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INVESTIGATION INTO THE POTENTIAL BENEFIT OF A KINETIC ENERGY RECOVERY SYSTEM ON A MOTORSPORT VEHICLE

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Declaration of Authenticity

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.

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Glossary Of Abbreviations

AC	Alternating Current
Ah	Ampere-hour
Dc	Direct Current
ESS	Energy Storage Solution
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
KERS	Kinetic Energy Recovery System
kg	Kilogram
kJ	Kilo joule
kW	Kilo watt
kWh	Kilo watt hour
LMP	Le Mans Prototype
Nm	Newton meter
Rad	Radians

Abstract

This report looks at the potential benefit that the installation of a hybrid system, namely KERS, can have on the performance on a motorsport vehicle, technology which will allow the installation of this to occur and function will be researched. Simulation with basic hand-calculations and a software package will be used to determine if the system is realistic whilst also determining the potential benefit and therefore displayed with tables and graphs. The final proposed system configuration is displayed with the cost of the components displayed.

1 Introduction

The report investigates the potential benefit or disadvantage of a Kinetic Energy Recovery System on a motorsport vehicle.

1.1 Aims

- Research KERS
- Research available technology for HEV
- To analyse the potential energy that could be recovered
- Simulate the effect of the power boost
- Simulate the effect of the additional mass
- Define system specifications
- Research suitable components
- Determine a suitable system

1.2 Reasons

The reasons for a KERS system is to provide a performance benefit to a motorsport vehicle. The primary benefit is that it uses no extra energy from the ICE due to the fact that all of its energy is recovered during braking, this energy is energy that would otherwise be lost as heat or sound otherwise.

As is shown in other forms of motorsport, namely Formula 1 and the LMP1 class of the World Endurance Championship, a hybrid system allows an overall faster vehicle along with the added potential for overtaking. In a road car application the KERS system can be used to improve fuel economy coupled with the performance benefit of an electric motor.

1.3 Plan

Initially the basic preliminary calculations will be conducted, then research will be conducted on current technology which could be used in the system, subsequently once components have been researched and sized a system can be created.

1.4 Gantt chart

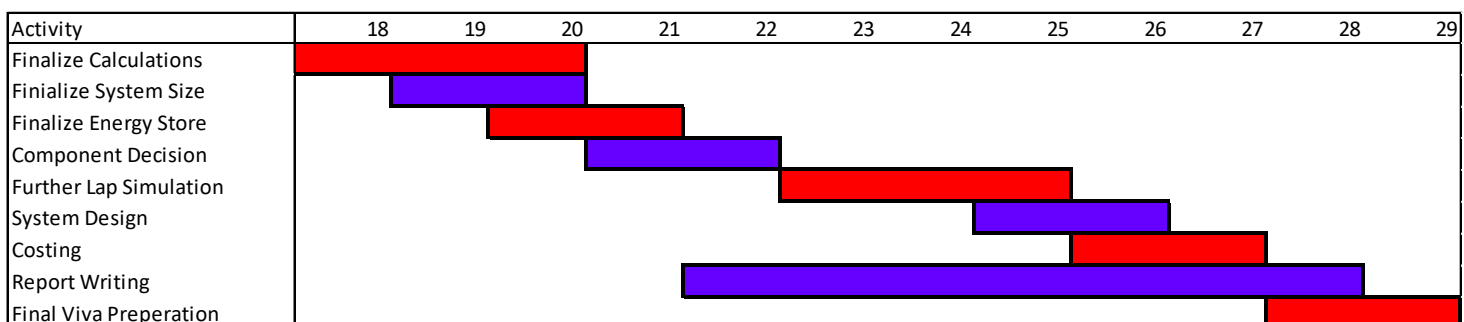


FIGURE 1 - WEEK 17 TO 29 GANTT CHART

Figure 1 displays the Gantt chart section for weeks 18 through unto the completion of the dissertation in week 29, the full Gantt chart including weeks 1 through to 17 is available in Appendix A.

2 Initial Research

2.1 Explanation of KERS

A Kinetic Energy Recovery System is a system whereby it is possible to store the kinetic energy of a vehicle as it is braking, store this energy, and then deploy the energy at another point on the track to provide a temporary power boost.

This power boost can be used in order to try to increase performance or increase the efficiency of the vehicle, in the case of this project purely the performance boost aspect will be evaluated.

This is an investigation in order to determine if a Kinetic Energy Recovery System would provide a performance benefit to the vehicle, the dissertation also includes the research and evaluation of the possible components that could be used if the system were to be constructed in reality. A Kinetic Energy Recovery System functions by recovering the kinetic energy that is lost when a vehicle is reducing its velocity, it captures the energy that is usually converted into heat energy by the brake disks and pads. This is achieved by rotating a motor/generator unit which in turn generates an electrical power, subsequently stored in an energy storage solution, and is then able to be deployed by the driver when deemed necessary further along the circuit. This power is generated by sending the electrical power back to the motor/generator so it can act as a motor and provide a power boost in addition to the vehicle's existing internal combustion engine.

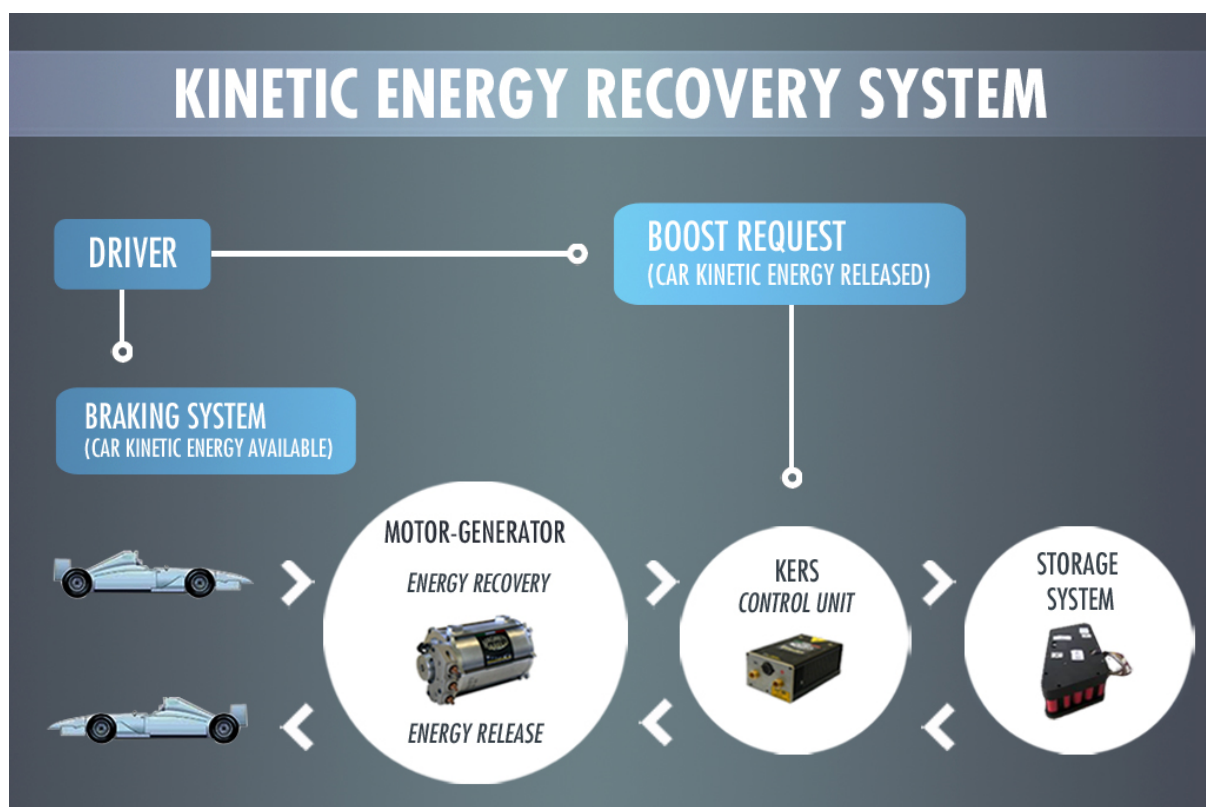


FIGURE 2- DIAGRAM OF KERS (MAGNETI MARELLI, 2009)

2.1.1 Regenerative braking

KERS primarily uses regenerative braking in order to harvest its energy. When reducing a vehicle's velocity a large amount of energy is available, the vehicle has all its kinetic energy to travel at its velocity and that energy needs to be dissipated in order to reduce the velocity, therefore the energy is converted into heat energy by the friction brakes.

The process at which the system recovers energy is called regenerative braking, this is the process where, during the braking phase of the vehicle, the kinetic energy present in the vehicle is captured by an electric MGU, this subsequently converts that energy into electrical energy which is then stored in an energy storage solution and is available to be used in the motor to provide either a performance boost or an efficiency gain.

The amount of energy that is available in a moving vehicle is given by equation

$$E_k = \frac{1}{2} \times m \times v^2 \quad (1)$$

(Husain, 2011), Where m is mass and v is velocity, this shows that a vehicle with mass of 1500kg and a velocity of 100kmh can produce 576000 J or 0.16kwh, therefore any amount of that energy that can be recovered could provide a boost in either efficiency but using as much of the chemical energy which is store in gasoline as possible or to increase performance.

The energy that is available to be regenerated does not solely depend on the system's components limitations but also the balance between the KERS and friction brakes in order to maintain vehicle behaviour (Boretti & Aris, 2015); the brake balance is extremely important especially if the motor is mounted on the rear axle, it is important to configure the system in such a way that the rear does not over brake the front axle possibly causing a lock up and loss of traction (Milliken & Milliken, 1995), however if the motor generator is on the front axle it can provide more use in stopping the overall vehicle and have less risk of changing car behaviour.

A KERS allows the user to adjust the brake balance in an alternative way to the traditional methods, which are brake pressure regulators in the master cylinder and dual master cylinders with an adjustable balance beam. (Milliken & Milliken, 1995) The system can control how much energy it harvests therefore controlling the brake balance on the axel it is mounted on.

2.2 Energy Storage

An energy storage system is defined as a device which has the ability to store energy and is then capable of both being recharged and discharged whilst the vehicle is in motion. The storage solution is the most critical component of the KERS due to its need to power the motor and recuperate energy, it can be possible however to pre-charge the storage system while the vehicle is stationary in the pits using an external generator.

In order to store the energy that is captured during the phase of recovery an energy storage solution becomes necessary. When the three primary solutions to the storage issue were researched it showed that batteries, super-capacitors and flywheels were the optimum options.

2.2.1 Battery

Batteries are a form of chemically storing energy. A variety of differing chemical types of battery cells are on the market and are available to be used as an energy storage system, the batteries to be investigated are secondary batteries which can be recharged by reversing the flow of current (Husain, 2011)

2.2.1.1 Lead based

This cell format used lead plates with sulphuric acid solution, these are a form of battery that have been around for a century. The benefit to a lead based system is they are a mature technology and, due to that, they are a low cost solution with a relatively high power output which means they are generally capable of providing a good starting current of ICE.

The disadvantages of lead based batteries is that they have a low energy density overall compared to other forms of cells and the amount of power that is able to be held from the cell depends on the cell's ambient temperature. These also suffer from a safety risk due to the presence of sulphuric acid and lead metal, both of which must be handled in the correct manner, coupled with the possible release of flammable hydrogen gas during certain charging conditions and it also needs to be recognised that they have a higher mass. (Husain, 2011) (Ehsani, et al., 2010)

2.2.1.2 Nickel based

Nickel as a metal has a lower mass than lead therefore the battery cell is lighter, along with a higher power density than lead-acid batteries, with a longer life cycle and abuse tolerance. Nickel-based batteries however suffer from a self-discharge problem which doesn't allow them to be used for long term storage, there's also an issue of high cost and poor charge acceptance. (Husain, 2011)

2.2.1.3 Lithium based

Lithium is the lightest of the three metals and has the highest thermodynamic voltage of the three, this therefore allows a higher specific energy and specific power. (Ehsani, et al., 2010). The nominal cell voltage of a lithium ion cell can be 3.6V which is equivalent to three NiMH or NiCad cells. (Husain, 2011) Lithium batteries must be carefully handled due to their potentially volatile nature and are classified as dangerous good by IATA. (IATA, n.d.)

2.2.2 Flywheel

A flywheel is a mechanical form of energy storage and when used in a mechanically-spun system there are no electrical losses, therefore in certain circumstances the flywheel can operate at up to 98% efficiency. There will be losses if the flywheel is run in an electrically driven system where a motor attached to the flywheel spins the motor to the desired rotational velocity.

Flywheels tend to run at a high RPM in order to store the required energy, current velocity ranges from 40,000 to 50,000 RPM.

2.2.2.1 Flywheel Energy Equation

The amount of energy that can be stored in a rotating flywheel is given by equation 2 (Ehsani, et al., 2010)

$$E_f = \frac{1}{2} \times J_f \times \omega^2 \quad (2)$$

Where J_f is the moment of inertia of the flywheel in kgm^2/s and ω_f is the angular velocity of it in rad/s . Appendix B displays the equation that is needed to calculate the moment of inertia.

2.2.3 Super capacitors

Ultra-capacitors are also a form of chemically storing energy, due to the nature of capacitors they have a high specific power but with a lower specific energy density compared to battery cells.

These are difficult to use as a primary source of energy in a system due to their low energy capacity and tendency to self-discharge, therefore they are used in conjunction with a lithium ion battery to provide stability for longer term storage. (Ehsani, et al., 2010)

2.2.3.1 Capacitance equation

Equation 3 (Ehsani, et al., 2010) states the equation for the amount of energy that is present in a capacitor.

$$E_{cap} = \frac{1}{2} \times C \times V^2 \quad (3)$$

C is the capacitance of the cell in Farads and V is the nominal voltage in Volts.

2.2.4 Comparison

Between all the methods of energy storage a graph can be seen of the differing energy and power densities.

