaUvzzgqgHV5-DQa89EDc>

[Accessed 15 December 2019].

Mitsubishi Electric, 2017. *Mitsubishi Electric Begins Mass-producing Auto Industry's First Crankshaft ISG System for 48V Hybrid Vehicles: News release Archives*. [Online]

Available at: <https://www.mitsubishielectric.com/news/2017/pdf/1026-b.pdf>

[Accessed 14 February 2020].

Moreels, D., 2017. *This New Generation of Direct-Drive Electric Machines will Power our Future: Magmax.* [Online]

Available at: https://www.magnax.com/magnax-blog/axial-flux-vs-radial-flux-for-direct-drive-generators?fbclid=IwAR06vIv6Db5gBqSSidGLcLK1qq_27t1i9HsvUEgxAlIPzxJkcZfZ5Z6qHYU
[Accessed 29 December 2019].

MoTeC, 2019. *MoTeC.* [Online]
Available at: <https://www.motec.com.au/>
[Accessed 16 October 2019].

NASCAR, 2019. <https://www.nascar.com/news-media/2018/05/29/brad-keselowski-blog-nascar-hybrid/>. [Online]
Available at: <https://www.nascar.com/news-media/2018/05/29/brad-keselowski-blog-nascar-hybrid/>
[Accessed 15 October 2019].

O'Kane, S., 2019. *IndyCar will race 900-horsepower hybrid cars starting in 2022.* [Online]
Available at: https://www.theverge.com/2019/8/1/20750192/indycar-hybrid-2022-specs-plans-electric?fbclid=IwAR3DrHtY3FfpWZvct1jsfzCkEXvG0QNOGn_u8qOcMQ_kstcEuvq7oixa0KU
[Accessed 19 October 2019].

Ratley, R., 2020. *Overview of the proposed Technical Regulations governing the use of Electric Vehicles in UK Motorsport.* Colnbrook: Motorsport UK.

Scarborough, C., 2012. *Red Bull KERS, Floor Mounted Super Capacitors?: Scarbs f1.* [Online]
Available at: <https://scarbsf1.wordpress.com/2012/04/17/red-bull-kers-floor-mounted-super-capacitors/?fbclid=IwAR2rQQSNxbT7Yb7KuozTDxwRzvLdhrstpRj16QAWjunYYIZCNPPWvGkKOfg>
[Accessed 28 December 2019].

Sevcon, 2016. *Gen5-s9: High Voltage Controllers: Products: SEVCON.* [Online]
Available at: <http://www.sevcon.com/products/high-voltage-controllers/gen5-s9/>
[Accessed 17 February 2020].

Shilpa, K., 2018. *Hybrid Cars & Different Types Of Hybrids Explained: Four Wheelers: Drive Spark.* [Online]
Available at: <https://www.drivespark.com/four-wheelers/2018/hybrid-systems-explained-different-types-of-hybrid-cars-026382.html?fbclid=IwAR1AO4GJ7TIC1X8geHEhiHLkHmXGCuFAbtIWWUBrRxkl67rZo3qpql3crm0>
[Accessed 24 November 2019].

Silverstone, 2016. *International Circuit: Track Hire: Silverstone.* [Online]
Available at: <https://www.silverstone.co.uk/track-hire/>
[Accessed 23 November 2019].

Skeleton Tech, 2016. *Infographic: Ultracapacitors or Batteries?.* [Online]
Available at: <https://www.skeletontech.com/skeleton-blog/ultracapacitors-or-batteries-infographic>
[Accessed 20 November 2019].

Slovick, M., 2019. *Lamborghini Hybrid Uses Supercapacitors in Place of Batteries: Automotive: Markets: Electronic Design.* [Online]

Available at: [https://www.electronicdesign.com/markets/automotive/article/21808589/lamborghini-hybrid-uses-supercapacitors-in-place-of-](https://www.electronicdesign.com/markets/automotive/article/21808589/lamborghini-hybrid-uses-supercapacitors-in-place-of-batteries?fbclid=IwAR06vIv6Db5qBqSSidGLcLK1qq_27t1i9HsvUEqxAIIPzxJkcZfZ5Z6qHYU)

[batteries?fbclid=IwAR06vIv6Db5qBqSSidGLcLK1qq_27t1i9HsvUEqxAIIPzxJkcZfZ5Z6qHYU](https://www.electronicdesign.com/markets/automotive/article/21808589/lamborghini-hybrid-uses-supercapacitors-in-place-of-batteries?fbclid=IwAR06vIv6Db5qBqSSidGLcLK1qq_27t1i9HsvUEqxAIIPzxJkcZfZ5Z6qHYU)

[Accessed 27 December 2019].

