



PRIFYSGOL CYMRU

Y Drindod Dewi Sant

UNIVERSITY OF WALES

Trinity Saint David

SWANSEA - ABERTAWE

Designing A Gearbox For The University's Electric Buggy

(Dissertation)

Module:- Major Project (M6X00467)

Supervisor:- Mark Sandford

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Gerwyn Richard James (P141063)

BEng Motorsport Engineering Yr3

Declaration of Authenticity

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



Signed:

Date:

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1.0 Introduction

1.1 The Project – Reasons and Relevance

When it came to deciding what project to do, I thought of my interests and some potential careers, and I've always had an interest in gearboxes and how they work. So I had a meeting with Mark Sanford to discuss potential projects, and he suggested designing a gearbox for the universities electric buggy. After giving it some thought, I've decided to take the project on because the thought of designing my very own gearbox is exciting. It will be difficult and tricky, but great experience, and an awesome challenge. It might be a career I would like to take on in the future after university. Mark Sanford will be my Project Supervisor throughout the year. This means we will have weekly meetings to discuss the progress of the project, and think of what to do next.

1.2 Aims of the Project

The aim of the project is to design a gearbox, a three speed or possibly more, to fit the university owned electric buggy. It is currently fitted with a fixed ratio, basically, two motors rotating with chains linked to the rear axle/shafts. This means that the buggy is very powerless and dead. The buggy also has no differential fitted. So the aim is to design a gearbox to improve the torque output at the wheels in order to gain acceleration, and to get more speed out of the buggy. This will also make the buggy more practical, a lower gear ratio for off road, and a quicker ratio for road usage. This will make the buggy more useful to the university, with the opportunity to take it off-roading.

1.3 Timescales and Provisional Work Plan

The first thing that would have to be done is to have a look at the buggy, and investigate how the chain drive works currently. It would be a good idea to look at the space where the gearbox will have to be fitted, and think of ideas of what type of gearbox to design, or how to fit it in place. Also, take some measurements such as the mass of the buggy, and tyre size (rolling radius). These will be useful for some simple calculations, such as calculating the max grip/traction and torque provided by the tyres in order to make the gearbox strong enough to handle the force. The mass will be helpful to calculating the max load when the buggy is travelling uphill etc. The current gear ratio will have to be calculated as well by counting the teeth on the gears.

Another thing that would have to be done is investigating into different types of gearboxes that would possibly suit the buggy and how they work. Epicyclic gearbox would be one type that would have to be researched, maybe something like a bicycle gearbox could be a possibility such, as Sturmey Archer 3 speeds. Different types of gears and gear sets will have to be investigated as well. It was suggested to take a look at HPC Gears. They specialise in making gears. Once we know what type of gearbox to base the gearbox on, gear ratios will have to be calculated. The spread and range of the gear ratios will have to be considered.

After all of research and calculations, the designing process of the gearbox can begin. This will take a lot of time and patience. The accuracy of the design will be crucial as well, so that the gears mesh together correctly, and so that the gearbox fits, because there isn't much room underneath the buggy. Once an initial design has been published, it can be checked for any errors or modifications that can be made to improve the design before submitting a final piece to be possibly manufactured.

Looking at the timescales for this project, to make sure that the project gets completed, all the research and calculations would probably have to be done before Christmas in order to have enough time to design the gearbox. The initial design would have to be done by the approximately mid-February, so that the design could be checked over for any errors, and a stress analysis can be carried out in order to make sure there isn't any weaknesses in the design. Once everything has been checked over, the final design can be done with all the modifications, and a stress analysis can be carried out. This will have to be done by mid-March. Then the design can possibly be sent off to be manufactured

if there is a company interested in doing so. This then, gives enough time to collect all the information gathered, and write about the whole of the project, from research, to calculations, and then to design and stress analysis by the 25th April.

1.4 Facilities Required

There are a few things required for this project, things like weighing scales, to weigh the buggy. The Solidworks software will also be needed for designing the gearbox, and for producing a stress analysis of the design. Also, maybe material will be required if some parts can be manufactured in house for the gearbox.

1.5 Industrial Partners

There will possibly be companies involved in this project when it comes down to manufacturing the gearbox. This means that companies would have to be contacted in order to find a company capable of manufacturing it, and at a reasonable price, with quality in mind. There will also be a timescale for it to be manufactured, because it would be excellent to have an end product to have on show and to talk about in the final viva. Therefore, the company must preferably be reasonably quiet with not a lot of work load, so that they have plenty of time to manufacture the gearbox in time for the viva.

2.0 Background Information

2.1 Gearbox

Before starting anything, it is important to know what a gearbox does, and how they are designed. A gearbox is simply a casing with a load of gears inside. It is used to reduce the speed of an input shaft by using different gear arrangements to decrease speed and increase torque of an output shaft. But the way these gears are arranged is the important bit. When two gears mate together, they create a gear ratio. Different gear ratios produce different speeds, and different torque outputs.

This means a gearbox can change a speed and torque of any motor to produce the correct torque for a certain condition, these conditions consist of standing starts, climbing hills, or cruising on a level surface. Look at a vehicle for example. A standard vehicle such as a car usually has 5 or 6 gear ratios, and then a reverse. The engine or power unit is the input to the gearbox, but this comes in at highspeed. Therefore, gear ratios are created to slow this speed down for different driving conditions. For example, the first gear ratio would be a low speed high torque gear ratio in order for the vehicle to take off from a standing start, like from junctions or traffic lights etc. But once the

vehicle is moving, less torque is required to move the vehicle, because it isn't a dead weight anymore, it's a moving weight. As the vehicle speed increases, the less torque required. The final gear ratio

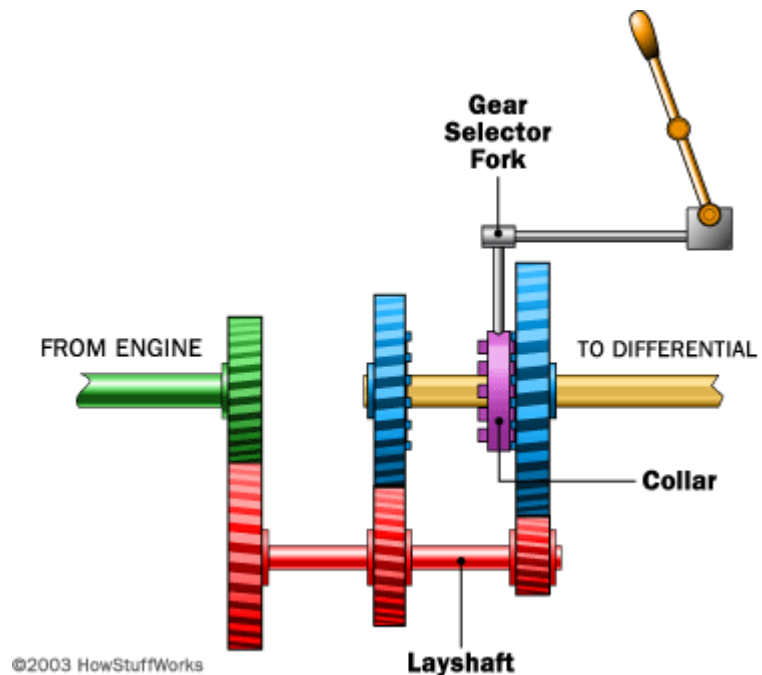
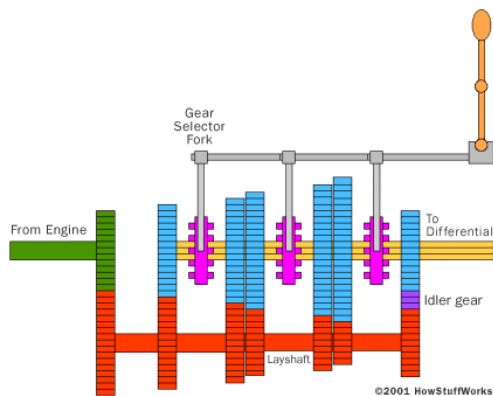


Figure 1

would be the highest speed, and lowest torque gear ratio in the gearbox. The other gear ratios are then used to increase speed and lower the torque output gradually from the first gear to the final gear. The reverse gear ratio changes the direction of the output, making the vehicle go backwards instead of forwards.

Different vehicles would require different gearboxes because every power unit or engine produces different torque outputs, therefore, different ratios would be needed. Also, some vehicles need different gear characteristics for their driving conditions, due to their usage, or job application. For example, a vehicle needing to reach high speed would need bigger gaps between gears to reach the high speed, hence a long gear ratio. This type of vehicle would need a lot of power and torque. A lower powered car with a low torque output would need a shorter ratio because it wouldn't have the torque needed to accelerate as quick. This means a smaller gap between gears. For vehicles such as Lorries, more gears are needed in the gearbox, due to the large weight that they carry. It is impossible to accelerate with this large mass, and with a limited amount of torque produced by an engine, more gears are fitted in order to gain acceleration. There are very small speed and torque differences between these gears, which helps these large vehicles to accelerate with the large mass.



These different gears are selected by different leavers and forks. These leavers are all connected to the gear stick or lever. Gear cables are also used. When a gear is selected on the gear leaver, the rods connected to it move to slide forks connected to a synchromesh, back or forth to connect two gears together which creates a ratio, one of the gears will be connected to the output shaft which then gets transferred to the wheels of the vehicle.

Figure 2

"The synchromesh device is a ring with teeth on the inside that is mounted on a toothed hub which is splined to the shaft. When the driver selects a gear, matching cone-shaped friction surfaces on the hub and the gear transmit drive, from the turning gear through the hub to the shaft, synchronizing the speeds of the two shafts. With further movement of the gear lever, the ring moves along the hub for a short distance, until its teeth mesh with beveled dog teeth on the side of the gear, so that splined hub and gear are locked together."

A simple 4-speed constant mesh gearbox as used on RWD vehicles

The gears are selected by a system of rods and levers operated by the gear lever. The drive is transmitted through the input shaft to the layshaft gear (cluster gear) and then to the mainshaft, except in direct drive – top gear – when the input shaft and the mainshaft are locked together.

The selector rods and forks move the synchromesh units back and forth, according to which gear is selected. Some gearboxes have only one selector rod, others three; but the principle is the same.

A spring-loaded ball at the base of the gear lever aligns with a recess in the selector rod, holding the lever in position until the driver changes gears.