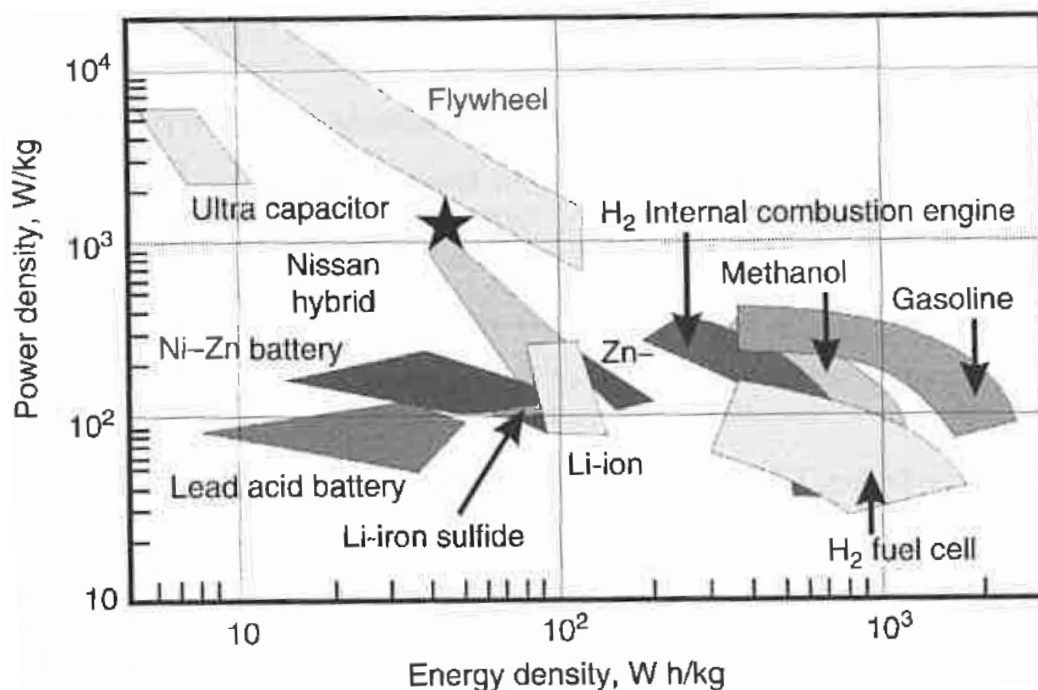


FIGURE 3 – A COMPARISON GRAPH BETWEEN ALL AVAILA ENERGY STORAGE METHODS (FUHS, 2009)

As is illustrated in the graph in figure 3 it is shown that the ultra-capacitors have a higher power density but lack in energy density, with certain forms of battery cells being the opposite to these with high energy density and a lower power density with the flywheel spanning between two other forms. Batteries tend to remain charged over time whist super capacitors do not.

2.3 Motors

Motors are the key component in KERS, they act as the generators that regain the energy during braking and are also the component that subsequently deploys the stored energy.

Motors tend to have an inherent benefit in performance compared to an ICE, they generate their maximum torque at 0RPM and are available in a range of power and available torques, another benefit is that motors are effected less by the change in air density associated with higher altitudes due to the fact they do not rely on air to combust.

The motor/generator unit will experience a wide amount of torque range, not only due to the need to decelerate the vehicle, but also to provide the power boost during deployment which could stress the component.

2.3.1 DC Motors

DC Motor are the most common form of motor used presently and are used in various applications with a wide variety of sizes and powers available, DC motors work on the principle of electromagnetism, equation 4 (Husain, 2011) gives the primary equation of electromagnetism which shows that a force will be generated when a current passes through a length of wire

$$F = BIL \quad (4)$$

Where B is the density of the magnetic field I is the current and L is the length of wire.

Wire are wound into coils for motors which therefore gives equation 5, this will generate a torque which is suitable for a motor. (Ehsani, et al., 2010)

$$T = BIL \cos \alpha \quad (5)$$

Where α is the angle between the wire and the magnetic field axis. Due the force acting at two points and in opposite directions that means a torque is produced which is denoted by T.

2.3.2 AC Motors

AC motors are a commutator less motors which means all the current stays on the outer ring of the motor, a series of stator slots receive currents in time with a sine wave which then varies which stator is active with a magnetic field therefore rotating the motor. Figure 4 illustrates which stators are coupled and shows that the magnetic field rotates around the mores therefore producing the moment.

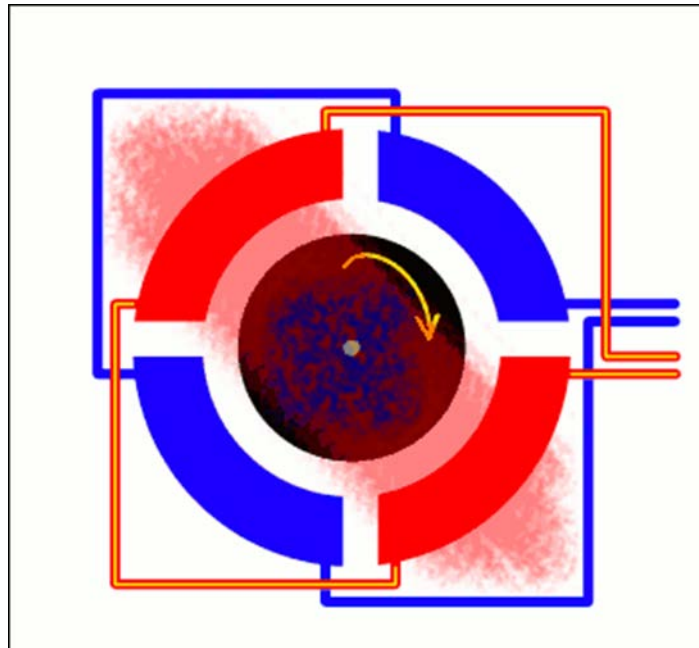


FIGURE 4 - DIAGRAM OF AN AC MOTOR (EXPLAINTHATSTUFF, N.D.)

2.4 Hybrid system configurations

Any vehicle that has two or more power trains is generally defined as a hybrid vehicle; when the vehicle uses an internal combustion engine and an electric system there are three possible configurations for the vehicle to use. The vehicle in this has started as a rear wheel drive and therefore, for simplicity, the vehicle will remain rear wheel drive as this is the most successful in racing and allows steering with the throttle. (Milliken & Milliken, 1995)

2.4.1 Series

A series coupling is the electronic coupling, this configuration uses a generator to convert the mechanical energy from the ICE into electricity in order for the motor generator used to provide the tractive effort this is illustrated in figure 5

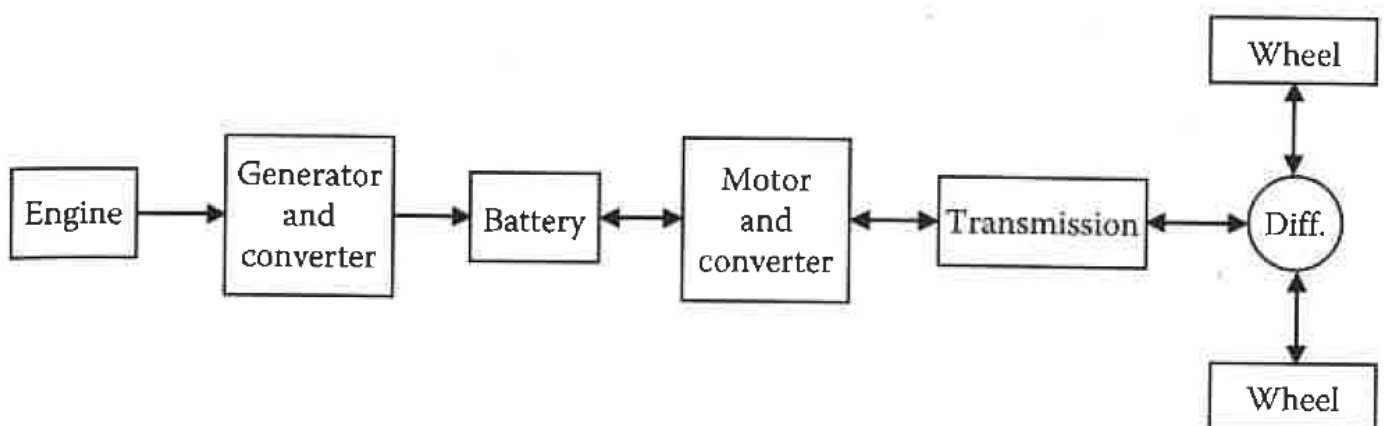


FIGURE 5 - SERIES CONFIGURATION DIAGRAM (HUSAIN, 2011)

The advantages of this configuration are numerous, one of the primary reasons is that since the engine is not mechanically coupled it can be run at whichever RPM is the most efficient to maintain both peak power and fuel efficiency, another benefit may be that a multi-gear transmission may not be necessary due to the use of a motor in this configuration which can be run at multiple RPM and Torque levels

The disadvantages of this system is that the energy from the ICE is required to change form twice, from the kinetic mechanical out into electrical which then has to convert back into kinetic mechanical energy, this will therefore induce losses at each transfer. The overall mass of the system will also increase compared to the other configurations due to the need of a generator and a motor which will be required to be sized accordingly, this could have two motors of differing sizes which would possibly require the use of the separate motor controller. This will also bring an increase of cost and mass into the system due the doubling of the controllers and motors and associated cooling and wiring.

2.4.2 Parallel

In a parallel configuration both the ICE and the electric motor are connected into a mechanical coupling this is then connected to the transmission of the vehicle which is shown in figure 6

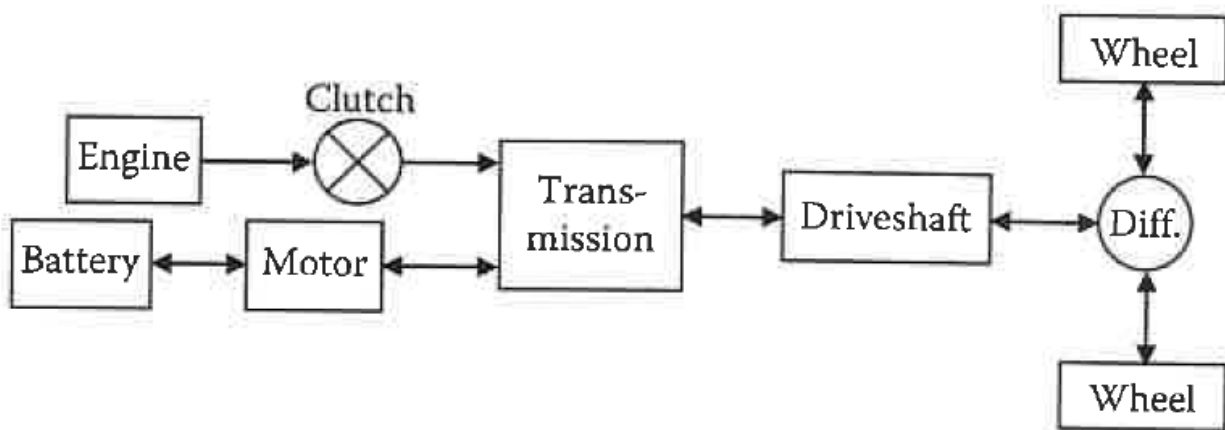


FIGURE 6 - PARALLEL CONFIGURATION DIAGRAM (HUSAIN, 2011)

The advantages to a parallel system are the following; both forms of propulsion systems are providing torque to the transmission therefore the losses will be reduced in comparison to the series configuration, the mass and possibly the cost of the system are also likely to be reduced without the added generator and therefore the traction electric motor will be smaller

The primary disadvantages of the parallel configuration would be the mechanical coupling between the engine and drive train as this cannot be changed, the complexity of the system can be increased due to the interaction between the two propulsion methods.

Another form of Series configuration that could be used is when the motor connects to the crankshaft in the engine and therefore the transmission does not need any modification, however that does require the engine to be modified to accept the motor shaft along with the seals to allow it to connect in place.

2.4.3 Series-Parallel

The series-parallel configuration combines both the previously mentioned series and parallel configurations together, in this configuration the ICE is connected to a coupling which is then connected to both a generator and the vehicles transmission. Shown in figure 7

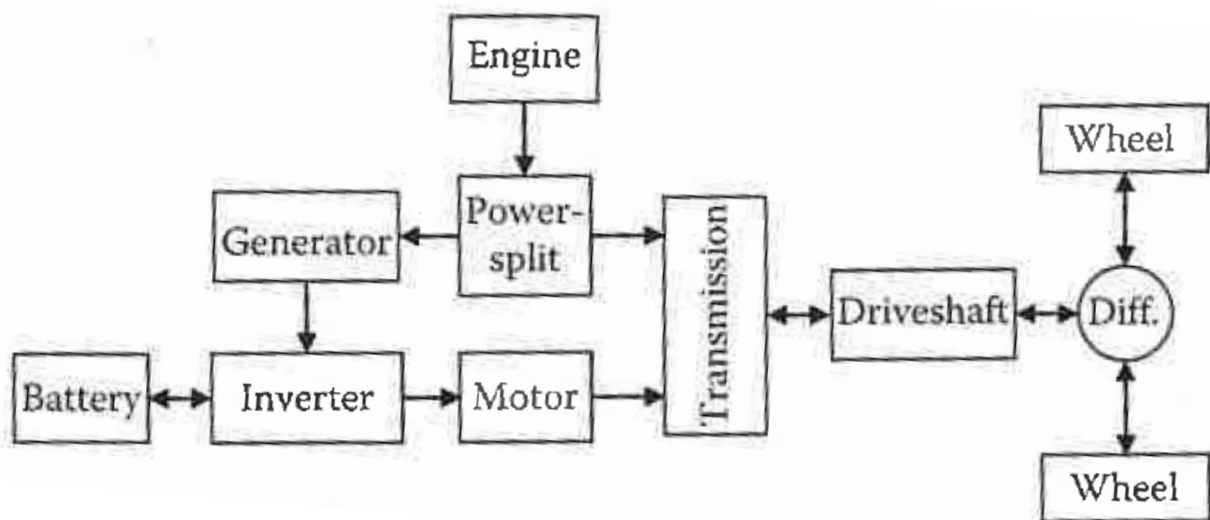


FIGURE 7 - SERIES PARALLEL CONFIGURATION DIAGRAM (HUSAIN, 2011)

The series parallel configuration is the most inefficient of the configurations due to the requirements of the series configuration whilst still remain connected in a parallel method, this method however has the advantage of providing redundancy in case of failure of either of the two propulsion methods.