SRCC, 2019. *About the SRCC: SRCC.* [Online]

Available at: [https://sports2000.co.uk/about-](https://sports2000.co.uk/about-srcc/?fbclid=IwAR02wIb3MYAZALM31Zt1LBq6K3zuPhpL23haGXhTgn3OE8FSG7boX-lqJ7M)

[srcc/?fbclid=IwAR02wIb3MYAZALM31Zt1LBq6K3zuPhpL23haGXhTgn3OE8FSG7boX-lqJ7M](https://sports2000.co.uk/about-srcc/?fbclid=IwAR02wIb3MYAZALM31Zt1LBq6K3zuPhpL23haGXhTgn3OE8FSG7boX-lqJ7M)

[Accessed 21 November 2019].

UWTSD, 2017. *University of Wales Trinity Saint David.* [Online]

Available at: www.uwttd.ac.uk

[Accessed 18 October 2019].

Volkswagen Motorsport, 2019. *Ready for the electric future: ID.R.* [Online]

Available at: [https://volkswagen-](https://volkswagen-motorsport.com/en/idr/article?tx_dataviewer_record%5Baction%5D=dynamicDetail&tx_dataviewer_record%5Bcontroller%5D=Record&tx_dataviewer_record%5Brecord%5D=2401&cHash=35dc24873ed9d294f2913c3477601392)

[motorsport.com/en/idr/article?tx_dataviewer_record%5Baction%5D=dynamicDetail&tx_dataviewer_record%5Bcontroller%5D=Record&tx_dataviewer_record%5Brecord%5D=2401&cHash=35dc24873ed9d294f2913c3477601392](https://volkswagen-motorsport.com/en/idr/article?tx_dataviewer_record%5Baction%5D=dynamicDetail&tx_dataviewer_record%5Bcontroller%5D=Record&tx_dataviewer_record%5Brecord%5D=2401&cHash=35dc24873ed9d294f2913c3477601392)

[Accessed 10 November 2019].

Wilkinson, L., 2019. *Volkswagen plans more ID.R record attempts for 2020: Volkswagen: News: Auto Express.* [Online]

Available at: [https://www.autoexpress.co.uk/volkswagen/101402/volkswagen-plans-more-idr-record-](https://www.autoexpress.co.uk/volkswagen/101402/volkswagen-plans-more-idr-record-attempts-for-2020?fbclid=IwAR0T-FMoy5bokigU2CKg_mKLCBS3Fs6XRXeFXsIQ42uCJGJuDD2KwQpHfm4)

[attempts-for-2020?fbclid=IwAR0T-FMoy5bokigU2CKg_mKLCBS3Fs6XRXeFXsIQ42uCJGJuDD2KwQpHfm4](https://www.autoexpress.co.uk/volkswagen/101402/volkswagen-plans-more-idr-record-attempts-for-2020?fbclid=IwAR0T-FMoy5bokigU2CKg_mKLCBS3Fs6XRXeFXsIQ42uCJGJuDD2KwQpHfm4)

[Accessed 15 November 2019].

Wright, D., 2005. *The Braked Wheel: Braking of Vehicles.* [Online]

Available at: [http://www-](http://www-mdp.eng.cam.ac.uk/web/library/enginfo/textbooks_dvd_only/DAN/brakes/vehicles/vehicles.html?fbclid=IwAR1_VfTEgUDMjxz0sN5xVv_J8FapogJmLwIAA0WjVaMIILCvuW1Ax7uNnaE)

[mdp.eng.cam.ac.uk/web/library/enginfo/textbooks_dvd_only/DAN/brakes/vehicles/vehicles.html?fbclid=IwAR1_VfTEgUDMjxz0sN5xVv_J8FapogJmLwIAA0WjVaMIILCvuW1Ax7uNnaE](http://www-mdp.eng.cam.ac.uk/web/library/enginfo/textbooks_dvd_only/DAN/brakes/vehicles/vehicles.html?fbclid=IwAR1_VfTEgUDMjxz0sN5xVv_J8FapogJmLwIAA0WjVaMIILCvuW1Ax7uNnaE)

[Accessed 16 November 2019].