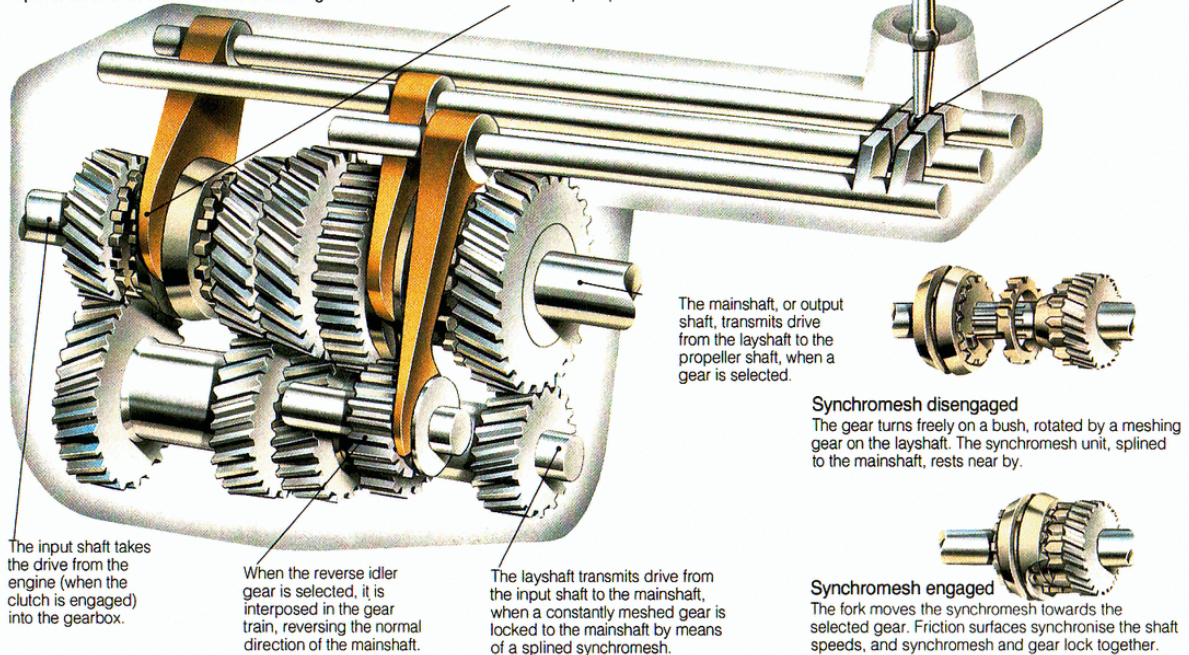


Figure 3

2.2 Gear Arrangements/Types

There are many different types of gearboxes which are designed and manufactured across the world for many different applications. The main difference between any individual gearbox is the performance characteristics produced. It all depends on what the gearbox is going to be used for before choosing what type of gearbox to use. Gearboxes are available in all different shapes and sizes, with a range of ratios to choose from, with backlash characteristics as well. Different gearboxes are more efficient than others too. All these different design factors affects the performance of the gearbox, and also affects the total cost of the gearbox to design, manufacture, and maintain. Several different types of gearboxes are listed below:-

- **Bevel :-** There are two types of bevel gears, straight and spiral teeth gears. Straight bevel gears mean the teeth are tapered and straight. This type of gear is usually used for slow speed applications. The teeth on a spiral gear are curved and oblique, and are used when high speed performance is required. These gears are mainly used in right angle applications when shafts are perpendicular to each other.

Figure 4

Figure 5



These types of gears are usually manufactured from cast iron, aluminium alloy, or other steel materials depending on the company manufacturing. Gears made from steel are typically noisy when coming into contact with another gear, and tend to wear.

Typical applications of bevel gears include

- Print Press
- Power Plants
- Automobiles
- Steel Plants
- Hand Drills
- Differential Drives

The advantages of these gear is that they can be used at right angles, and are usually quite durable. But accuracy is key when cutting the teeth of these gears, because poorly cut teeth creates a lot of vibration when in operation which will make the gearbox very noisy.

- Helical :-

Helical gears are cut at angles so that they can connect gradually to another gear. This helps reduce the noise when in operation, and helps make the gearbox run smoother. They are usually used in high horsepower and efficient applications.



Figure 6

These types of gears are usually made out of cast iron, aluminium alloy or any other iron material.

Some applications of helical gears are

- Oil Industry
- Blowers
- Food and Labelling
- Cutters
- Elevators

The design of the helical gears means they can either be used in parallel or cross orientation. They are very smooth, quiet, and also very efficient. Another good thing about these gears is the capability to be used in high horsepower applications.

- Spur :-

Spur gears have straight cut teeth and mounted on parallel shafts. Because of this, they tend to be very noisy due to the colliding teeth which makes these type of gears prone to wear. These gears come in a wide range of sizes and ratios which means they can be used for applications requiring certain speeds or torque outputs.



Figure 7

Spur gears are usually created from metals such as steel or brass and plastics such as nylon or polycarbonate. They are usually used in applications such as

- Packaging
- Speed Control
- Construction
- Power Plants

The good thing about spur gears is how cost effective they are, with a wide range of ratios from low to high. It also makes the gearbox very compact, with a very high torque output as well. But they are very noisy and wear a lot.

- Worm :-

Worm gears have a lot of advantages, with these types of gears being able

withstand high shock loads, while being very quiet, and no maintenance is required. But one bad point is that they aren't very efficient compared to other gear types. These gears can also be used at right angles like the bevel gears. The design of the worm gear means it can turn a gear easily, but the gear cannot move the worm gear. This is very useful for braking systems, because the gears can be locked easily.



Figure 8

These worm gears are usually created from aluminium, stainless steel or cast iron. They are used in applications where high speed and high load is being applied, and where right angles configuration is required. Some of the applications they are used for are

- Mining
- Rolling Mills
- Presses
- Elevators/Escalators Drive Systems

Worm gears are very good because of their high precision, and the right angled configuration. They are also very quiet and have very little maintenance, they are very reliable. But the problem is the limitations with these gears, with them being non reversible, this means worm can move the gear, but the gear can't move the worm. They also have low efficiency compared to the other gears listed.

- Planetary :- This is named planetary due to the similarities of looking like a solar system, with the sun in the middle, and the planets moving round the outside. Basically, there is a sun gear in the middle, with planet gears round the outside, and then an internal ring gear round the outside of them holding it all together. The planet gears mesh with both the sun gear and the ring gear.

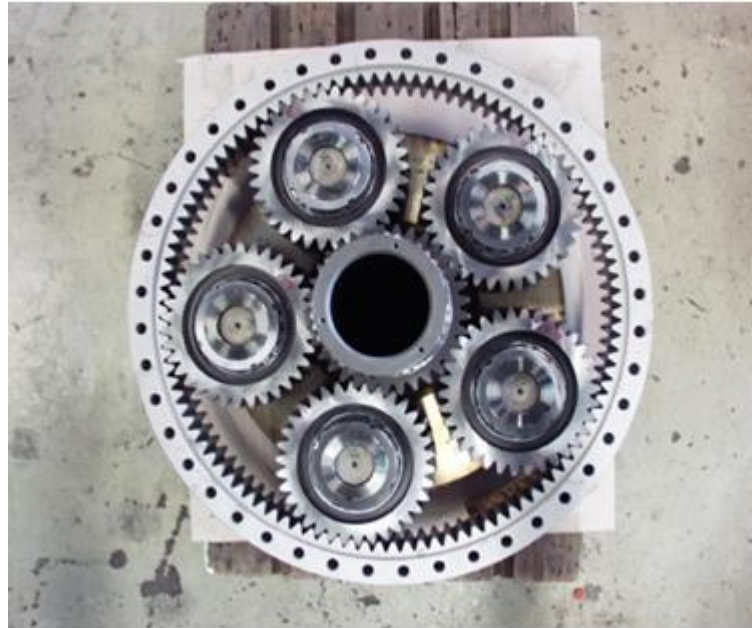


Figure 9

These gears are manufactured from aluminium, stainless steel or brass. Planet gears are very useful for applications needed low backlash, a high torque to weight ratio, and applications that require the gears to be resistant to shock. They are used for applications such as

- Slewing Drives
- Lifts
- Cranes
- Machine tools
- Automotive

Planet gears have many advantages, with high power density and their compact design being a couple. They also have a very high efficiency when being used in a power transmission application. They also have very good stability, and the load is distributed between many gears (planets) instead of just one gear. But one problem with this type of gear is that there is a very high load on the bearings. Also, they are a very complex design, and their inaccessibility is a disadvantage as well.

- Hypoid :-

Hypoid gears are very similar to spiral bevel gears. The main difference is the centre lines of both gears don't intersect each other like bevel gears do. The gears are offset instead. They also combine the sliding movement of a worm gear with the high pressure rolling movement of the spiral bevel gears.

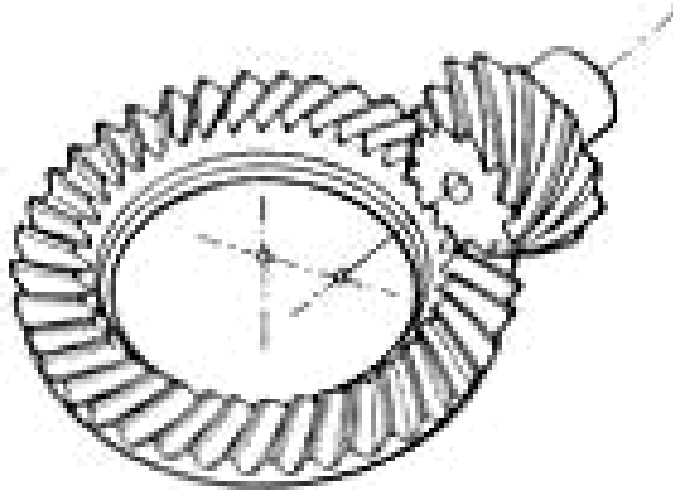


Figure 10

They are usually used in applications such as differentials in vehicles etc. Both gears are made out of steel, which means this gear set has special lubrication requirements. They require anti-weld and oiliness additives to be added in the lubrication so they can be able to withstand the high pressures provided on the teeth, and the high rubbing speeds, which could make the teeth weld together if they aren't lubricated properly.

2.3 How to Choose a Gearbox

There are many things which affect the decision of what gearbox to use, ranging from which gear ratios are required, to how much torque that the gearbox needs to withstand, and what torque output that is needed from the gearbox.

- **Gear Ratios :-** A gear ratio is the ratio between the drive gear and the driven gear. To decide on what gear ratios to choose, you need to know what torque and speed output is needed from the gearbox in low gear and high gear for the application it is required for. There is no point in using random gear ratios, and then not being able to turn from a standing start because the gear ratios are too highly geared, or not reaching the speed required because the gear ratios are too low geared. Also, it would be useful to know what application it is being used for, does the gear ratios need to be chosen for high acceleration, or does it need to be chosen for high torque and speed requirements, or do they need to be selected to support both. Does the gear ratios need to be chosen for cruising, or speed. This helps decide how many gears are required too, because as stated before, some application need a lot of gears with small gaps in-between each ratio.
- **Torque :-** It is important to know how much torque will be put through the gearbox, because the gearbox will need to be strong enough to be able to cope with the torque put through it. The gears will need to be made strong enough or there could be major damage if teeth start shearing and braking, it could wreck the whole gearbox. Therefore, the max torque that will be put through a gearbox has to be known before beginning to design it. This will help decide whether a gearbox needs to be heavy duty or not. There's no point designing every gearbox to be heavy duty because the weight will be too high for some

application's, and the cost will be higher because there will be more material being used.

- **Application :-** This will probably be one of the first things to know before beginning to design a gearbox. It is important to know what you are designing it for before beginning to think what design to go for. Will the gearbox need to have an output at a perpendicular direction to input like a front wheel drive car, or is it in the same direction as input. Some designs will be required to be very strong, and withstand a lot of shock and vibrations, such as off-roading, or in different power tools or machinery. The gearbox will have to cope with high stresses, forces, and oscillations if this is the case. Some will need to be lightweight and strong for racing applications, strong enough to take the power and torque from the power unit, but very light to be as close as possible to the weight limit. Every gram counts when it comes to racing. Some gearboxes will need to be very compact to fit in small places, and some won't have any limitations at all.
- **Gear Arrangement :-** Different gear arrangements are more complex than others. But the more complex gear arrangements such as a planetary arrangement can take a lot more torque and can cope with higher loads. This is due to the loads being shared with more gears the same time. The more planet gears that get added, the more torque that the arrangement can take. They are also a lot more efficient because less heat is produced because the load is shared, hence more energy can be put through the gearbox instead of losing it to heat energy. The more complex the planetary arrangement is, the better the stability and the rotational stiffness of the arrangement. All these points and principals applies to other gear arrangements as well. Simply the more gears sharing the same driven gear, the stronger the arrangement is, and the more load that can be put through the arrangement. The trouble with more complex arrangements though is the difficulty in designing them. They cost a lot more money as well.

