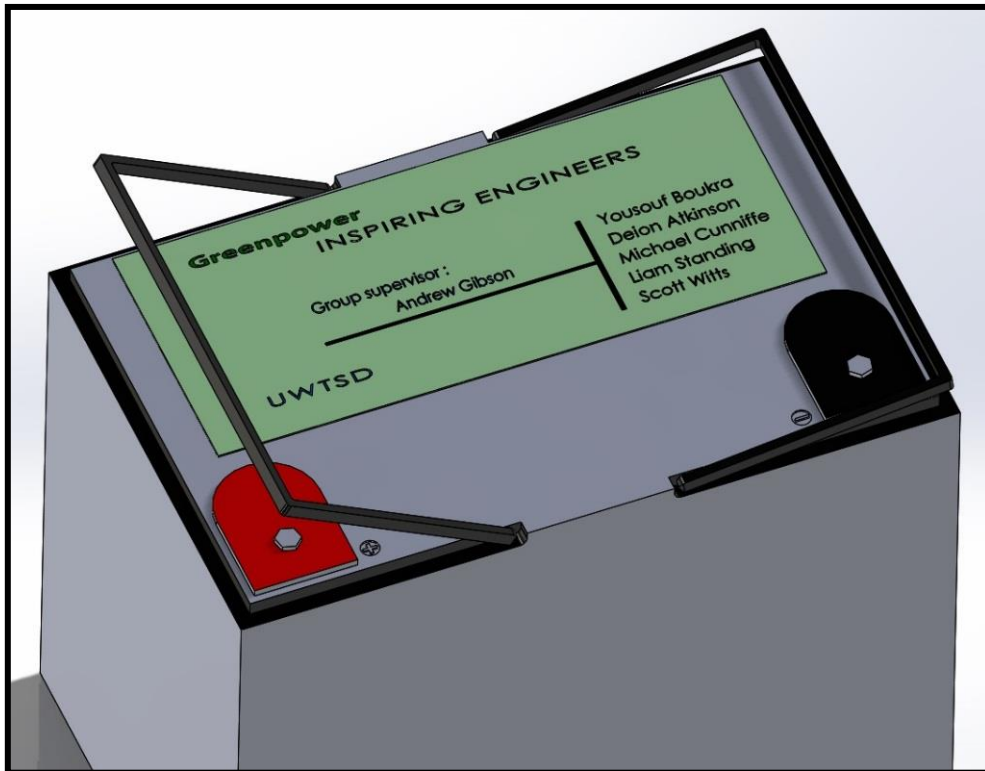


## Electric Car Group-Project



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## 1. Introduction:

Greenpower car is a single seater electric car built with the very basic technology which includes a 24 DC motor powered by 2 Lead-Acid batteries, and box section steel chassis. This report will cover the necessary changes that can be done to improve the car within the Greenpower 2019 regulation, as well as advanced development using the latest technology without considering the regulations and costs. The chassis of a vehicle is the starting point of designing/building a vehicle, the chassis design is crucial for many reasons and one of them being the centre of gravity. The vehicle's centre of gravity will determine many factors such as braking, accelerating and cornering (Reimpell, 2001). This report will look into the enhancement of the chassis to enable the car to be competitive. To be able to compete against other greenpower cars the chassis will need to be lighter, this will allow the batteries to last longer therefore, have a better result. Different materials will be considered and compared, and a decision made as to what material is best for the application. To do so, the current chassis needed to be designed using CAD software and analysed using numerical method by utilising FEA simulation which will be discussed in detail further down. Not only taking the chassis into consideration, the wishbones will also be analysed and enhanced by looking at different materials and design options. The suspension wishbones can be made lighter and stronger by using specialised material, these materials will be discussed and compared to ensure the best one for the application is chosen.

Another aim in this group project was to determine the best possible setup that can be achieved with minimal changes to the chassis. This includes theoretically moving the positions of when the suspension A arms mount to the chassis, changing the wheel sizes, changing the speed of the vehicle and changing the weight of the driver. In order to achieve this the data was collected from the Greenpower vehicle using measuring equipment, scales, rolling road and steering and suspension software (Wingeco). Then using a series of equations in Microsoft excel characteristics of what each setup causes the vehicles dynamics to do. This includes whether the vehicle was oversteering, understeering or neutral steering and the change in the distribution of the weight of the vehicle. From comparing the different setups and determining the trends of the vehicle dynamics, a proposed design is outlined in the conclusion.

Furthermore, the drivetrain aim during the report is to theoretically install a speed controller to the vehicle to control the motor speed in order to reach and maintain a constant speed of 35kph while taking into consideration of the motors temperature and current draw to make sure the battery doesn't discharge before the end of the race. Physical testing and calculations are done to determine the vehicles top speed by changing the gear ratio and motors speed, and the data retrieved from the dyno testing provided an understanding into how the motor temperature effects the rate at which the battery discharges at. Methods of cooling are discussed within the report including the advantages and disadvantages. The cost and pricing of the speed controller and gearing have been sourced while taking into consideration the requirements of the equipment and components. The Battery used to power the 24V DC motor is Lead-acid AGM technology, this paper will highlight the operation principles of this

technology as well as the new technology which include the Li-ion battery and how this last one is capable of delivering better performance than the current battery forced by the greenpower regulations.

*-Deion Atkinson -Yousouf Boukra -Scott Witts -Liam Standing -Michael Cuniff*

## 2. Chassis design and constraints:

When designing an automotive chassis there are many more design constraints than there is with a motorsport space frame chassis. If the vehicle was to be fitted with an engine then that would be a major factor to consider but, as the green power car is fitted with a motor and batteries behind the driver the front can be modified to only have to suit the driver's legs and the front suspension. In regard to the rear of the vehicle, where the batteries are kept, this needs to be specifically designed to be able to store the batteries safely. Another aspect to take into consideration is the battery cooling, the design of the chassis could make this easier for the engineer designing the cooling system, therefore there are many aspects to consider when designing a chassis. In motorsport cars have to be scrutineered and checked before every event, this is to ensure that the vehicle is within the regulations. These regulations are a set of rules that every competing team has to adhere to in order to keep the competition as fair as possible. With the green power vehicle, it states that the chassis must remain un-modified other than the sheet underneath the driver, the sheet that creates the battery tray and the motor mounting tabs (Greenpower, 2019). If the vehicle was to go into competition in the future the chassis couldn't be modified but, as it isn't going racing, the project is discussed outside of the regulations and without a budget.

*-Deion Atkinson*

### **Current Chassis:**

The current chassis that was supplied to the group is a fully welded 2-part space frame chassis, it is made out of 30mm x 30mm x 1.5mm box section steel. The chassis currently weighs in at 24.95 kg when bolted together. Not taking the regulations and a budget into consideration, as mentioned above, this report will revise different materials that would be perfect for enhancing the chassis. The most efficient type of chassis is the space frame chassis which is also possible to build in limited production. According to (Costin, 1966), the best example of a space frame chassis with high torsional rigidity would be a square section rectangular box tied in with ends and sides. This type of chassis would be the strongest and cheapest to build, hence why the green power chassis is built in this form.

After looking at (MetalSupplies, 2016), the box section used to create the chassis weighs 1.68 kg per meter therefore, if the chassis weighs 24.95 kg the total meterage is;

$$\frac{24.95}{1.68} = 14.81 \text{ meters}$$

Taking T45 tubing into consideration, according to (AerocomMetals, 2019), the weight of a 25mm x 2mm round tube in T45 is 1.08 kg per meter. Using the meterage from the equation above it will be evident that using T45 will make the car much lighter and stronger.

$$14.81 \times 1.08 = 15.99 \text{ kg}$$

$$24.95 - 15.99 = 8.96 \text{ kg}$$

After creating the chassis in T45 tubing, in theory, the chassis should weigh 8.96 kg lighter than it currently stands at. This would be an incredible weight loss and would be very beneficial, as noted by (Suh, 2017), the weight of an electric vehicle will increase energy consumption and for the Green power vehicle, battery life and efficiency is key therefore, the car will need to be as light as possible for it to be competitive.

A numerical analysis was created on Solid works to compare the strength of T45 against the current box section material that the chassis is created out of. Examples of the analysis can be seen in appendix 1.A. by looking at the FEA results it shows that the steel box section material deflects 8mm under a 100 N of force while the T45 tubing on the other hand, shows much stronger characteristics and only deflects 2mm under a 100 N of force. This validates what (Proformance, 2019) have mentioned, that T45 is very strong and therefore used for many applications in the motorsport industry.

*-Deion Atkinson*

#### **BS4 T45 Carbon based steel:**

This type of material has been very popular for the past 70 years and, as mentioned by (Costin, 1966), the majority of current production race chassis are made of electric resistance welded tubing. This material is particularly suitable for welding and, although some of the quality properties vary, they are usually first class.

#### **Its Use and Why?**

This type of steel tube is used in many different applications within the engineering industry, it has many properties that can give many advantages within motorsports. As noted in (Proformance, 2019) the material has been around for over 60 years and was first used within the aerospace industry, used as airframe structures due to its high strength and ease of forming and welding. its excellent strength to weight ratio enables it to have many different applications in different industries but, its most popular use within motorsport is roll cages, space frame chassis and suspension components. Its properties are; Tensile 700 – 900 Mpa, 0.2% yield 620 Mpa minimum, Hardness test 201 minimum – 262 maximum HB (Proformance, 2019)

While the aerospace industry was using a lot of carbon-based steel products other industries started to take notice, especially the motorsport industry. Engineers wanted vehicles to be faster, lighter and safer and for this to happen, the best quality material was needed. The issue the engineers faced was that the materials had poor elongation properties, this meant that the material would stretch and bend in ways that the engineers weren't happy about. This is when the carbon-based steel started to take over in motorsport applications, too (Proformance, 2019).

### Advantages of T45 tubing?

There are many advantages of using this material for the advancement of the green power vehicle, these are noted as; ease of forming, high strength, easy to fabricate and weld, no pre or post heat treatment required, can improve/keep the structural strengths without increasing the weight (Smith, 2016).

-Deion Atkinson

### **Cold Drawn steel (CDS):**

This type of material is a steel that is drawn passes through a series of dies to achieve the desired shape. The dies apply a specific amount of pressure by using a machine press and the steel starting stock will have to be passed through a series of dies more than once to achieve the finish product. The cold in the name refers to this type of steel being manufactured at room temperature which required additional pressure to bring to shape, this gives the steel some extra qualities and a visually aesthetic appearance which is important when it comes to customer service (CapitalSteel, 2019).

### Benefits of CDS?

Hot formed steel will change shape and size during the cooling process, due to this the cold drawn steel can be manufactured to more precise measurements along with sharper corners for those who need them. Cold drawn steel has a better finish to it than hot rolled steel, this makes it more appealing to the public eye. Yield and tensile strength sees an improvement over hot rolled steel (CapitalSteel, 2019).

According to (CapitalSteel, 2019) CDS is used at a high demand rate in the automotive industry, especially for components such as axes, spokes and wheel spindles. The material has also high demand in industries that make things such as bolts, tools, fasteners and cables. This high demand gives the material a good name and therefore, could be very useful towards the build of the green power electric car chassis.

### T45 Vs CDS:

In relation to this, as mentioned by (CustomCages, 2019), T45 is significantly stronger than CDS, its tensile strength is two thirds higher and the point at which the metal begins to deform nearly doubles the performance of CDS. This gives the upper hand to T45 tubing because it can deliver the same amount of strength as the CDS but with a thinner wall thickness, meaning the car will be lighter, but still as strong. For example, when custom cages built a roll cage for a Ford Fiesta mk6 out of T45 tubing, it was 10 kg lighter than the equivalent CDS design. However, weight reduction comes at a higher cost and therefore, most roll cages and chassis built with T45 tubing are usually used in higher end of motorsport for example, used by teams competing in the British, European and world championship. This means that CDS is the alternative to T45 tubing where the cost of the build comes as a priority (CustomCages, 2019).

-Deion Atkinson

**Aluminium:**

Aluminium alloy 6082 is known as a medium strength alloy, it is the strongest version of the 6000 series alloys and is known as a structural material. This type of alloy is used in many different applications, these being highly stressed applications. It has a tensile strength of 340 Mpa and proof stress of 290 Mpa (Aalco, 2013). It also has advantages similar to the other two materials, its easily fabricated and has good weldability properties. Another advantage aluminium has is its light weight, according to (Thyssenkrupp, 2017)'s website, the density of aluminium is 2,700 kg per meter cubed therefore, it's a light weight material which would work for the green power vehicle. Its properties are much lower than the properties of T45 tubing but, as can be seen at (Statusracingteam, 2014), this team built an aluminium space frame chassis and drilled holes on the non-structural members. After successfully competing with the aluminium space frame chassis it signals that the chassis had worked for the team, therefore making it a very adequate material to use.

-Deion Atkinson

### 3. Wishbones Enhancement:

**Current Wishbones:**

The green power vehicle is equipped with a double a-arm suspension design, this is when there are two suspension arms connected to the hub that has a shock absorber fitted to the bottom one and the chassis. The difference between a conventional double a-arm design and the green power vehicle is that the green power vehicle doesn't



Figure 1 current wishbones

have a shock absorber, it has a link fitted with a rose joint on each end. This makes the car solid without any suspension travel, only height adjustment with the rose joints.

The wishbones that were supplied with the car are made of pressed plate steel, the bottom wishbone is slightly larger than the top to compensate for the angle of the chassis. They have been supplied with adjustable rose joints acting as bottom ball joints, this allows the camber to be changed depending on what set-up is required. Before building the vehicle in the workshop every part was separately weighed, the top wishbone weight was 0.4 kg and the bottom one is 0.75 kg. figure xx is an example of both wishbones fitted onto the vehicle.

-Deion Atkinson

**T45 Carbon-based steel:**

Constructing the wishbones using T45 tubing would make the wishbones much stronger due to the materials properties, as mentioned above in the chassis section. Due to its high strength, the wishbones wouldn't need the pressed-plate reinforcement

that they are currently fitted with. By removing the pressed plate steel, it would make the wishbones lighter without losing out on strength properties. As can be seen on (Proformance, 2019)'s website, they produce oval tubing specially made to construct wishbones. This shows that the material is widely used in the motorsport industry and gives the group confidence that it will be the right material for the job.

*-Deion Atkinson*

### **Carbon Fibre tubes:**

Carbon fibre is a very well-known composite in the motorsport industry for its high strength and stiffness. In recent years the material has become the predominant structural material at high level international motorsport and is also gaining widespread popularity in collegiate design competitions (Mcdonald, 2011). There are two different methods of manufacturing carbon fibre tubes, these are known as pultruding and roll-wrapping. A pultruded tube means that 100% of the fibres are aligned with the axis of the tube, this causes delamination when exposed to the exterior of the car therefore they must be protected at all times. On the other hand, the roll-wrapped tube has multi-directional fibre alignment giving these types of tubes excellent torsional strength, axial strength and lateral strength. This makes the roll-wrapped better for the green power car application but are much more expensive than other materials and also requires experience to fit (Bookholt, 2010).

### Advantages:

A significant amount of weight can be saved by using carbon fibre to manufacture suspension arms while maintaining the stiffness and strength of other materials such as steel. This manufacturer of carbon fibre tubes, (Carbonfibretubeshop, 2019), states that the density of carbon fibre is 4 times less than steel but, for the green power vehicle application this material would be perfect because of the low speed racing.

### Disadvantages:

When using steel tubes for similar applications, the customer can rely on the material properties as they don't massively vary, but with carbon fibre tubes the properties vary from manufacturer to manufacturer meaning that they aren't consistent. This forces the engineer or designer to test the material properties and ensure that the tube is strong and stiff enough for its application before fitting. Another disadvantage of using carbon fibre tubes for suspension is that the material doesn't yield but shatters when loads greater than its capabilities are applied. This usually occurs when compressive loads are applied due to its best capabilities being under tension. But, as briefly mentioned above, after testing the vehicle on the dynamometer its max speed is 31km/h therefore, the carbon fibre material is strong enough to handle the loads that would be applied because of its use within Formula 1 and other motorsports.

*-Deion Atkinson*

#### 4. Lead Acid Battery:

Batteries operate through electrochemical discharge reactions by converting chemical energy into electrical energy, and it composed of one or more cells. Each batteries cell contains a positive electrode, negative electrode, separator, and electrolyte. There are two major classes of cells, primary and secondary. Primary cells are the one which are not rechargeable and need to be replaced once they are depleted, while secondary cells such the one of lead acid batteries are rechargeable and that through a DC charging source to restore reactants to their fully charged state. Lead-lead dioxide (lead-acid) is not the only secondary cells type, there is other similar cells include nickel-cadmium, nickel-iron, nickel-hydrogen, nickel-metal hydride, silver-zinc, silver-cadmium, and lithium-ion which will be discussed in detail in other section of this report. The chemical reactions of lead-acid battery are represented in the following equations: for positive electrode (charge)  $\text{PbO}_2 + \text{H}_2\text{SO}_4 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{PbsO}_4 + 2\text{H}_2\text{O}$ , for negative electrode (discharge)  $\text{Pb} + \text{H}_2\text{SO}_4 \rightarrow \text{PbSO}_4 + 2\text{H}^+ + 2\text{e}^-$ , and for overall reaction is  $\text{PbO}_2 + \text{pb} + 2\text{H}_2\text{SO}_4 \rightarrow 2\text{PbSO}_4 + 2\text{H}_2\text{O}$ . When the cell is charger, the sulfuric acid ( $\text{H}_2\text{SO}_4$ ) concentration increases and reaches high level when the cell is completely charged. In contrast, when the cell is discharged, acid concentration decreases (David, 2001). Lead acid batteries have been around for more than a century, when the battery is fully charged, the electric potential that exists between the cathode and anode is 2 volte. During discharge, electrons are passed externally through the load while internal chemical reactions at the interface of the electrolyte and the electrodes work to balance the charge equilibrium. Lead acid batteries are divided into two categories: sealed/valve regulated and flooded (VRLA or SLA), those two types are similar in their internal chemistry. However, the most significant differences are the design considerations of the system level. Flooded lead acid batteries require three things that sealed/valve regulated batteries don't: Upright orientation to prevent electrolyte leakage, ventilated environment to diffuse gases created during cycling, and routine maintenance of electrolyte. VRLA batteries are divided into two categories, Gel and AGM (Absorbed Glass Mat). The difference between those two type is the different methods of containing the electrolyte. In Gel batteries, to change the electrolyte state from liquid to gel, a thickening agent is added. While in AGM cells, a glass matrix is utilised to contain the liquid electrolyte. Lead acid batteries can also be divided into two classes 'deep cycle' and 'shallow cycle' types. Shallow cycle VRLA batteries are often utilised for automotive start, light, ignition (SLI), as that type must is used to deliver high power pulses for short durations. While the other class is often discharger at a low rate over the course of multiple hours (Greg. Et al, Jake. Et al, Said. 2012).

-Yousouf Boukra

Batteries are rated in term of their nominal voltage and ampere-hour capacity. Voltage rating depends on how many cells are connected in series and the nominal voltage of each cell, for lead-acid each cell provides an open circuit output voltage of about 2.13 volts when fully charged and will be considered discharged when its voltage drops to 1.95 volts. A 12 volts car battery will have up to six lead acid cells that are connected in series, the total open circuit output voltage of these six cells will be approximately

12.78 volts when the battery is fully charged. And it is considered fully discharged when the voltage drops to 11.7 volts. Batteries can be connected in series to get the benefit of more power for every amp of current supplied and to increase the watt hour rating. For example, if two 12 volts batteries are connected in series and each battery provide 10 amp of current which gives 120 watts. The total power supplied by two batteries connected in series will be 240 watts from an output of 24 volts system that provide 10 amps. In contrast, when batteries are connected in parallel, the capacity in terms of amp hours and kilowatt hours doubles, while voltage remains the same. As explained by Peukert's law: when the current supplied from a battery increases, the capacity decreases. and the reverse of this is true, as current supplied from battery decreases, the capacity increases. Because it takes less current to supply power in a 24 volt system, the battery system capacity will increase (capnfatz, [Online]).

-Yousouf Boukra

## 5. Current Battery capabilities and replacement possibilities:

The current Greenpower car battery have a limited energy available from the two 12V lead-acid batteries wired in series, generating 24V which is required to power the 24 volt DC motor. That lead-acid batteries are supplied by Yuasa and the model is REC36 which is an AGM built battery type. The approximate power figures for those batteries should be about 17 to 18A for 90 minutes as mentioned by Gary Coulden-Smith. Greenpower regulations permitted the batteries to be at a maximum temperature of 25°C or ambient temperature plus five Celsius when ambient is above 20°C. Only one set of two main batteries will be allowable to use in a race, and no external energy source is permitted (Greenpower Regulations, 2019). The regulations does not allow any modification to be made on the batteries, or replacement of better technology batteries. Therefore, the alternative replacement possibilities discussed below are beyond the regulations, but it has been completed to have an insight into the new technology available in the market.