2.5 Current KERS Applications

A number of motorsport series use KERS to provide a performance boost to their vehicles, most notable at the time of writing is the Formula 1 series which employ a KERS system along with a heat recovery system. (Fédération Internationale de l'Automobile, 2018). The current system provides a 121.1kW boost. This is an increase from their initial introduction of KERS which was in 2009 which provided 60kW for 6.6 seconds.

Other series that have, or are, using KERS are the LMP1 class cars in the World Endurance Championship and Le Mans. In 2016 each of the vehicles in the LMP1 used a hybrid KERS, each vehicle had a varying amount of power that was able to be deployed along with a differing storage pack, this was due to the regulations that stated how much energy each vehicle could use over one lap of Le Mans. The other vehicle mentioned in the table is a Porsche 911 GT3 which was run at the Nürburgring 24 hour endurance race as an experimental entry with a modified system that was used in the Audi R18 LMP1 (Bamsey, 2011). It should also be noted there was another vehicle researched which was the 2016 Nissan Lmp1 vehicle as it had a flywheel system however as the vehicle failed to function properly it would not be wise to include it in the report.

TABLE 1 - KERS COMPARISON TABLE BETWEEN DIFFER MOTORSPORTS VEHICLES (COLLINS, 2011) (RACE ENGINE TECHNOLOGY, 2013) (BORETTI & ARIS, 2015) (HEEPS, 2010) (TMG, 2014) (TOYOTA GAZOO RACING, 2018) (FÉDÉRATION INTERNATIONALE DE L'AUTOMOBILE, 2018)

VEHICLE	STORAGE MEDIUM	STORAGE SIZE	BOOST	MASS
2009 FORMULA 1	Various	400 kJ	60 kW	24kg
AUDI R18 E-TRON QUATTRO (2012-2015)	Flywheel	700 kJ	200 kW	70kg
AUDI R18 E-TRON QUATTRO (2016)	Battery	6 MJ	350 kW	
TOYOTA TS050 (2012-15)	Capacitor	6MJ	350 kW	
TOYOTA TS050 (2016-18)	Battery	8MJ	368 kW	
PORSCHE 911 GT3 (2010)	Flywheel		120 kW	160 kg
2016+ FORMULA 1	Various		121 kW	

It can be seen from the data in table 1 on each of the vehicles the amount of energy stored varies by the vehicle and its available subsequent boost. Vehicle class is not the only factor is the variation of each storage amount and boost. Some of the vehicles are older and in that time frame electric vehicle technology has advanced allowing improvements in both areas.

3 Methodology and Product Research

3.1 Initial calculations

To determine the feasibility of a KERS system, basic hand calculations were conducted; the process of determining the amount of current available was first seen in the journal Race Car Engineering (Nowlan, 2017). Initial data was acquired from analysis video and data from a real-world run by the MCR on both Snetterton and Silverstone. The data analysis was the time spent on various throttle and brake positions, it was separated into full throttle, part throttle and brake. The data presented in table 2 is averaged from number of flying laps.

TABLE 2- TIME SPEND IN VARIOUS PEDAL POSITIONS

	FULL THROTTLE	PART THROTTLE	BRAKE
SILVERSTONE	36	22.4	10.8
INTERNATIONAL			
SNETTERTON 300	67.3	29.06	20.76

From these values it is possible to calculate the Ah that are used during discharge and charging.

$$I = \frac{P}{V} \quad (6)$$

Equation 3 needs to be used twice with the P being changed for both discharge and charge rates.

Equations 4 and 5 are both used assuming there will be a battery cell, further calculations could prove that battery cells are insufficient however these equations are only preliminary equations

$$Ah_{Discharge} = I_d \times \frac{T_{Throttle}}{3600} \quad (7)$$

$$Ah_{Charge} = I_c \times \frac{T_{Brake}}{3600} \quad (8)$$

$$Ah_{total} = Ah_{Discharge} - Ah_{Charge} \quad (9)$$

From these equations the values obtained were calculated in excel and are shown in figure 3.

TABLE 3 - CURRENT CALCULATIONS FROM SNETTERTON

Snetterton 300			
Output Power	400000	Cell Voltage	3.5
Input Power	150000	Cell Capacity	7.7
Voltage	700		
Throttle Time	67.3		
Part Throttle	29.06		
Brake	20.76		
Id	571.4286	Ic	214.2857
Ahd	12.98889	Ahc	1.235714
Aht	11.75317		

TABLE 4 - CURRENT CALCULATIONS FROM SNETTERTON

Silverstone International			
Output Power	400000	Cell Voltage	3.5
Input Power	150000	Cell Capacity	7.7
Voltage	700		
Throttle Time	36		
Part Throttle	22.4		
Brake	10.8		
Id	571.4286	Ic	214.2857
Ahd	7.492063	Ahc	0.642857
Aht	6.849206		

As seen in tables 3 and 4 the currents for both charging and discharging are the same across both circuits due to the components remaining constant, from the data it is seen that Silverstone international does not provide as much of a charge as Snetterton which is due to the layout of the circuit having no large braking zones whereas Snetterton 300 has two large primary braking zones. The better circuit for KERS therefore would be Snetterton 300. The Ahtotal figure refers to the amount of Amp-hours the battery would require to complete the lap fully electrically.

The figures also make sense due to the difference in length between the tracks at 2.979km for Silverstone International (RacingCircuits, n.d.) And 4.779km for Snetterton 300 (RacingCircuits, n.d.)

3.2 Simulation

In order to determine if there was a possible benefit of a KERS on the vehicle a lap simulator was required to be used.

Different options to simulate a vehicle's performance needed to be explored in order to produce accurate and repeatable results; the main options to simulate a vehicle's theoretical performance are using OptimumG, Chassissim and a MATLAB script developed by a formula student team. The MATLAB script was considered, however software versions limitations between the available computers in the university and the simulator file prevented it from being used, Chassissim was also considered but as it requires a unique piece of software it was therefore impracticable to be employed. It therefore became clear that OptimumG was the preferable choice.

OptimumG is a software package which can calculate the theoretical maximum possible performance available from a given vehicle, the software eliminates the variability of a driver by calculating purely from the vehicle's given parameters.

The model in OptimumG is that of a point mass, quasi-steady state model (OptimumG, 2017) which will use Newton's equations of motion for a point moving along a curved path (Boretti & Aris, 2015)

Whilst the code does not account for all factors that could change the lap time and performance of the vehicle such as temperature, camber and gradient of the track (Boretti & Aris, 2015), it is adequate to determine what effect extra mass and power have on the lap time of the vehicle.

To determine the correct amount of boost that would be ideal for the vehicle a series of runs would be conducted where the power output of the vehicle is changed, the data will not be measured in time but in distance in order to allow for comparisons between differing runs at the same point on the circuits.

3.2.1 Software setup

A vehicle profile was required for the simulation to produce results which could be analysed for the desired vehicle so a profile for the MCR vehicle was created with data provided by TeamMCR and from researched data.

The track data was provided on the software's website as a download, the Snetterton 300 circuit was available to be used as it was downloaded however only a model for Silverstone GP was available and therefore it had to be used as best-fit, as the two circuit layouts overlap it is still possible to analyse certain corners and sectors.

VEHICLE SETUP

General Data

Vehicle Type: **Prototype Car**

Mass: **594.000** kg

Driven Type: ☒ 2WD ☐ AWD

Aero Data

☒ Drag-Lift ☐ Efficiency-Lift

Drag Coefficient: **0.800** -

Downforce Coefficient: **0.580** -

Front Area: **1.200** m²

Air Density: **1.220** kg/m³

Tire Data

Tire Radius: **0.277** m

Rolling Resistance: **0.150** -

Longitudinal Friction: **2.200** -

Lateral Friction: **2.200** -

FIGURE 8 - INITIAL SET-UP DATA

Figure 8 displays some of the initial set up settings that were inputted in the software, data such as the mass, aerodynamic coefficients, engine data and tyre size were provided by team MCR whilst the friction of the tyres was the value given by the manual of OptimumLap for slick tyres.

3.2.2 Runs

It is accepted that the software will provide lap times that will be faster than real-world times, this is due to the fact the software uses the equations for perfect conditions and no variation for driver skill or preference.

An initial run was conducted using the vehicle parameters as they are in reality which have been inputted in figure 6, this was used as a baseline to compare against all the system data.

For each subsequent run the power would be increased by a factor of 10kW whilst keeping the mass the same, this is to provide a pure view of the difference increasing power would make.

Once the run with increased boost was conducted the mass of the vehicle was increased to account for the KERS system mass.

After the initial mass sweep was completed another mass sweep was conducted with additional mass to simulate a slightly larger storage system.

The software simulates an entire lap of the desired circuit however; for comparison, only one corner was analysed in order to determine the loss of lap time, due to the increase in mass of the system, and at the end of the Hanger Straight it was possible to determine the extra velocity at the end of the run into the braking zones.

The data will be recorded in the scale of per meter in order to provide a suitable comparison between all runs at the same location on the track. The vehicle enters the back straight which will be used for comparison on Snetterton at 2552m and it lasts for 778m finishing at 3330m where the braking zone for the following corner begins. The corner that will be analysed will be the Wilson hairpin which begins at 650m and ends at 860m for 210m, this corner should illustrate the reduction in corner speed.

For Silverstone points 747m to 920m will be analysed for the straight whilst points 1193m to 1740m will be analysed for the corner difference.

These points will be analysed for each run on the sweep.

During each run one variable would be altered in order to determine the effect of the single change because, as stated by Milliken, "If two changes are made at once it is usually impossible to determine the effects of either." (Milliken & Milliken, 1995).

3.2.2.1 Initial Snetterton sweep

The initial sweep was conducted by only increasing the power output by the vehicle, the steps selected were 10, 20, 30, 40, 50 and 100. These values were chosen due to a ramp up to the continuous torque output of the motor with the 100 being the maximum peak torque that the motor would deliver.

The first run conducted was the base car on the circuit, this produced a lap time of 108.67 seconds which is nearly 10 seconds faster than a real-world race, this can still be used however as a comparison base.

3.2.2.2 Mass increase

The first mass increase was 40kg bring the total vehicle mass to 634kg, 40kg was calculated by the combined mass of the motor, controller, a storage solution and 10kg in order to account for other ancillary components and the for wiring between the components and motor cooling requirements.

3.2.2.3 Extra mass increase

The second mass increase was an additional 60kg from the base mass, this is to account for a possible large energy storage system or a larger motor and controller. This sweep is conducted in order to assess the impact on performance if the system is required to be heavier than 40kg.

3.3 System Sizing

3.3.1 Storage sizing

The size of the ESS was determined by the amount of energy that was available during the braking phase of the vehicle. The values were determined by the simulations in 4.2 and by analysing previous successful KERS systems employed in motorsport.

It was chosen that the storage would be 400kJ or 0.11kWh.

The amount was chosen as a compromise between storing a large amount of energy and the size and mass of the storage system, taking into account losses and other potential factors 400kJ was the best amount to store

3.3.2 Motor sizing

From the initial calculations runs shown in 3.1, it was determined that a power boost of 40kW was the ideal value for the KERS system.

The ideal motor selection therefore was a motor with a peak power output of 40kW, the peak power output of the motor will be sufficient as the motor is not active for long periods, it will therefore have time to cool between uses.

40kW was decided as it is approximately 26.4% of the initial value of the ICE.

3.5 Product Research

As the desired system sizes have been determined from simulation it is possible to research suitable products which would fulfil the necessary requirements, the primary research will be conducted exploring the possible motors and the ESS.

3.5.1 Motor Research

From the sizing requirements shown in 3.3 the motors to be researched are motors that are near the 40kW peak power threshold, this allows the scope of product research to be narrowed down

3.5.1.1 EMRAX

Emrax produce a range of motors that are suitable for EV's along with potentials KERS, the most suitable for a small KERS application would be the EMRAX 188 this is due to it being the smallest motor in their product catalogue.

3.5.2 ESS Research

The technologies that can establish an ESS are laid out in section 2.2; with this research of technology in the previous section it is then necessary to research components that could be used in a practical system. The components researched were products that are available to order at the time of writing and from the evaluation of the available storage methods it was initially narrowed down to battery cells and super capacitors due to their availability on the market.

3.5.2.1 Battery cell

From the initial technology research it was decided that the battery technology to focus on would be lithium based cells due to their increased power density compared to other chemistries, the cells primarily reached were ones developed by A123 Systems due to their proven record in motorsport. The two pouch cells available for use were the AMP14 and AMP20 with both being similar but differing in physical dimensions along with the capacities being different. The AMP-14 was decided to have the best characteristics in order to provide enough current to the motor, it also allows for a fast recharge which will be necessary during regenerative braking.

3.5.2.2 Capacitor Research

From product research it is shown that the Maxwell 3V 3300mF capacitor is the most suitable capacitor available to be used.

TABLE 5 - DECISION TABLE FOR THE CAPACITORS (MAXWELL, N.D.) (IOXUS, 2016)

	Nominal Voltage	Nominal Capacity	Mass	Specific energy	Maximum Voltage	Short Current	
	V	F	kg	Wh/kg	V	A	KW/kg
K2	3	3000	0.52	7.2	3.25	1100	7.7
Ioxus iRB3000K270C1	2.85	3150	0.51	6.3	3	15500	10.1

The chosen capacitor to pursue was the Maxwell K2 capacitor due to its higher voltage, which will reduce the number of capacitors in order to reach the desired voltage.

3.6 Ancillary Components

Whichever the storage solution selected there will also be a motor controller required and this will need to be tailored to each individual motor. As the motor to be employed is selected, the controller selection can be tailored to that specific choice.

If the ESS would be too large to be packaged in the vehicle then a possible DC-DC converter could be used in order to boost the voltage to the input of the motor, the motor selected avoids this issue by using the low voltage motor therefore the primary factor of energy delivery will be the current that the ESS is able to delivery and receive.

As there are a number of manufacturers available a controller decision table was produced.

As the EMRAX 188 was selected the controllers required can be narrowed down to a smaller number, Emrax have a number of recommended controllers which can be used and these are shown in figure 9

Motor type	Recommended controller
EMRAX 188 High Voltage	Unitek; Sevcon;
EMRAX 188 Medium Voltage	Unitek (Bamocar D3 400 V; Sevcon
EMRAX 188 Low Voltage	Sevcon; Emsiso (2x emDrive 200 or 1x emDrive 500)

FIGURE 9 - RECOMMENDED CONTROLLERS FOR THE EMRAX MOTOR (EMRAX, N.D.)