2.4 Where are Gearboxes Used

Gearboxes are used in a variety of industries:

- **Aerospace –** In the aerospace industry, gearboxes are used in space and air travel, i.e. airplanes, missiles, space vehicles, space shuttles and engines.
- **Agriculture –** In the agriculture industry, gearboxes are used in machinery, like mowers for example, or balers, irrigation, pest and insect control, tractors and pumps.
- **Automotive –** In the automotive industry, gearboxes are used in cars, helicopters, buses and motorcycles, lorries.
- **Construction –** In the construction industry, gearboxes are used in heavy machinery such as cranes, forklifts, bulldozers and tractors.

- Food Processing – In the food processing industry, gearboxes are used in conveyor systems, the processing of meat and vegetable products, and packaging applications.
- Marine Industry – In the marine industry, gearboxes are used on boats and yachts.
- Medical – In the medical industry, gearboxes are used in surgical tables, patient beds, medical diagnostic machines, dental equipment and MRI and CAT scan machines.
- Power Plants – In power plants, gearboxes are implemented in transformers, generators and turbines.

3.0 The Project

The first thing to look at with this project is the specifications of the buggy, the power the motors produce, the way they are mounted, the amount of room, the weight, rolling radius of tyres, anything that can be used to help design and produce a gearbox for the buggy. The current ratio can be calculated as well. From doing this, targets for the gearbox can be made to improve the buggy, to make it more useful and practical. Once all this is done, the gearbox can be designed.

3.1 The Buggy

As stated before, the buggy is currently fitted with two equally powered motors supplying torque to the rear wheels via two chains linked to the rear axle. The buggy use to be fitted with a standard combustion engine before being modified for electrical power for university purposes. This can be seen with all the old brackets still situated on the frame of the buggy to mount the old engine. It also seems like the old different lengths shafts have been used. This means the motors are set up offset to the centre of the buggy because of these shafts.

The spreadsheet of the specifications of the motor has a misprint so that it shows values for a slightly smaller motor. But the power output for a slightly bigger motor has been given, therefore, to get the values for the motor fitted, the middle value between the two motors was found as an estimate for the power outputs of the motors fitted to the buggy. The two motors fitted to the buggy produce 200 amps each. The approximate power and torque outputs are 13 KW, and 43.25 Nm. The maximum motor speed of the motor is 3500 RPM.

The corner weights of the buggy was measured so that different calculations could be made. The weights came out as the following.

LF	RF
81.5 Kg	79 Kg
LR	RR
179.5 Kg	175 Kg

This gives a weight a total weight of 515 kg and a weight split of 68.8 % towards the rear of the buggy.

For the calculations to be done on the buggy, a mass needs to be added to represent the people driving and sitting in the passenger seat of the buggy. Not everyone weighs the same, so a mass needs to be estimated for this. The extra mass used for the calculations will be 200kg, this will represent two people sitting in the buggy.

The rolling radius and circumference of the wheels was also measured so that calculations could be made to work out the gear ratios and speeds to try and find the best gear ratios. Because the tyres are very stiff, the tyre doesn't seem to have a flat section where it's in contact with the ground, therefore, the rolling radius can be measured as half the tyre diameter. The value for diameter was measured to be 0.6m, therefore the rolling radius is 0.3m. Using this value, the circumference of the tyre can be calculated using $2\pi r$, which gives a value of 1.88m.

3.2 Current ratio

The current ratio of the fixed ratio of the buggy could be calculated very easy. This is done by putting the buggy on the university car lift, and counting the number of teeth on the two gears, that is the motor side and then axle side. The motor gear had 8 teeth on it, and the axle side had 55. As a ratio, it is 55:8. Therefore, if we do 55 divided by 8, we get 6.875:1 gear ratio.

To work out the speed of the buggy using this ratio, the first thing to do is the max revolutions per minute (RPM) needs to be transferred to revolutions per second (RPS). The max RPM for the buggy is 3500. If this value is divided by 60 to get this into seconds, the value comes out to be 58.33 RPS. If this is divided by the gear ratio, the RPS of the wheel can be found. This gives an answer of 8.48 RPS for the wheel rotation. Therefore, to work out the speed of the buggy, this is simply multiplied by the circumference of the tyre. The speed of the buggy is equal to $8.48 \times 1.88 = 15.95$ m/s. To convert this into MPH, this value is multiplied by 2.24, and this gives a value of 35.73 MPH. This is the maximum speed of the buggy with the current specifications.

3.3 Issues

The main issue with the current design of the buggy and where the motors are placed is the space to fit a gearbox in the space in-between the two motors. There will need to be modifications so there is enough room to fit a gearbox in, especially because there will have to be enough space for two gearboxes due to there being two motors. But, with the motors not being central, then it might be possible to move only one motor to a similar mounting point just like the other side. This will help gain some room.

Unfortunately, if more room is needed, the wishbones will need to be modified, because the wishbones currently mount near where the motors are situated. This may become a lot of work, and be difficult to modify to benefit the motors for space, but for the geometry of the rear wheels to still work and move in a similar to original set-up. If the motors are being moved to a different mounting point, the drive shafts will also need to be modified to suit. Both drive shafts will have to be the same length instead of using the original length shafts. This means the rear mounting points of the shafts need to be modified to be situated central instead of offset. The chains connecting the motors and shafts may also need to be modified longer or shorter depending on the movement of the motor, and where the gearboxes will be mounted.

The benefits of doing this is that it will improve the centre of gravity and balance of the buggy, because the motors will be situated equal distances from the centre of the buggy, and gearboxes will be sitting central. This will help in the handling of the buggy.

From looking at the issues found above, the gearbox needs to be as small and compact as possible to fit in the space that is provided. The space seems fairly small, and it will be a tight fit to try and fit two gearboxes in the area. Therefore size is key when designing the gearbox.

3.4 Targets

There needs to be set targets before designing the gearbox, targets that can be aimed for while designing. With no targets, there is no plan, there is no way of knowing what to design. This makes it easier to know where to start, and what to do. Making targets gives a starting point of what to think about while designing.

The main aim was to make the buggy more practical. With it only containing one fixed gear at the moment, the obvious thing to do was to add more gears, but for what speed or torque. With the option to use the buggy for off-roading, it would be a good idea to design gears for that purpose. The current electric motor has quite a bit of torque, therefore it doesn't need that many gears, but it would be favourable to calculate a ratio so that the buggy could get up very steep hills. This would be ideal for off-roading purposes, creating a ratio to challenge getting up any hill, bank or dune thrown in front of the buggy. Deciding on the angle of hill is the difficult part. It was decided that a slope angle of 45 degrees would be a good aim. This will be the lowest gear ratio in the gearbox.

It's already known what the current ratio is. But there have been some complaints that the buggy is a little slow around town. The suggestion for improving this is to create a lower gear ratio so that the buggy can go faster, at least so that it hits the max speed limit of towns which ranges up to 40mph usually. Therefore, the aim is to create a ratio to do this speed or above.

Therefore, there is a low gear target and a high gear target to aim for, so the gears in-between can now be discussed. Because there isn't a big gap between the gears to be fair, there is probably only need for one gear in the middle. So this should be aimed for somewhere in-between the highest and lowest gear ratio.

From discussions earlier in this paper, it is already known that the gearbox needs to be as compact as possible due to the lack of space to fit the two gearboxes in the frame of the buggy. But with the gears aiming to be small, they also need to be very strong. Therefore, a planetary type design should be looked at, because of the strength in their designs, and the shared load between more gears. Also, if the buggy will be used for off-roading, it will incur a lot of vibrations and shocks. For this reason, the gearbox needs to be able to cope with these vibrations and loads, and be able to last through all conditions. The gearbox can't be too heavy either because the extra weight will make it harder for the buggy to go up hills, and put more strain on everything.

3.5 Suggested Gearboxes

From looking at the targets laid out for this gearbox, it is thought that three speed gearbox designs was the way forward, because other gears would be pointless and only add weight. Therefore, some research needs to be done into different three speed gearboxes, to think about some ideas to use for this gearbox design. It also needs to be remembered that this design need to be strong as well.

It was suggested by the supervisor to look at Epicyclic gearboxes, and Sturmey Archer gearboxes. These are well known three speed gearboxes. It was also suggested to look at some other options too.

3.5.1 Epicyclic

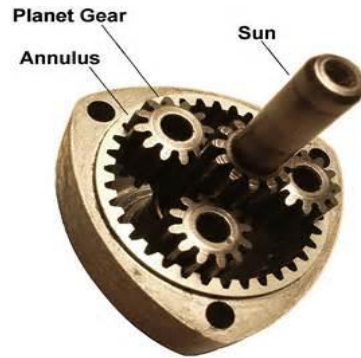


Figure 11

Let's look at Epicyclic gearboxes first. This gearbox is based on a planetary arrangement, using a centre gear called the sun, which features with three planet gears on the outside which are connected to a coupling, and then an outer gear which is called the annulus. These gears can be locked in place in different ways to provide a different gear ratio each time, for example, locking the planet carrier would give one ratio, while locking the annulus would give another ratio and locking the sun would give another. This means it is possible to get three different ratios from this small gear arrangement. It is pretty simple the way it works, and it's very compact and effective, but designing the locking system for each gear would be quite complicated.

To get more gear ratios from the epicyclic style gearbox, the input and output could be changed. What this means is change which gear takes the input, for example the annulus, and let the sun be the output, or make the sun the input and let the planet carrier be the output, but this makes the gearbox a lot more complicated than what is needed for the design of the gearbox for the buggy.

The different arrangements give out different ratios. There are three different arrangements. These arrangements are planetary, star, and solar. The range of ratios that each arrangement is capable of is as follows.

- Planetary - Range = 3:1 – 12:1
- Star - Range = -2:1 - -11:1
- Solar - Range = 1.2:1 – 1.7:1

A planetary arrangement is when the input is the sun, and the output is the planet carrier. This means the annulus is fixed. The star arrangement is when the input is the sun and the output is the annulus. The planet carrier is fixed. The solar arrangement is when the input is the planet carrier and the output is the annulus with the sun being fixed. Below is a simple table to show the arrangements, and a calculation of how to get the ratios for each arrangement.

	Input	Output	Stationary	Calculation
A	Sun (S)	Planet Carrier (C)	Ring (R)	$1 + R/S$
B	Planet Carrier (C)	Ring (R)	Sun (S)	$1 / (1 + S/R)$
C	Sun (S)	Ring (R)	Planet Carrier (C)	$-R/S$

Figure 12

The benefits of this gearbox is the strength of it, because of the way the torque gets shared between the planets, the more planets that gets used, the more gears the torque gets shared between, and hence the more torque the gearbox can cope with. Also, these types of gearboxes are light, compact, and small as stated before, especially to other types of gearboxes. These gearboxes are very efficient in most cases too. This is because of its planetary arrangement, and from research done earlier in this paper, planetary arrangements create less heat energy, and hence, more torque can be applied, and hence, more efficient. Another benefit is if they're design is not too complicated, and they are tooled properly, they can be less expensive than other gearboxes too.