-Yousouf Boukra

The best alternative replacement for Lead-Acid AGM is the Lithium-ion batteries. Lithium-ion (Li-Ion) batteries are often used today as electrical energy accumulators in electric, Hybrid, and plug-in Hybrid vehicles, Li-Ion systems offer a rated voltage of approximately 3.7V per cell, while the voltage limit in use is between 2.8V and 4.2V. the positive electrode (cathode) of a lithium-ion cell is structured with metal oxide for lithium ions storage capabilities, this metal oxides the active material which consist of nickel, manganese, or cobalt. The basic mechanism of this technology is that the charged lithium ion is moved back and forth between the cathode and anode during charge and discharge process (Figure 2). During discharge process, the lithium ions travel in a reversible mechanism from positive electrode

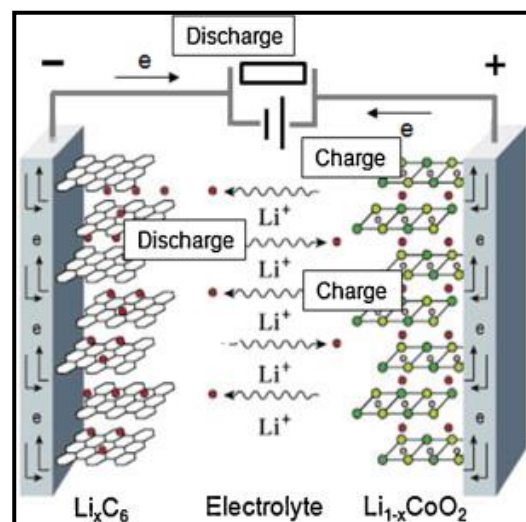


Figure 2 Li-ion Battery method of operation

(cathode) toward the negative electrode (anode). Anode is usually constructed from an active material (Graphite) (Bosch. 2014). Lithium-ion cells are all 'deep cycle' type, which mean they have the ability to be fully charged and discharged.

Lithium-ion batteries will supply better energy to drive the motor than Lead-acid batteries in term of energy density, specific energy, state of charge window, temperature sensitivity, efficiency, and voltage increments. A comparison between VRLA lead acid (which is the type of the current battery used in GreenPower car 'Yuasa REC36') and Lithium-ion has been completed in a recent studies published by AllCell Technology LLC. The comparison results presented on that paper was as following: energy density was 100Wh/L for Lead-acid and 250Wh/L for Li-ion, while specific energy in term of Wh/Kg was 40 and 150 for lead-acid and Li-ion respectively. Typical state of charge window for lead acid was 50% and for Li-ion 80%. Lead-acid battery degrades significantly when temperature is above 25°C, whereas Li-ion temperature sensitivity is above 45°C. Efficiency of Lead-acid is 100% @ 20hr rate / 80% @ 4hr rate / 60% @ 1h rate, and for Li-ion efficiency is much better as the following figures shows, 100% @ 20hr rate / 90% @ 4h rate / 92% @ 1hr rate. Voltage increment was also proven on that paper to be 3.7V for Li-ion and 2V for Lead-acid (Greg. Et al, Jake. Et al, Said. 2012).

-Yousouf Boukra

## 6. CAD modelling process:

Modelling of the Greenpower car chassis and its component has been designed using Solidworks 2018 version available at the university. A wide research has been conducted for different methods and techniques to approach the design including, Extrude Boss and Cut, Sweep & Loft features, and weldment tool.

### Extrude Boss AND Extrude Cut Features

Due to the chassis complexity, this feature was not suitable to complete the hall chassis. Furthermore, the research that has been made on how engineers approach a chassis design shows that this features are not the most effective when cading a similar model. However, many of the other parts such as the wishbones, the steering hub, battery...and other components has been completed adopting the Extrude boss and Extrude Cut features (Paul. 2017).

### Advanced Modelling with Sweep & Loft

Those are an advanced features in Solidworks and allow the designer to create a geometry which is in our model (square box sections) and (Circular section tubing) in different angles and through various inclinations (Paul. 2017).

### Weldments – Structural Members

This feature has been added to Solidworks specifically to use when modelling tubing, square box section, beams and angled iron. It allows designers to create the model based on 2D or 3D sketch and it also can be set to give you mitred corners (Paul. 2017).

Both of rear-end and front-end part of the chassis has been designed using advanced sweep and loft tools, with minimum use of extrude boss and extrude cut features. Each end of the chassis has been designed separately (rear-end by Yousouf and front-end by Michael), however, a significant amount of collaboration between group members

was required to approach the design of both parts in parallel including measuring the 2 sections together to ensure 100% success on assembly phase. (all the CAD parts are on appendix C).

-Yousouf Boukra

## 7. Finite Element Analysis Via Solidworks Simulation:

'Solidworks simulation is a commercial implementation of FEA capable of solving problems commonly found in design engineering, and it belong to the family of engineering analysis software products.' Some of the cases that Solidworks Simulation can analyse include, displacements analysis, natural frequencies, Stress (which will be explained in detail when covering the FEA results of the chassis structure as this is the case study that has been completed), Vibration, heat flow, etc (Paul Kurowski, 2018). Finite element analysis also commonly called FEA is described by Randy Shih as a method of numerical analysis which is used for solving engineering problems such as machine design, acoustics, fluid dynamics and many others, in this case it will be used for the chassis design structure analysis.

In order to decrease the complexity of the rea-end cad model of the chassis designed, a second model was created specifically to run within the solidworks simulation. The model has been created using the Weldment / Structural Members features, the process of designing that model started with the creation of the 3D sketch of the rea-end of the chassis using the previous model as a reference of measurement. Post creating the 3D sketch, a Weldment tool was utilised to create the structural members that form the chassis structure. The new designed rear-end of the chassis successful run within the FEA analysis within solidworks, however, its very important to take in consideration that the second model is not as complete as the first model and that may alter the overall strength of the rear-end. First, all the plates that existed in the complete model which forms the driver seat and head-protection plate was eliminated in order to simplify the model and speed-up the analysis process as this last one takes a considerable amount of time to be finished with respect to the computer hardware's available at university. Second, other technique has been applied to simplify more the model and avoid meshing problems, that technique was suggested by professor Kelvin Lake after discussing some of the meshing problems found in the first model. The idea was to eliminate curved geometry, creating straight tube in different inclinations which are lot easier to mesh. Therefore, and due to this changes that have been put on the analysed model, the results can not be taken as an exact reference for rea-end chassis overall strength, but it is useful to approximately determine the strength of the main elements forming that part of the chassis.

-Yousouf Boukra

### FEA Results:

#### Torsion Analysis

The chassis was fixed exactly at the suspension mounts and a moment was created by applying 2 forces at the other end to simulate the torsion test experienced while the car is cornering. Loads were calculated using the rea-end chassis weight of 17.65 assuming a force of 3G that the chassis is experiencing, each Node represent a force of 264.75 N (figure 3). the result is demonstrated on figure 4.

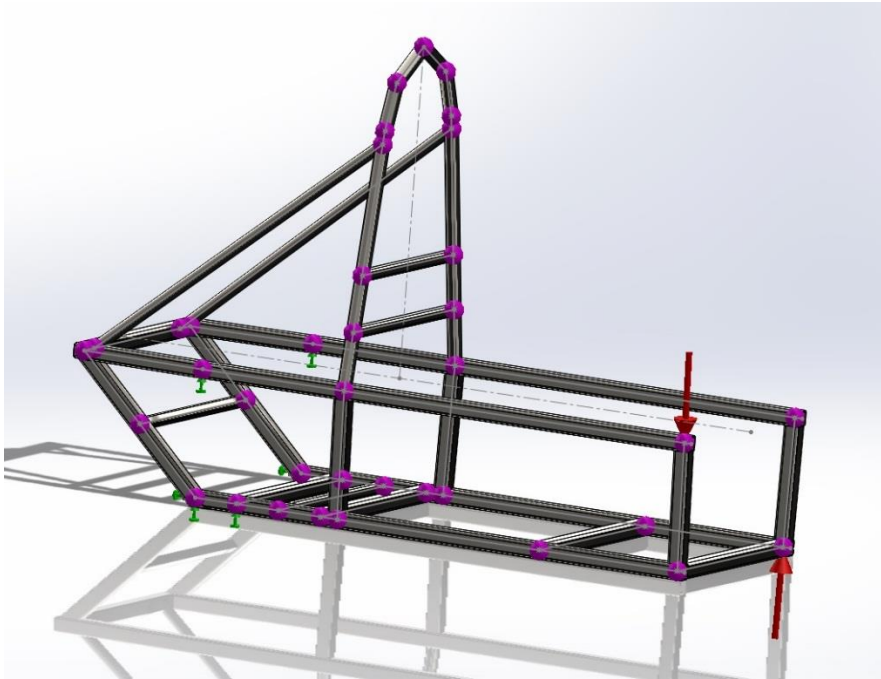


Figure 3 FEA torsion screenshot A

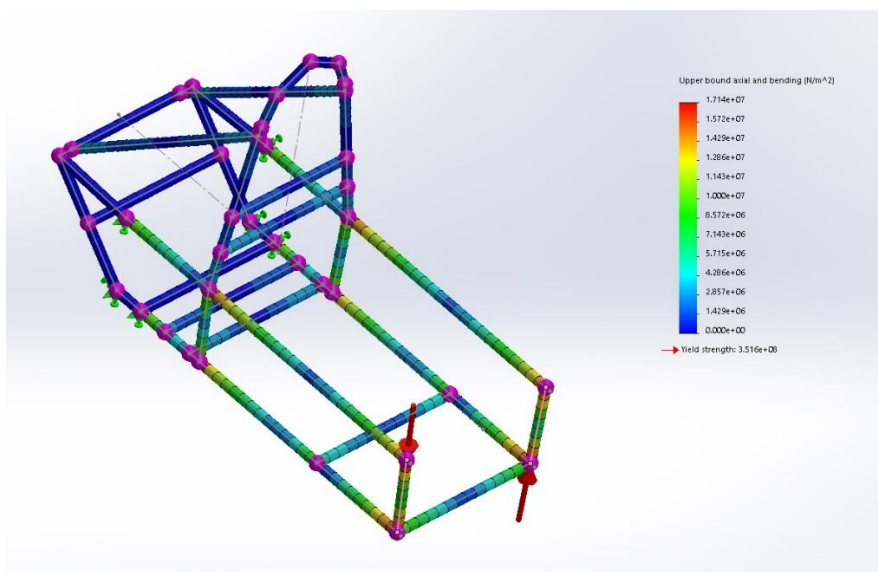


Figure 4 FEA torsion screenshot B

-Yousouf Boukra

### Bending Analysis

Similar to bending analysis, the chassis has been fixed in the suspension mounting and the load had been applied at the other end. Each Node carried a load of 132N figure 5. The results of this bending analysis are presented on figure 6 below.

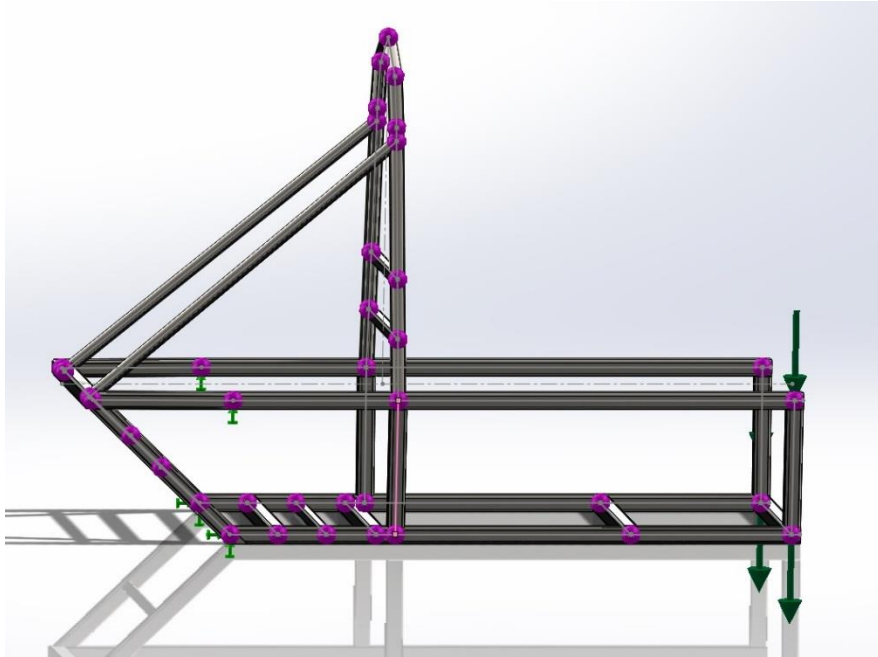


Figure 5 FEA bending screenshot A

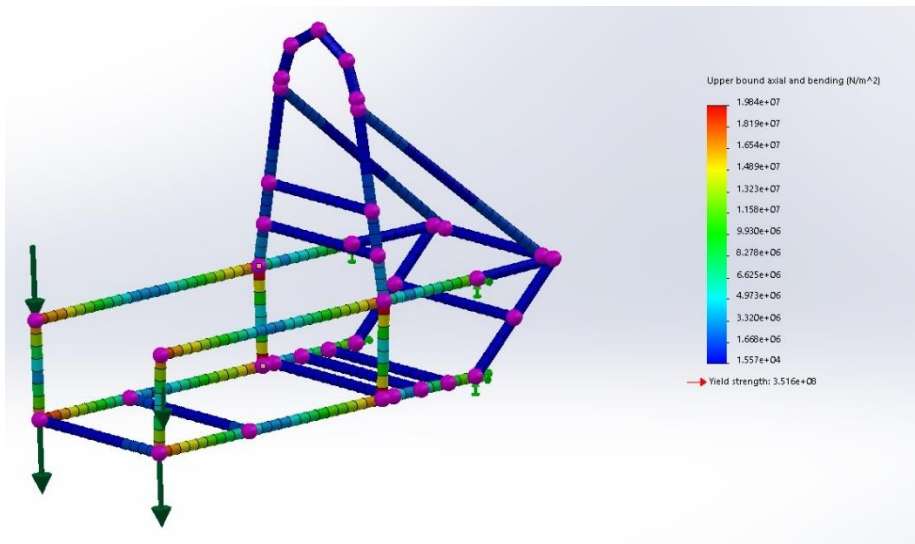


Figure 6 FEA bending Screenshot B

-Yousouf Boukra

## 8. Speed Controllers:

The speed controller manipulates the voltage supplied to the motor which regulates the speed or direction of the motor, as confirmed by 4QD (2019). As the vehicle would not need to be reversed the cost of the speed controller can be reduced by applying a basic controller without the option of reversing. There are many advantages installing a speed controller to the vehicles, the first is that it provides control of the motor when the vehicle accelerates from stationary by what is known as a soft start which prevents the motor from stalling, as confirmed by 4QD (2019).

When the motor fitted reaches 130 amps it stalls, drawing up to 20 times its normal operating current, as found by 4QD (2019), preventing the motor from stalling would prevent any unnecessary current being drawn from the battery. The use of a speed controller can prevent the motor from stalling, as confirmed by 4QD (2019). Speed controllers can provide protection against reverse polarity which is caused if the positive connects to the negative battery terminal, as confirmed by 4QD (2019). Pulsed width modulator (PWM) speed controller – The PWM works by switching the motor on and off in a series of pulses in order to maintain, increase or decrease the speed of the motor, the width of the pulses are modulated to control the speed as confirmed by 4QD (2019).

Metal oxide semiconductor field effect transistors (MOSFET) can switch high currents at high speeds and switching or amplifying signals, as confirmed by 4QD (2019). Below in figure ? is an example of how the MOSFET operates, it acts as a switch between the positive and negative of the battery to control the on and off duration of the MOSFET. Waveform A is off most of the time while switching on for a small duration which would result in the motor speed being low. Waveform B is on 50% of the time and off 50% of the time providing a balance between the low and high speed of the motor. Waveform C is shown to be on most of the time while switching off for a small duration, the MOSFET is able to switch on and off at a rate of 20kHz which is 20 thousand times a second, meaning the inductive motor doesn't realise that it is being switched on and off, as confirmed by 4QD (2019).

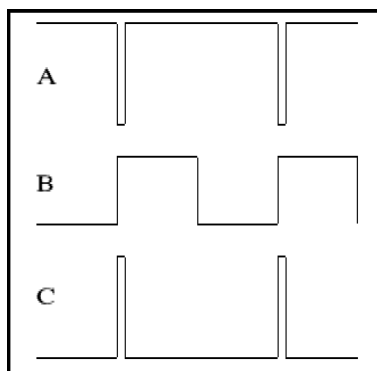


Figure 7 PWM waveform

PWM controllers are almost 100% efficient as they cannot dissipate heat effectively therefore only a marginal amount of the power drawn from the battery is wasted in the PWM controller, as confirmed by 4QD (2019).

-Scott Witts

## 9. Gearing:

The use of a chain driven gearing system can be used, however it was found by previous Greenpower competitors that the chain can derail from the gears as the vehicle is subjected to vibrations and bumps while on the track, to prevent this happening a chain guide can be fitted close to the point at which the chain attaches to the sprocket, as confirmed by Greenpower (2019).

Constant gear – The use of a single constant gear is the simplest to construct and it reduces the amount of control the driver has over the vehicle by eliminating the need to change gear. The friction losses would be lower than the friction losses caused by multiple gears. A constant gear setup would be more beneficial if the track allowed the vehicle to maintain a constant steady speed throughout the race, otherwise if the vehicles speed is required to decrease and increase due to sharp corners, or uphill conditions then the motors current draw would increase during these conditions and could cause overheating of the motor which reduces its efficiency and reliability, as confirmed by Greenpower (2019) and Twigg (1996).

Multiple gears – The use of multiple gears can be used to maintain the current supplied to the motor within a narrower range, by reducing the motors rpm to maintain or increase the vehicles speed. Closer gear ratio can allow for a narrower rpm range which can be more beneficial when attempting to maintain the motor at its most efficient or powerful range, a closer gear ratio would be more efficient when pulling away from slow speeds, during uphill, downhill, fast and slow conditions, as found by Greenpower (2019), Zammit (1987) and Twigg (1996). This system provides more responsibility for the driver compared to the constant gear setup, therefore the driver would require a rev counter, ammeter or an electronic indicator system to assist the driver when a gear change is required, as expressed by Greenpower (2019).

*-Scott Witts*

## 10. Cost of speed controller and gearing:

The options found in (figure xx) is confirming that the suitable speed controllers include the Porter-10, 4QD-200 and 4QD-300. The Porter-10 controller would be the cheapest option, costing £64.50 and the lightest option weighing only 145 grams, it provides reverse polarity protection but does not operate a reversing option which is not required. The 4QD-200 costs £249.99 and weighing 1300 grams, the 4QD-300 costs £315 and weighing 1650 grams, both are too advanced for the motor provided and therefore applying one of these speed controllers would not be necessary, which would save the team a funding of £185.49 - £250.50 by selecting the Porter-10 controller.

Greenpower supply axle sprockets at costs of £55.04-£76.34, they range from 24 teeth to 72 teeth, however the 72 toothed sprocket is a lot cheaper at £34.84, but this is already fitted to the vehicle. As the chain provided is longer when used with a 72 toothed then there is no need to purchase a new chain as the 60 toothed sprocket that is required to make a 5:1 ratio when combined with the 12 toothed motor sprockets requires a shorter chain, the 60 toothed sprocket costs £69.04 from Greenpower.