X-Engineer, 2019. *Mild Hybrid Electric Vehicle (MHEV) – control functions: Hybrid: Vehicle: Automotive Engineering: Home: X-Engineer.* [Online]

Available at: [https://x-engineer.org/automotive-engineering/vehicle/hybrid/mild-hybrid-electric-vehicle-](https://x-engineer.org/automotive-engineering/vehicle/hybrid/mild-hybrid-electric-vehicle-mhev-control-function/?fbclid=IwAR1_VfTEgUDMjxz0sN5xVv_J8FapogJmLwIAA0WjVaMIILCvuW1Ax7uNnaE)

[mhev-control-function/?fbclid=IwAR1_VfTEgUDMjxz0sN5xVv_J8FapogJmLwIAA0WjVaMIILCvuW1Ax7uNnaE](https://x-engineer.org/automotive-engineering/vehicle/hybrid/mild-hybrid-electric-vehicle-mhev-control-function/?fbclid=IwAR1_VfTEgUDMjxz0sN5xVv_J8FapogJmLwIAA0WjVaMIILCvuW1Ax7uNnaE)

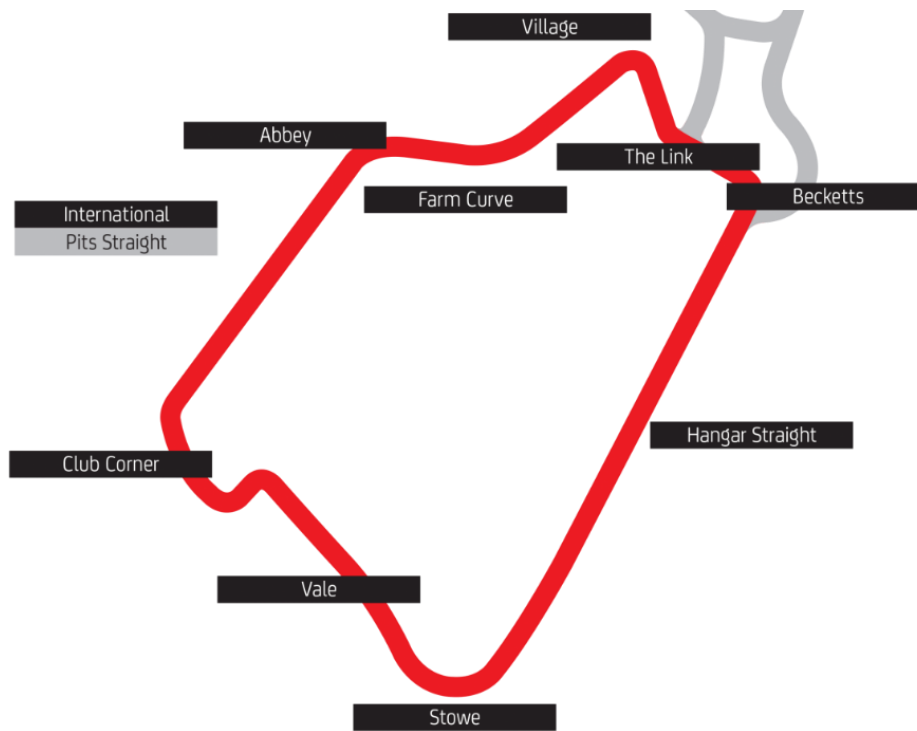
[Accessed 28 December 2019].

YASA, 2018. YASA P400 R Series: YASA. [Online]
Available at: <https://www.yasa.com/yasa-p400/>
[Accessed 10 November 2019].

Zaheer, H., 2019. *Evolution of Li-ion Batteries: From the Garage to the Grid: Energy Storage: Distributed Energy Resources.* [Online]
Available at: <https://www.tdworld.com/distributed-energy-resources/energy-storage/article/20972265/evolution-of-liion-batteries-from-the-garage-to-the-grid?fbclid=IwAR2SgnctvzTaW30nzMrfJ1IAbpPVPFluhKfaWLuahnWViGKYzRoYlwav0O4>
[Accessed January 2020].