3.5.2 Sturmey Archer

Sturmey Archer is a company that designs mini gearboxes for bicycles. They use a hub gear set-up. This hub is mounted to the rear wheels. They make hubs with different amount of gears, in the case of this paper, the three speed hub that Sturmey Archer have designed is the one that will be looked at.

This gearbox design also uses a planetary arrangement. It is very similar to an epicyclic style gearbox. The arrangement is situated inside a hub, hence why the name given is three speed hub gearbox. Below is a figure showing the layout of the gearbox, with the labels stating what everything is.

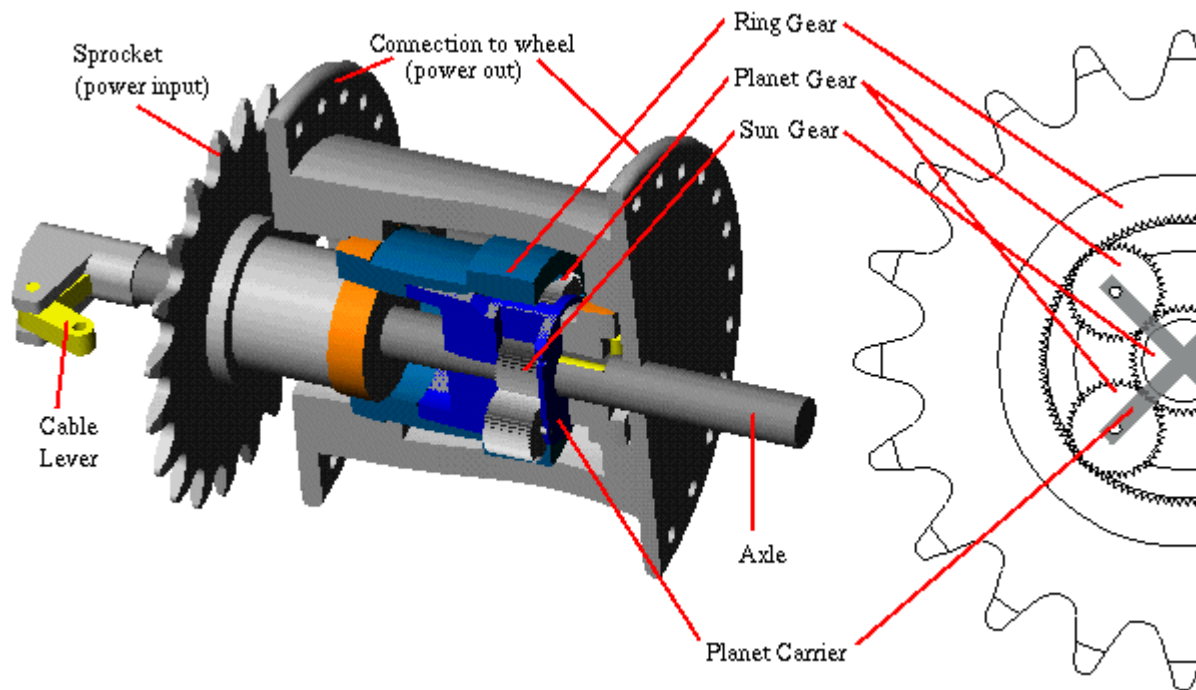


Figure 13

As can be seen from the figure above, the input comes from the pedal power of the person riding the bike, and is connected to the rear sprocket and hub using a chain. This gets transferred into the planetary arrangement. The torque from the gear arrangement then goes through to the output which is the rear axle, and hence the rear wheel. This system uses a solar arrangement, which is when the sun is fixed permanently.

The shaft that the cable lever is connected to, moves and locks a different part of the gearbox up, giving a different ratio. The cable lever is connected to a gear lever on the handle bar of the bicycle via a gear cable. This creates the three different speeds. On the system discussed below, there are the same number of teeth on the sun and the planet gears. Below shows the three different positions for the gear arrangement in order to achieve the three different speeds.

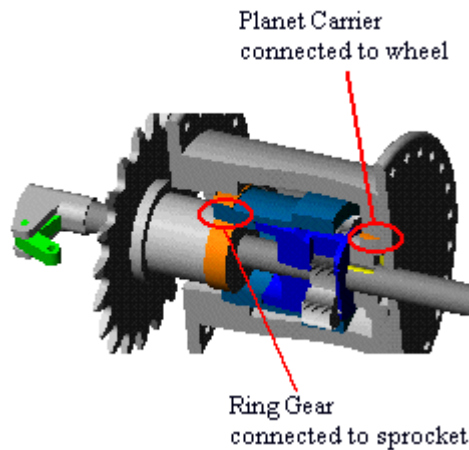


Figure 14

Speed 1

This figure shows where the planet and ring gear are connected in order to get the first speed, which is at a ratio of 4:3. This means the sprocket rotates 4 times while the wheel rotates 3 times.

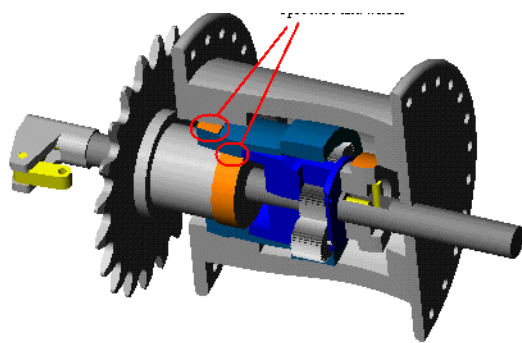


Figure 15

Speed 2

This figure shows the ring gear, which is the annulus connected to the sprocket and wheel, creating a one to one gear ratio (1:1). This means the sprocket and wheel rotate at the same speeds.

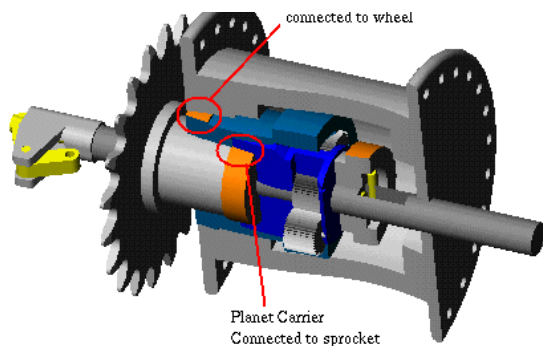


Figure 16

Speed 3

This figure shows the planet carrier connected to the sprocket while the ring gear is connected to the wheel. This gives the opposite effect to the first ratio, therefore a 3:4 ratio is created. This means the sprocket rotates 3 times while the wheel rotates 4 times. This will be the top gear from the hub gearbox.

The complicated part about this system is the way the gears are fixed together. This will be a difficult task to use this type of selector for the buggy due to two gearboxes being used. Otherwise, this would be a very good and simple idea to use.

The good thing about these type of gear hubs is that they are very small and compact, because they have to fit the rear axle of the bike. They also are very lightweight, because if they are too heavy, they will add too much weight to the bike. This type of system on a bike is between 94% and 98% efficient as well.

3.5.3 Austin 7

Another type of gearbox that was looked at is the more conventional type gearbox of the Austin 7, which was a three speed.

This gearbox contains 4 shafts, the first being the input shaft. This is what connects the engine to the gearbox. The engine rotates this shaft via the clutch. This then rotates the lay-shaft. These two shafts are constantly in mesh. Then there is the main-shaft which carries two gears.

The main-shaft is connected to the input shaft via a dog to get a 1:1 ratio. To get the other two ratios, the gears on the main shaft are slid by a gear fork which is connected to a gear lever by rods, to mesh with the gears on the lay-shaft to create the other two ratios.

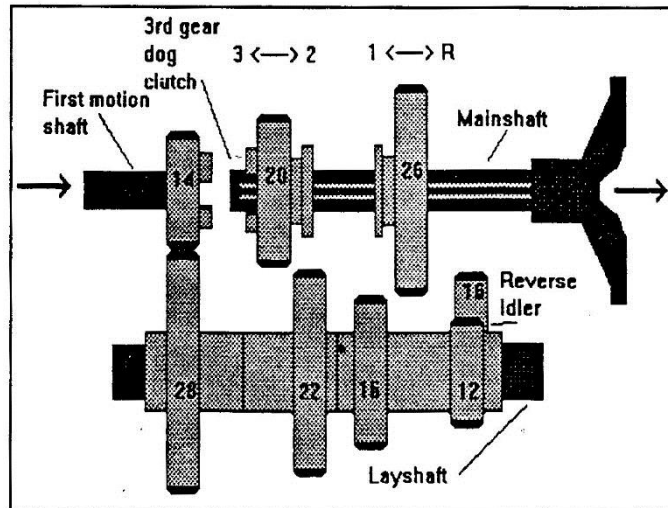


Figure 1

Figure 17

The other shaft carries the reverse idler. This is how a reverse ratio is created. An extra gear is placed in-between a gear on the lay-shaft and a gear on the main-shaft which will rotate the main-shaft in the opposite direction, hence creating a reverse gear.

First gear is when the input and lay-shaft are connected, and the 26 tooth gear and 16 tooth gear connects the lay-shaft to the main-shaft. Second gear is the same, other than 20 tooth gear and the 22 tooth gear connects the lay-shaft and main-shaft instead. Third gear is the 1:1 ratio stated earlier. To get reverse, the lay-shaft is connected to the main-shaft via the 12 tooth gear, the reverse idler and the 26 tooth gear on the main-shaft. The tables below show the speeds and ratios of the gears.

Engine RPM at various Road Speeds			
MPH	1st Gear	2nd Gear	3rd Gear
10	2060	1153	
15	3090	1729	
20		2305	1268
25		2881	1585
30		3458	1902
35		4034	2219
40			2536
45			2853
50			3170

Figure 19

Gear	Gearbox		Overall
Reverse	4.33	28/14 X 26/12	21.19
1st	3.25	28/14 X 26/16	15.89
2nd	1.82	28/14 X 20/22	8.89
3rd	1.00	(Direct)	4.89

Figure 18

The trouble with this type of gearbox is the size of it. It will be too big to fit it in the space given underneath the buggy. It will take too much space up, especially because two gearboxes are needed. The other problem with this gearbox is the noise level. This gearbox is fitted with straight cut gears, and hence create a lot of noise when the gears are in contact. It will seem very noisy especially because the electric motors are very quiet. Also, the gears are very long in this gearbox, with big gaps in-between gears, but this could be changed with a close ratio conversion, or create better ratios to suit the buggy instead.

3.5.4 Bicycle Sprocket Set-up



This could be the other option, but space is a problem with this set-up too, the bicycle sprocket gear set. This would be easy to design, but it wouldn't be practical. Because of the speed target that was aimed for the buggy, the sprockets would need to be very large in diameter in order to get a gear ratio small enough to reach that speed. Also, the sprockets would need to be made very strong, to cope with the torque needed to move the mass of the buggy up steep hills and at high speed, which will only add weight to the total mass of the buggy.

Figure 20

3.5.5 Gearbox to be Designed

For the gearbox to be designed for the buggy, it is thought that an epicyclic style gearbox would be best suited. This is down to many reasons. The first reason would be because of their very compact design, meaning a lightweight gearbox, and a gearbox size that will fit in the buggy with the space that's given. Also, this type of gearbox is very strong, it can withstand high torques and loads, and it can withstand a lot of vibrations and shocks, which is what the gearbox will have to cope with if the buggy will be going off-roading.