In order to reduce the size of the ESS it had been decided to use the low voltage variant of the motor, due to this decision the Unitek controller must be discounted as they are not recommended.

TABLE 6 - DECISION TABLE OF MOTOR CONTROLLERS (SEVCON, 2017) (UNITEK INDUSTRIE ELEKTRONIK GMBH BAMOCAR D3, 2018) (EMSISO, 2017)

	POWER (KW)	VOLTAGE (V)	MASS (KG)	KW/KG
SEVCON GEN4 HVLP	20	700	7	2.857143
SEVCON GEN4-S8	60	120-400	7	8.571429
SEVCON GEN4-S10	150	50-800	10.9	13.76147
SEVCON GEN5-S7	30	120-400	6.8	4.411765
SEVCON GEN5-S9	60	120-450	6.9	8.695652
UNITEK BAMOBIL D3	10.8	48	4.2	2.571429
UNITEK BAMOCAR D3	150	450	8.5	17.64706
EMSISO EMDRIVE 150	8	60	1.5	5.333333
EMSISO EMDRIVE 500	60	120	5.2	11.53846
EMSISO EMDRIVE H300	120	400	7.7	15.58442

Other ancillary components that would be required is a battery monitoring system if battery cells are employed in the system. This component monitors the battery and does not allow it to either under-charge or over-charge which is important for the life span of the cells along with its overall safety.

4 Simulation Results and Analysis

4.1 Power output

From the various spread of simulation runs it was determined that a 40kW deployment system would be ideal to provide an accepted amount of boost. The storage was calculated to be 400 kJ, this number was selected to allow for full capture of the available kinetic energy at the biggest stopping point and this size also allows a reasonable amount of time for deployments. A 40kW 400kJ system was previously employed in Formula 1 in 2009 as shown in 2.5 and it is therefore capable of being achieved using current components. The compromise with mass was also taken into account while selecting the size of the storage system.

4.2 OptimumG Simulation results

From the simulations conducted on OptimumG it can be seen that, as the boost increases, the maximum velocity of the vehicle increases correspondingly, however the velocity mid-corner does decrease in certain corners on the circuits.

The entire lap was simulated with the additional power boost compared to the base line due to software limitations, however, by looking at sectors individually, it is possible to see the effect the boost would have on the vehicle. Unfortunately the mass penalty would be present across the entire lap therefore the lower corners speed are to be expected.

When analysing the mass-sweeps consistent distance-marker points are used, the distance points allow only the improvement in that sector to be shown rather than the entire lap.

4.2.1 Snetterton Initial boost sweep

TABLE 7 - LAP TIME AND CORNER DATA FROM THE INITIAL BOOST SWEEP

Amount of Boost	Mass kg	Lap Time s	% Improvement	Max Velocity m/s	% Improvement	Straight				Wilson			
						Entry Time s	Exit Time s	Sector Δ s	% Improvement	Entry Time s	Exit Time s	Sector Δ s	% Improvement
0	594	108.66	0	185.86	0	60.69	76.51	15.82	0	13.82	19.47	5.65	0
10	594	107.31	1.24240751	189.11	1.748628	60.02	75.42	15.4	2.654867257	13.53	19.17	5.64	0.17699115
20	594	106.07	2.383581815	192.75	3.707091359	59.43	74.57	15.14	4.298356511	13.28	18.91	5.63	0.353982301
30	594	104.95	3.414319897	195.75	5.321209513	58.89	73.81	14.92	5.689001264	13.06	18.68	5.62	0.530973451
40	594	103.93	4.353027793	198.72	6.919186484	58.39	73.11	14.72	6.953223767	12.85	18.47	5.62	0.530973451
50	594	102.53	5.641450396	203.05	9.248897019	57.69	72.1	14.41	8.912768647	12.52	18.13	5.61	0.707964602
100	594	98.91	8.972943125	218.86	17.75529969	55.99	69.61	13.62	13.90644753	11.88	17.47	5.59	1.061946903

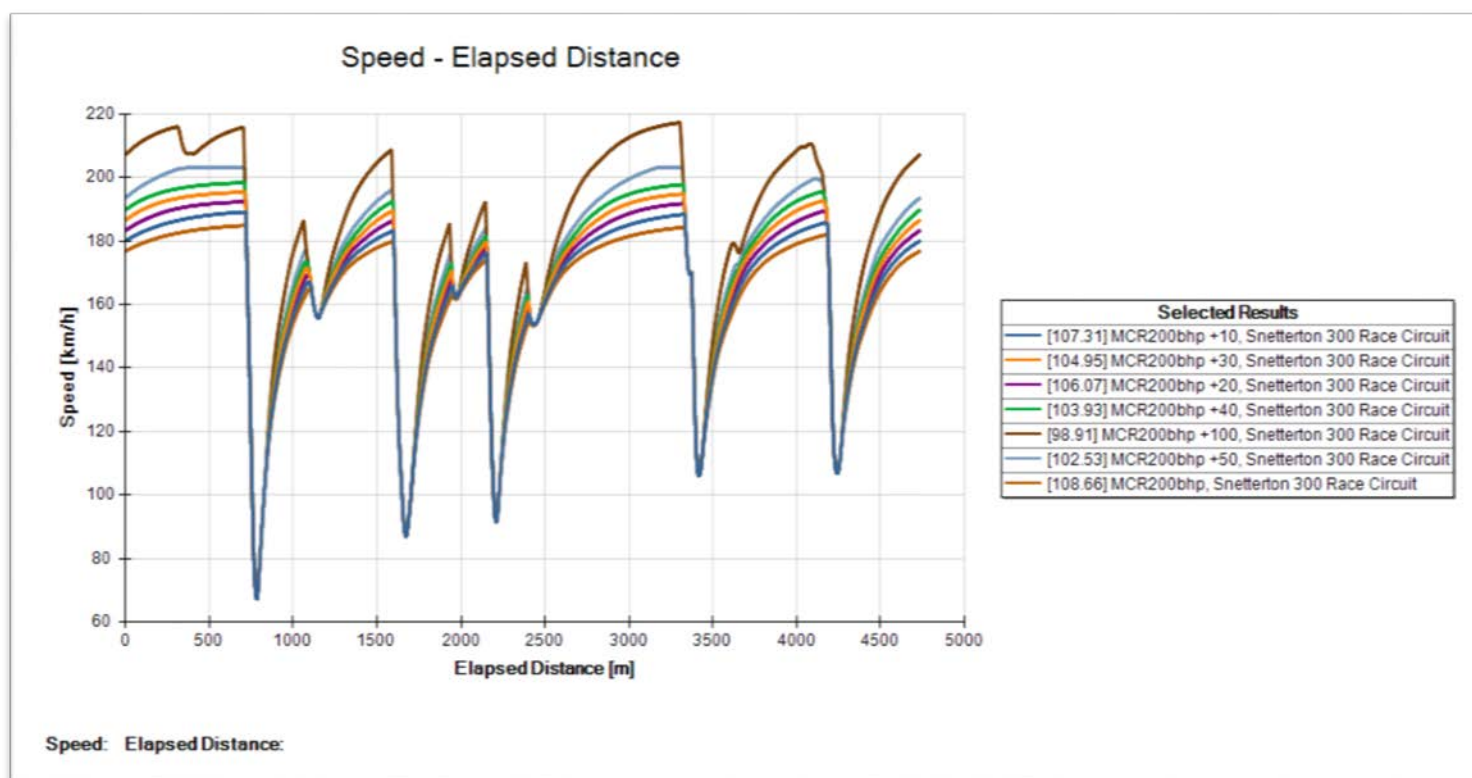


FIGURE 10 - GRAPH DISPLAYING VELOCITY WITH INITIAL BOOST ADDITION

4.2.2 Snetterton 40kg increased mass sweep

TABLE 8 - LAP TIME AND CORNER DATA WITH 40KG EXTRA MASS

Amount of Boost	Mass	Lap Time	% Improvement	Max Velocity	% Improvement	Straight				Wilson			
						Entry Time	Exit Time	Sector Δ	% Improvement	Entry Time	Exit Time	Sector Δ	% Improvement
	kg	s		m/s		s	s	s		s	s	s	
0	634	109.86	0	183.61	0	61.32	77.16	15.84	0	14	19.68	5.68	0
10	634	108.47	1.265246678	188.05	2.418168945	60.62	73.2	12.58	20.58080808	13.72	19.37	5.65	0.528169014
20	634	106.29	3.249590388	191.23	4.150100757	59.33	74.58	15.25	3.724747475	13.43	18.9	5.47	3.697183099
30	634	106.02	3.495357728	194.24	5.789445019	59.43	74.52	15.09	4.734848485	13.2	18.84	5.64	0.704225352
40	634	104.95	4.469324595	197.22	7.412450302	58.91	73.79	14.88	6.060606061	12.99	18.62	5.63	0.88028169
50	634	103.53	5.761878755	203.05	10.58765862	58.19	72.76	14.57	8.017676768	12.64	18.26	5.62	1.056338028
100	634	99.75	9.202621518	217.53	18.47393933	56.41	70.17	13.76	13.13131313	11.99	17.59	5.6	1.408450704

4.2.3 Snetterton 60kg mass increase sweep

TABLE 9 - LAP TIME AND CORNER DATA FOR 60KG MASS INCREASE

Amount of Boost	Mass	Lap Time	% Improvement	Max Velocity	% Improvement	Straight				Wilson			
						Entry Time	Exit Time	Sector Δ	% Improvement	Entry Time	Exit Time	Sector Δ	% Improvement
	kg	s		m/s		s	s	s		s	s	s	
0	654	110.48	0	183.43	0	61.59	77.58	15.99	0	14.1	19.77	5.67	0
10	654	109.05	1.294351919	186.94	1.913536499	60.92	76.59	15.67	2.001250782	13.81	19.47	5.66	0.176366843
20	654	106.88	3.258508327	190.48	3.843428011	59.64	74.99	15.35	4.002501563	13.52	19.01	5.49	3.174603175
30	654	106.55	3.557204924	193.49	5.484380963	59.7	74.87	15.17	5.128205128	13.28	18.92	5.64	0.529100529
40	654	105.47	4.534757422	196.48	7.114430573	59.17	74.13	14.96	6.441525954	13.06	18.7	5.64	0.529100529
50	654	104.3	5.593772629	203.05	10.69617838	58.45	73.11	14.66	8.317698562	12.72	18.34	5.62	0.881834215
100	654	100.7	8.852280956	216.86	18.22493594	56.62	70.45	13.83	13.50844278	12.04	17.65	5.61	1.058201058

As can be seen between tables 8 and 9 the lap times increase with an extra 20kg from the 40kg run, however it is seen that the time spent navigating the Wilson Hairpin is consistent in each sweep along with each mass change, this is due to the corner being slow and therefore the extra mass does not affect the vehicle too much.

The baseline vehicle was run with the additional mass but without no boost to simulate and display what would happen to the vehicles performance once the system cannot provide any more boost and only the stock ICE is able to be used. It is seen from the tables that the addition of 40 (40 what?) results in a 1.2 second slower lap time, subsequently adding the maximum mass of 60kg results in a lap time that is 1.82 seconds slower than base, these times are without intervention of the KERS in any way.

However whilst looking at the sectors only it is seen that the Wilsons hairpin delta time does not change much between each sweep and remains within 1% except for the 10 boost in tables 8 and 9 with outliers at 3% delta this could be due to software set up issues or possibly data extraction errors.

4.2.4 Snetterton Mass comparisons

Graphs were produced for a lap of Snetterton displaying the difference in lap times between each of the mass configurations. Each graph contains the base run for the vehicle, the vehicle with added boost, added boost with an additional 40kg with is denoted by M at the end of the vehicle name, and the boost with 60kg added to base mass denoted by N at the end of the vehicle name.