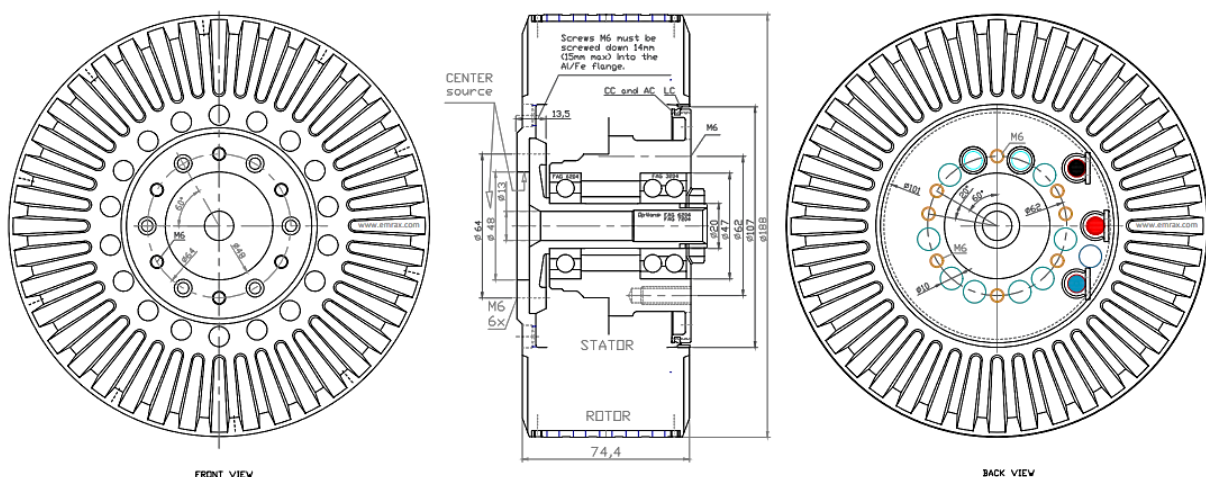
Zytec, 2019. *Motorsport Energy Recovery System (ERS): Zytek Automotive.* [Online]
Available at: <http://www.zytekautomotive.co.uk/products/motorsport/hybrid-systems/>
[Accessed 20 October 2019].

Appendix C - The Silverstone International Track (Silverstone, 2016)



----- end of Appendix C -----

Appendix D - Motor Dimensions (EMRAX, 2017)

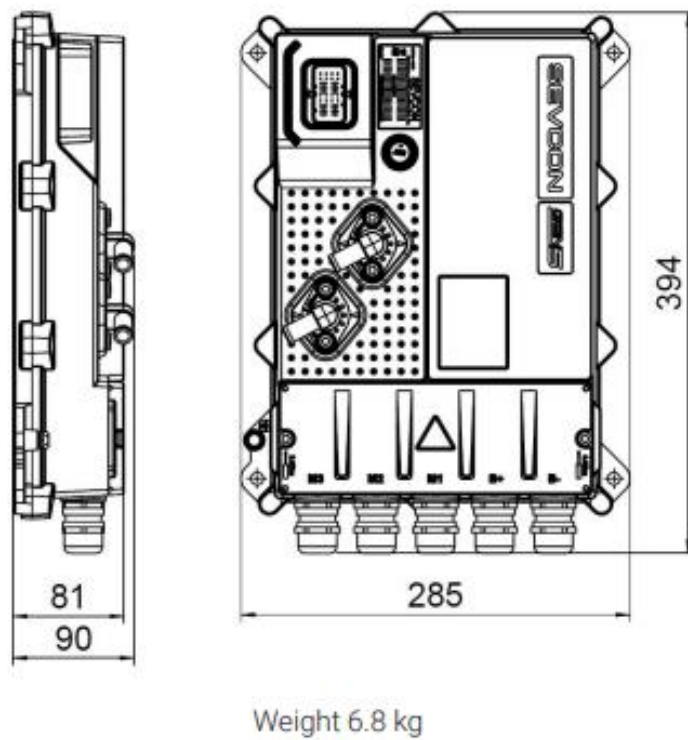


Bearings 6204/6204 - Front and back bearing are for radial forces (standard).
Bearings 6204/7204 - Front bearing is for radial forces, back bearing is for axial-radial forces. Bearing combination is for pull mode (for e.g. air propeller).
Bearings 6204/3204 - Front bearing is for radial forces, back bearing is for axial-radial forces. Bearing combination is for pull-push mode. "D" bearing orientation.