They are a three speed gearbox as well, which is what is needed for the buggy. But it was found that it would be nearly impossible to get the ratios needed from a singular epicyclic gearbox, because of the complexity of the design. To get the ratios, it would need to have different parts being fixed to get different ratios each time. This would get too complicated, therefore, to make things easier, it was decided that two epicyclic gearboxes would be joined together. This would give extra options for ratios.

One ratio would be in one epicycle, another in the other epicycle, and then a direct drive from the motor straight to the chain, this would be the same as the current set-up of a fixed drive. This would give the three ratios for the gearbox, which is the main target. The ratio in the epicycle would need to be multiplied by the final drive to get the actual ratio when that gear is selected. The selector would be the difficult part with this type of design, to be able to select the two different epicyclics and the direct drive. Also, the selector needs to be able to select the gearbox on the other motor at the same time with accuracy. The gears need to be selected with accuracy or it will damage the gearboxes, chipping teeth if the gears don't mesh properly.

Another thing that had to be discussed was which arrangement to use, planetary, star or solar. The best ratios seem to be under the planetary set-up. The other ratios seem too low. Although, with two epicyclics being used, it is possible to use different arrangements on both. This will make it a little more complicated. Therefore it would be easier to keep the same arrangement on both epicycles.

3.6 Gear ratios

From looking at the targets set out, the gear ratios needed to reach these targets can be calculated. Let's start with the target of reaching 40 MPH. Firstly, this needs to be converted into m/s. If 40MPH gets divided by 2.24 which gives a value of 17.86 m/s. This can be rounded to be 18 m/s, which is 40.26 MPH. Divide 18 m/s by the circumference and this gives a value for the RPS of the wheel. This is equal to the RPS of the motor divided by the ratio to get this speed. Therefore, if $58.33/\text{Ratio} = 9.57$ is transposed so that the ratio can be found, $\text{Ratio} = 58.33/9.57$. The ratio comes out to be 6.095:1. The ratio 6:1 will make things easier to calculate and design, so this is the ratio that will be used.

To find a ratio for travelling up slopes of 45 degrees, the force going down the slope needs to be calculated first. Trigonometry is used to work this out. From using this, the equation for the force going down the slope is $mg\sin(\theta)$. For the mass m , the mass of the buggy plus the 200kg for two people will be used, g is gravity, and the angle is 45 degrees which is the slope angle. Therefore, the answer for the force down the hill is $(515+200)(9.81)\sin(45) = 4959.75 \text{ N}$. This means the force going up the hill needs to be higher than this in order for the buggy to begin to move. This can then be converted into torque if multiplied by the rolling radius of 0.3 m, which gives a value of 1487.93 Nm of torque at the wheels. The max motor torque is 43.25 Nm. To get a ratio from this, simply divide the torque needed by the motor torque, and a gear ratio is calculated. The ratio is $1487.93/43.25$ which equals 34.4030:1. But this ratio is only to match the force going down the hill, therefore the ratio needs to be slightly higher so that the buggy can actually move up hill. The ideal ratio would probably be about 36:1 for the lowest gear in the gearbox.

To get a middle gear, it needs to be approximately in the middle of the two gears calculated. Therefore, this ratio should be aiming for approximately 18:1, but this is dependent on what gear ratios would fit together in the style of gearbox that is being designed. It depends on which ratios that will fit together in this three speed gearbox.

3.7 Gear Ratio Discussions

The ratios that were looked at first was a 6:1, 18:1 and 36:1. But, it was decided to look at other possible ratios as well, to see if better ones were found. This would mean changing the final drive. The possible final drive ratios to try were 4:1 and 5:1 instead of the more favourable 6:1. The same calculations can be done for the 4:1 and 5:1 as the 6:1 final drive. For the ratios below, the fastest gear will be just the final drive, the middle gear ratio will be one epicyclic ratio multiplied by the final drive, and then the lowest ratio will be when the torque travels through both epicycles and the final drive.

Beginning with the 4:1, and the values that are already known, the motor RPS which is 58.33, and circumference of the tyre 1.88, the speed for the buggy using only the final drive, basically a 1:1 ratio through the gearbox, the speed is 27.42 m/s. This gives a top speed of 61.34 MPH, which would be amazing to get this much speed out of the electric powered buggy, but unfortunately, there is doubt that the motor would have enough torque to turn this gear ratio, it would put too much strain on the electric motor. To get similar ratios to the 6:1 final drive, for the middle gear, the best ratio under the 4:1 final drive would be to multiply that by a 4:1 gear ratio, which will give a ratio of 16:1 which is

pretty close to the 18:1 that was aimed for. This ratio gives a speed of 6.85 m/s, which is 15.33 MPH. Another ratio that could be used as a mid-range gear could be a 3:1 with the 4:1 final drive. This will give a speed of 9.13 m/s, which is 20.44 MPH. This is a massive jump to the top gear speed though, a jump of over 40 MPH, that is massive, therefore a 4:1 is not the best option. This could be a low gear too, if the 3:1 ratio then travels through the 4:1 ratio of the second epicyclic and then multiplied again by the final drive to give a final ratio of 36:1. This final drive does give the option of having the perfect low gear of 36:1 by using a 9:1 epicyclic multiplied by the 4:1 final drive. But as stated before, using this final drive is not practical, therefore this won't be used.

From looking at the 5:1 final drive, if the 1:1 direct drive ratio is used, a top speed of 21.93 m/s is reached, which is 49.06 MPH. A possible option for the mid-range gear ratio could be 3:1 which comes out to be 15:1 when multiplied by the final drive. This ratio would give a speed of 7.31 m/s, which is 16.35 MPH. This value is maybe slightly low for what is needed. A ratio of 3:1 can be used in the other epicyclic in-order to multiply the ratio to 45:1 from $((5 \times 3) \times 3)$. Using this ratio, a speed of 2.44 m/s can be reached, which is 5.45 MPH, which seems a little low for what is needed, although this would mean the buggy would get up any slope put in front of it.

3.8 Design

From looking at all the possible designs and ratios for this gearbox, and thinking of the practicality that is needed from the gearbox, a design was basically finalised. The gearbox would be two epicyclics as stated earlier, but with the ring gear acting as the casing because this part of the gearbox needs to be fixed anyway. This would make it easier, and save weight of putting a case around the ring gear. It also makes it easier to decide on tooth counts, because there is less choice because the ring gear would need to have the same tooth count in both gear sets. The difficult part would be the selector, selecting both epicyclics separately. Also, this needs to be able to be used in both gearboxes too, so that all the parts are matching, and so there are less things to design, and the selector inside the gearbox is less complicated. The torque needs to be transferred to the output easily as well, because otherwise the gearbox will be less efficient and energy will be lost. To simplify this, it was thought that only using one planet carrier would be best, with this being the only output from the gearbox. This would mean a well-designed planet carrier would be needed. This also means that all the gears will rotate freely even if not selected.

3.9 Final ratio decision

After some discussions, a final gear ratio was decided, which was a 6:1, 3:1 and a 1:1, with a final drive of 6:1. The top speed of each ratio is as follows.

Gear Selected	-	1:1		
Total Gear Ratio	=	1:1 x 6:1	=	6:1
Max Speed	=	40.9 MPH		
Gear Selected	-	3:1		
Total Gear Ratio	=	3:1 x 6:1	=	18:1
Max Speed	=	13.6 MPH		
Gear Selected	-	6:1		

$$\text{Total Gear Ratio} = 6:1 \times 6:1 = 36:1$$

$$\text{Max Speed} = 6.8 \text{ MPH}$$

From knowing the ratios, gear teeth can be calculated for each gear. The ideal number of teeth for the final drive would be 48 teeth on the axle side, and 8 teeth the motor side, because the current set-up uses and 8 tooth sprocket. The equation to work out the number of teeth on each gear in an epicyclic is

$$N_r/N_s + 1 = \text{Ratio}$$

where N_r is the number of teeth on ring gear, and N_s is the number of teeth on the sun gear.

The number of teeth on the ring gear needs to be the same for each ratio because of the fact that the design is using the same internal gear for both epicyclics, which as stated before, the internal gear can be used as a casing because this needs to be fixed anyway.

$$N_r/N_s + 1 = 3 \text{ for the } 3:1 \text{ ratio,}$$

$$\text{Therefore } N_r/N_s = 2.$$

$$\text{For the } 6:1, N_r/N_s + 1 = 6,$$

$$\text{Which means } N_r/N_s = 5.$$

It was found from trial and error that the ring gear would need to have multiples of 20 as the number of teeth. For example, the ring gear would have to have 40, 60, 80 or 100 as the number of teeth. It was decided to use $N_r = 100$, because the more teeth there are, the stronger the gears, plus the less wear each gear will occur. From knowing this, the number of teeth on the sun can be calculated and then the number of teeth on the planets can be found. The number of teeth on the planets is found by using the equation

$$N_r = (2 \times N_p) + N_s$$

where N_p is the number of teeth on the planets. The number of teeth on the sun and planets can be seen below.

$$\begin{aligned} \bullet \quad 3:1 \quad - \quad \text{Sun} \quad - \quad 100 / N_s &= 2 \\ 50 &= N_s \end{aligned}$$

$$\text{Planets} - \quad 100 = (2N_p) + 50$$

$$50 = 2N_p$$

$$25 = N_p$$

$$\begin{aligned} \bullet \quad 6:1 \quad - \quad \text{Sun} \quad - \quad 100 / N_s &= 5 \\ 20 &= N_s \end{aligned}$$

$$\text{Planets} - \quad 100 = (2N_p) + 20$$

$$80 = 2N_p$$

$$40 = N_p$$

These can now be used to size up gears in the next section of this paper.

3.10 Sizing Gears

There are many different measurements that are needed for sizing gears for designing and manufacturing. It is not possible to design a gear without knowing what tooth profile to use, what diameter gear, the bore size, the amount of teeth, the size of the teeth, the gap between the teeth, only to name a few values that are needed. This is only to size the teeth, the gears will also need to be checked to see if they are strong enough to cope with the torque, power and forces put upon them during their usage. The measurements can be calculated using formulas. Before discussing the formulas, it is useful to know what the every measurement is, this is shown in a labelled diagram below with an explanation for what each label means.