-Scott Witts

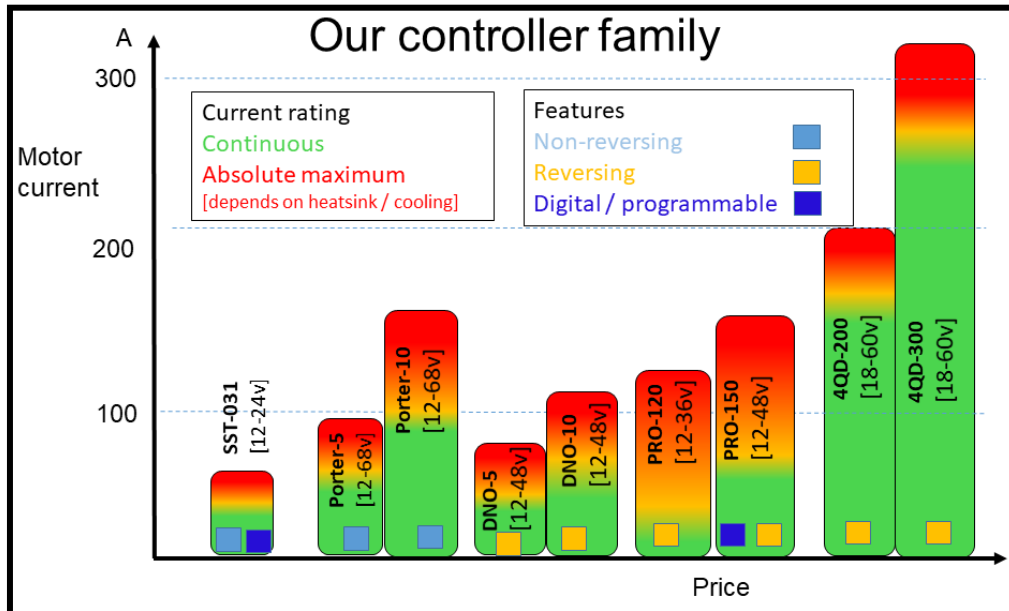


Figure 8 speed controllers available from 4QD

## 11. Drivetrain results, analysis and discussion:

### Dyno testing

The Greenpower car was put onto the vehicle dyno at the university campus, the vehicle was on the dyno for 21 minutes at a constant speed while monitoring the temperature increase of the motor and the batteries discharge rate by recording the battery voltage every minute, the results can be found in table 1. Once the vehicle was finished a set of data was produced displaying the vehicles speed, motor temperature, speed and power, the data will be analysed and used to perform calculations and predictions to achieve the drivetrain target.

The dyno test could have been performed for longer until each battery had discharged to 10.5V as this would have given a complete set of recorded data for the whole duration of the battery's capability, however due to time restrictions this was not possible. Although the calculations are correct theoretically, due to time restrictions not all considerations were measured, these include the aerodynamic drag, rolling resistance, the conditions of the track and windy conditions.

-Scott Witts

## Results Analysis

The maximum power was recorded at a motor speed of 1217rpm and produced 0.64 horsepower which converts to 477.25 watts, this value is below the maximum power found on the performance graph in Appendix A, this is due to the losses from the motor to the wheel. The maximum vehicle speed was recorded at 30.62kph at a rpm of 2131 while producing 0.01 horsepower/7.45 watts, the reason it produced very little power is because at 2132rpm the motors power curve shown in Appendix A is at its minimum. From the results found during testing the most power produced during the test was between 900-1300rpm and producing power between 0.57-0.64 horsepower.

It is found that the battery voltage decreased by 1.4 volts after the first minute of testing, this is due the vehicle being stationary at the beginning of the test and as the motor requires the most amount of current to accelerate from stationary rather than a rolling start, this increases the motors current demand and increases the current draw from the battery. As discussed previously in the report, the battery can draw up to 20 times the current when the motor stalls which is what happened as the vehicle attempted to accelerate on the dyno from stationary.

Once the motor reached its peak rpm it maintained a steady battery voltage of 24.3v for 6 minutes and decreased at a low rate until the motors temperature reached approximately 50.C. From the results it is found that the battery's discharge rate can be reduced by preventing the motors temperature to exceed 50.C, this would increase the distance the vehicle can travel before the battery discharges.

Unfortunately a dyno test was not performed with a speed controller fitted, however the predictions based on the research made it is found that the rate that the motors temperature increases at can be reducing when using a speed controller, this is because the motor is able to operate at a more controlled speed range to reduce the heat produced by the unnecessary current draw. The battery's discharge rate can be reduced by fitting a speed controller as it can allow for a smoother start which would reduce the initial battery drain by reducing the speed the motor accelerates from stationary. The motors speed can be controlled within an efficient area which is found on the performance graph in Appendix A to be at 1850rpm while drawing 15 amps, although this is not taking into consideration of any other loads acting on the motor, as expressed by Greenpower (2019).

| Time (min) | Motor Temperature<br>(.C) | Voltage (v) |
|------------|---------------------------|-------------|
| 0          | 14                        | 25.7        |
| 1          | 18                        | 24.3        |
| 2          | 28                        | 24.3        |
| 3          | 32.3                      | 24.3        |
| 4          | 35.5                      | 24.3        |

|    |      |      |
|----|------|------|
| 5  | 36.3 | 24.3 |
| 6  | 37.4 | 24.3 |
| 7  | 38.2 | 24.2 |
| 8  | 39.5 | 24.2 |
| 9  | 41.2 | 24.2 |
| 10 | 41.7 | 24.2 |
| 11 | 42.7 | 24.2 |
| 12 | 43   | 24.2 |
| 13 | 43.6 | 24.2 |
| 14 | 44.5 | 24.1 |
| 15 | 45.5 | 24.1 |
| 16 | 46.3 | 23.8 |
| 17 | 47.2 | 23.6 |
| 18 | 48.2 | 23.6 |
| 19 | 49   | 23.6 |
| 20 | 50.1 | 23.5 |
| 21 | 51.5 | 22.8 |

Table 1 Dyno testing results

From the performance graph in Appendix A it shows that to run at the motors most efficient area of 73% which is found at 1850rpm while drawing around 15 amps from the battery to the motor. The use of gearing can help to maintain the motor at its most efficient rpm while increasing the vehicles speed. The use of a speed controller can aid at ensuring that a smooth start is made from the vehicle and the speed controller can be used to adjust the speed when required during the race, the controller must be powered off the main battery as stated in the regulations by Greenpower (2019).

-Scott Witts

## 12. Calculations:

### Calculation at a gear ratio of 6:1

The wheel diameter is 20 inches, this is multiplied by 25.4 to give 0.508m, the circumference of the tyre is calculated by the tyre diameter multiplied by pi which gives 1.6 metres, this is multiplied by 3.281 to give the circumference of the tyre as 5.25 feet. The wheel speed is calculated by the motor speed multiplied by the motor sprocket which is divided by the wheel sprocket.  $\frac{\text{Motor sprocket teeth}}{\text{Wheel sprocket teeth}}$ .

The vehicle speed is calculated by the wheel speed multiplied by the tyre circumference which equals the distance travelled in feet per minute. The value is multiplied by 60 to convert to feet per hour and then divide by 5280 to convert the value to miles per hour, as expressed by Greenpower (2019) and confirmed by Champion and Arnold (1970) and Zammit (1987). The motor sprocket was measured at having 12 teeth and the wheel sprocket measured with 72 teeth giving a gear ratio of 6:1, as expressed by Champion and Arnold (1970) and Zammit (1987). Calculations are performed to predict the top speed produced using the 6:1 ratio currently applied to the vehicle, the most efficient, maximum and power output rpm ranges are used.

### Most efficient rpm

$$1850\text{rpm} \times \frac{12}{72} = 308\text{wrpm}$$

$$308 \times 5.25 = 1617 \text{ ft/min} \times 60 = 97020 \text{ ft/hr} \div 5280 = 18.4 \text{ mph} \times 1.6 = 29.44 \text{ kph}$$

### Maximum rpm achieved during testing

$$2131\text{rpm} \times \frac{12}{72} = 355.16\text{wrpm}$$

$$355.16 \times 5.25 = 1864.63 \text{ ft/min} \times 60 = 111877.5 \text{ ft/hr} \div 5280 = 21.19\text{mph} \times 1.6 = 33.9\text{kph}$$

### Most power produced at 900-1300rpm

$$900\text{rpm} \times \frac{12}{72} = 150\text{wrpm} \quad 1300\text{rpm} \times \frac{12}{72} = 216.6\text{wrpm}$$

$$900\text{rpm} - 150 \times 5.25 = 787.5 \text{ ft/min} \times 60 = 47250 \text{ ft/hr} \div 5280 = 8.94\text{mph} \times 1.6 = 14.32\text{kph}$$

$$1300\text{rpm} - 216.6 \times 5.25 = 1137.15 \text{ ft/min} \times 60 = 68229 \text{ ft/hr} \div 5280 = 12.92\text{mph} \times 1.6 = 20.68\text{kph}$$

By applying multiple gears, the gear ratio can be changed to increase acceleration by using a higher gear ratio or increase the top speed by reducing the gear ratio, the size of the motor sprocket or wheel sprocket can be replaced to change the gearing ratio, as confirmed by Zammit (1987) and Champion and Arnold (1970). For the following calculations only the wheel sprocket will vary in size and the motor sprocket will remain with 12 teeth, if the gear ratio is too low then the motor can overheat, as confirmed by Greenpower (2019).

-Scott Witts

## Gear ratio alterations

Using the previous calculation method, a table was created to show the calculated top speed for each gear ratio that can be added to the vehicle as a constant single gear or the option to combine the gear ratios by adding multiple gears. To maintain a constant speed of 35kph throughout the race on a level track with no sharp corners or hill climbing required, then the ideal gear ratio can be calculated by the equation:

$$\text{gear ratio} = \frac{\text{rpm} \times \text{wheel diameter}}{19.1 \times \text{average speed m/s}} = \frac{1850 \times 0.508}{19.1 \times 9.72} = 5.1 \quad \frac{900 \times 0.508}{19.1 \times 9.72} = 2.5 \quad \frac{1300 \times 0.508}{19.1 \times 9.72} = 3.6$$

as confirmed by Zammit (1987), Twigg (1996) and Greenpower (2019).

The calculations are showing the same information found in table 2, displaying that an ideal gear ratio at the most efficient motor speed of 1850, producing approximately 250 watts of power, 1.4Nm of torque, drawing 15 amps from the battery and providing an efficiency of approximately 73% would be 5.1:1 to achieve a constant speed of 35kph, however this does not take into considerations of the aerodynamic drag, rolling resistance and the vehicles mass. 35kph can also be achieved with the most amount of power produced between 900 and 1300rpm, while still producing between 7.5-4.7Nm of torque, however the current draw between this rpm range is found from the performance graph in Appendix A, a current of 47 amps is drawn at 1300rpm while decreasing to 47 amps at 900 rpm. The efficiency of the motor at 900rpm is only approximately 42% and increasing to 60% at 1300rpm.

| Number of teeth on Motor sprocket | Number of teeth on wheel sprocket | Gear ratio | Calculated top speed (kph) at 1850 rpm | Calculated top speed (kph) at 900-1300 rpm |
|-----------------------------------|-----------------------------------|------------|----------------------------------------|--------------------------------------------|
| 12                                | 96                                | 8:1        | 22.07                                  | 10.74 - 15.51                              |
| 12                                | 90                                | 7.5:1      | 23.55                                  | 11.45 – 16.55                              |
| 12                                | 84                                | 7:1        | 25.22                                  | 12.27 – 17.72                              |
| 12                                | 78                                | 6.5:1      | 27.17                                  | 13.22 - 19.09                              |
| 12                                | 72                                | 6:1        | 29.44                                  | 14.32 - 20.68                              |
| 12                                | 66                                | 5.5:1      | 32.1                                   | 15.62 – 22.56                              |
| 12                                | 60                                | 5:1        | 35.32                                  | 17.18 – 24.82                              |
| 12                                | 54                                | 4.5:1      | 39.24                                  | 19.09 – 27.58                              |
| 12                                | 48                                | 4:1        | 44.15                                  | 21.48 – 31.02                              |
| 12                                | 42                                | 3.5:1      | 50.45                                  | 24.54 - 35.45                              |
| 12                                | 36                                | 3:1        | 58.86                                  | 28.63 - 41.36                              |
| 12                                | 30                                | 2.5:1      | 70.64                                  | 34.36 – 49.64                              |
| 12                                | 24                                | 2:1        | 88.3                                   | 42.95 – 62.05                              |

Table 2 Calculated speeds achievable through different gear ratios.

-Scott Witts

### 13. Cooling:

By applying a cooling method to the motor, it will help to maintain its efficiency, the first option which requires no energy to power is to install a heatsink with fins and ducting to guide the passing air to the motor. The second option is fan assisted cooling, this method can be used although this would be drawing current from the battery which would reduce the overall amount of current that can be supplied to the motor before the battery discharges. The regulations state that auxiliary devices can be powered by a maximum of one PP3 battery or six AA batteries, however it is stated in the Greenpower regulations that the motor can only be cooled by passive or forced air and any prior energy input or power from batteries other than the main vehicle batteries is not allowed, as stated by Greenpower (2019).

Options of applying a fan powered by the main battery would discharge the battery quicker and reduce the overall distance the vehicle will travel. Although the fan may cool the motor which reduces current drawn from the battery to the motor, applying cooling ducts to capture the passing air and increasing its velocity and guiding it to the motor demands no energy input and eliminating unnecessary battery drain, as confirmed by Greenpower (2019).

-Scott Witts

### 14. Methodology:

#### Collection of data

In order to develop or see a need to develop the steering and suspension the current characteristics must be taken in to account. To do this measurements of the vehicle will need to be taken. These measurements taken from the vehicle will involve positions of the suspension mounting, corner weights and vehicle dimensions.



Figure 10 Measuring suspension and vehicle dimensions



Figure 9 Measuring suspension and steering positions

-Liam Standing

In images 10 and 9 above the measurements are being taken. The lines marked out on the tape are for a Wingeo model of the car. In image 10 note the line from the front to rear as y (centreline of the car) on the vehicle and the line from wheel centre to wheel centre as x (this is when the steering is central). The measurements of the vehicle dimensions were taken which can be seen in table 3.



Figure 11 Vehicle corner weights

The corner weights of the car were taken with and without a person inside it. This was done with a set of scales and the results of this can be seen in table 4. In image 11 the corners weights and total weight of the vehicle can be seen.

For the following calculations the values of the car and driver will be used as this would be the actual corner weights if the vehicle if used as standard. These will more accurately represent the true characteristics of the vehicle.

In this case the driver weighed 64kg.

The last few measurements needed can be gathered from the model of the vehicle made in Wingeo, a rolling road run of the car and internet research. From the Wingeo model the roll centre can be found (Image 12), on a rolling road the maximum speed can be found (image 13) and from the internet research the tightest corner out of all the Greenpower circuits can be found. This information can be seen in table 3.

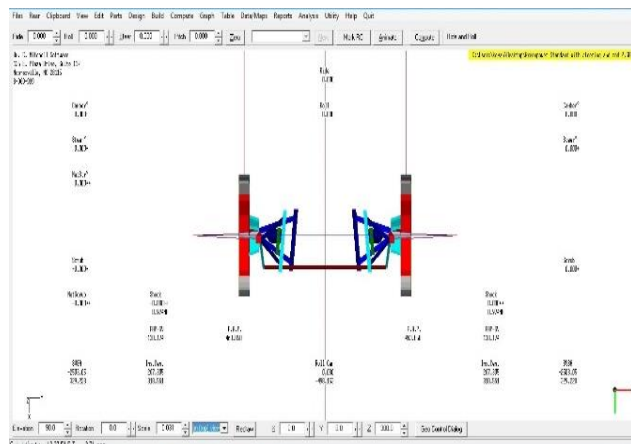


Figure 12 Wingeo model

-Liam Standing



Figure 13 rolling road run showing top speed of 30km/h, UWTSD Dyno Technician

-Liam Standing

**Measurements taken from the vehicle.**

| Symbol | Measurement              | Imperial (lb, ft) | Metric (kg, m) |
|--------|--------------------------|-------------------|----------------|
| Tf     | Front Track              | 2.7427822         | 0.836          |
| Tr     | Rear track               | 2.62467           | 0.8            |
| L      | Wheel base               | 4.5226378         | 1.3785         |
| Rrf    | Rolling Radius front d/2 | 0.74475066        | 0.227          |
| Rrr    | Rolling Radius rear      | 0.74475066        | 0.227          |

Table 3 measurement from Greenpower car

In table 3 above shows the recorded measurements taken from the vehicle. These measurements were taken in the workshop while also gathering Wingeo positions of the suspension mounting and steering. The method of how this data was collected is explained prior and seen in image 10 and 9.

| Symbol | Measurement                  | Imperial (lb, ft) | Metric (kg, m) |
|--------|------------------------------|-------------------|----------------|
| wf     | total weight front           | 152.119           | 69             |
| wr     | total weight rear            | 173.0629          | 78.5           |
| tw     | total vehicle weight         | 325.1819          | 147.5          |
| wfl    | f left corner weight static  | 76.05948          | 34.5           |
| wfr    | f right corner weight static | 76.05948          | 34.5           |
| wrl    | r left corner weight static  | 85.9803           | 39             |
| wrr    | r right corner weight static | 87.08259          | 39.5           |

Table 4 Greenpower car weights with driver

Measurements seen in table 4 are the four corner weights of the vehicle. These were recorded from the corner scales discussed prior and seen in image 3.

| Symbol | Measurement                                 | Imperial (lb, ft) | Metric (kg, m) |
|--------|---------------------------------------------|-------------------|----------------|
| R      | corner radius                               | 49.2126           | 15             |
| v      | speed                                       | 27.88714          | 8.5            |
| g      | gravity                                     | 32.2              | 9.81           |
| hf     | Height of Front roll centre above ground    | 0.0984252         | 0.03           |
| hr     | Height of Rear roll centre above ground [m] | 0.0984252         | 0.03           |

Table 5

Table 5 above shows other relevant information used in the calculations for steering and suspension. The car must be able to steer around the tightest corner of all the circuits that it participates in. From looking at the circuits the tightest corner would be a 15 meter radius corner at the Grampian Transport museum (GTM, 2019) in Alford. This track (410m length) is an oval and with two of these 15 meter radius corners ( $R=15$ ). The aim would be that on this corner the car would be traveling at full speed. On a rolling road run of the Greenpower the maximum speed reached was 30.6km/h (Image 13). Hence this in the form of meters per second has been used, 8.5m/s in Table 3. This has a slight overestimation of the vehicles top speed as the rolling road doesn't provide air resistance than the car has to overcome. Gravity is the acceleration due to gravity.  $H_f$  and  $H_r$  are the Wingeo calculations for the height of the front and rear roll centres (Image 12).

-Liam Standing

### Ackermann steering

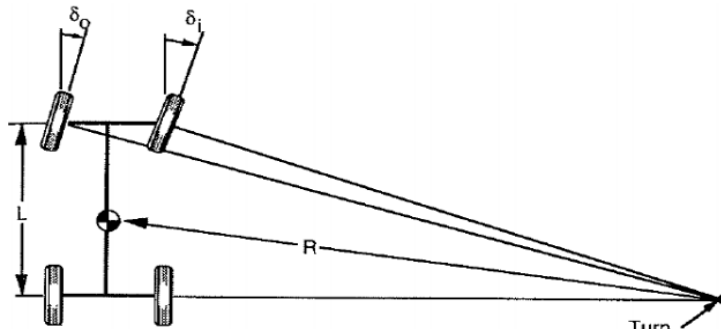


Figure 14, Gillespie Ackermann steering fig6.1 pp 197, 1992

To find the angle of the wheels the Ackermann equations below has been used for the inside wheel (Equation 1), outside wheel (Equation 2) and the Ackermann angle (Equation 3). The results of these calculations can be seen in Table 4.

$$\text{Equation 1} \quad \delta_i = \frac{L}{\left(R - \frac{T_f}{2}\right)}$$

$$\text{Equation 2} \quad \delta_o = \frac{L}{\left(R + \frac{T_f}{2}\right)}$$

$$\text{Equation 3} \quad \delta = \frac{L}{R}$$

| Symbol     | Measurement           | Imperial (lb, ft) | Metric (kg, m) |
|------------|-----------------------|-------------------|----------------|
| $\delta_o$ | outside steer angle   | 0.089408481       | 0.089408484    |
| $\delta_i$ | inside steer angle    | 0.094534354       | 0.094534357    |
| $\delta$   | ackermann angle (L/R) | 0.091899997       | 0.0919         |

Table 6 Steering angles of the wheels (Radians)

Values in table 4 are expressed in radians and note the values should be the same between imperial and metric, the slight difference is down to conversions of units.