4.2.3 10N/m boost comparison

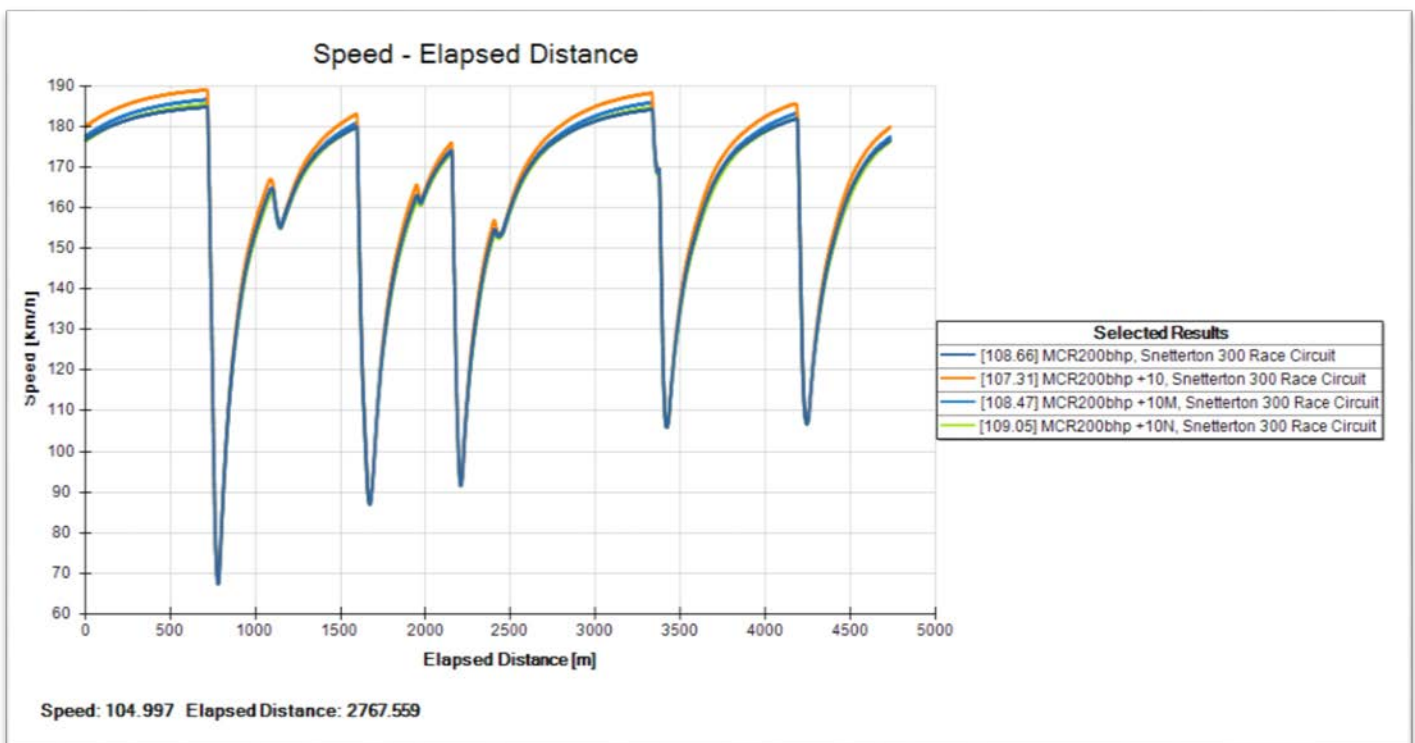


FIGURE 11 - 10 BOOST WITH VARIOUS MASSES AT SNETTERTON

4.2.4 20 N/m boost comparison

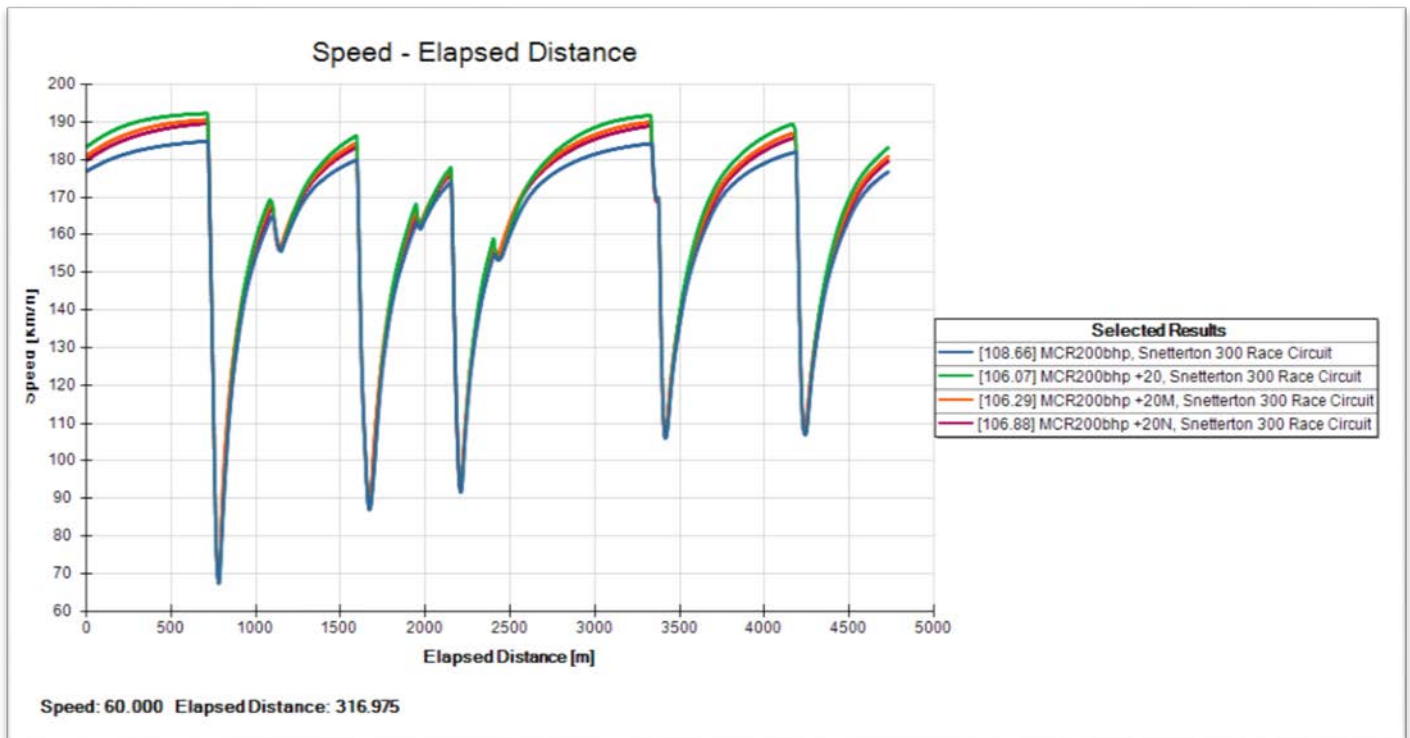


FIGURE 12 - 20 BOOST WITH VARIOUS BOOST AT SNETTERTON

4.2.5 30 N/m boost

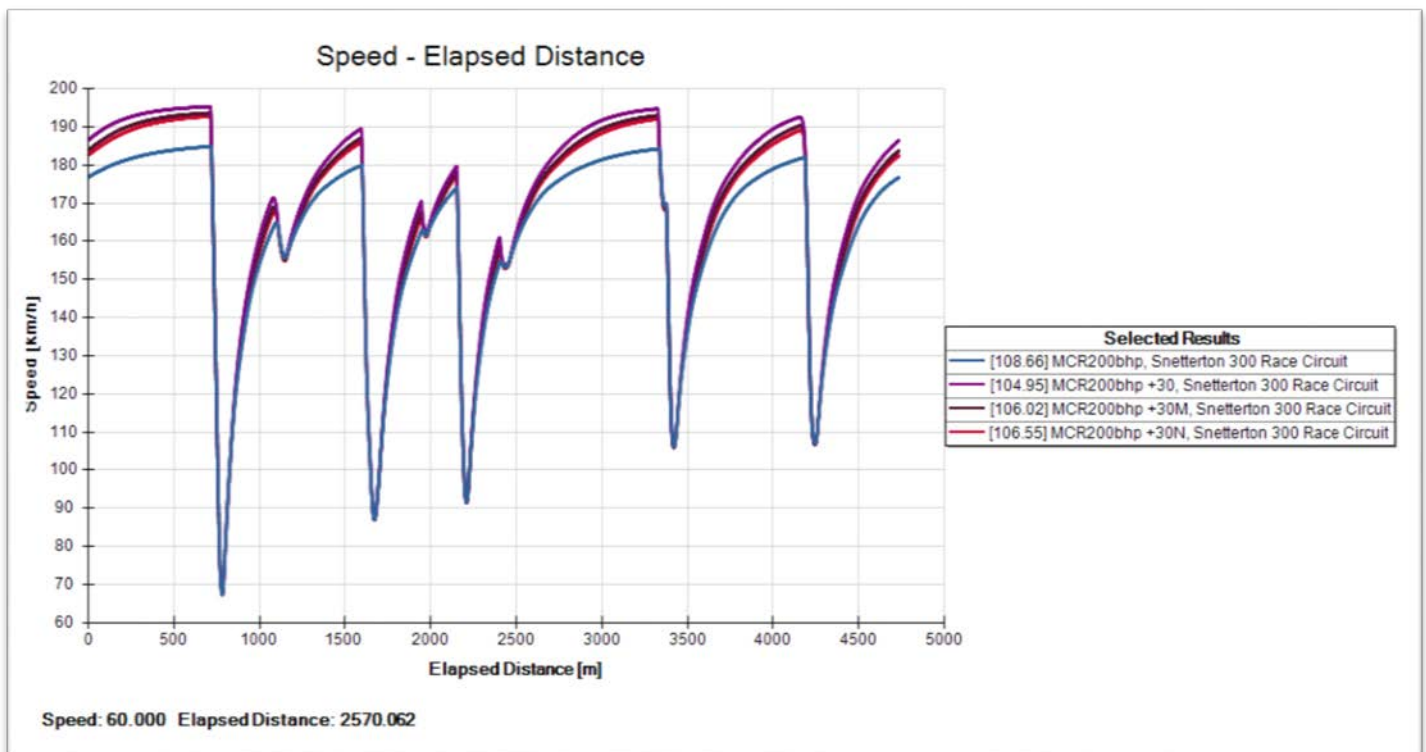


FIGURE 13 - 30 BOOST WITH VARIOUS MASSES AT SNETTERTON

4.2.6 40 N/m boost

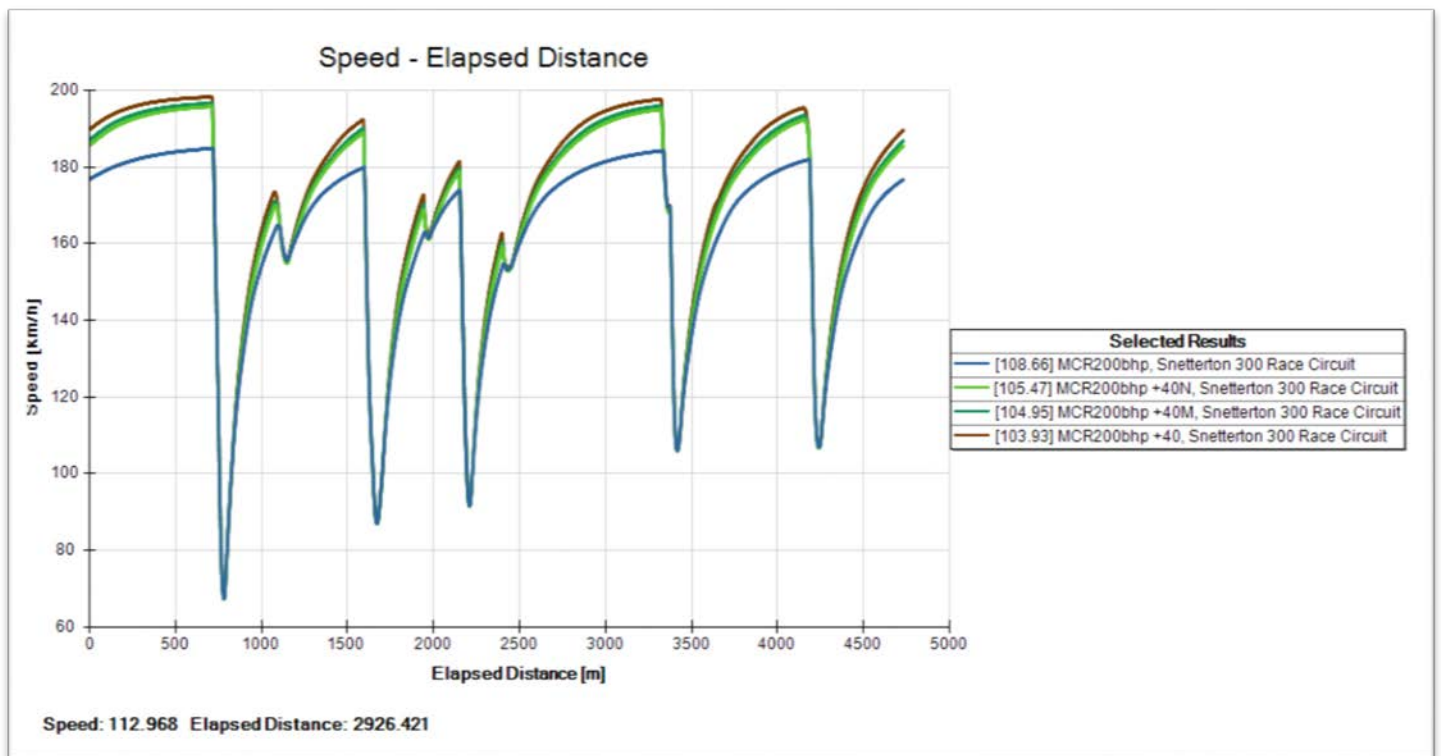


FIGURE 14 - 40 BOOST WITH VARIOUS MASSES AT SNETTERTON

4.2.7 50 N/m boost

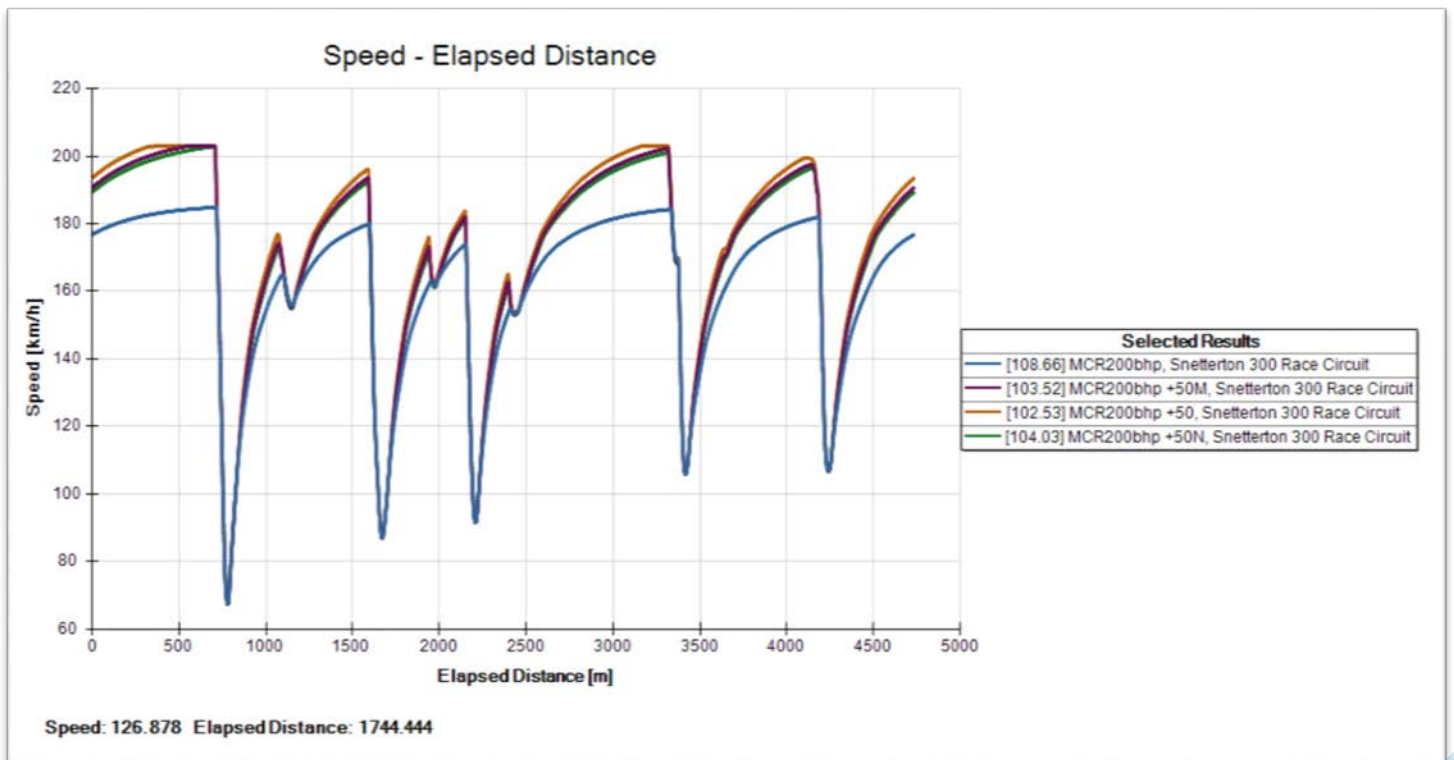


FIGURE 15 - 50 BOOST WITH VARIOUS MASSES AT SNETTERTON

4.2.8 100 N/m boost

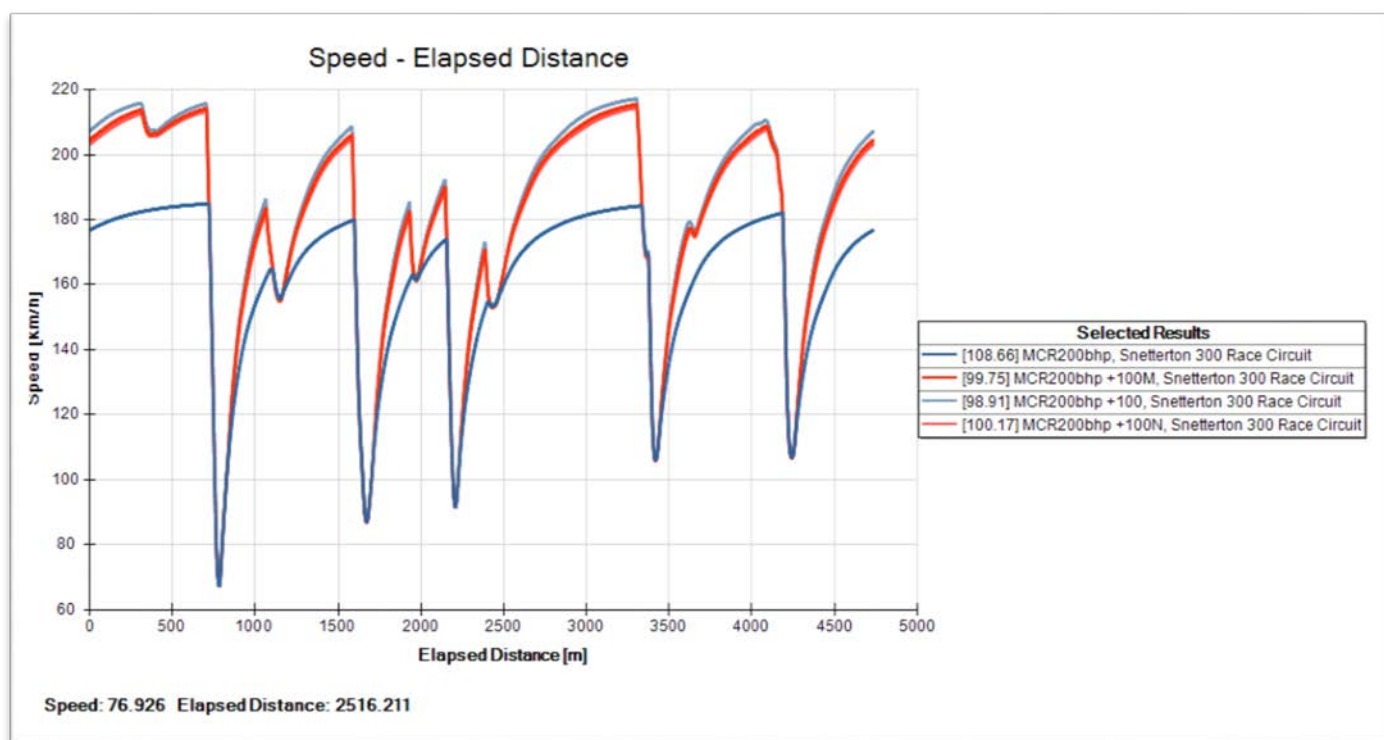


FIGURE 16 - 100 BOOST WITH VARIOUS MASSES AT SNETTERTON

4.2.5 Silverstone Initial boost

For all the sweeps run on Silverstone on OptimumG the full GP circuit was used, this was due to the fact the software had no capability of simulation Silverstone International, the areas selected however (the Hanger Straight and Village Corner) for analysis are present on both configurations of the circuit.

TABLE 10 - DATA FROM THE BOOST INCREASE SWEEP

Amount of Boost	Mass	Lap Time	% Improvement	Max Velocity	% Improvement	Straight				Village			
						Entry Time	Exit Time	Sector Δ	% Improvement	Entry Time	Exit Time	Sector Δ	% Improvement
	kg	s		m/s		s	s	s		s	s	s	
0	594	125.74	0	185.85	0	27.91	39.02	11.11	0	15.3	21.09	5.79	0
10	594	123.97	1.407666614	189.73	2.087705139	27.52	38.43	10.91	1.800180018	15.03	20.81	5.78	0.172711572
20	594	122.42	2.640369015	192.75	3.712671509	27.18	37.89	10.71	3.600360036	14.79	20.56	5.77	0.345423143
30	594	121.02	3.753777636	195.74	5.32149583	26.88	37.41	10.53	5.220522052	14.57	20.34	5.77	0.345423143
40	594	119.73	4.779704151	198.72	6.924939467	26.6	36.96	10.36	6.750675068	14.28	20.14	5.86	-1.208981002
50	594	117.84	6.28280579	203.05	9.254775356	26.18	36.12	9.94	10.53105311	14.07	19.82	5.75	0.690846287
100	594	112.74	10.33879434	218.853	17.75786925	25.09	34.6	9.51	14.40144014	13.3	19.04	5.74	0.863557858

4.2.6 Silverstone 40kg increase

TABLE 11 - DATA FROM THE 40KG INCREASE SWEEP

Amount of Boost	Mass	Lap Time	% Improvement	Max Velocity	% Improvement	Straight				Village			