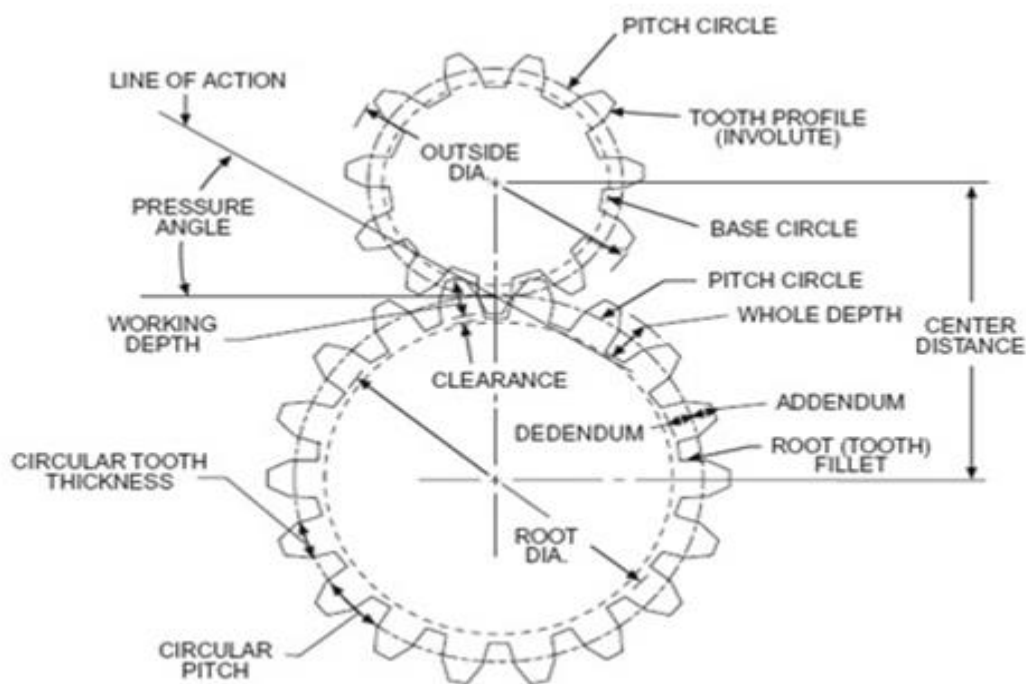


Figure 21

- Addendum – The height of the gear tooth above the Pitch Circle Diameter (PCD).
- Base Circle – An imaginary circle used in involute gearing to generate the involutes that form the tooth profiles.
- Bore – The diameter of the hole in a sprocket, gear, bushing, etc, so that the gear can slide onto a shaft.
- Center distance – Distance between the axes of two meshed gears.
- Circular Thickness – The thickness of the tooth on the Pitch Circle Diameter, this is also known as Circular Pitch.
- Dedendum – The depth of the tooth below the Pitch Circle Diameter.

- Diametrical Pitch – The teeth per inch of the diameter of the Pitch Circle.
- Gear Center – The center of the Pitch Circle.
- Gear Ratio – The ratio between the numbers of teeth on meshing gears.
- Line of Contact – The line or curve along which two tooth surfaces are tangent to each other.
- Involute – The curve which describes a line which is unwound from the circumference of the gear.
- Pitch Circle – The curve of intersection of a pitch surface of revolution and a plane of rotation.
- Pitch Diameter – The diameter of the Pitch Circle.
- Pitch Radius – The radius of the Pitch Circle

All these need to be known for every gear so that all the gear can be designed. The formulas for these can be found in the HPC Gears Handbook. These formulas are listed below.

- $PCD = \text{Number of teeth} \times \text{Module}$
- $OD (\text{outer diameter}) = (\text{Number of teeth} + 2) \times \text{Module}$
- $DP (\text{Diametrical Pitch}) = 25.4 / \text{Module}$
- $\text{Module} = CP / \pi$
- $CP = \text{Module} \times \pi$
- $\text{Addendum} = \text{Module}$
- $\text{Dedendum} = 1.25 \times \text{Module} \quad (\text{for Modules between } 1.25 \text{ and } 8)$
 $\quad = 1.4 \times \text{Module} \quad (\text{for modules between } 0.25 \text{ and } 1)$

All these need to be found for every gear being designed for the University's Electric Buggy. Basically, all these calculations depend on the Module chosen for the gears. The module of a tooth indicates the size of the tooth. For the teeth of the gears to mesh together properly, the modules of every gear being meshed together need to be the same size. Otherwise, the gears simply won't mesh together. They won't line up.

It was decided to do all calculations using a module of 1.5 to start with. Then using these values, the strength of the gear can be found to see if the gears are strong enough to cope with the force and torque put through them. Obviously, the gears need to be able to take a torque of at least 43.25 Nm of torque, because the electric motors of the buggy produces this value. The number of teeth on every gear has already been stated in the finalised gear ratio section of this paper. The module and teeth numbers simply get plugged into these equations, the values for each gear is listed below.

- Sun of 3:1 Ratio - PCD = $50 \times 1.5 = 75 \text{ mm}$
OD = $(50 + 2) \times 1.5 = 78 \text{ mm}$
DP = $25.4/1.5 = 16.93$
CP = $1.5 \times \pi = 4.77 \text{ mm}$
MOD = 1.5
Addendum = 1.5 mm
Dedendum = $1.25 \times 1.5 = 1.875 \text{ mm}$
Whole Depth = 3.37 mm
Tooth Width = 20 mm
- Planet of 3:1 Ratio - PCD = $25 \times 1.5 = 37.5 \text{ mm}$
OD = $(25 + 2) \times 1.5 = 40.5 \text{ mm}$
DP = $25.4/1.5 = 16.93$
CP = $1.5 \times \pi = 4.77 \text{ mm}$
MOD = 1.5
Addendum = 1.5 mm
Dedendum = $1.25 \times 1.5 = 1.875 \text{ mm}$
Whole Depth = 3.37 mm
Tooth Width = 20 mm
- Sun of 6:1 Ratio - PCD = $20 \times 1.5 = 30 \text{ mm}$
OD = $(20 + 2) \times 1.5 = 33 \text{ mm}$
DP = $25.4/1.5 = 16.93$
CP = $1.5 \times \pi = 4.77 \text{ mm}$
MOD = 1.5
Addendum = 1.5 mm
Dedendum = $1.25 \times 1.5 = 1.875 \text{ mm}$
Whole Depth = 3.37 mm
Tooth Width = 20 mm
- Planet of 6:1 Ratio - PCD = $40 \times 1.5 = 60 \text{ mm}$
OD = $(40 + 2) \times 1.5 = 63 \text{ mm}$
DP = $25.4/1.5 = 16.93$
CP = $1.5 \times \pi = 4.77 \text{ mm}$
MOD = 1.5
Addendum = 1.5 mm
Dedendum = $1.25 \times 1.5 = 1.875 \text{ mm}$
Whole Depth = 3.37 mm
Tooth Width = 20 mm
- Ring Gear - PCD = $100 \times 1.5 = 150 \text{ mm}$
OD = $(100 + 2) \times 1.5 = 153 \text{ mm}$
DP = $25.4/1.5 = 16.93$
CP = $1.5 \times \pi = 4.77 \text{ mm}$
MOD = 1.5
Addendum = 1.5 mm
Dedendum = $1.25 \times 1.5 = 1.875 \text{ mm}$
Whole Depth = 3.37 mm
Tooth Width = 20 mm

After finding these, the strength of the gears needed to be found. The formula for strength is

$$\frac{X_b Y S_b F}{DP}$$

This value is given in lbs. Therefore, the value will need to be converted into Newton's by dividing the value by 0.2248. The only thing that is known in this equation at the moment is DP. The others can be found using the HPC Gears Handbook. The handbook also gives an equation for wear as well. The equation is

$$\frac{X_c Z S_c F}{K}$$

This also gives the results in lbs. The meaning for each part in both formulas is as follows.

- X_b = Speed Factor for Strength
- X_c = Speed Factor for Wear
- Y = Strength Factor
- Z = Zone Factor
- S_c = Material Rating (Surface Stress)
- S_b = Material Rating (Bending Stress)
- K = Pitch Factor
- F = Face Width (Inches)
- DP = Diametrical Pitch

The value for these can be found in tables also found in the HPC Gears handbook. To find X_c , the max RPM speed of the gearbox, and the amount of hours a day the gearbox will be in use. It's better to be a little conservative when choosing the hours, the hours that's been chosen for the buggy is 4 hours a day, but it is doubtful that it gets used this much a day once the gearbox is fitted. Unfortunately, there is no value for 3500 RPM, which is the max RPM of the motor. But there is for 3000 and 4000 RPM, therefore the mid-point between these two values can be used for X_c . X_b is found in the same way as X_c using another table.

To find a value for Z , the number of teeth on both meshing gears are needed. One of the teeth numbers of a gear designed for the buggy is unfortunately not in the table, which is 25 teeth. The number of teeth given is 26 and 20. These can be used to find a value for 25 teeth. This is done by first finding the difference between the two values, then dividing this number by the difference between the teeth numbers, which is 6. Then simply minus the value from the value given for 26 teeth. Y is found in exactly the same way but from another table.

S_c and S_b can be found from material ratings of the chosen material. A list of the materials usually used to construct gears from is listed below with their different stress values.

• Delrin (Polyacetal)	-	$S_c = 500$	$S_b = 3900$
• EN32A	-	$S_c = 1400$	$S_b = 17000$
• EN32A (Case Hardened)	-	$S_c = 9200$	$S_b = 40000$
• EN24	-	$S_c = 3000$	$S_b = 32000$
• EN24 (Induction/Through)	-	$S_c = 5000$	$S_b = 26500$
• EN36 (Case Hardened)	-	$S_c = 11000$	$S_b = 50000$
• EN58AM	-	$S_c = 1800$	$S_b = 20000$

Higher the S_c and S_b values are, the stronger the gears are, and the less wear they will have. The most popular gear material is EN24, so this will be the material that gets used for the find strength and wear of the gears.

K is found very easily, it is the Diametrical Pitch to the power of 0.8, and the DP is already known from the calculations done earlier for the gears. F is the Face width of the gears, which is basically the thickness of the gear itself without the boss. This can be found by looking the gear up in the HPC Gears handbook, for example, if a spur gear with a module of 1.5 is looked up in the book, it gives a diagram of the gear at the top of the page, with the thickness of the gear, the boss, and the bore stated on the diagram.

The list of all the values needed for the strength and wear values that are the same for all the gears are listed below.

- $X_b = 0.227$
- $X_c = 0.27$
- $S_c = 3000$
- $S_b = 32000$
- $DP = 16.93$
- $K = 9.62$
- $F = 20 \text{ mm} = 0.7874 \text{ inch}$

Below is the list of values that are different for every gear, and the values given for strength and wear.

- Sun – Planets 3:1 Ratio
 - $Y = 0.697$
 - $Z = 2.173$
 - Wear
 - $= 144.13 \text{ lbs}$
 - $= 641.13 \text{ N}$
 - Strength
 - $= 235.43 \text{ lbs}$
 - $= 1047.29 \text{ N}$
- Planets – Ring 3:1 Ratio
 - $Y = 0.653$
 - $Z = 2.57$
 - Wear
 - $= 170.46 \text{ lbs}$
 - $= 758.27 \text{ N}$
 - Strength
 - $= 220.57 \text{ lbs}$
 - $= 981.18 \text{ N}$
- Sun – Planets 6:1 Ratio
 - $Y = 0.574$
 - $Z = 1.75$
 - Wear
 - $= 116.07 \text{ lbs}$
 - $= 516.33 \text{ N}$
 - Strength
 - $= 193.88 \text{ lbs}$
 - $= 862.47 \text{ N}$

- Planets – Ring 6:1 Ratio
 - Y = 0.734
 - Z = 3.5
 - Wear = 232.14 lbs
= 1032.66 N
 - Strength = 247.93 lbs
= 1102.88 N

Unfortunately, the value that is given from the motor is a torque value, therefore the values that have been calculated need to be changed so that it gives a torque value. The equation for Torque is $T = F r$, where F is the force and r is the radius of the gear. The radius is found by dividing the PCD by 2. The Torque values for all the gears are listed below.