## Steady state cornering at high speeds

For steady state cornering as the speed increases characteristics can change. This can be down to lateral acceleration, roll and weight transfer amongst other things. Find these other information has to be calculated such as equations 4-9 shown below.

$$\text{Equation 4} \quad b = \frac{swf * L}{tsw}$$

$$\text{Equation 5} \quad c = L - b$$

| Symbol | Measurement         | Imperial (lb, ft) | Metric (kg, m) |
|--------|---------------------|-------------------|----------------|
| swf    | sprung weight front | 149.719           | 66.6           |
| swr    | sprung weight rear  | 170.6629          | 76.1           |
| tsw    | total sprung weight | 320.3819          | 142.7          |
| b      | front L to cg       | 2.409145094       | 0.735135599    |
| c      | cg to rear L        | 2.113492706       | 0.643364401    |

Table 7 sprung weights and cg

Table 7 above shows the values of b and c using equations 4 and 5 respectively. To find the sprung weight of the vehicle front and rear the weight of the wheels (1.2kg) has been removed for each corner. Below equations 6-8 have been used to calculate the cornering stiffness, the results of which are in Table 6.

$$\text{Equation 6} \quad fy = \frac{tw * v^2}{R}$$

$$\text{Equation 7} \quad fyr = \frac{tw * b}{L * (\frac{v^2}{R})}$$

$$\text{Equation 8} \quad f_{yf} = fy - fyr$$

| Symbol          | Measurement            | Imperial (lb, ft) | Metric (kg, m) |
|-----------------|------------------------|-------------------|----------------|
| f <sub>yf</sub> | front cornering force  | 2401.413529       | 331.5804135    |
| f <sub>yr</sub> | rear cornering force   | 2737.342601       | 378.8779199    |
| f <sub>y</sub>  | sum of cornering force | 5138.75613        | 710.4583333    |

Table 8 cornering forces

Real  $\delta$  (wheel angle) at speed is different to that which is displayed in the Ackermann. The real wheel angle is calculated using equation 9 below.

$$\text{Equation 9} \quad \delta = 57.3 * \frac{L}{R} + \left( \frac{wf}{f_{yf}} - \frac{wr}{f_{yr}} \right) * \frac{v^2}{g * R}$$

Wheel angle from Ackermann =  $5.265482137^\circ$  (table 4 value converted to degrees) and the wheel angle from the equation above (equation 9) gives  $\delta = 5.365690887^\circ$ . As speed increases the difference between these two increases as Ackermann doesn't take in to account the speed.

-Liam Standing

### Understeer, oversteer or neutral.

The ratio between  $k_{wcf}$  and  $k_{wcr}$  gives a characteristic of the steering whether it be understeer, oversteer or neutral steer. The values of these have been calculated from equations 10 and 11 and results shown in table 7.

$$\text{Equation 10} \quad k_{wcf} = \frac{wf}{f_{yf}}$$

$$\text{Equation 11} \quad k_{wcr} = \frac{wr}{f_{yr}}$$

| Symbol    | Measurement                 | Imperial (lb, ft) | Metric (kg, m) |
|-----------|-----------------------------|-------------------|----------------|
| $k_{wcf}$ | f load and corner stiffness | 0.063345608       | 0.208094318    |
| $k_{wcr}$ | r load and corner stiffness | 0.063222959       | 0.207190749    |
| U/N/O     | under neutral or oversteer  | 1.001939938       | 1.004361049    |

Table 9 steering characteristics

In table 9 the UNO values are to represent neutral steer if equal to 1, oversteer if less than 1 and understeer if more than 1. Simply put this shows that there is a very small characteristic in the car to understeer hence this would be classed as neutral steer.

-Liam Standing

### Calculating lateral acceleration, yaw and sideslip angle

$$\text{Equation 12} \quad a_y = \frac{v^2}{R \cdot g}$$

$$\text{Equation 13} \quad K = \left( \frac{wf}{f_{yf}} - \frac{wr}{f_{yr}} \right)$$

$$\text{Equation 14} \quad r = 57.3 \cdot \frac{v}{R}$$

$$\text{Equation 15} \quad r_{gain} = \frac{r}{\delta}$$

$$\text{Equation 16} \quad a_y \text{ gain} = \frac{a_y}{\delta}$$

$$\text{Equation 17} \quad B = 57.3 \cdot \frac{c}{R} - wr \cdot \frac{v^2}{f_{yr} \cdot g \cdot R}$$

| Symbol     | Measurement                | Imperial (lb, ft) | Metric (kg, m) |
|------------|----------------------------|-------------------|----------------|
| Kay        | understeer grad * lat accl | 0.145777707       | 0.099820887    |
| $a_y$      | lat accl.                  | 0.490767474       | 0.490995583    |
| K          | understeer gradient        | 0.297040279       | 0.203303024    |
| r          | yaw velocity               | 32.47             | 32.47          |
| r gain     | yaw velocity gain          | 6.000021201       | 6.05141084     |
| $a_y$ gain | Lateral accl gain $a_y/d$  | 0.090687257       | 0.091506498    |
| B          | sideslip angle             | 2.429787792       | 2.355922269    |

Table 10 lateral acceleration, yaw and sideslip angle

Lateral acceleration is calculated as seen equation 12. This equation uses the corner radius hence why the tightest corner has selected to provide the largest possible lateral acceleration the vehicle can experience. From the understeer gradient (equation 3) the values show can be used to determine understeer, oversteer or neutral steer characteristics. When  $k=0$  it's neutral,  $k$  is more than 0 then its

understeer, if more than 0 it's oversteering. With the value shown this is slight understeer as confirmed previously by UNO. The yaw velocity (yaw rate) is calculated using equation 14 to be 32.47 degree/sec. other values from equations 15-17 will be discussed in the results.

-Liam Standing

### Cornering weight transfer

In this section the change in weight between the wheels will be calculated for the corner previously stated.

| Symbol | Measurement                                          | Metric (kg, m) |
|--------|------------------------------------------------------|----------------|
| wtsrcf | Front WT due to sprung mass at RC Height             | 0.218696152    |
| wtsrcr | rear WT due to sprung mass at RC Height              | 0.261136669    |
| WTusf  | Front WT due to Unsprung mass at wheel centre height | 0.059632464    |
| WTusr  | Rear WT due to Unsprung mass at wheel centre height  | 0.062315925    |
| WTsf   | Front weight transfer due to sprung mass [N]         | 0              |
| WTsr   | Rear weight transfer due to sprung mass [N]          | 0              |
| WT f   | Weight transfer front                                | 0.278328616    |
| WT r   | Weight transfer rear                                 | 0.323452594    |
| Fz fl  | Left front vertical force [N]                        | 338.7233286    |
| Fz fr  | Front Right vertical force [N]                       | 338.1666714    |
| Fz rl  | Rear Left vertical force [N]                         | 382.9134526    |
| Fz rr  | Rear Right vertical force [N]                        | 387.1715474    |

Table 11 corner weight transfer

$$\text{Equation 18} \quad WTf = WTsrf + WTusf + WTsf$$

$$\text{Equation 19} \quad WTr = WTsrr + WTusr + WTsr$$

$$\text{Equation 20} \quad WTsrf = \frac{swf * ay * hf}{Tf}$$

$$\text{Equation 21} \quad WTusf = \frac{(wf - swf) * ay * Rrf}{Tf}$$

$$\text{Equation 22} \quad Fzfl = (wfl * g) + WTf$$

$$\text{Equation 23} \quad Fzfr = (wfr * g) - WTf$$

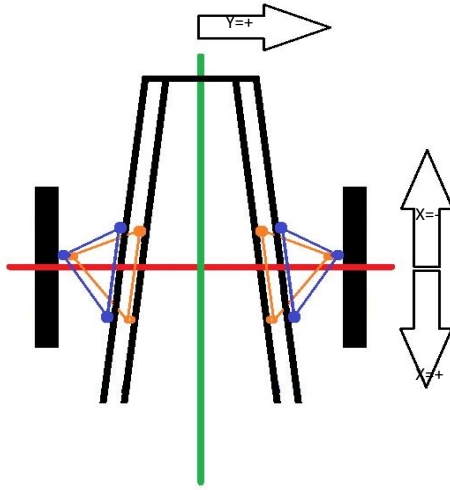
Equations 18 and 19 are for the front and rear weight transfers respectively. In these equations 20 and 21 are required but are shown as required for front calculations. In addition, WTsf is required however is not included as there is no springs on the suspension. From this the corner weights can be calculated using equations 22 and 23. Note that these equations differ depending on the direction of the corner. Such as if the inside wheel in the equation is minus the weight transfer and the outside wheel is positive the weight transfer. Therefore, in table 9 the values show the car turning right (clockwise around the track). Also note in the table the rear values are different due to the 0.5kg weight difference in the rear (Image 11).

This concludes the gathering of data of the standard car which is further discussed in the results section. Next the spreadsheets that has been made for the past

calculations shall be used to test possible developments and other variables that effect the vehicle.

-Liam Standing

### Testing possible improvements



As previously mentioned the measurements seen in image 10 and 9 had a line from wheel centre left to wheel centre right and a centreline perpendicular to it. As seen in image 15 these two lines are the x (red) and y (green) respectively. In Image 6 a negative value of x means the position/distance from the x line is in front of the vehicle. A positive x value is position/distance from the x line towards the rear of the vehicle. When  $x=0$  the item is on the x line. Y is positive in all cases as a negative y would be the opposite wheel as it would fall on the other side of the y line. Also, the lower A arm is orange and the upper is blue.

Figure 15 diagram of measurements on Greenpower

The first possible improvements to consider are what results come from changing the positioning of the mounting points of the A arms in relation to the standard chassis. As the car gets narrower to the front of the chassis the track and wheelbase change in relation to mounting points of the A arms. The standard car positions of the can be seen in table 12 below.

| LOWER                            |       | STANDARD SETUP 1 |
|----------------------------------|-------|------------------|
| distance between mounting points | Lax   | 163.9            |
| front mount from x               | Lafx  | -64.7            |
| ball joint from x                | Labjx | -8               |
| rear mounting from x             | Larx  | 99.2             |
| front mount from y               | Lafy  | 163.25           |
| ball joint from y                | Labjy | 368              |
| rear mounting from y             | Lary  | 180.75           |
| UPPER                            |       | STANDARD SETUP 1 |
| distance between mounting points | Tax   | 165.1            |
| front mount from x               | Tafx  | -59.8            |
| ball joint from x                | Tabjx | 16               |
| rear mounting from x             | Tarx  | 105.3            |
| front mount from y               | Tafy  | 218.25           |
| ball joint from y                | Tabjy | 332              |
| rear mounting from y             | Tary  | 235.76           |

Table 12 , mounting positions of A arms to chassis (mm)

In table 10 the standard positions of the upper and lower A arms are shown as well as the distance between the front and rear points to chassis (Tax and Lax) in the x axis. This distance will remain fixed as this would mean the original A arms can be used. The ball joint mentioned in upper and lower is where the A arms connect to the top and bottom of the wheel hub. These will move relative to the mounting points on the chassis.

-Liam Standing

### Setup 2: Equal front and rear track.

Using simple triangle trigonometry for the positions mentioned in table 10 a triangle for the chassis mounting positions and angles has been produced for the upper and lower A arms. These angles and side lengths can be seen in table 11. Note that in this table side “a” is the calculated distance between the front and rear centre mounting points along the chassis frame that can be seen in image 15. Side “b” is the x distance between the front and rear mounting points noted as Lax and Tax. Side “c” is the change in y distance between front and rear. Angles “ab” and “ac” are calculated while angle “bc” is 90° due to the x and y lines being perpendicular.

|          | Lower     | Upper     |
|----------|-----------|-----------|
| a        | 164.83161 | 166.02593 |
| b        | 163.9     | 165.1     |
| c        | 17.5      | 17.51     |
| angle ac | 83.905    | 83.946    |
| angle ab | 6.095     | 6.054     |
| angle bc | 90        | 90        |

Table 13 trigonometric of the upper and lower A arms (mm and degrees)

From table 3 the difference from the Tf to Tr is 0.036m (36mm) to make these equal the Tf will have to be reduced 0.018m (18mm) in y axis on each side of the front. Using the relationship in table 11 the positions for both A arms at the same track can be seen in table 12.

|                                  |       | Setup 1          | Setup 2          | Setup 3        | Setup 4        |
|----------------------------------|-------|------------------|------------------|----------------|----------------|
| LOWER                            |       | STANDARD SETUP   | SETUP (y=-36)    | SETUP (X=+100) | SETUP (X=-500) |
| Change in x                      | X     | 0                | -168.582857      | 100            | -500           |
| change in y                      | Y     | 0                | -18              | 10.67724222    | -53.3862111    |
| distance between mounting points | Lax   | 163.9            | 163.9            | 163.9          | 163.9          |
| front mount from x               | Lafx  | -64.7            | -233.282857      | 35.3           | -564.7         |
| ball joint from x                | Labjx | -8               | -176.582857      | 92             | -508           |
| rear mounting from x             | Larx  | 99.2             | -69.38285704     | 199.2          | -400.8         |
| front mount from y               | Lafy  | 163.25           | 145.25           | 173.9272422    | 109.8637889    |
| ball joint from y                | Labjy | 368              | 350              | 378.6772422    | 314.6137889    |
| rear mounting from y             | Lary  | 180.75           | 162.75           | 191.4272422    | 127.3637889    |
| UPPER                            |       | STANDARD SETUP 1 | SETUP 2 (X=-360) | SETUP (X=-100) | SETUP (X=-500) |
| Change in x                      | X     | 0                | -168.582857      | 100            | -500           |
| change in y                      | Y     | 0                | -18              | 10.67724222    | -53.3862111    |
| distance between mounting points | Tax   | 165.1            | 165.1            | 165.1          | 165.1          |
| front mount from x               | Tafx  | -59.8            | -228.382857      | 40.2           | -559.8         |
| ball joint from x                | Tabjx | 16               | -152.582857      | 116            | -484           |
| rear mounting from x             | Tarx  | 105.3            | -63.28285704     | 205.3          | -394.7         |
| front mount from y               | Tafy  | 218.25           | 200.25           | 228.9272422    | 164.8637889    |
| ball joint from y                | Tabjy | 332              | 314              | 342.6772422    | 278.6137889    |
| rear mounting from y             | Tary  | 235.76           | 217.76           | 246.4372422    | 182.3737889    |

Table 14 front track changes and respective suspension positioning

Note that the deduction of track to be equal front to rear can be achieved by moving the x positions forward 168.582857mm. This therefore increases the wheelbase by this amount.

-Liam Standing

### Setup 3: maximum front track

In table 12 the change for maximum track is shown as moving the x positions 100mm (wheelbase reduced) towards the rear of the car. Any further back and the chassis frame is restricted. This has the effect of increasing the track (change in y) by 10.67724222mm on each side of the front wheels. This results in a track of 0.8573544844m ( $0.836\text{m} + 0.0213544844\text{m}$ ). Positions of the A arms can be seen in table 12.

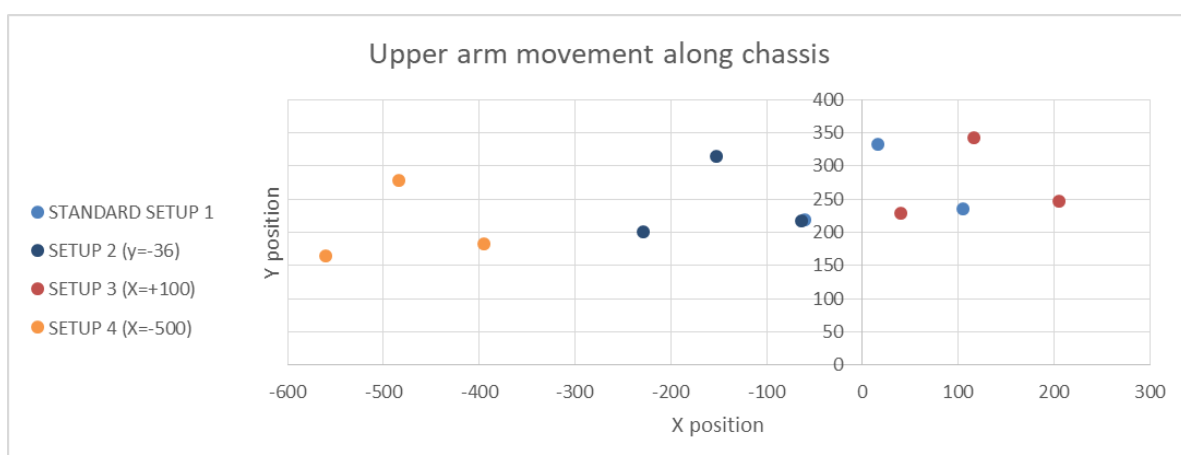
-Liam Standing

### Setup 4: minimum front track

For minimum track the x positions have been moved 500mm (wheelbase increase) towards the front of the car. This is as far forward the A arms can be without changing or adapting the vehicle chassis. This reduces the track as seen in table 12 by 53.3862111mm on each side resulting in a track of 0.7232275778m ( $0.836\text{m} - 0.1127724222\text{m}$ ). These positions can also be seen in table 12.



graph 2 lower arm positions in relation front track changes using existing chassis



graph 1 upper arm positions in relation front track changes using existing chassis

Graphs 1 and 2 show the positions of A arm mounting of setups 1 to 4. Note that the two graphs are similar apart from the distance between y positions on the upper arm

are shorter as the chassis sticks out more at the top. See image 1 and 2. For more clarification on the positions outlined in graphs 1 and 2 see image 6.

-Liam Standing

#### Setup 5: Largest wheels

Using the standard set up the radius of the tyres can be changed to see the effect this has on the vehicle characteristics and cornering forces. The maximum diameter wheels in accordance to the current regulations (Greenpower, 2019) is 520mm. This would be a setup 5 and the value changed is the rolling radius in table 1 would change to 0.26m.

#### Setup 6: Smallest wheels

Following suit to setup 5 the smallest radius wheel will also be calculated to see variation compared to the standard characteristics and cornering forces. In accordance to regulations (Greenpower, 2019) the minimum diameter is 300mm giving a rolling radius of 0.15m in table 1.

#### Setup 7: Speed increase by 10km/h

This would be a speed increase from 8.5m/s in table 3 to 11.2788m/s or 40.6km/h. This would show that if the vehicles speed can be increased without changing the other variables then this would be approximate changes in characteristics and forces.

#### Setup 8: Speed increase by 20km/h

This follows suit of setup 7 by increasing the speed from 8.5m/s to 14.0555m/s or 50.6km/h. using this setup, setup7 and setup 1 the trends between speeds can be found.

#### Setup 9: Driver weight increase

As the percentage corner weight change is known when the car has a driver or not the increase of driver weight can be distributed using this percentage. For this set up the driver weight has been increased by 10kg to 74kg and distributed. The front left (wfl) and right (wfr) corner weights both change from 34.5kg to 37.546875kg. The rear left (wrl) changes from 39kg to 40.93925kg and the rear right (wrr) corner weight changes from 39.5kg to 41.43925kg. These would be seen in table 2.

#### Setup 10: Speed increase by 10km/h and driver weight increase

This is comprising setup 7 and setup 9 together

#### Setup 11: Speed increase by 20km/h and driver weight increase

Similar to setup 10 this setup comprises of a mixture of setup 8 and setup 9.

-Liam Standing

## 15. Results:

### Gathering testing results

All the setups from 2 to 11 are compared to the standard set up as seen in table 13 in the results section. Some benefits by using this system include. Setups 2-8 is based on the vehicle weight being the same. This would be true in the case of 2, 3 and 4 as the mounting points of the original A arms are being moved hence no different components. In cases 5 and 6 as long as the same weight of wheel is used the calculations are not affected. Similar in cases 7-8 if the vehicle speed can be improved while keeping the weight the same.