						Entry Time	Exit Time	Sector Δ	% Improvement	Entry Time	Exit Time	Sector Δ	% Improvement
	kg	s		m/s		s	s	s		s	s	s	
0	634	127.11	0	183.61	0	28.22	39.49	11.27	0	15.48	21.3	5.82	0
10	634	125.3	1.423963496	188.05	2.418168945	27.83	38.89	11.06	1.863354037	15.21	21.01	5.8	0.343642612
20	634	123.66	2.714184565	191.23	4.150100757	27.47	38.33	10.86	3.63797693	14.95	20.74	5.79	0.515463918
30	634	122.2	3.862796003	194.24	5.789445019	27.15	37.82	10.67	5.323868678	14.72	20.51	5.79	0.515463918
40	634	120.86	4.917001023	197.22	7.412450302	26.85	37.36	10.51	6.743566992	14.52	20.3	5.78	0.687285223
50	634	118.85	6.498308552	203.05	10.58765862	26.42	36.71	10.29	8.695652174	14.2	19.97	5.77	0.859106529
100	634	113.5	10.70726143	217.01	18.19073035	26.08	36.18	10.1	10.38154392	14.08	19.72	5.64	3.092783505

4.2.7 Silverstone 60kg increase

TABLE 12 - DATA FROM THE 60KG INCREASE SWEEP

Amount of Boost	Mass	Lap Time	% Improvement	Max Velocity	% Improvement	Straight				Village			
						Entry Time	Exit Time	Sector Δ	% Improvement	Entry Time	Exit Time	Sector Δ	% Improvement
	kg	s		m/s		s	s	s		s	s	s	
0	655	127.9	0	182.8	0	28.1	39.8	11.7	0	15.7	21.6	5.9	0
10	655	125.99	1.493354183	186.89	2.237417943	27.99	39.14	11.15	4.700854701	15.3	21.12	5.82	1.355932203
20	655	124.31	2.806880375	190.43	4.173960613	27.63	38.57	10.94	6.495726496	15.08	20.84	5.76	2.372881356
30	655	122.82	3.97185301	193.45	5.826039387	27.27	38.05	10.78	7.863247863	14.81	20.6	5.79	1.86440678
40	655	121.46	5.035183737	196.44	7.461706783	26.99	37.57	10.58	9.572649573	14.6	20.38	5.78	2.033898305
50	655	119.44	6.614542611	203.05	11.07768053	26.57	36.93	10.36	11.45299145	14.29	20.07	5.78	2.033898305
100	655	114.22	10.69585614	216.83	18.61597374	25.42	35.11	9.69	17.17948718	13.49	19.25	5.76	2.372881356

4.2.8 Silverstone Mass comparisons

The same sweeps that were conducted were done on the Silverstone GP track as well. Similarly each graph contains the base run for the vehicle, the vehicle with added boost, added boost with an additional 40kg with is denoted by M at the end of the vehicle name, and the boost with 60kg added to base mass denoted by N at the end of the vehicle name.