- 3:1 Sun - Planets
 - Sun Radius = $75/2 = 37.5$ mm
Torque = 39.27 Nm
 - Planet Radius = $37.5/2 = 18.75$ mm
Torque = 19.64 Nm
- 3:1 Planets -Ring
 - Planet Radius = $37.5/2 = 18.75$ mm
Torque = 18.4 Nm
 - Ring Radius = $150/2 = 75$ mm
Torque = 73.59 Nm
- 6:1 Sun - Planets
 - Sun Radius = $30/2 = 15$ mm
Torque = 12.94 Nm
 - Planet Radius = $60/2 = 30$ mm
Torque = 25.87 Nm
- 6:1 Planets -Ring
 - Planet Radius = $60/2 = 30$ mm
Torque = 33.09 Nm
 - Ring Radius = $150/2 = 75$ mm
Torque = 82.72 Nm

From looking at the values for torque above, it seems that the gears are too weak to cope with the torque provided by the motor. The values needed to be above 43.25 Nm of torque, which none of the planets and sun gears are above. Therefore, the module needs to be increased in order to cope with higher torque. A new module size of 3 was decided to be used in the calculations to see if that would increase the strength of the gears enough to cope with 43.25 Nm of torque. The only values that needed to be modified for a module of 3 to do this was K, F and DP. The new values for these were as follows.

- DP = $25.4/3 = 8.47$
- K = 5.52
- F = 30mm = 1.18 inch

From using these, the new forces came out to be the following.

- Sun – Planets 3:1 Ratio
 - Wear = 376.61 lbs
= 1675.31 N
 - Strength = 706.01 lbs
= 3140.62 N
- Planets – Ring 3:1 Ratio
 - Wear = 290.28 lbs
= 1291.29 N
 - Strength = 330.85 lbs
= 1471.76 N
- Sun – Planets 6:1 Ratio
 - Wear = 303.3 lbs
= 1349.19 N
 - Strength = 581.42 lbs
= 2586.39 N
- Planets – Ring 6:1 Ratio
 - Wear = 606.6 lbs
= 2698.39 N
 - Strength = 743.49 lbs
= 3307.34 N

From converting these values into torque, the answer came out to be as follows.

- 3:1 Sun - Planets
 - Sun Torque = 235.55 Nm
 - Planets Torque = 117.77 Nm
- 3:1 Planets -Ring
 - Sun Torque = 220.76 Nm
 - Planets Torque = 55.19 Nm
- 6:1 Sun - Planets
 - Sun Torque = 77.59 Nm
 - Planets Torque = 155.18 Nm
- 6:1 Planets -Ring
 - Sun Torque = 496.10 Nm
 - Planets Torque = 198.44 Nm

From looking at the values above, a module of 3 seems a little over engineered. The only value that's within 20 Nm of the torque value of the motor is the planets, and this is shared between the four planets that are being used anyway. This means the gears are definitely strong enough. It might be possible to use a gear module of 2.5, but a 3 would be fine, because they are stronger, which means they will deal with vibrations better and shocks better, plus more load can be applied to them, especially if the motors got upgraded on the buggy someday. This means the gears can finally be sized for designing and manufacturing. Here is the list of measurements for the gears, so that they can be designed.

- Sun of 3:1 Ratio (50 Teeth)-
 - PCD = $50 \times 3 = 150$ mm
 - OD = $(50 + 2) \times 3 = 156$ mm
 - DP = $25.4/3 = 8.47$
 - CP = $3 \times \pi = 9.42$ mm
 - MOD = 3
 - Appendum = 3 mm
 - Dedendum = $1.25 \times 3 = 3.75$ mm
 - ID = $150 - (2 \times 3.75) = 142.5$ mm
 - Whole Depth = 6.75 mm
 - Tooth Width = 30 mm
 - Bore = 25mm
 - Boss Diameter = 60mm
 - Boss Width = 20 mm

- Planet of 3:1 Ratio (25 Teeth)-
 - PCD = $25 \times 3 = 75$ mm
 - OD = $(25 + 2) \times 3 = 81$ mm
 - DP = $25.4/3 = 8.47$
 - CP = $3 \times \pi = 9.42$ mm
 - MOD = 3
 - Appendum = 3 mm
 - Dedendum = $1.25 \times 3 = 3.75$ mm
 - ID = $75 - (2 \times 3.75) = 67.5$ mm
 - Whole Depth = 6.75 mm
 - Tooth Width = 30 mm
 - Bore = 25mm
 - Boss Diameter = 50mm
 - Boss Width = 20 mm

- Sun of 6:1 Ratio (20 Teeth)-
 - PCD = $20 \times 3 = 60$ mm
 - OD = $(20 + 2) \times 3 = 66$ mm
 - DP = $25.4/3 = 8.47$
 - CP = $3 \times \pi = 9.42$ mm
 - MOD = 3
 - Appendum = 3 mm
 - Dedendum = $1.25 \times 3 = 3.75$ mm
 - ID = $60 - (2 \times 3.75) = 52.5$ mm
 - Whole Depth = 6.75 mm
 - Tooth Width = 30 mm
 - Bore = 25mm
 - Boss Diameter = 50mm
 - Boss Width = 20

- Planet of 6:1 Ratio (40 Teeth)-
 - PCD = $40 \times 3 = 120$ mm
 - OD = $(40 + 2) \times 3 = 126$ mm
 - DP = $25.4/3 = 8.47$
 - CP = $3 \times \pi = 9.42$ mm
 - MOD = 3
 - Appendum = 3 mm
 - Dedendum = $1.25 \times 3 = 3.75$ mm
 - ID = $120 - (2 \times 3.75) = 112.5$ mm
 - Whole Depth = 6.75 mm
 - Tooth Width = 30 mm
 - Bore = 25mm
 - Boss Diameter = 60mm
 - Boss Width = 20
- Ring Gear (100 Teeth) -
 - PCD = $100 \times 3 = 300$ mm
 - ID = $(100 + 2) \times 3 = 294$ mm
 - DP = $25.4/3 = 8.47$
 - CP = $3 \times \pi = 9.42$ mm
 - MOD = 3
 - Appendum = 3 mm
 - Dedendum = $1.25 \times 3 = 3.75$ mm
 - OD of Teeth = $300 + (3.75 \times 2) = 307.5$ mm
 - Whole Depth = 6.75 mm
 - Tooth Width = Whole Length of Gearbox
 - Total Length = 510 mm
 - OD of Case = 350 mm

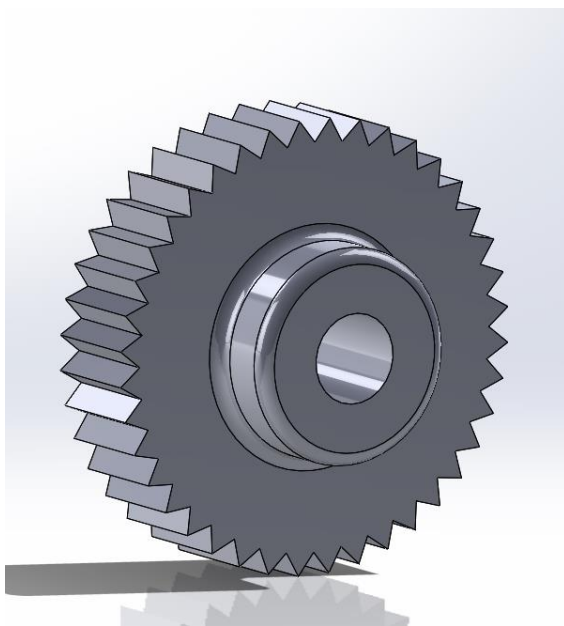


Figure 22

Here is a photo of one of the gears that has been designed in solid works. Obviously, the teeth wouldn't quite look like this, they would be curved more. But this is a good way of seeing how it would look approximately look once finished designing.

3.11 Selector

The selector is possibly the hardest part to design of the whole gearbox. This because of the complexity of it to be able to select the different gear ratios without over complicating the gearbox, and so that it can be used the same way in the other gearbox.

The solution that was thought of was a gear selector fork that would be able to be used both sides, and be able to slide in and out of the gearbox with a good seal, and could be fixed to a rocker, which is then connected to the gear lever.

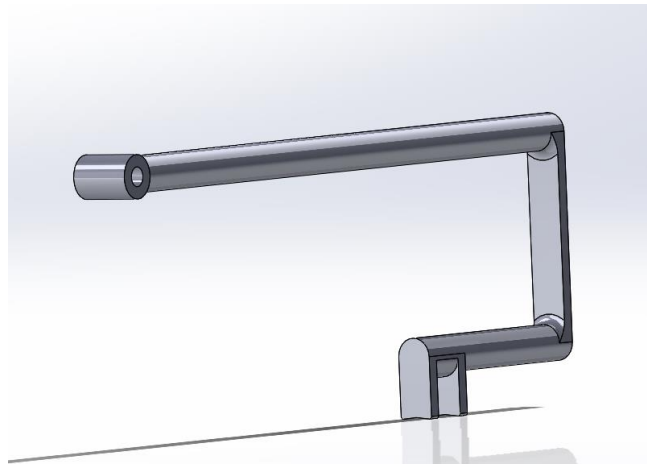


Figure 23



Figure 24

The rocker would be similar to this one on the left, with one selector being fixed to the bottom, one selector fixed to the top, like the one on the left, with the centre on a shaft so it can rotate. But the one for the buggy will have an extended section so that the gear cable or rod can rotate the rocker back and forth to select the different gears.

The selector that has been designed can be seen here on the right and below. The big radius is so that the fork can slide the selector to select different gears. As can be seen in the photo on the right, the inside of the selector is splined. This is so that the gearbox can slide onto the motor so that both are connected constantly. The splines go in as far as nearly the last gear to be selected so that the selector can slide along the motors shaft when selecting another gear.

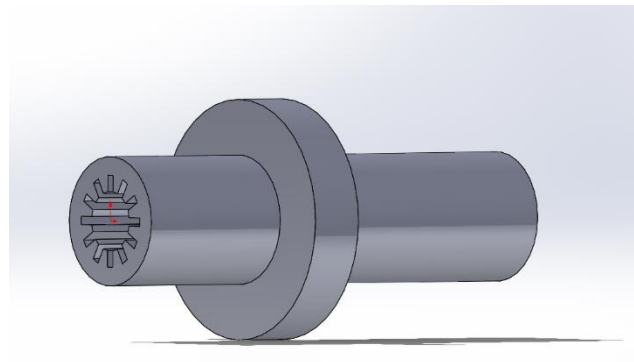
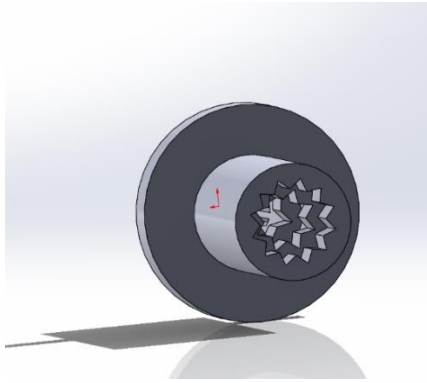


Figure 25



Looking at the photo on the left, the different sized teeth can be seen. This is so that the selector can select different gears, each teeth size is a different gear. There is also space in-between the teeth so that the gears that aren't selected can rotate freely without friction. This design took a lot of thought, and hopefully will work without problems when tried out in a simulation.

Figure 26

3.12 Final Design

The gearbox was designed in solidworks, this meant creating all the parts and then joining them all up in the assembly at the end.

The photo that can be seen on the right is a photo of the planet carrier carrying all the planet gears. As can be seen, there was only just enough room to fit four planets in, with the planets at the front being so big. The 6:1 ratio is at the front, with the 3:1 situated closer to the main section of the planet carrier.