-Liam Standing

### Results

| Symbol         | Measurement                                          | Setup 1     | Setup 2     | Setup 3     | Setup 4     | Setup 5     | Setup 6     | Setup 7     | Setup 8     | Setup 9     | Setup 10    | Setup 11    |
|----------------|------------------------------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| metric (kg, m) |                                                      |             |             |             |             |             |             |             |             |             |             |             |
| TT             | Front Track                                          | 0.836       | 0.8         | 0.857354484 | 0.723227578 | 0.836       | 0.836       | 0.836       | 0.836       | 0.836       | 0.836       | 0.836       |
| Tr             | Rear track                                           | 0.8         | 0.8         | 0.8         | 0.8         | 0.8         | 0.8         | 0.8         | 0.8         | 0.8         | 0.8         | 0.8         |
| L              | Wheel base                                           | 1.3785      | 1.5585      | 1.2785      | 1.8785      | 1.3785      | 1.3785      | 1.3785      | 1.3785      | 1.3785      | 1.3785      | 1.3785      |
| Rrf            | Rolling Radius front d/2                             | 0.227       | 0.227       | 0.227       | 0.227       | 0.26        | 0.15        | 0.227       | 0.227       | 0.227       | 0.227       | 0.227       |
| Rrr            | Rolling Radius rear                                  | 0.227       | 0.227       | 0.227       | 0.227       | 0.26        | 0.15        | 0.227       | 0.227       | 0.227       | 0.227       | 0.227       |
| R              | corner radius                                        | 15          | 15          | 15          | 15          | 15          | 15          | 15          | 15          | 15          | 15          | 15          |
| V              | speed                                                | 8.5         | 8.5         | 8.5         | 8.5         | 8.5         | 8.5         | 11.27778    | 14.05556    | 8.5         | 11.27778    | 14.05556    |
| g              | gravity                                              | 9.81        | 9.81        | 9.81        | 9.81        | 9.81        | 9.81        | 9.81        | 9.81        | 9.81        | 9.81        | 9.81        |
| do             | outside steer angle                                  | 0.089408484 | 0.101201299 | 0.082865172 | 0.122285329 | 0.089408484 | 0.089408484 | 0.089408484 | 0.089408484 | 0.089408484 | 0.089408484 | 0.089408484 |
| di             | inside steer angle                                   | 0.094534357 | 0.106746575 | 0.087740833 | 0.128326987 | 0.094534357 | 0.094534357 | 0.094534357 | 0.094534357 | 0.094534357 | 0.094534357 | 0.094534357 |
| d (L/R)        | ackermann angle                                      | 0.0919      | 0.1039      | 0.085233333 | 0.125233333 | 0.0919      | 0.0919      | 0.0919      | 0.0919      | 0.0919      | 0.0919      | 0.0919      |
| d degrees      | ackermann angle degrees                              | 5.265482138 | 5.953031493 | 4.883510275 | 7.175341456 | 5.265482138 | 5.265482138 | 5.265482138 | 5.265482138 | 5.265482138 | 5.265482138 | 5.265482138 |
| wf             | total weight front                                   | 69          | 69          | 69          | 69          | 69          | 69          | 69          | 69          | 75.09375    | 75.09375    | 75.09375    |
| wr             | total weight rear                                    | 78.5        | 78.5        | 78.5        | 78.5        | 78.5        | 78.5        | 78.5        | 78.5        | 82.3785     | 82.3785     | 82.3785     |
| tw             | total vehicle weight                                 | 147.5       | 147.5       | 147.5       | 147.5       | 147.5       | 147.5       | 147.5       | 147.5       | 157.47225   | 157.47225   | 157.47225   |
| swf            | spring weight front                                  | 66.6        | 66.6        | 66.6        | 66.6        | 66.6        | 66.6        | 66.6        | 66.6        | 72.69375    | 72.69375    | 72.69375    |
| swr            | spring weight rear                                   | 76.1        | 76.1        | 76.1        | 76.1        | 76.1        | 76.1        | 76.1        | 76.1        | 79.9785     | 79.9785     | 79.9785     |
| tsw            | total sprung weight                                  | 142.7       | 142.7       | 142.7       | 142.7       | 142.7       | 142.7       | 142.7       | 142.7       | 152.67225   | 152.67225   | 152.67225   |
| bs             | front L to cg                                        | 0.735135599 | 0.83112719  | 0.681806938 | 1.001778907 | 0.735135599 | 0.735135599 | 0.735135599 | 0.735135599 | 0.722137535 | 0.722137535 | 0.722137535 |
| c              | cg to rear L                                         | 0.643364401 | 0.72737281  | 0.596693062 | 0.876721093 | 0.643364401 | 0.643364401 | 0.643364401 | 0.643364401 | 0.656362465 | 0.656362465 | 0.656362465 |
| lyf            | front cornering force                                | 331.5804135 | 331.5804135 | 331.5804135 | 331.5804135 | 331.5804135 | 331.5804135 | 331.5804135 | 331.5804135 | 361.149976  | 361.149976  | 361.149976  |
| lyr            | rear cornering force                                 | 378.8779199 | 378.8779199 | 378.8779199 | 378.8779199 | 378.8779199 | 378.8779199 | 378.8779199 | 378.8779199 | 397.3413599 | 397.3413599 | 397.3413599 |
| ly             | sum of cornering force                               | 710.4583333 | 710.4583333 | 710.4583333 | 710.4583333 | 710.4583333 | 710.4583333 | 710.4583333 | 710.4583333 | 758.4913375 | 758.4913375 | 758.4913375 |
| bs             | steering angle                                       | 5.365690887 | 6.05290887  | 4.983690887 | 7.27590887  | 5.365690887 | 5.365690887 | 5.365690887 | 5.365690887 | 5.33273905  | 5.33273905  | 5.33273905  |
| kwdc           | f load and corner stiffness                          | 0.208094318 | 0.208094318 | 0.208094318 | 0.208094318 | 0.208094318 | 0.208094318 | 0.208094318 | 0.208094318 | 0.207929544 | 0.207929544 | 0.207929544 |
| kwer           | r load and corner stiffness                          | 0.207190749 | 0.207190749 | 0.207190749 | 0.207190749 | 0.207190749 | 0.207190749 | 0.207190749 | 0.207190749 | 0.207324251 | 0.207324251 | 0.207324251 |
| UN/O           | under neutral or oversteer                           | 1.004361049 | 1.004361049 | 1.004361049 | 1.004361049 | 1.004361049 | 1.004361049 | 1.004361049 | 1.004361049 | 1.002919543 | 1.002919543 | 1.002919543 |
| Kay            | understeer grad * lat accel                          | 0.099820887 | 0.099820887 | 0.099820887 | 0.099820887 | 0.099820887 | 0.099820887 | 0.099820887 | 0.099820887 | 0.06689905  | 0.06689905  | 0.06689905  |
| ay             | lat accel. (v^2/Rg)                                  | 0.490995583 | 0.490995583 | 0.490995583 | 0.490995583 | 0.490995583 | 0.490995583 | 0.490995583 | 0.490995583 | 0.864344694 | 0.864344694 | 0.864344694 |
| K              | understeer gradient                                  | 0.203303024 | 0.203303024 | 0.203303024 | 0.203303024 | 0.203303024 | 0.203303024 | 0.203303024 | 0.203303024 | 0.136190735 | 0.136190735 | 0.136190735 |
| Vchar          | characteristic speed                                 | 61.73668132 | 65.64373721 | 59.45525705 | 72.06850193 | 61.73668132 | 61.73668132 | 61.73668132 | 61.73668132 | 75.42953723 | 75.42953723 | 75.42953723 |
| ay G1.1        | Lateral accel gain ay/d                              | 0.091506498 | 0.081121174 | 0.098520473 | 0.067484393 | 0.091506498 | 0.091506498 | 0.091506498 | 0.091506498 | 0.092071931 | 0.092071931 | 0.092071931 |
| r              | yaw velocity                                         | 32.47       | 32.47       | 32.47       | 32.47       | 32.47       | 32.47       | 32.47       | 32.47       | 43.0811196  | 43.0811196  | 43.0811196  |
| o/s 1          | yaw velocity gain                                    | 6.05141084  | 5.364024397 | 6.51251595  | 4.46290642  | 6.05141084  | 6.05141084  | 6.05141084  | 6.05141084  | 6.088803465 | 6.088803465 | 6.088803465 |
| B              | slip angle                                           | 2.355922269 | 2.676834392 | 2.177637756 | 3.247344833 | 2.355922269 | 2.355922269 | 2.355922269 | 2.355922269 | 2.405993225 | 2.405993225 | 2.405993225 |
| slip=0         | velocity at zero sideslip                            | 41.77872169 | 44.42272194 | 40.23482511 | 48.77051731 | 41.77872169 | 41.77872169 | 41.77872169 | 41.77872169 | 42.18956646 | 42.18956646 | 42.18956646 |
| do             | outside wheel angle                                  | 5.109143707 | 5.78732868  | 4.737020207 | 6.971819282 | 5.109143707 | 5.109143707 | 5.109143707 | 5.109143707 | 5.109143707 | 5.109143707 | 5.109143707 |
| di             | inside wheel angle                                   | 5.400370615 | 6.09305504  | 5.01438195  | 7.31262853  | 5.400370615 | 5.400370615 | 5.400370615 | 5.400370615 | 5.400370615 | 5.400370615 | 5.400370615 |
| wf             | f left corner weight static                          | 34.5        | 34.5        | 34.5        | 34.5        | 34.5        | 34.5        | 34.5        | 34.5        | 37.546875   | 37.546875   | 37.546875   |
| wr             | r left corner weight static                          | 34.5        | 34.5        | 34.5        | 34.5        | 34.5        | 34.5        | 34.5        | 34.5        | 37.546875   | 37.546875   | 37.546875   |
| wf             | f right corner weight static                         | 39          | 39          | 39          | 39          | 39          | 39          | 39          | 39          | 40.93925    | 40.93925    | 40.93925    |
| wr             | r right corner weight static                         | 39.5        | 39.5        | 39.5        | 39.5        | 39.5        | 39.5        | 39.5        | 39.5        | 41.43925    | 41.43925    | 41.43925    |
| uswf           | unsprung weight fl                                   | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         |
| uswr           | unsprung weight fr                                   | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         |
| uswf           | unsprung weight rl                                   | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         |
| uswr           | unsprung weight rr                                   | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         | 1.2         |
| hf             | Height of Front roll centre above ground             | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        |
| hr             | Height of Rear roll centre above ground [m]          | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        | 0.03        |
| wtsrcl         | Front WT due to sprung mass at RC Height             | 0.218696152 | 0.202577654 | 0.229594536 | 0.186433456 | 0.218696152 | 0.218696152 | 0.218696152 | 0.218696152 | 0.240181362 | 0.240181362 | 0.240181362 |
| wtsrcl         | rear WT due to sprung mass at RC Height              | 0.261136669 | 0.231473866 | 0.281152799 | 0.192583586 | 0.261136669 | 0.261136669 | 0.261136669 | 0.261136669 | 0.276141561 | 0.276141561 | 0.276141561 |
| Wtusf          | Front WT due to Unsprung mass at wheel centre height | 0.059632464 | 0.05523739  | 0.062604156 | 0.050835309 | 0.059632464 | 0.059632464 | 0.059632464 | 0.059632464 | 0.060000943 | 0.060000943 | 0.060000943 |
| Wtusr          | Rear WT due to Unsprung mass at wheel centre height  | 0.062315925 | 0.05523739  | 0.067092442 | 0.045956872 | 0.062315925 | 0.062315925 | 0.062315925 | 0.062315925 | 0.062700985 | 0.062700985 | 0.062700985 |
| Wtsf           | Front weight transfer due to sprung mass [N]         | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 0           |
| Wtsr           | Rear weight transfer due to sprung mass [N]          | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 0           | 0           |
| Wtrf           | Weight transfer front                                | 0.278328616 | 0.257815045 | 0.292198901 | 0.237268765 | 0.278328616 | 0.278328616 | 0.278328616 | 0.278328616 | 0.300182304 | 0.300182304 | 0.300182304 |
| Wtrr           | Weight transfer rear                                 | 0.232452594 | 0.286711256 | 0.348245241 | 0.238540458 | 0.232452594 | 0.232452594 | 0.232452594 | 0.232452594 | 0.238842546 | 0.238842546 | 0.238842546 |
| Fz f           | Left front vertical force [N]                        | 338.7233286 | 338.7233286 | 338.7233286 | 338.7233286 | 338.7233286 | 338.7233286 | 338.7233286 | 338.7233286 | 338.7233286 | 338.7233286 | 338.7233286 |
| Fz r           | Right front vertical force [N]                       | 338.1666714 | 338.1666714 | 338.1666714 | 338.1666714 | 338.1666714 | 338.1666714 | 338.1666714 | 338.1666714 | 338.1666714 | 338.1666714 | 338.1666714 |
| Fz fl          | Left front vertical force [N]                        | 382.9134526 | 382.9134526 | 382.9134526 | 382.9134526 | 382.9134526 | 382.9134526 | 382.9134526 | 382.9134526 | 382.9134526 | 382.9134526 | 382.9134526 |
| Fz rl          | Right front vertical force [N]                       | 387.1715474 | 387.1715474 | 387.1715474 | 387.1715474 | 387.1715474 | 387.1715474 | 387.1715474 | 387.1715474 | 387.1715474 | 387.1715474 | 387.1715474 |
| Fz f           | Left front vertical force kg                         | 34.52837193 | 34.52837193 | 34.52837193 | 34.52837193 | 34.52837193 | 34.52837193 | 34.52837193 | 34.52837193 | 34.52837193 | 34.52837193 | 34.52837193 |
| Fz r           | Right front vertical force kg                        | 34.47162807 | 34.47162807 | 34.47162807 | 34.47162807 | 34.47162807 | 34.47162807 | 34.47162807 | 34.47162807 | 34.47162807 | 34.47162807 | 34.47162807 |
| Fz fl          | Left front vertical force kg                         | 39.03297172 | 39.03297172 | 39.03297172 | 39.03297172 | 39.03297172 | 39.03297172 | 39.03297172 | 39.03297172 | 39.03297172 | 39.03297172 | 39.03297172 |
| Fz rl          | Right front vertical force kg                        | 39.46702828 | 39.46702828 | 39.46702828 | 39.46702828 | 39.46702828 | 39.46702828 | 39.46702828 | 39.46702828 | 39.46702828 | 39.46702828 | 39.46702828 |

Table 15 Setups 1-11 showing all data calculated for analyses

In table 15 the results of setups 1 to 11 are shown using the equations 1-23 and tables 1-9 data dependent on if a setup change affects the data or results in the tables. In table 15 some value are highlighted green, these are values that have changed from the original setup (setup 1). Values shown as white are the same as the original setup. Blue values are inputs for the calculations that can be changed in the table. Out of the

blue values some are red. These highlight the inputs that have been changed in accordance to the setup change.

An analysis of this table (table 15) is carried out in the analysis section.

*-Liam Standing*

## 16. Analysis:

Table 13 of results of different setups shows certain trends.

The Ackermann angle in all the setups is less than the steering angle of the vehicle. As the steering angle considers the speed of the vehicle and the Ackermann angle doesn't it shows that from low speeds to high speeds the steering angle has to increase to go around the same radius. The difference is very small ( $0.5^\circ$  in most of the setups) however the increase in steering input with speed is a characteristic of an understeering vehicle. This is very small understeer so can be classed and neutral steer.

The UNO and K values also back up the claim of the vehicle having a very small understeer if not neutral steer characteristic. However, these aren't all the parts to consider. Roll steer, camber thrust and other variables can cause the vehicle to have a tendency to understeer or oversteer. These other variable can looked in to in future developments.

Accessing K in setup 7 and 8 shows the effect the change of speed has to steering characteristic. From setup 7 to 8 the speed increase while the k value decreases. This shows that as the car currently is if the speed can be increased without changing other variables that the small understeer characteristics can become completely neutral or go oversteer (k goes negative). The K value is also changed in setup 9 as the weight increased the K value became more oversteer. Based on this if the vehicle was lighter the K value would be higher therefore more understeering.

Setups 5 and 6 have little to no effect on the standard vehicle characteristics. With this it shows that the wheel size doesn't benefit the handling from any of the calculations shown. But with larger wheels the motor and gearing can do less rotations to cover the same amount of distance. Hence larger wheels are a benefit as long as the weight is not different.

Setups 2-8 have little to no change on the cornering forces experienced on the wheels. The maximum change from these setups not exceeding 0.1kg. The main changes come in setups 9-11 where the driver's weight is considered which is expected. Hence while cornering the values of corning forces don't change much due to lack of weight transfer due to lack of suspension.

Looking at the track, rolling radius and speed changes the cornering forces and steering angle don't change much. The relationship between wheelbase and steering angle is interesting. The larger the wheelbase the more steering angle is required. All the steering angle at the wheels are very small in all the setups. This means that the steering ratio between the steering wheel and the road wheels would have to be very large to prevent twitchy steering. The steering angle so small that is best to increase

it by increasing the wheelbase (setup 4). With this and increasing the steering ratio the vehicle can have a better handling capability.

-Liam Standing

## 17. Possible implementations to consider:

Increase the wheelbase of the vehicle. Looking at the results and as discussed in the analysis section the best setup would require a larger wheel base than the standard. This will give a larger steering angle in the wheels requiring the steering ratio to be high to control twitchy steering movement. In addition, the ratio will give a driver more control as the feedback is direct linkage steering and a high steering ratio will multiply the input steering force.

The weight seen in setup 9 has a direct trend to cause oversteer in the vehicle. Therefore, the weight of the vehicle must be limited as much as possible. For this the current suspension in use is good. As there is no springs there is a lack of roll in the vehicle. This means that with the lack of roll the weight transfer is less meaning the cornering forces are low.

Rolling radius of the vehicle can be increased to 520mm diameter mentioned in the regulations to give the benefit to the motor and improvement in speed. This can benefit a different section while got giving any improvements to the steering and suspension.

Assumptions include the standard vehicles top speed, Corner measurements, weight differences and rolling radius change.

The standard vehicles top speed was taken as 8.5m/s as noted on the rolling road run in image 5. However, this is not real world as air resistance and wind can cause speed to be less than this. Therefore, an assumption was made that the maximum speed achievable by the standard car would be 8.5m/s.

Corner measurements seen in table 10 are taken as symmetrical about the centerline. This is an assumption as the one corner of the vehicle was measured. Over time the cornering forces on the chassis can cause flex and twist meaning it would be more accurate to measure both left and right. However, as the car is relatively unused the assumption was made that it's symmetrical.

From setups 2-8 the weight of the vehicle does not change. In the case of setups 2-4 the position of the A arms are moved therefore no weight is added or removed. In the case of setups 5 and 6 the wheels are assumed to be the same weight of 1.2kg. 7 and 8 setups results assume the car speed can be increase while keeping the current weight distribution the same.

Lastly in the case of setups 5 and 6 the rolling radius change. However, the speed does not. With larger wheels going the same speed as described as setup 5 the motor of the car would be running a lower rpm, hence using less power. If the motor for setup 5 ran at the same speed with the standard rolling radius the speed would increase from 8.5m/s to 9.73568m/s ( $0.227 \times 2 = 0.454 \times \pi = 1.42683m$   $8.5/1.42683 = 5.95954rps$   $0.26 \times 2 = 0.52 \times \pi = 1.63362m$   $5.95954 \times 1.63362 = 9.73568m/s$ ).

-Liam Standing

## 18. Suspension Geometry:

The chassis on the Greenpower kit car supplied to us for the group project has no actual suspension, it is a solid suspension linkage that is linked together by rose joints. So, for adjusting camber angles and caster angles is only done by taking the linkage apart also the adjustment that can be done are very little because the rose joints don't have a lot of tread on them to adjust. Since the chassis has a solid linkage from the steering to wheels, this means the whole vehicle is not sprung by any suspension where everything is just solid. Race cars and road cars have suspension by damping motions where the suspension components and linkage are unsprung masses and the vehicle itself is the sprung mass, this greenpower chassis differs because now the vehicle has no damping motion because it has no suspension.



For example, components such as springs and dampers in cars giving outcomes like the travel of bump and rebound and how the toe angles and camber angles change throughout this motion are designed for a reason whether it be for comfort reasons or faster cornering. It all depends on what the suspension is designed for like In the BTCC touring cars are made to have little body roll by giving the cars harder springs, lower ride height etc, the outcome is travelling around corners faster. This is totally opposite to a Rolls Royce where they have so much travel and softer damping in the suspension that the body can roll over the tyres smoother in corners and bumps also due to its compliance in the bushings linkage of the suspension. The handling characteristics for either the BTCC touring car and Rolls Royce are totally different because of the way they transfer weight. As said by Allan "weight transfer is affected by roll rate" during cornering and a suspensions "roll velocity" depending on the damping. We know our greenpower car is very stiff as it has a solid suspension linkage from the steering to the wheels as stated above because it uses no bushings to add compliance only nuts, bolts and rose joints where needed to link certain parts so our chassis doesn't roll. Therefore, our greenpower cars only springing motion comes from the deflection of the tyres. So in a greenpower race condition where we want as little rolling resistance as possible, we would have run with high tyre pressures and the tyre deflection would be miniscule so weight transfer of our vehicle couldn't be determined not only we can't

change the setup of the rear of the car because it's a solid rear axle with no adjustments available. This suspension design on the greenpower seriously hinders us from improving the handling of the vehicle drastically so calculating weight transfer from side to side and front to rear to improve this vehicle is pointless with this design. "The ratio of front to rear weight transfer is directly proportional to the ratio of front to rear roll resistance" (Allan. 2006). "This means that the end of the car in which is stiffer will receive a major part of the sprung transferred weight and its exact share will be governed by its stiffness relative to the stiffness of the other end of the car" (Allan. 2006). The statement by Allan doesn't just apply to vehicles which have for example independent suspension designs with travel in there damping but still all major race cars have a certain design for suspending their sprung mass to improve handling by transferring weight front to rear and side to side and distributing roll stiffness front to rear and side to side (roll couple), so while cornering the front of the car may roll less than the rear of the car.