4.2.8.1 10 n/m boost

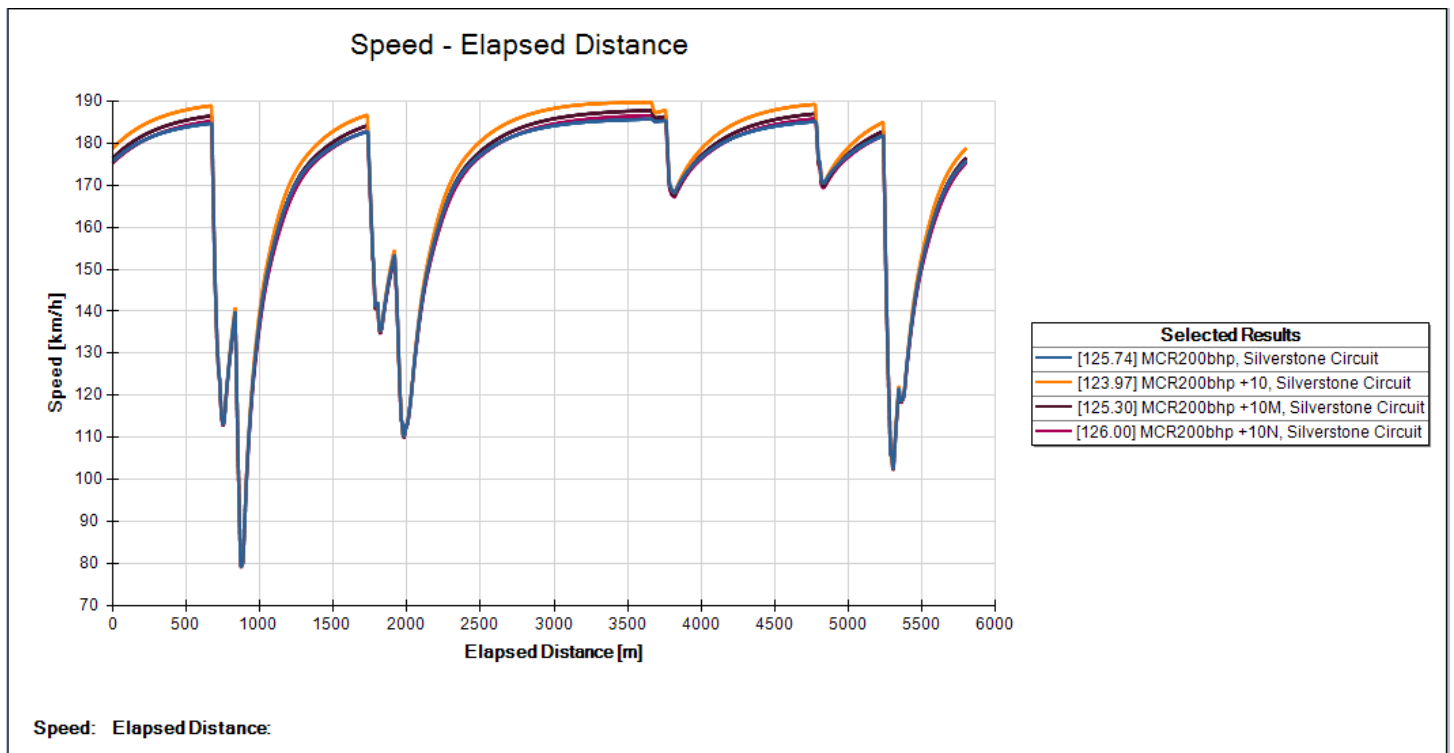


FIGURE 17 - 10 BOOST WITH VARIOUS MASSES AT SILVERSTONE

4.2.8.2 20 n/m boost

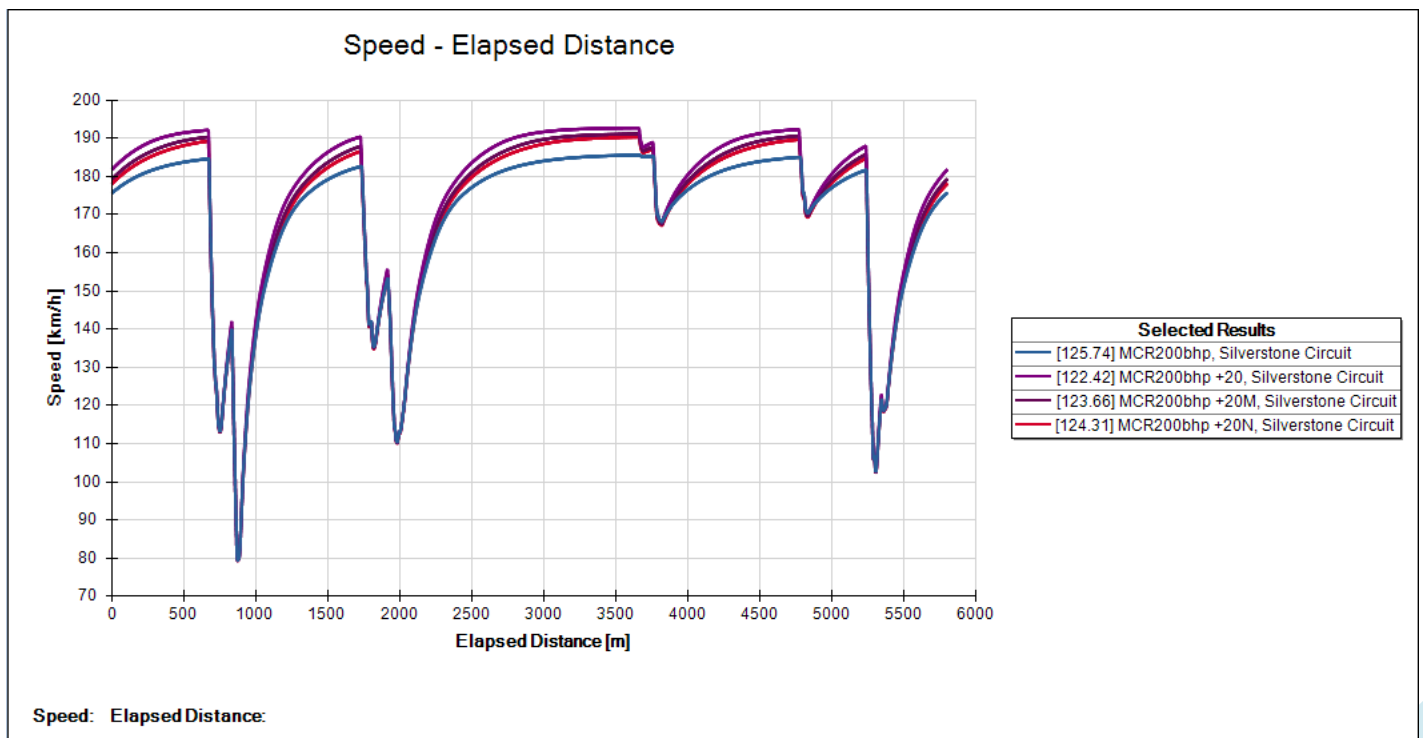


FIGURE 18 - 20 BOOST WITH VARIOUS MASSES AT SILVERSTONE

4.2.8.3 30 n/m boost



FIGURE 19 - 30 BOOST WITH VARIOUS MASSES AT SILVERSTONE

4.2.8.4 40 n/m boost

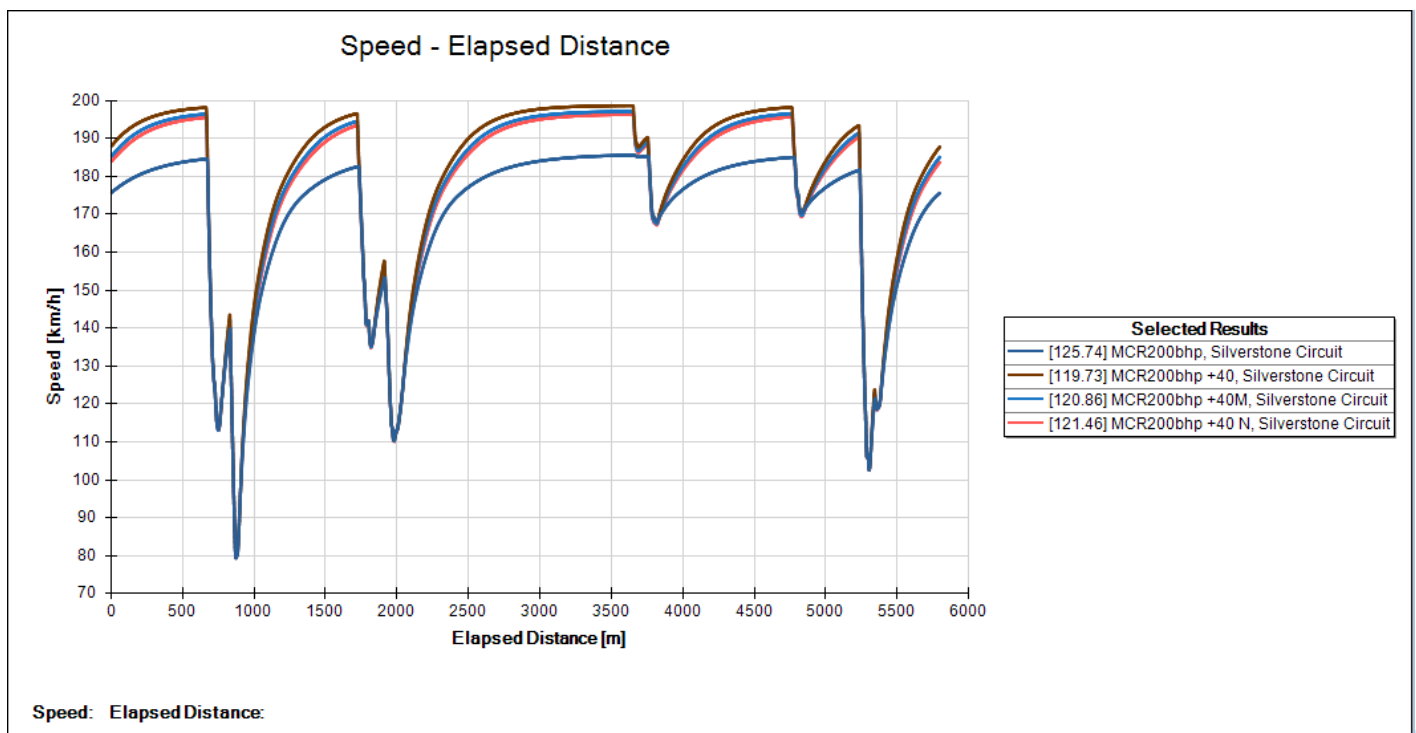
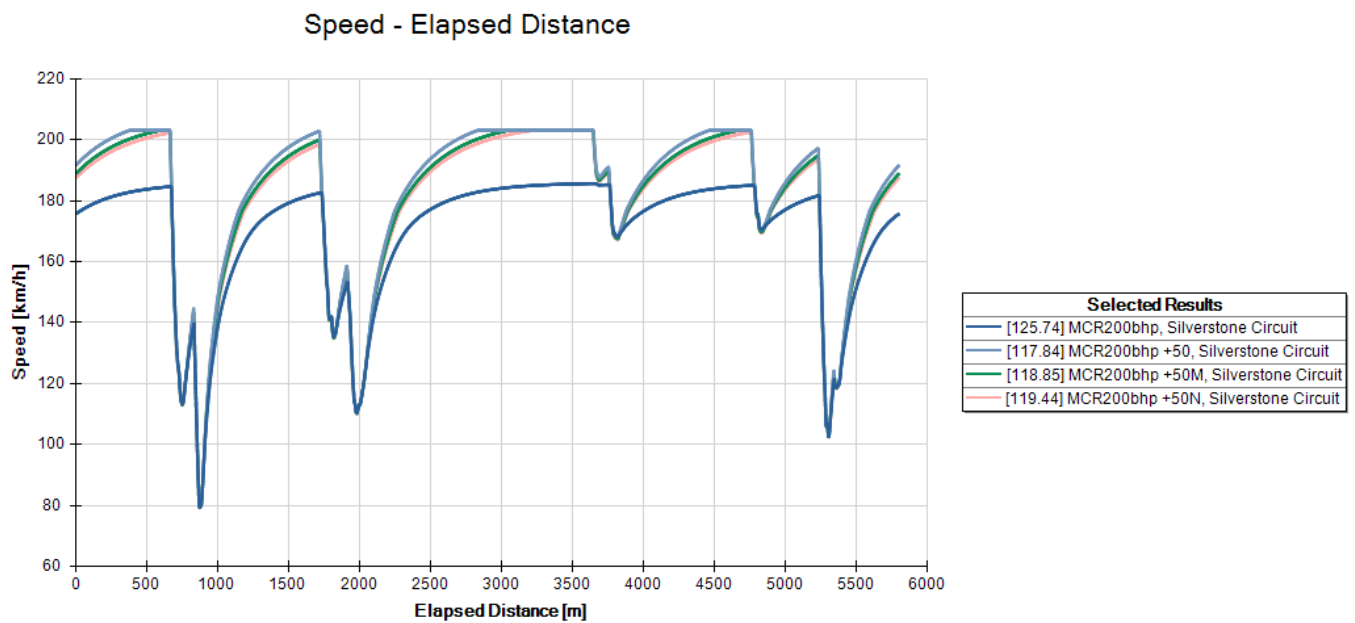


FIGURE 20 - 40 BOOST WITH VARIOUS MASSES AT SILVERSTONE

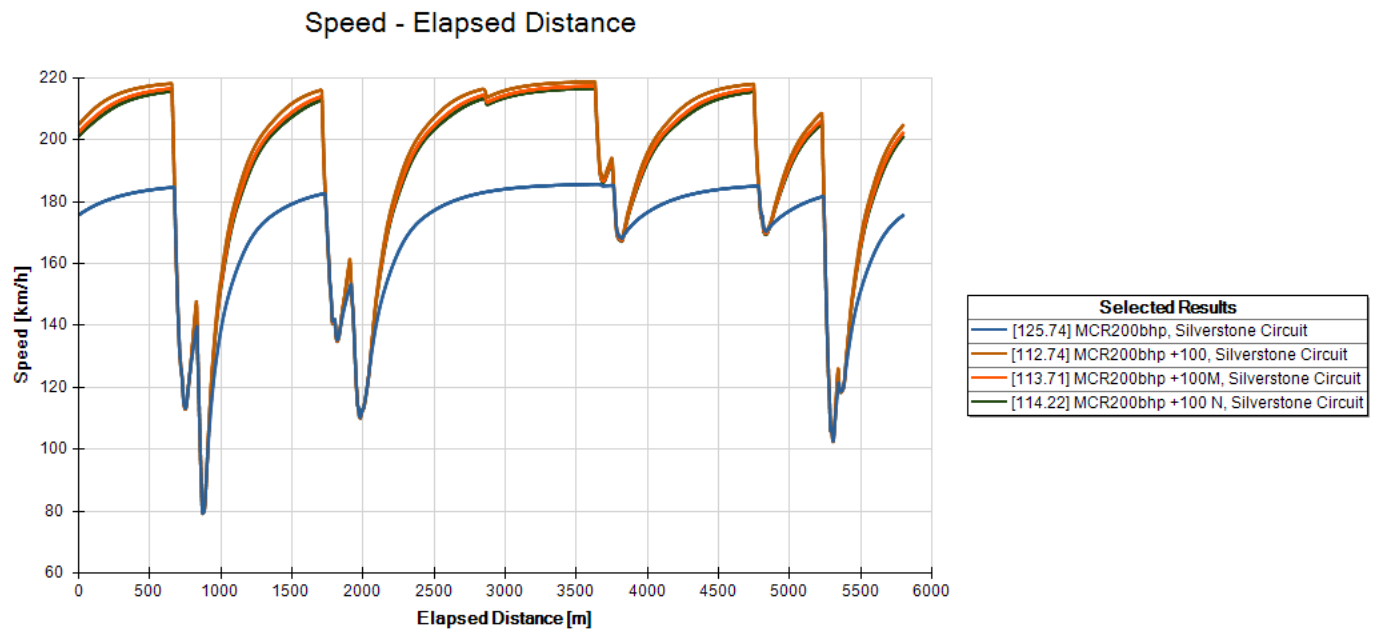
4.2.8.5 50 n/m boost



Speed: Elapsed Distance:

FIGURE 21 - 50 BOOST WITH VARIOUS MASSES AT SILVERSTONE

4.2.5.6 100 n/m boost



Speed: Elapsed Distance:

FIGURE 22 - 100 BOOST AT VARIOUS MASSES AT SILVERSTONE

From all the sweeps it is clear that the higher the boost the better the lap time gain compared to the base line, however the graphs do not show if at any point what would happen if the system runs out of boost and only has baseline power.

As was to be expected the sweeps with the increased mass had a higher lap time then those without the additional mass but had the boost. It is seen that both the additional 40kg sweep and the additional 60kg produced close times to each other along with being only slightly away from each other on the lap velocities. Therefore from the graphs illustrated that a large storage system can be accommodated without effecting the vehicles performance too much. As the sweeps were conducted independently from the mass and boost it is clear the patter follows for every run.

It is seen in the mass sweep in tables 10,11 and 12 that the biggest improvement in lap times were achieved on the straights with the increased maximum velocity with a potential gain of 8%, it is also seen that the viillag3e corner does not lose much lap time, this is due to it being a slow corner, however the differences between each delta varies with each run with a major outlier at 100 boost at 40kg in table 11, this could be an issue with the software set up or the run calculation and should be repeated.

4.3 Energy storage calculations

All the calculations are based on storing 400kJ of energy, with the addition of specifics for each technology some calculations require Wh hours to determine this value, and the conversion is:

$$1J = 2.7778 \times 10^{-7} kWh$$

Using this conversion it was determined that 400kJ is 0.111kWh which converts to 111.11Wh.

4.3.1 Pure battery

In order to achieve the desired voltage for battery cells they must be added in series in order to achieve it, while the capacity of the cell is enhanced by adding an equal pack in parallel to itself.

$$\frac{\text{Desired Voltage}}{\text{Cell voltage}} = \text{Number of cells} \quad (10)$$

TABLE 13 - A123 SYSTEM CELL DATA (A123 SYSTEMS, 2013) (A123 SYSTEMS, 2011)

	Capacity	Voltage	Mass	Discharge current	Charge Current	Wh	W/kg
	Ah	V	kg	A	A		
AMP-20	20	3.3	0.496	600	200	65	2400
AMP-14	14	3.3	0.51	500	100		2700

The costs of the AMP20 and AMP14 are \$75 (buyA123Batteries, n.d.) And \$66 (buyA123batteries, n.d.) respectively.

From the data in table 13 and using equation 10 in order to achieve the voltage level desired 31 cells would be needed in either cell variant due to both having nominal voltage of 3.3V

However in order to achieve the desired Wh another row will needed to be added in parallel which will take the number of cells up to 62 cells, the mass of the pack will therefore be 30.75kg.

4.3.2 Pure capacitor

Bu using equation 2 with the values of 400kJ and 100V the capacitance of the cell must be 80 Farads.

This is confirmed by using equation 11 also.

$$F = \frac{A \times s}{V} \quad (11)$$

Where A is the amps, s is time in seconds and V is the voltage

This produced a result of 80 Farads by using the motor specifications of 800 amps at 100V for a deployment time of 10 seconds.