EMRAX 188
100Nmp, 70kWp at 7000RPM, weight: 7,0kg

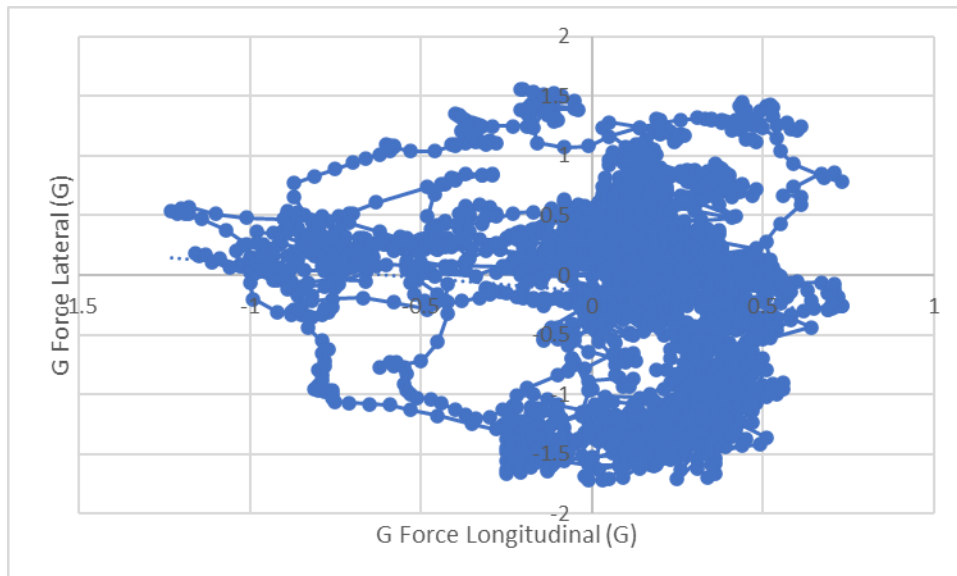
----- end of Appendix D -----

Appendix E - Engineering drawing (Sevcon, 2016)



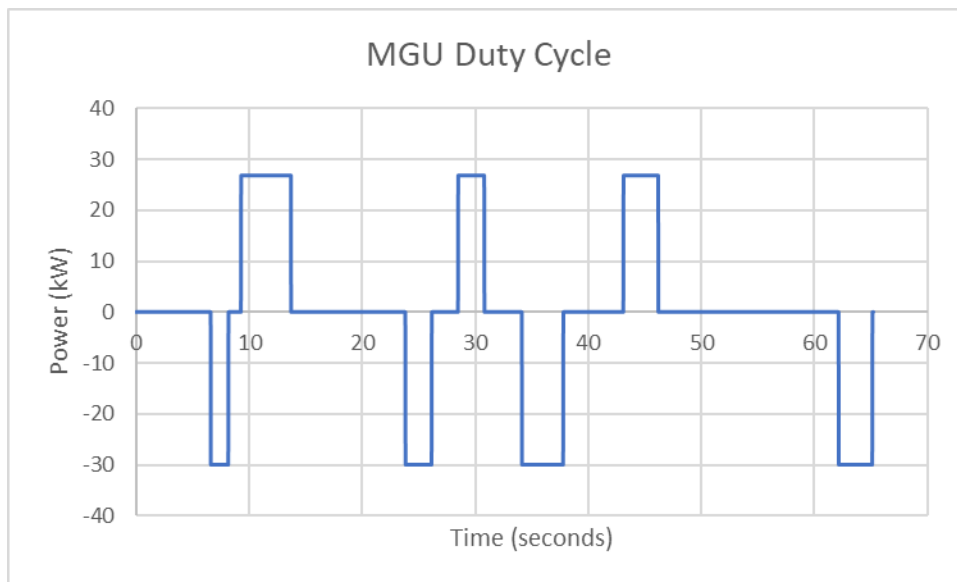
----- end of Appendix E -----

Appendix F - Standardised Friction Ellipse



----- end of Appendix F -----

Appendix G – MGU Duty Cycle



----- end of Appendix G -----