*-Michael Cuniff*

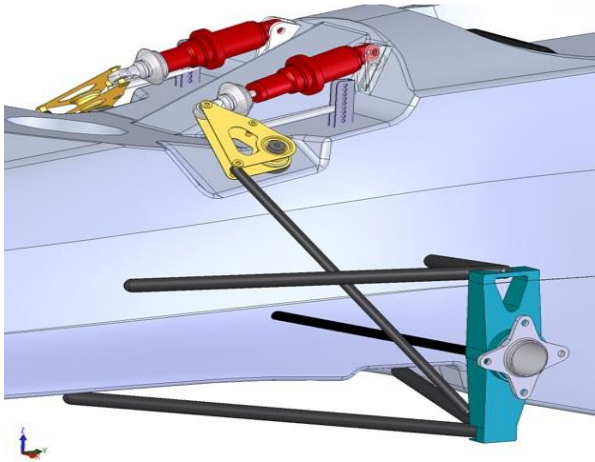
According to (Puhn. 1976) This has a major impact on how the weight transfer is distributed. The distribution of weight alters the vehicles balance which in turn effects the handling performance of the vehicle therefore to improve the vehicles handling ability you must "consider the roll stiffness distribution between front and rear also left and right with the roll angle". As stated above our GreenPower car suspension design doesn't allow for much adjustments and its lack of damping means that it can't transfer weight smoothly which would mean for our group to get some real performance benefits in the greenpower challenge, consideration of redesigning parts of the chassis would have to be done.

*-Michael Cuniff*

Although our greenpower cars travel can't be controlled in a bump and rebound motion due to its design flaws, for the greenpower challenges racing purposes their isn't a reason for the chassis to have suspension as the motor only produces 0.5hp and cant travel more than 30kmh also the tracks the greenpower challenge are raced on are smooth. Initially it is important to know the flaws in our car so that we can understand the best way to improve its performance on a budget and only make improvements where and if necessary. Even though our greenpower chassis has a double wishbone set up like a Formula ford 1600, it lacks the onboard pushrod/rocker arm damper components for suspending the chassis which we don't really need if the car is only travelling 30kph but if at greater speeds them components such as springs and dampers would be needed. For example, the diagram below describes the importance of having each component: "the upper A-arm (upper wishbone) serves to carry some of the load generated on the suspension of the tyre, this force is considerably less than the load carried by the lower A-arm in a pushrod set up". "The arm only has to provide a restoring force to the moment generated by the tyre on the lower ball joint". (John C. 1996)

*-Michael Cuniff*

Examples of double wishbone pushrod suspension.



## Wingeo Software

Another problem we had when trying to define the geometry of our car was when we tried to put the Vehicles parameters into the WinGeo3 software (a kinematic suspension software) that all of our group had previous knowledge of using. The university technician explained that trying to define the car through WinGeo3 would be useless to us because the car doesn't have any suspension components for bump and rebound. The whole point of the WinGeo3 software is to measure a vehicles range of movement and predict handling outcomes and then simulate the collected data to simulate suspension behaviour eg) Bump steer, camber, toe changes. If our greenpower had suspension like the formula ford 1600, we would be able to define the suspensions geometry in depth to have predicted graphs of Camber and toe throughout its travel of bump and rebound which we feel we missed out on. For example, here are a list of kinematic calculations we could have done. (The following calculations were found in RefAutomotive science and mathematics, Published by Routledge. 2008, By Allan W.M. Bonnicksen)

-Michael Cuniff

1) Suspension Leverage (SL) : This is also known as the motion ratio and it is calculated by measuring the change in travel of the wheel divided by the change in damper length or spring travel.

$$SL = \frac{6.2}{2.9} = 2.07$$

2) Wheel rate (KW) : Wheel rate is basically the spring rate but measured at the wheel instead of where the spring attaches the linkage. This is the most accurate

spring rate acting on the tyre. It is the (spring rate) multiplied by the (suspension leverage squared)

$$KW = \frac{KS}{SL^2}$$

3) Natural frequency of the sprung mass/unsprung mass : It is explained as any mass supported by a spring and displaced from its equilibrium position will naturally vibrate with simple harmonic motion. This vibration occurs at a constant frequency and is known as natural frequency. A ride frequency is an undamped natural frequency of the chassis. The higher the frequency the stiffer the ride. So, the weight sits on the springs which are deflected because of the mass on top of them, if the vehicles suspension is to be in a condition where it's at full rebound then it lands then the car will bounce up and down at the spring's natural frequency. "energy is given to the spring by the suspension parts and the road wheels, this motion is then deflected. The wheels try to return back to their original position rebounding the stored energy" (Xu Wang. 2016)

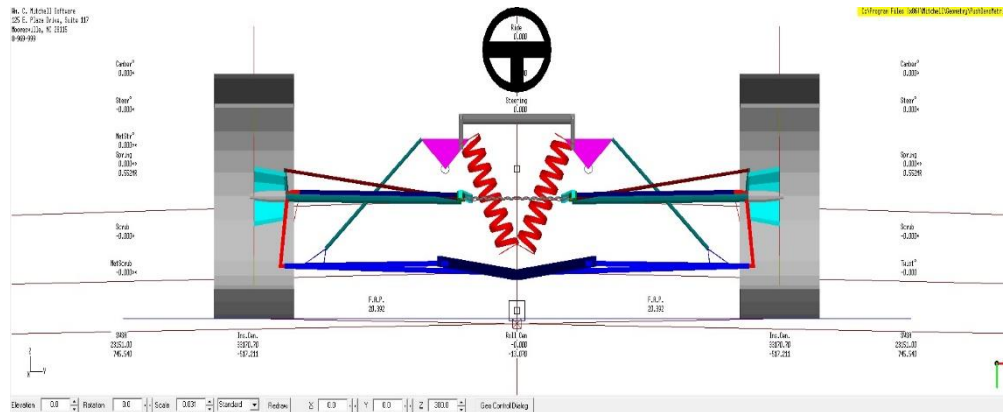
$$F = \frac{1}{2\pi} \sqrt{\frac{KW}{MS}} \quad FUS = \frac{1}{2\pi} \sqrt{\frac{\text{unsprung rate}}{MUS}}$$

It would have been helpful doing some calculations, retrieving some of the data and creating graphs to help present the project better.

The software had limitations which didn't suit our GreenPower car design. The only reason we could have used the software which would have been useful would be to find out the steering angle lock which we decided to measure on turning tables. The scales only went up to 30.9 degrees which our steering lock exceeded so we set the scales to 0 again and turned until full lock was achieved. 30.9 deg + 13.3 deg = 43.2 degrees lock from dead centre. The problem with the lock we had was that the steering turned until the wheel collided with the chassis in which the regs state "the wheel must not collide with the body". Therefore, limits would have to be set on the steering linkage, or a new design developed.

-Michael Cuniff

Example of a WinGeo3 schematic on a double wishbone onboard pushrod suspension



-Michael Cuniff

## 19. Rolling Resistance:

Sometimes called rolling friction is the resistance between an object eg a wheel on a surface. A vehicle rolling will gradually slowdown due to the rolling friction of the rubber on a surface. Since speeds are rarely more than 30kmh, the tyres are very narrow, and the contact patch is very small especially with raised tyre pressures which is very important when it comes to the efficiency of the greenpower car to be sustainable during the race. Tyre manufacturers for greenpower that make the bicycle tyre like Schwalbe suggest "running 85psi to 125psi" because "rolling resistance reduces as tyre pressure increases" (Keun-Wook. 2017). Rolling friction is related to the flex of the tyre walls and the contact area of the tyre. For example at the same psi wider bicycle tyres have less flex in there walls and lower rolling resistance although higher air resistance. Although this would definitely make our car more uncomfortable. When we assembled the greenpower car in the university workshop the tracking of the front end was very unequal so one wheel was toed-out the way whilst the other was toed-in slightly. With one wheel travelling in a different direction than the track of the vehicle gives rise to tyres wearing unevenly and raises friction between tyre and ground which in turn puts more work on the motor and strains our battery.

-Michael Cuniff

## 20. Bodywork aerodynamic:

To take full advantage of the greenpower challenges regs the aero of the car would have to be considered by means of a shaped bodywork on the exterior of the chassis. Motorsport disciplines where the regs are stringent on what can be altered to an engine, dimensions on the car and materials used etc has seen empirical study into how air flows over, around and beneath a race car. The "airfoil" below shows the air moving over and under it and how the front end and rear end shape flows air above and beneath it and the shape creates downforce.

So, to build a race car you must consider the aerodynamic drag and the detrimental effects that downforces and drag (the force needed to push an object through the air must overcome this) would have on our little GreenPower car's motor and battery. The aerodynamic drag or "wind resistance" is equal to the frontal area of the object multiplied by the drag coefficient (this is calculated using the shape of the object) and the speed squared (Joseph. 1995).

*-Michael Cuniff*

### **Tips we should consider when designing the outer body**

Closed wheels or open wheels? Endurance LMP1/2 cars have gone through radical changes over the years by "covering their wheels completely with body work because the wheel moving at high speeds on an open wheels creates distortions in the airflow in the direction flowing over the vehicles". (Joseph. 1995) Closed wheel LMP1 endurance cars have been able to do faster lap times than open wheel formula 1 cars in recent years due mainly due to the extra body work on their cars that shape the air more efficiently which is what we need to use the greenpower car's motor/battery as efficiently as possible. Panel gaps: Since back in the late 60s Le mans endurance cars have been covering any panel gaps with tape for air to not be distorted from the bodywork even when joining panels for maximum efficiency.

*-Michael Cuniff*

## 21. Conclusion:

The outcome from the drivetrain report is that the vehicle would reach 35kph and maintain it for longer if fitted with a speed controller to provide a soft start to the vehicle where the acceleration from stationary is controlled to prevent the motor from stalling or drawing too much current. The speed controller would maintain the motors rpm at 1850rpm with a single fixed gear ratio of 5:1 to provide a speed of 35kph. From the battery discharge results from the dyno testing it is safe to say that the battery discharge rate would be decreased by controlling the initial current draw from stationary to 35kph, the cooling efficiency of the motor would be increased as there was no assist of air from a fan during the dyno test and due to improvements made to the ducting and the use of the passing air at 35kph the cooling system would be more effective at cooling the motor.

*-Scott Witts*

With Regards to energy source which will be necessary to power the 24V DC motor, the Li-ion battery has been proven to be a better alternative for Lead-acid batteries as it has been proven by David Vutetakis, Et al. Greg Albright, Jake Edie, and Said Al-Hallaj. Lead-acid batteries can't operate at high temperature and compared to Li-ion, are heavier. In Contrast, Li-ion cells can offer more power to be used at less weight and at a higher efficiency rate up to a temperature of 45°C.

*-Yousouf Boukra*

With regards to steering, the best possible improvement at this time with the current knowledge and understanding is to move the positions for the mounting points of the chassis to the positions of setup 4 (Table 12). These can be seen in graphs 1 and 2. This does change the track of the front however as seen in the analysis the change in track has a minimal effect of the vehicle characteristics. In conjunction the rolling radius of the wheel would be increased to setup 5 of 520mm diameter.

*-Liam Standing*

The standard chassis of the green power vehicle has proven to be very heavy and could be developed into being a light competitive car. Taking T45 into consideration, after talking to professional contacts such as Darrian cars UK and Ramsport UK, would be the best material to use for the chassis enhancement. This is concluded by analysing its purposes within the motorsport industry and its properties. Aluminium would be the second choice, but this chassis would require more material because of its low strength values compared to the T45 tubing, as mentioned by (Proformance, 2019). If the competing team had a budget, this choice would differ because of the price difference between aluminium and T45. As can be seen on (Aluminiumwarehouse, 2016), structural aluminium can be bought at 2 pound per meter whereas T45, according to Darrian cars UK, is 15 pound per meter.

*-Deion Atkinson*

When looking at the wishbones, weight can be saved by using stronger material and making them out of tubular material. T45 was considered here as well as carbon fibre tubes, both of these materials are widely used for the same application within the motorsport industry. Taking T45 into consideration, it has good weldability and is easy to fabricate as on the other hand, carbon fibre requires years of experience. Similar to the chassis material choice, without a budget the carbon fibre would be chosen as its used within formula one and is lighter than the T45 tubing.

*-Deion Atkinson*

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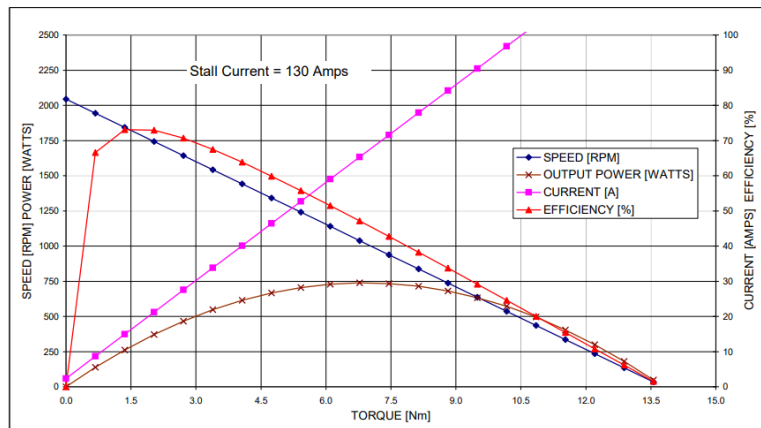
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## Appendices

### Appendix A:

#### Motor performance graph



Scott Witts

Liam Standing

[illegible]

Appendix C:

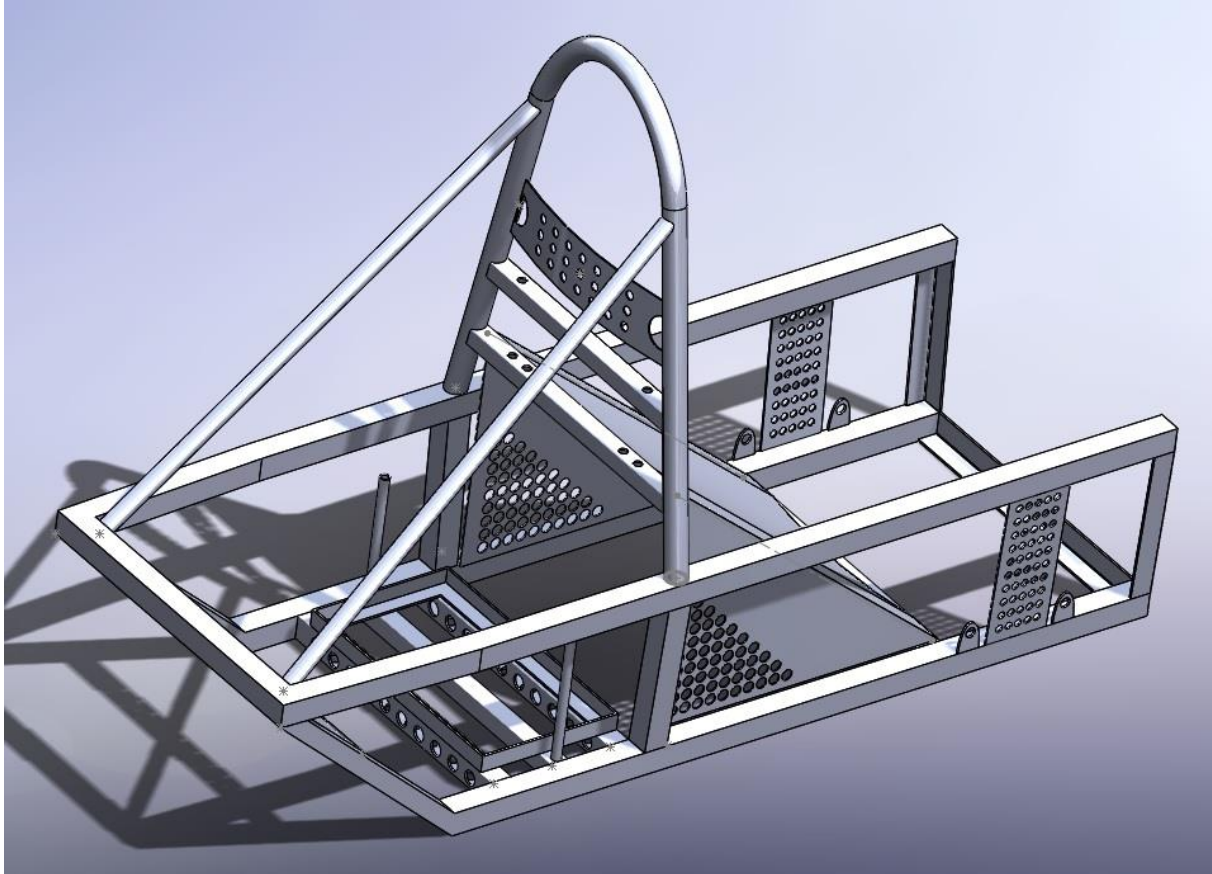
## Greenpower car's regs dimensions

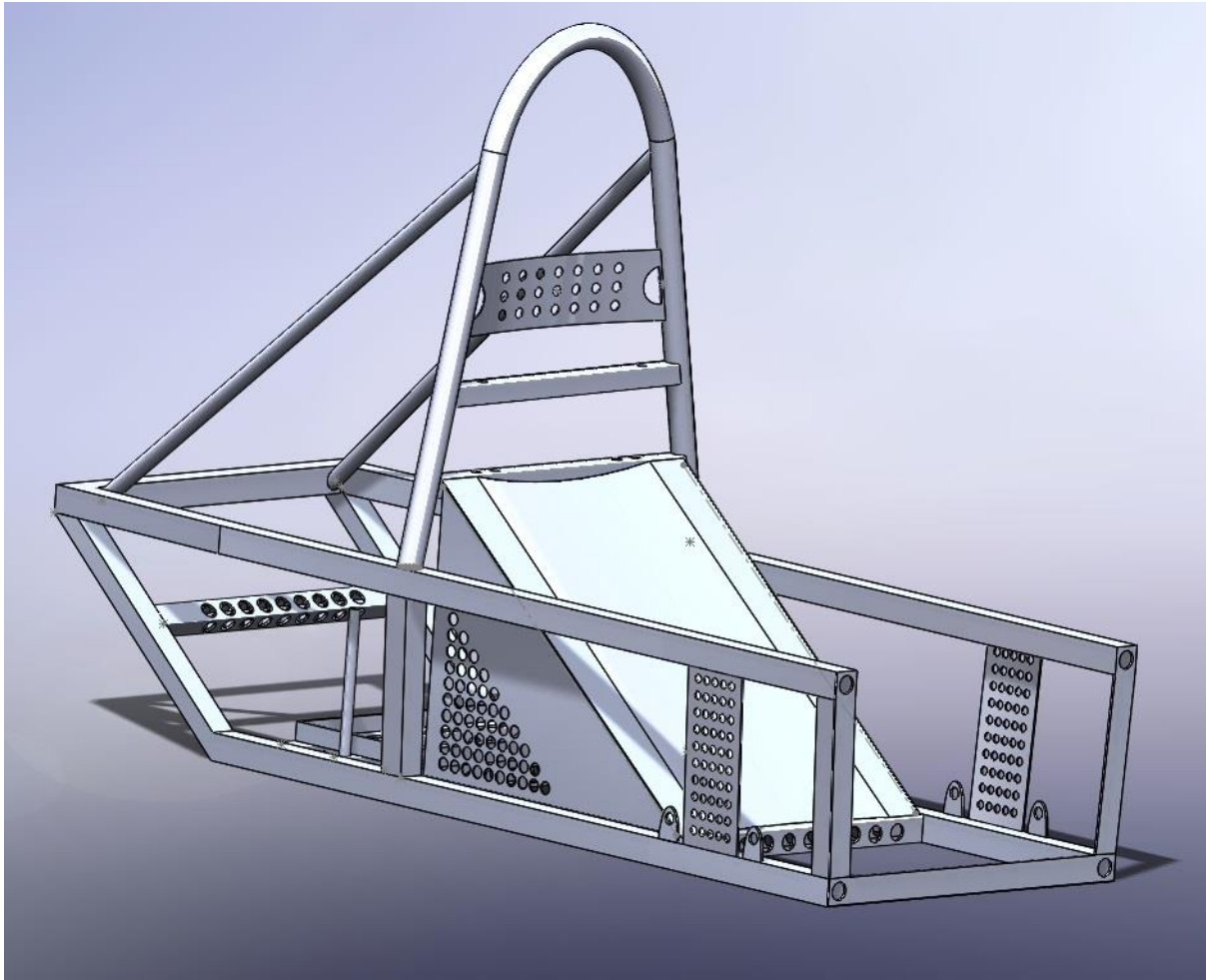
|                  | Regs Dimensions               | Greenpower car supplied dimension       |
|------------------|-------------------------------|-----------------------------------------|
| Vehicle track    | Must no be >500mm             | Track rear = 850mm, Track front = 875mm |
| Vehicle length   | Must not be <2800mm           | Vehcile length = 2150mm                 |
| Vehicle width    | Must not be <1200mm           | Vehicle width = 880mm                   |
| Vehicle height   | Must not be <1200mm           | Vehicle height = 995mm                  |
| Ground clearance | Must not be >30mm             | Ground clearance = 50mm                 |
| Tyre diameter    | Must not be >300mm nor <520mm | Tyre diameter = 406mm                   |
| Wheel size       | Must not be <20"              | Wheel size = 20"                        |