A Maxwell capacitor costs £41 (Digi-Key, 2018)

TABLE 14 - DATA OF THE MAXWELL CAPACITOR (MAXWELL, N.D.)

Voltage	3 V
Capacitance	3000 F
Stored Energy	3.75 Wh
Mass	0.52 kg
Maximum Current	1100 A

To achieve the desired voltage using the capacitors they must be connected in series to increase the voltage, therefore 34 will need to be used to achieve 100V, connecting in series has the effect of reducing the capacitance of the collection of capacitors the reduction is shown in equation 12, which is recurring for each of the capacitors in the chain.

$$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \dots + \frac{1}{C_{n-1}} + \frac{1}{C_n} \quad (12)$$

(Sparkfun, n.d.)

Using equation 12 for 34 capacitors, with each one having a capacitance of 3000F, using them in series reduces the overall capacitance to 88.24F.

With each capacitor's mass at 520g this brings the total pack mass to 17.68kg.

4.3.3 Pure flywheel

As there is no commercial flywheel system that would be suitable for this system then the flywheel will be discounted for the recommended system specification.

To design a flywheel system would require a large number of variables as shown by the number of inputs into the moment of inertia equation which is displayed in appendix B, this could change and effect the efficiency of the system and therefore it's not worth designing a flywheel when other technologies are suitable.

4.3.4 Battery and Capacitor hybrid

From the calculations above it is not necessary to use a hybrid system if the desire is to deploy the boost a short time after it has been captured, if it was however necessary to be stored for use at a later time as a battery would be able to store it for longer than a capacitor.

A 50/50 split of battery cell and capacitor would have a mass of 24.21kg.

5 System specifications

The proposed system would be connected into the vehicle in a series configuration, this is due to the fact that the existing vehicle architecture will remain in place and will be required to carry out much of the propulsion of the vehicle, also by adding minimal components the mass cost should be reduced.

The proposed system from the research and simulation conducted provides a system that is composed of the following components

Emrax 188 motor: This is an efficient and powerful motor with a peak power sufficient for KERS use with the added capacity in order to increase the power output.

Emsiso em500 controller: This is a suitable controller for the EMRAX motor and the lightest out of the recommended motors that can be used.

As the storage solution is a pack of capacitors a battery monitoring system is not necessary.

5.1 Energy storage system specifications

Either pure capacitor or the hybrid can be used for this vehicle, the lighter pure capacitor should be used as the mass of the vehicle itself is low, therefore the less that is added will be preferred.

From analysis the calendar at which the vehicle races also displays there is little benefit in storing the energy to deploy at a further point.

The motor will be arranged in a hybrid configuration with the ICE as the KERS is only designed to be an extra boost not the primary source of propulsion for the vehicle.

The final system therefore will have a working power of 40kW, with the possibility of running a higher power of 70 kW with a modified storage solution. The controller will not need to be modified as it has the capability to also run higher.

5.2 Storage Selection

For the ESS final solution it was decided that a pack of Maxwell K2 3000F capacitors would be used, these were chosen due to their ability to recover the majority of the energy that is available in braking and then the capability to deploy it as quickly as the motor requires.

5.3 Motor Selection

Research has shown a variety of motors available on the market. Due to the variety of available choice all the possible motors available were inputted into a decision table, this allowed a comparison between all the motors whilst also displaying their vital characteristics such as peak power and mass. The key values that were explored were the peak power, peak torque and the mass of the motor, from these values it is possible to calculate the Kilowatt per Kilogram and the Newton-meter per Kilogram of each of the motors.

To compare these values a decision table was produced which is shown in figure 15 which is also shown in full detail in appendix C which includes other parameters such as voltage and continuous power and torque.

TABLE 15 - MOTOR DECISION TABLE (EMRAX, N.D.) (ZYTEK AUTOMOTIVE, N.D.) (LYNCH MOTORS, N.D.) (ASHWOODS ELECTRIC MOTORS, N.D.) (PARKER, N.D.) (YASSA MOTORS, 2017)

Motor	Peak Power (kW)	Peak Torque (Nm)	Average mass (kg)	Peak kW/kg	Peak Nm/kg
Emrax 108	70	100	6.9	10.14492754	14.49275362
Emrax 208	80	180	9.2	8.695652174	19.56521739
Emrax 288	100	240	12.15	8.230452675	19.75308642
Zytek ERS	50	40	8.5	5.882352941	4.705882353
Zytek 25kW	25	64	12.8	1.953125	5
Zytek IDT 120-55	55	120	62	0.887096774	1.935483871
Lynch LEM-200	12		11	1.090909091	0
Ashwoods IPM-200-66	32		17	1.882352941	0
Parker GVM210-050-CR	36.7	82	36.5	1.005479452	2.246575342
Yassa-750	200	790	33	6.060606061	23.93939394

From the data observed in the comparison table it was decided that the motor selected to create the KERS would be an Emrax 188; as can be seen in table 15 the 188 motor was the lightest, with a high power density, and its peak power is also the optimum choice for this application. The Yassa-750 however has the highest nm/kg however it is oversized for the application of KERS on the MCR.

The Emrax 188 has 70kW of peak power which will be sufficient for the requirements of the KERS system, also important for a lower powered system is the motors mass which from the comparison table was shown to be the lowest of the researched motors.

5.4 Ancillary Component Selection

As illustrated by table 15 the Unitek Bamocar D3 provides the best kW/kg however that controller is not recommended by EMRAX for the low voltage motor. Whilst the Sevcon controllers provide a higher kW/kg than the Emsiso the overall mass of the Emsiso is lower and therefore more suitable for a lower powered KERS application. (Emsiso, 2017)

Such systems such as the Emsiso BMS05 are available on the commercial market. However they add an additional mass of the component itself along with more wiring in order to connect to each cell. The Emsiso BMS05 has a mass of 0.54kg and can monitor 24 cells (Emsiso, 2017) therefore if more than 24 are required then additional units are required.

6 Potential costs

The EMRAX motor is priced at 2,740€ (EMRAX, 2018)

Each Maxwell capacitor costs £41 therefore the total for 34 cells will be £1401.48

There is no public cost for the Emsiso EmDrive 500 however it has been researched that the Unitek Bamocar D3 costs €3000 (Unitek, 2018) therefore it is expected that the Emsiso would be around a similar cost.

Additional costs would be incurred by the process of installation with all the wiring that is needed to connect the components together, costs will also be incurred whilst connecting the motor to either the vehicles transmission or through the engine into the crankshaft, another source of additional cost would be programming the controller to work in the correct configuration the cost could be reduced by doing the work in-house however that would be at the expense of the extra time involved.

Therefore is estimated that adding a KERS would cost approximately £6431.3 which is only the cost of the primary components without the addition of wiring and installation, the additional cost to the vehicle would be in mass and it would weigh an additional 29.78kg again without the additional mass of wiring and integration with the existing ICE and transmission.

7 Conclusion

Looking at all the collected simulated data it was determined that in most circumstances a KERS system would provide a clear benefit to a motorsport vehicle. The additional velocity at the ends of most straights would provide a benefit to both lap times and the potential to gain position during races. Having additional velocity compared to other competitors can prove beneficial as it is said by Boretti that KERS can “act as a strategic device to boost performance or to gain position or improve lap time” (Boretti & Aris, 2015)

The benefit of KERS does depend on a number of variables such as the vehicle to be used on and circuits can have a factor in the effectiveness of the system, however the system can be tailored for each different vehicle and therefore be suitable for a number of them.

It was shown in simulation however that a KERS would provide a benefit to the MCR race car in lap time, the effect during the race cannot be simulated due to the unpredictable nature of racing however the difference in lap time can be used as a rough indicator of tangible benefits.

All the aims stated at the beginning of the report were successfully achieved; the benefit was calculated, components researched and a system was proposed. The accuracy of the simulation is dependent on the factors listed in section 3.2 about the software however it is accurate enough to design a possible system that could be used.

It is seen that KERS does provide a benefit to lap times and also maximum velocity, by looking at the data calculated it was simulated that maximum velocity could potentially increase by 19% even with the heaviest mass penalty and a possible overall lap time improvement of up to 10% however that assumes constant deployment.

8 Further Work

Additional simulation using a Driver in the loop simulator could be used to refine the control strategy of the KERS such as when is the ideal location to automatically deploy the stored energy, or if it would be better in a race situation to allow the driver to control the deployment themselves.

Further refined sweeps with varying masses could be conducted once the deployment strategy has been defined in order to assess the impact of deployment strategy on lap time. Sweeps could be conducted on circuits with known gradient variations to assess how the system would perform on those gradients and to determine the possible advantages or disadvantages of the system.

Following the final mass sweeps an investigation into the exact vehicle behaviour due to the additional KERS, the effect of the latitudinal and longitudinal acceleration and load transfer could be analysed compared to the stock vehicle and the subsequent effect it could have on the transient stability

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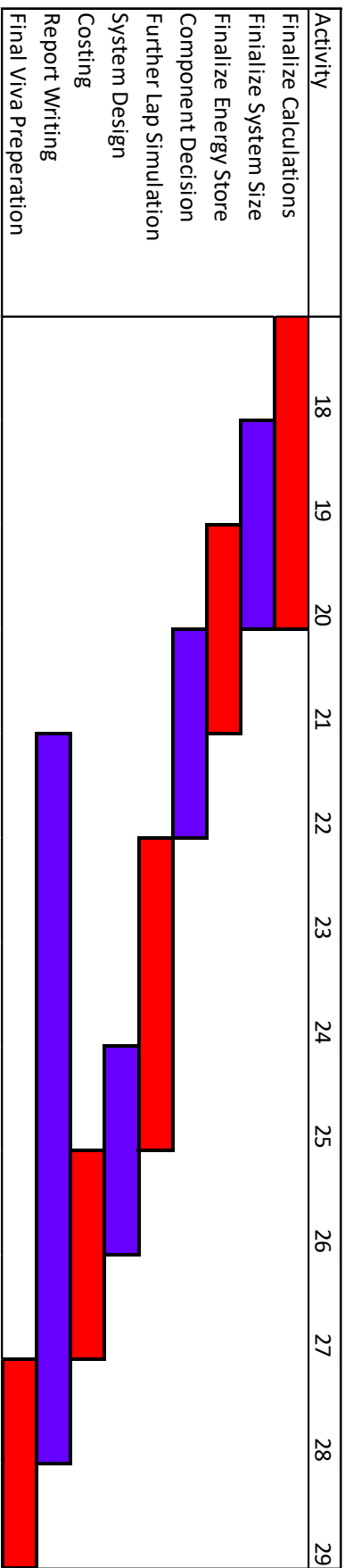
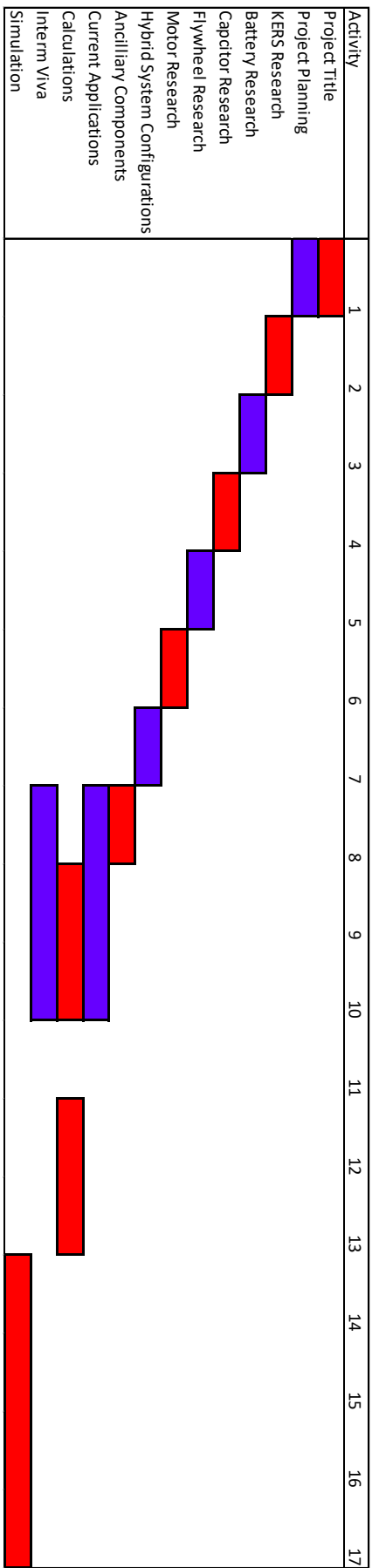
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Appendix A – Full Gantt Chart



Appendix B – Further Equations

$$J_f = 2 \times \pi \times \rho \times \int_{R_1}^{R_2} W(r)r^3 dr \quad (13)$$

Where J_s is the moment of inertia, ρ is the density of the material $W(r)$ is the width of the flywheel corresponding to the radius denoted by r (Ehsani, et al., 2010)

Appendix C – Motor decision Table

		Peak Power (kW)	Cont Power (kW)	Peak Torque (Nm)	Cont Torque (Nm)	Mass (kg)	Average mass (kg)	Battery voltage (V)		Peak kW/kg	Peak Nm/kg
Emrax 108		70	30	100	50 6.8-7		6.9 100-400			10.14492754	14.4927536
Emrax 208		80	40	180	80 9.1-9.4		9.2 125-470			8.695652174	19.5652174
Emrax 288		100	55	240	125 12-12.3		12.15 130-670			8.230452675	19.7530864
Kyburz e-Rod		45								✓ #DIV/0!	✓ #DIV/0!
Zytek ERS		50		40		8.5	8.5 180-340			5.882352941	4.70588235
Zytek 25kW		25	15	64	47	12.8	12.8 250-425			1.953125	5
Zytek IDT 120-55		55		120	62#		62 250-400			0.887096774	1.93548387
Lynch LEM-200		12				11	11			1.090909091	0
Ashwoods IPM-200-66		32	13			17	17			1.882352941	0
Amtek DT5-15-10-RxW-6000		5.8		15		14	14			0.414285714	1.07142857
Amtek DT10-220-20-RxW-2500		23.5		220		83	83			0.28313253	2.65060241
Parker GVM210-050-CR		36.7	26.9	82	36.7	36.5	36.5			1.005479452	2.24657534
Yassa-750		200	100	790	400	33	33			6.060606061	23.9393939