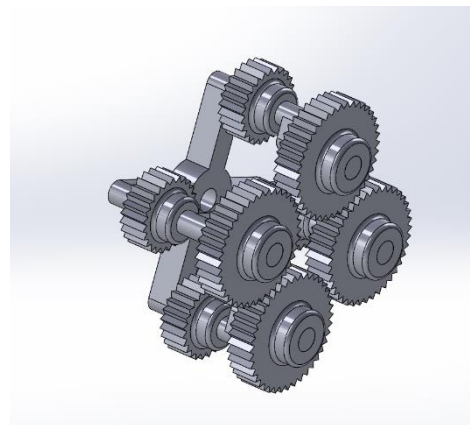
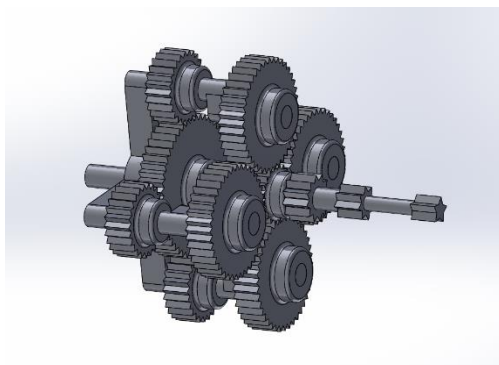


Figure 27



The photo to the left shows the whole gear cluster, with the selector shafts, and the two suns added. As can be seen, the 6:1 selector gear is closest to the cluster, with the 3:1 sitting in the middle, and the 1:1 gear selector sitting right at the front.

Figure 28

The figure on the left shows the cluster sitting inside the casing. It is easier to see how minimal the space is in-between the big planets in this figure. The teeth of the casing can also be seen. It is very nice to see that this all works out nicely, and actually fix together.

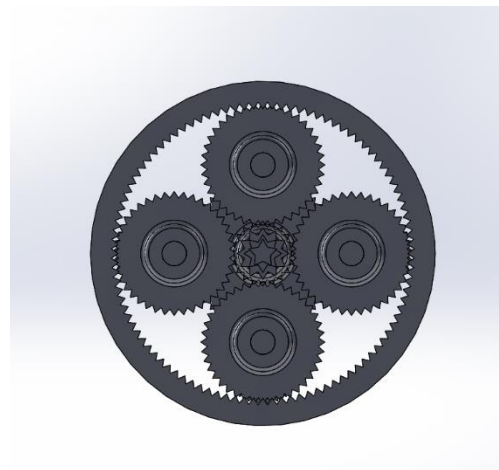


Figure 29

The two figures below shows everything other than the casing itself. This figure makes it easier to see how the selector would work as well. It is currently selecting the 6:1 gear in its current position. The motor spline would be placed through the casing the same side the selector comes out the casing. The shaft coming out the other end is the output of the gearbox. The final drive gear or sprocket is needed to be fitted to this shaft, and the chain will connect this to the rear axle.

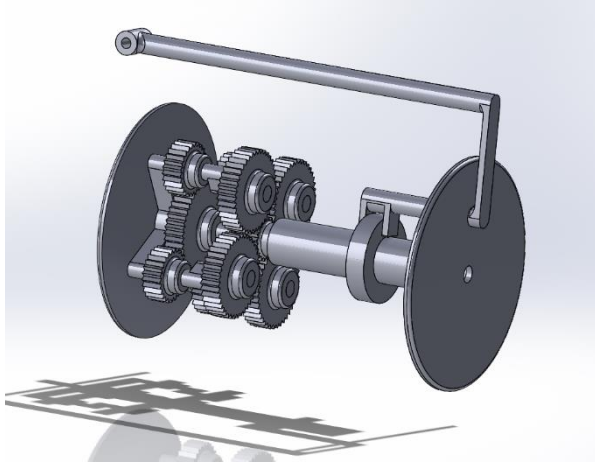


Figure 31

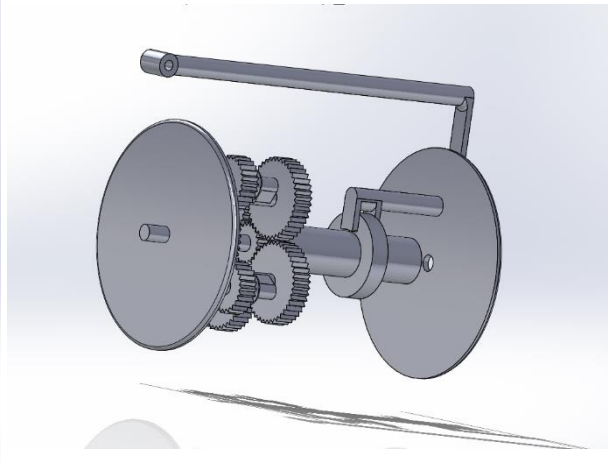


Figure 30

The two figures below shows how the gearbox would look with the casing around it. It looks very basic on the outside, but very complex on the inside.

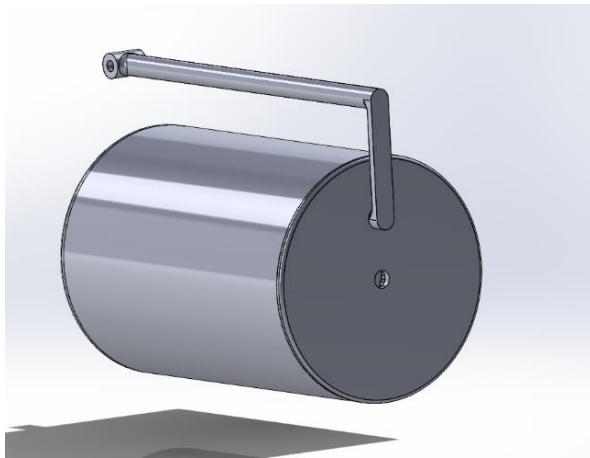


Figure 33

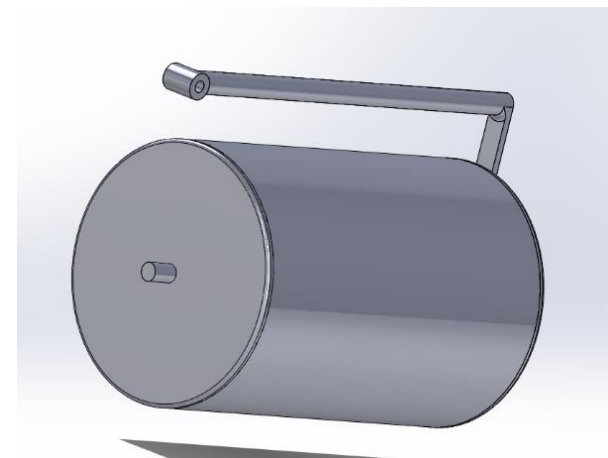
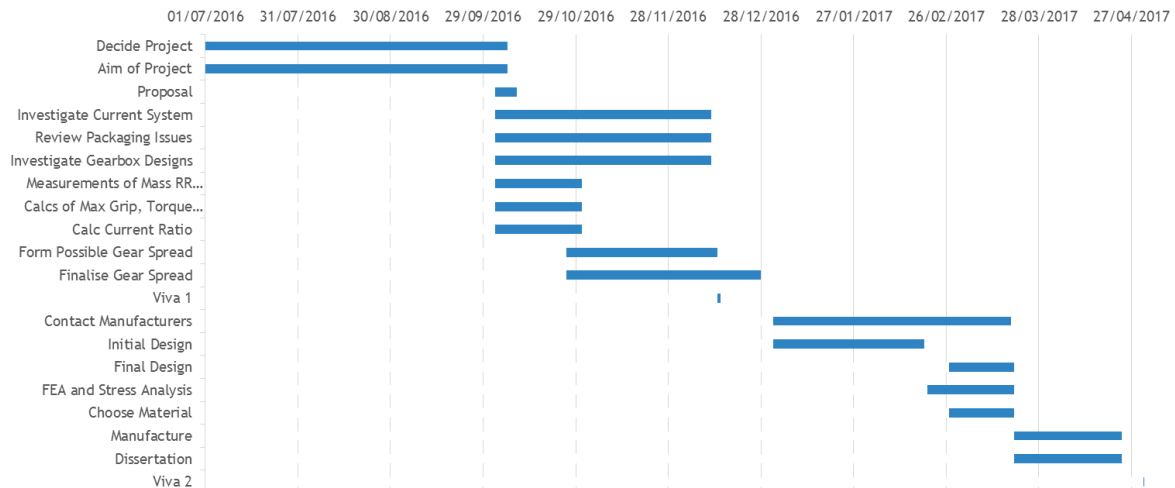


Figure 32

4.0 Timescale

Below is the original timescale for the project when the project had been decided and all the stuff to do had been listed. Unfortunately, the project fell behind schedule, with the design still needing some tweaks, and bearings and seals needing to be researched, and inserted into the design. Also, the gearbox hasn't undergone a stress analysis yet, to see if there are any weak points in the design, or if anything needs improving. More time should've been spent on the project, earlier in the year so that the project could've been finished and sent off for manufacturing. Hopefully, the design can be finalised before the viva so that a simulation run of the gearbox model can be shown to prove that it does work.



There were several milestones during the project, with the first one being deciding on the project and the aim of the project. Without completing these two tasks, the project could not have been started. The next one was probably the measurements of the buggy. This needed to be done before any calculations could be done on the type of gear ratios needed, the current gear ratios, and thinking of how to improve the current design. A finalised gear ratio was a big one to be honest, because this meant that the gears could now sized and designing could start taking place. Both viva's are major milestones in the project, making sure that work is completed in time for the presentations, that a PowerPoint has been done, and that it is known what is done, and what is needed to be done. Getting a final design is also a major milestone, without this, the manufacturing cannot begin, and the project cannot be finalised. Dissertation is probably the most important milestone of all, with all work done by that point needing to go into one document with hopefully a completed project. The dissertation is possibly the hardest thing to do, sitting down and writing everything that was completed over the past year.

Other milestones would include assignment deadlines, which did push the project behind schedule which is very unfortunate. More organisation is needed, and getting priorities right on which work to spend time on at which point in time. Being more organised would've helped in completing this this project.

5.0 Conclusion

The conclusion of this project is that there is a gearbox design that has been created for the university's electric buggy. The design just needs finishing off, with seals and bearings being added to the design. The ratios have been finalised, and should improve the practicality of the buggy a lot. With this gearbox, it should be able to go off-roading with enough torque to be able to go up any hill put in front of it. The buggy will also be able to go faster with this gearbox design, with a ratio fitted that means the buggy can exceed 40 MPH. The gearbox has been designed, with strength in mind, meaning it can cope with any force that is applied to the buggy. This also means that the gearbox reliability should be good, with a 'made to last' used during design. Hopefully this gearbox does get finished and gets manufactured. This would make the project worthwhile.

6.0 Evaluation

More time needed to be spent on the project to get it completed on time. Being more organised would've helped, with other university assignments getting in the way of spending time on this project. If organisation was better, the design would've been completed and ready for manufacture.

Further work could've been carried out as well, such as researching seals, so that the gearbox could be sealed, and looking up bearings, and how they could be placed and where in the design. Also, it would've been a good idea to have the two gearboxes in design, and create a gear lever to see how the selector works, and if it works properly.

More modules could've been looked at also, with the opportunity to make the gearbox lighter if the smaller gears would cope with the torque put out by the motor. If the design was complete, a stress analysis could've been done on the model to see if there are any weak points in the model, or if the model is too heavy duty and could be lightened. Oils could be investigated as well, the best grade for this type of gearbox, and the amount to put in the gearbox, the gears need to be well lubricated.

All these reasons all go back to time, the more time spent on the project, the more things that could've been done.

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