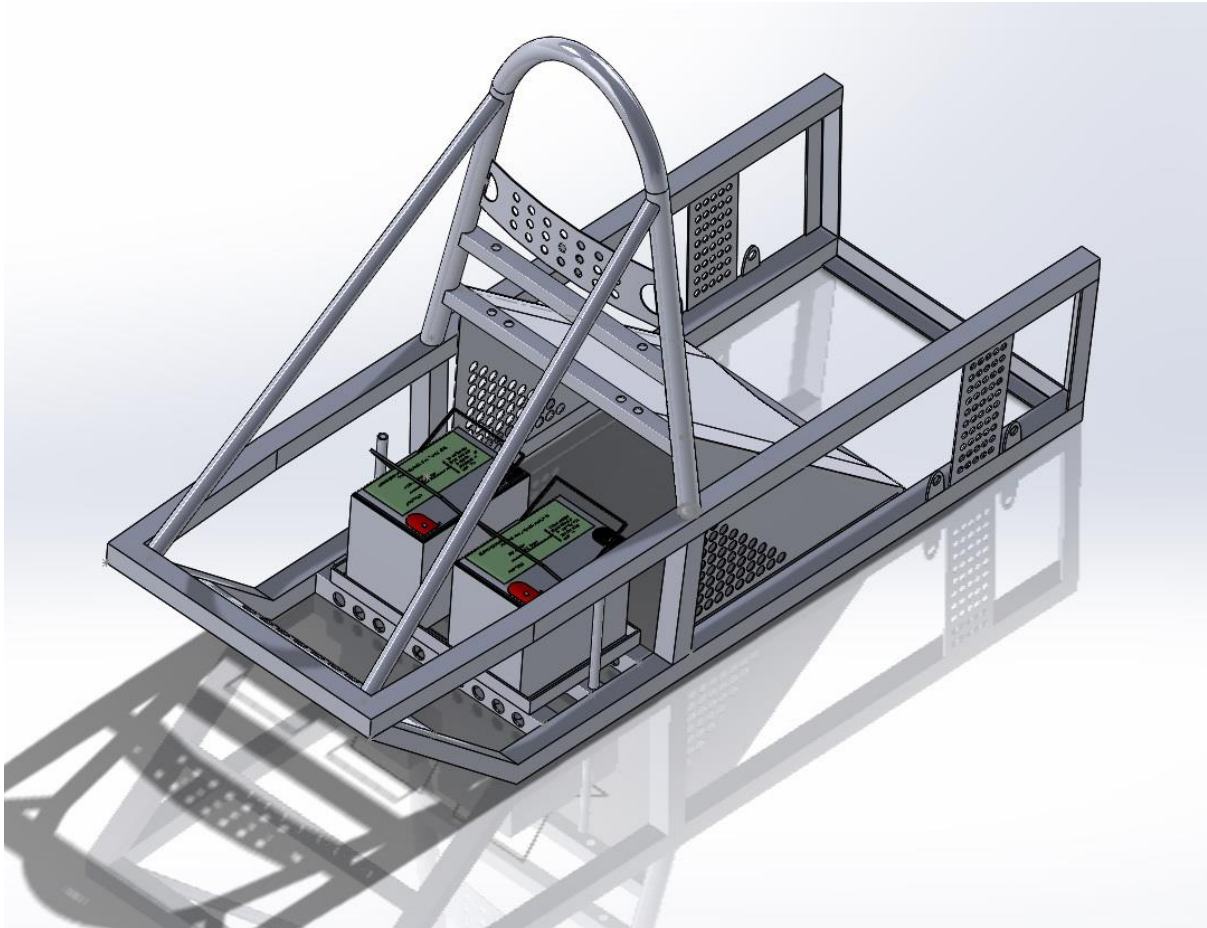
Michael Cuniff

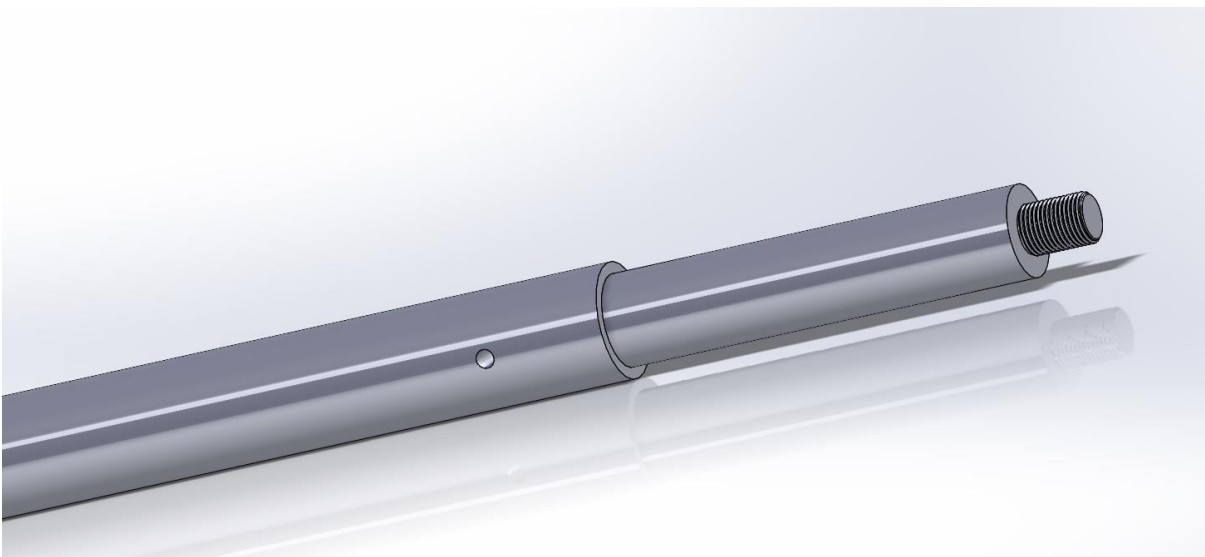
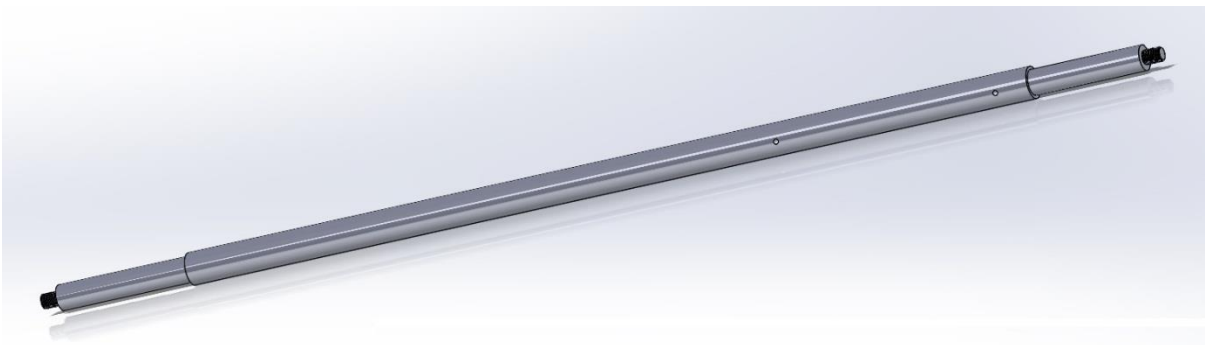
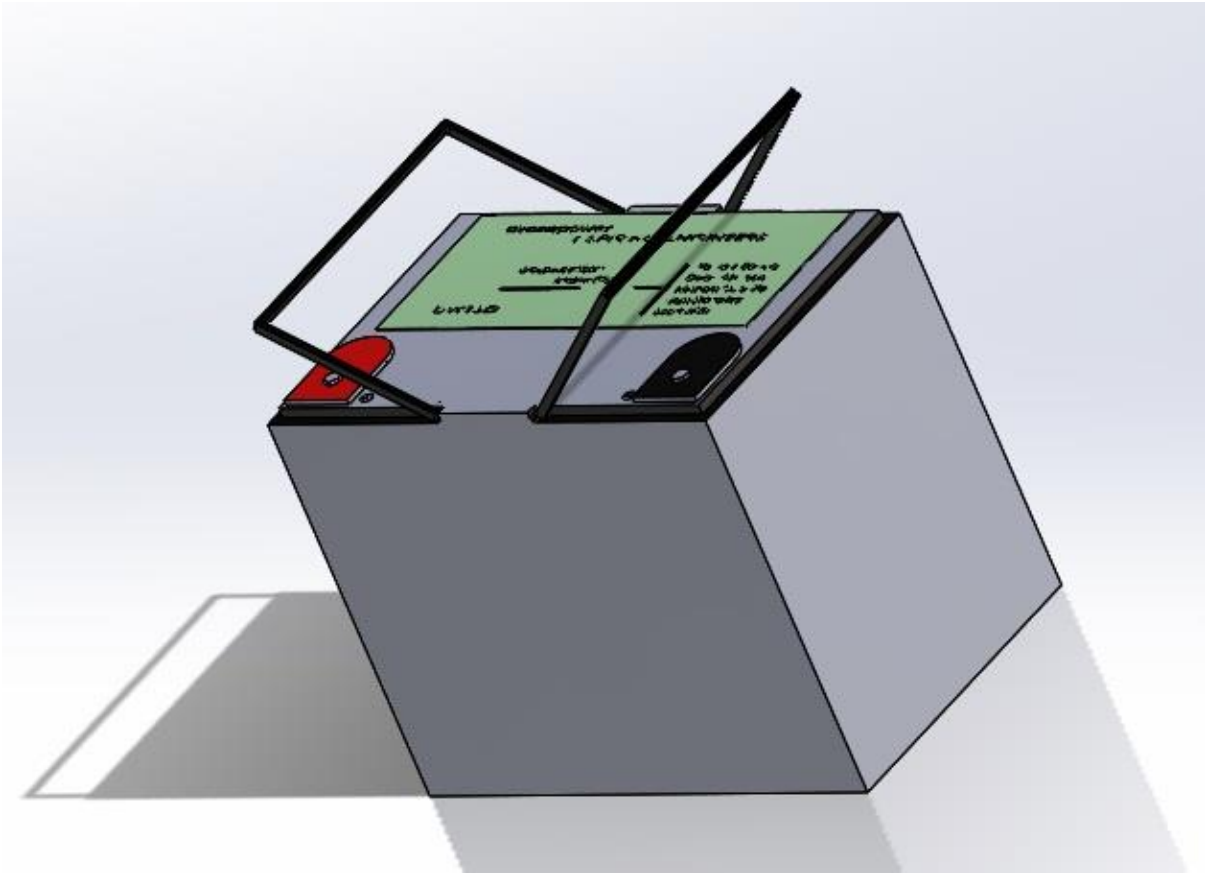
Appendix D:**CAD WORKS COMPLETED**

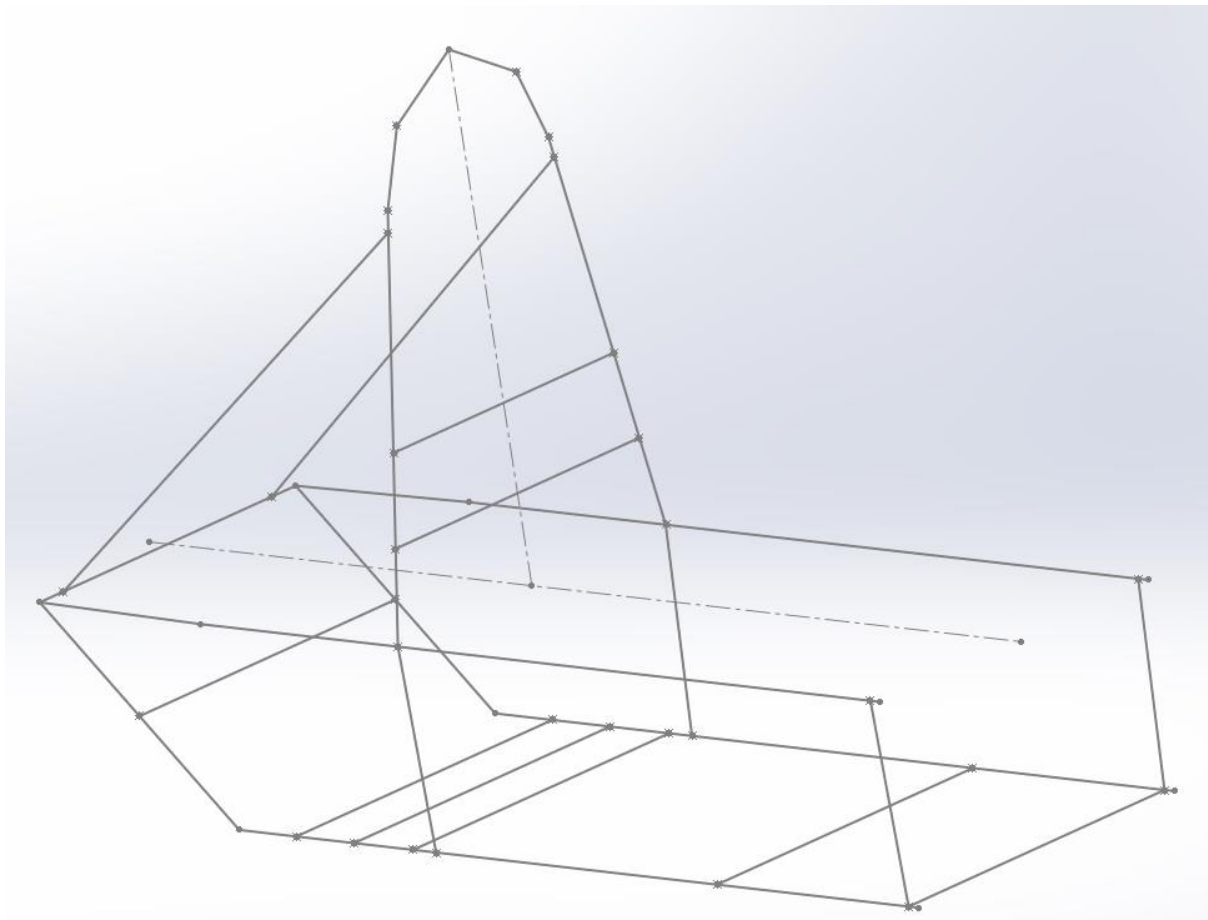
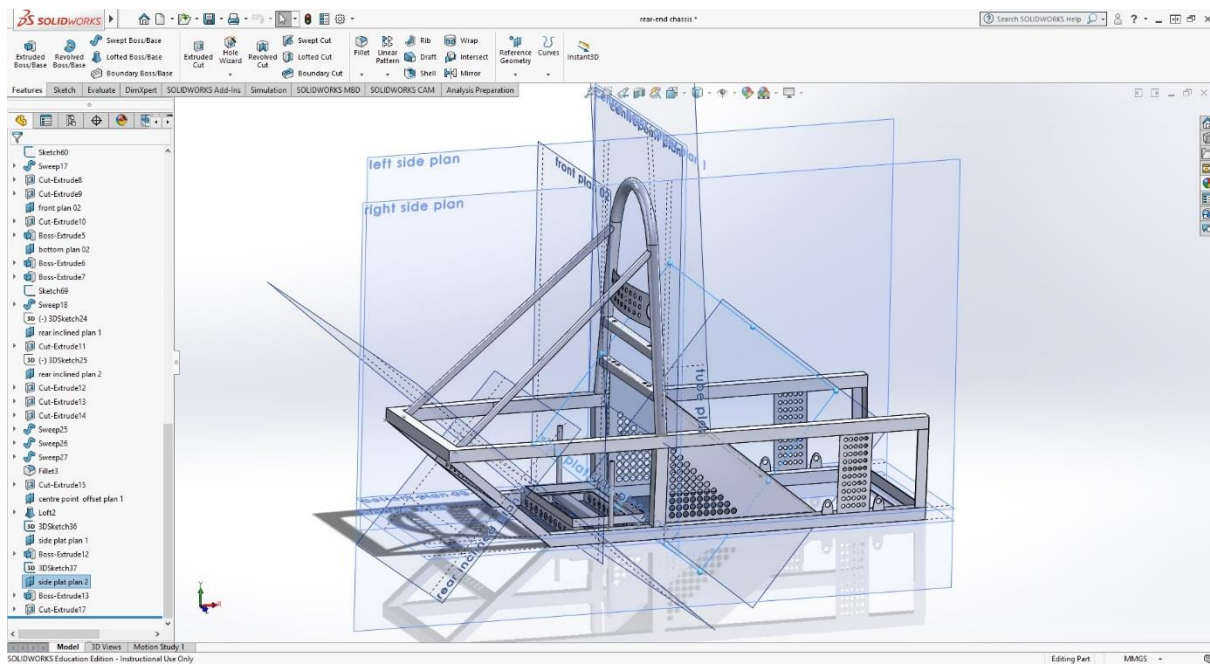
Yousouf Boukra

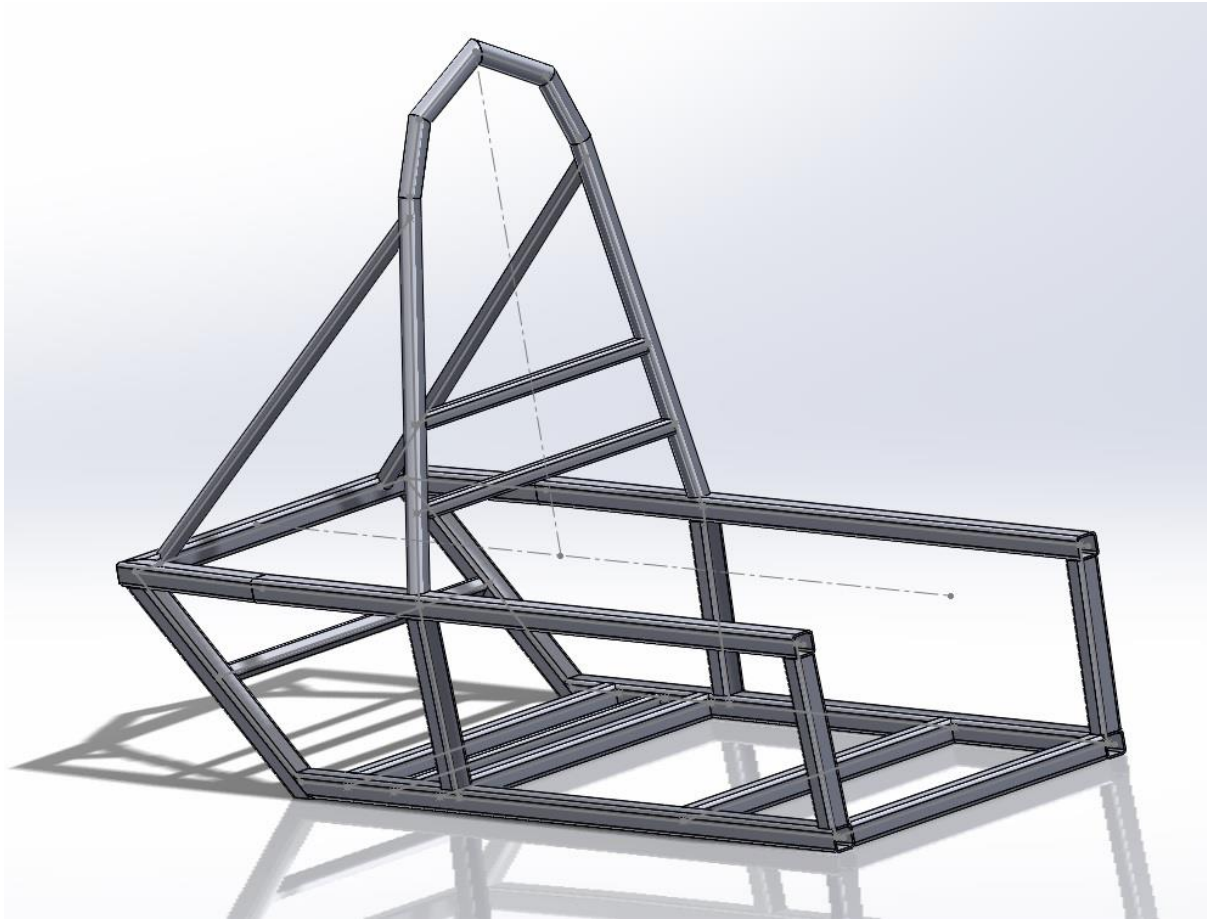




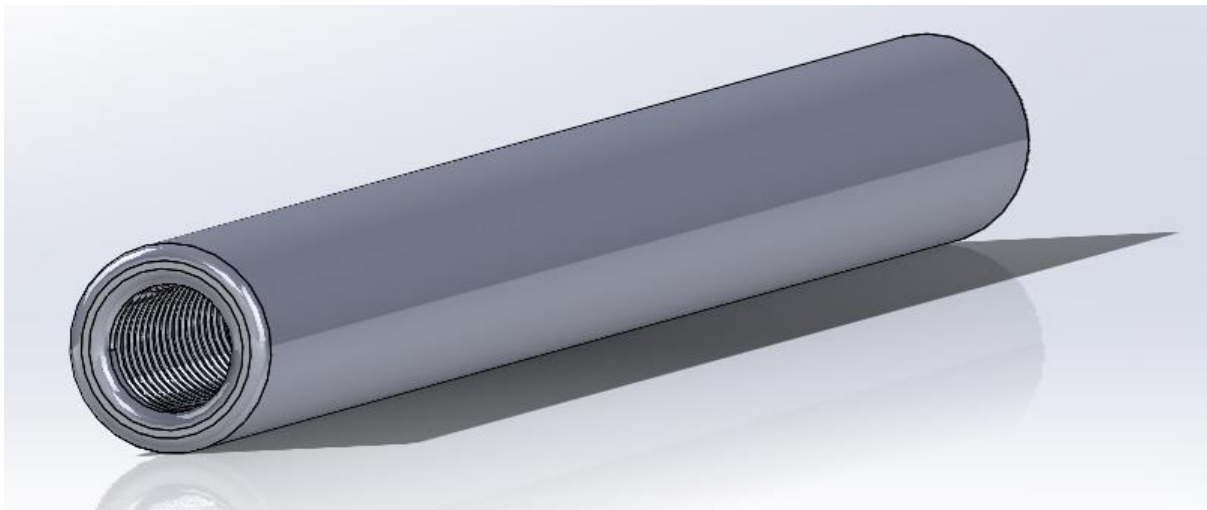
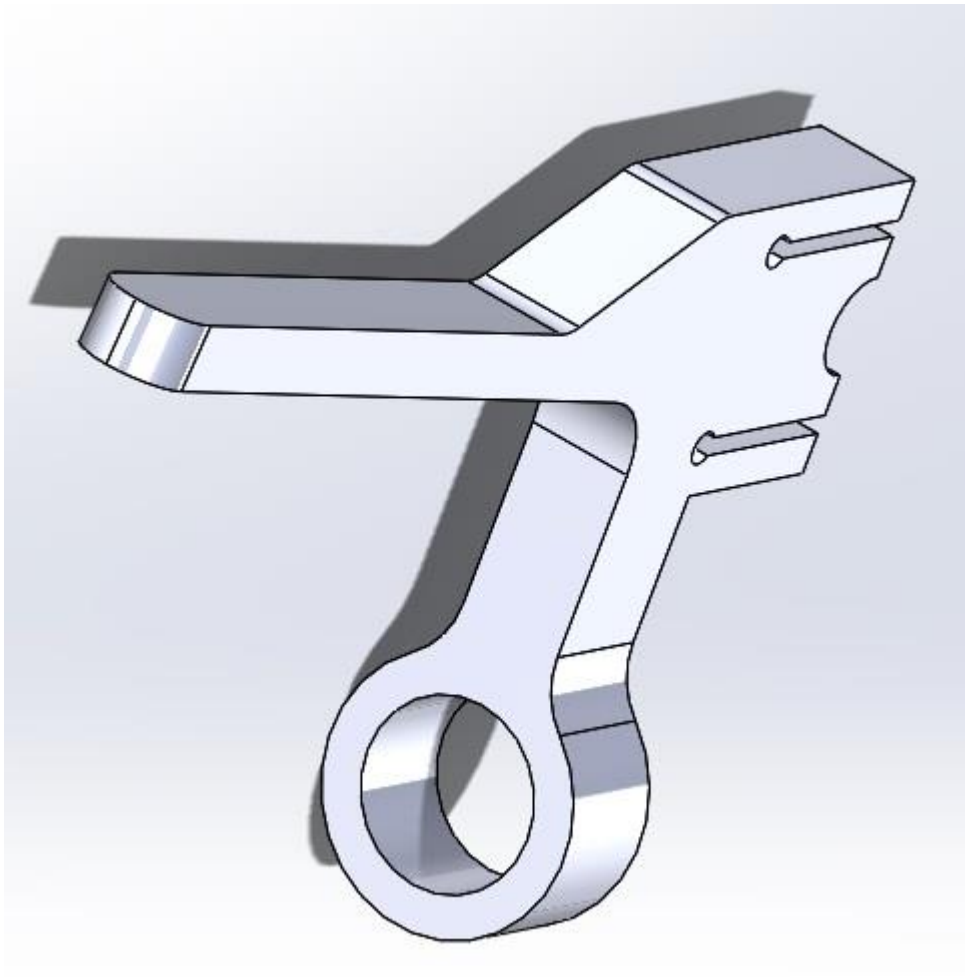


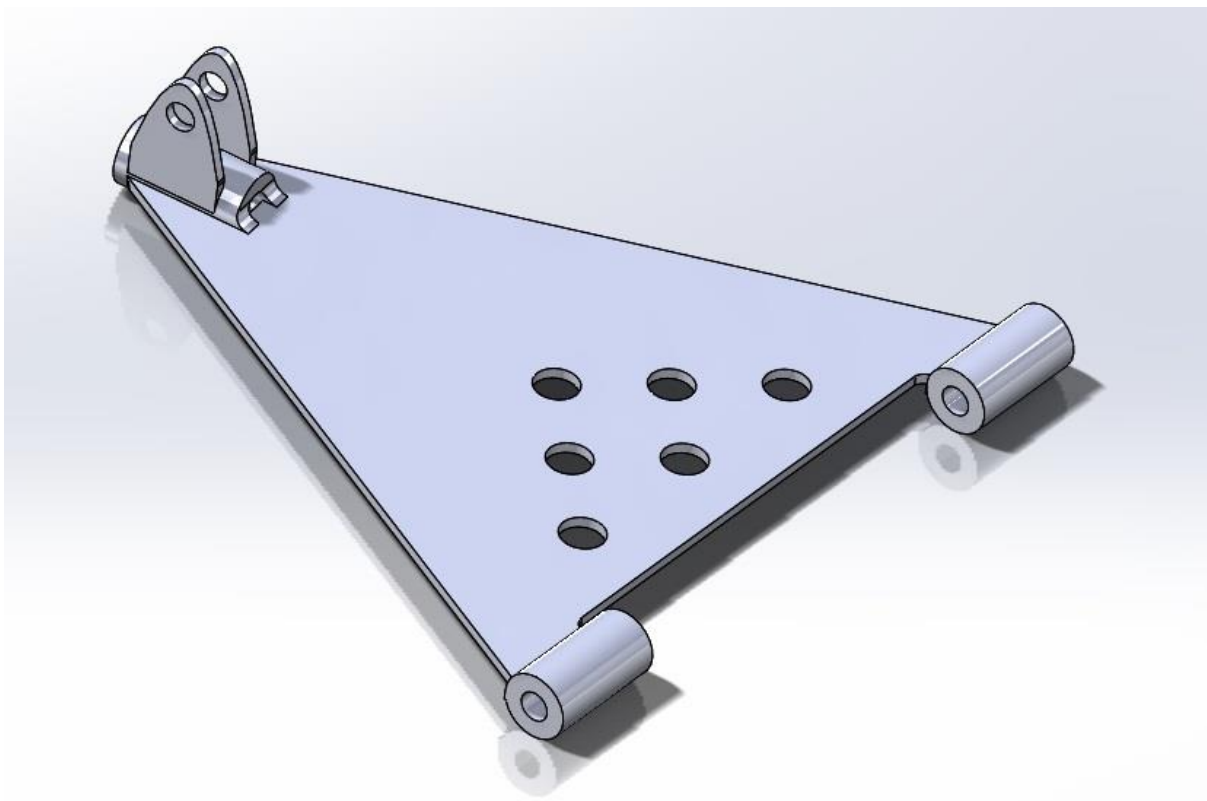
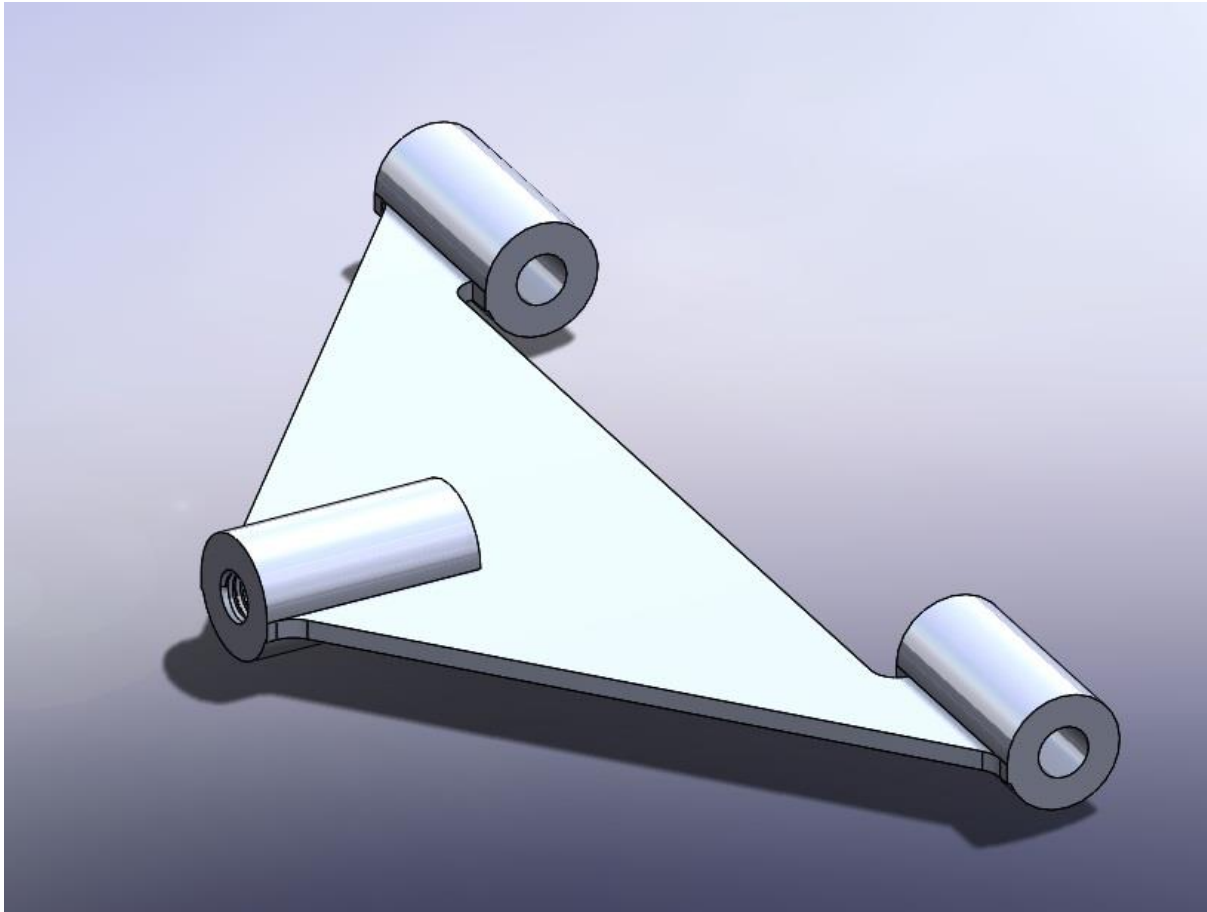




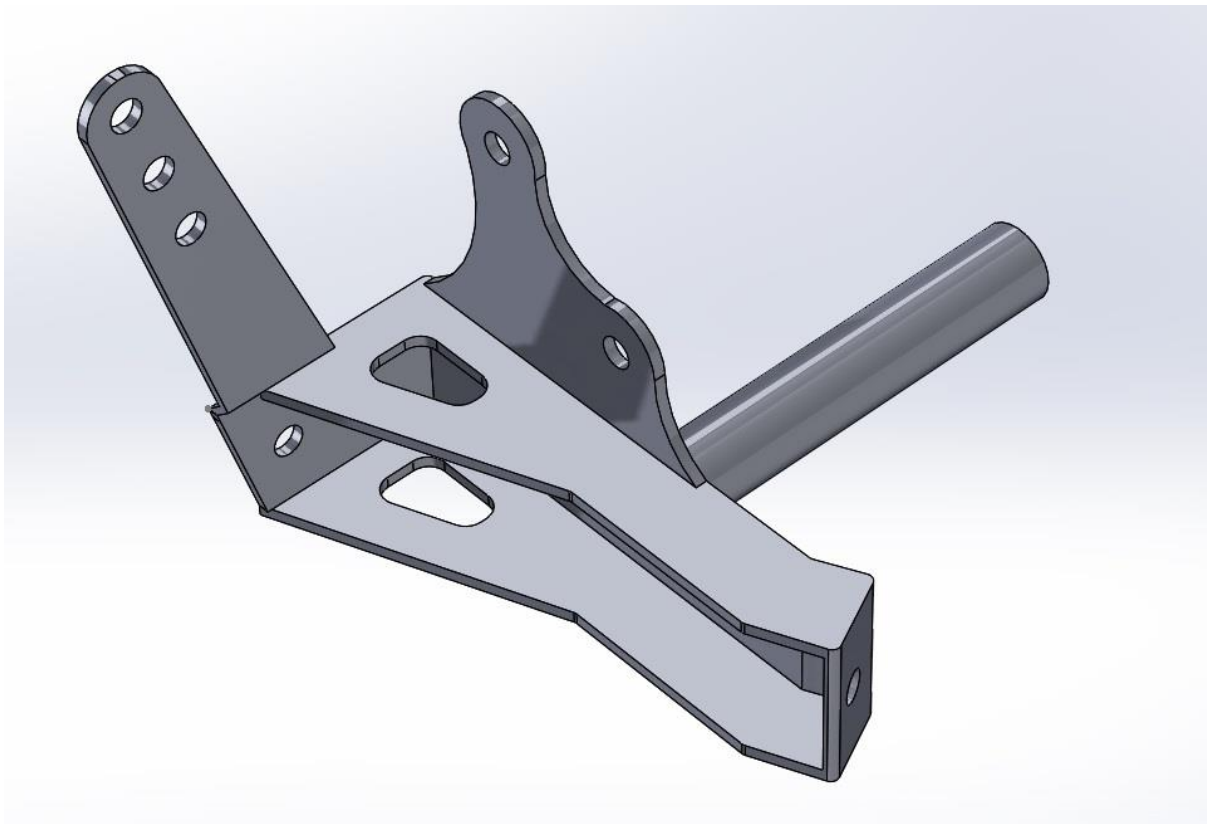


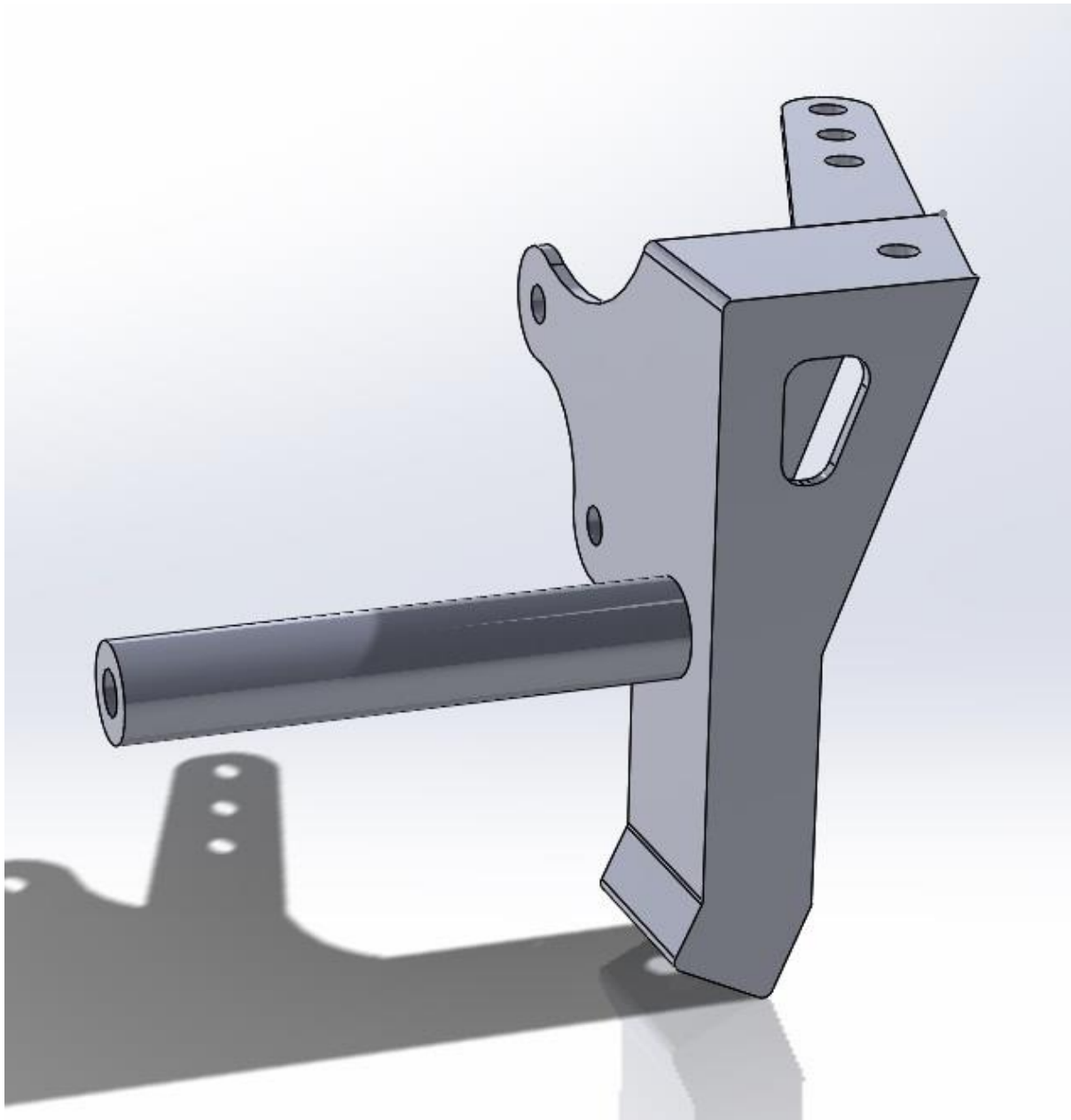
Deion Glyn Atkinson





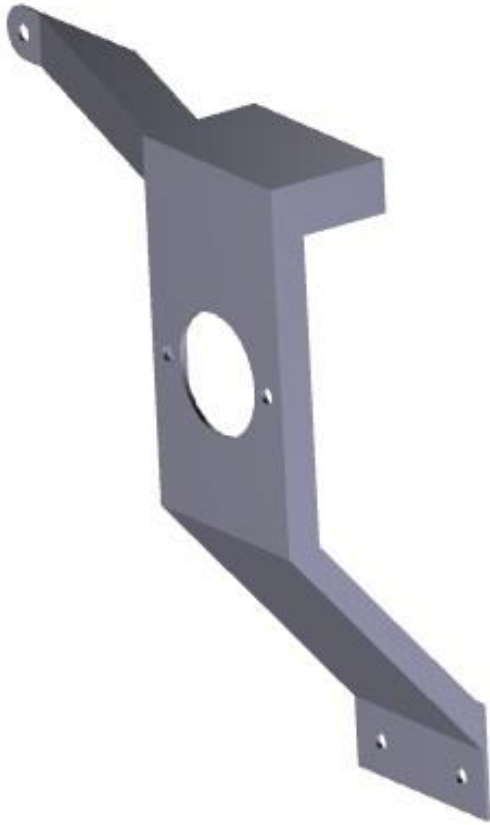
Scott Witts





Liam Paul Standing





Michael Cuniff

