Drive Shaft Bicycle

A Baccalaureate thesis submitted to the
Department of Mechanical and Materials Engineering
College of Engineering and Applied Science
University of Cincinnati

in partial fulfillment of the
requirements for the degree of

Bachelor of Science

in Mechanical Engineering Technology

by

Robby Elkin

Keaton Glaser

Kyle Rechel

April 2021

Thesis Advisor: Ahmed Elgafy, PhD

Table of Contents

List of Figures

List of Tables

Abstract

The purpose of this project was to design and build a more efficient bicycle that utilized a drive shaft system. Robby Elkin was in charge of the bicycle gearing and ordering parts, Keaton Glaser was in charge of the drive shaft, pedaling shaft, and was project manager, and Kyle Rechel was in charge of the frame design and fabrication. The main goals for this project were to build a bicycle that had an efficiency that was equal or greater than that of the average bicycle while still being light weight, low maintenance, durable, and affordable for the average consumer. The largest challenges in this project were getting all of the parts required while remaining within budget, welding consistently without the use of weld fixtures, and accurately measuring efficiency of the finished product.

Problem Statement

We plan to design a more efficient way of transportation through an advanced chainless bike system. It is suggested by Stanford University that a perfectly efficient bike can travel roughly three times the distance for the same amount of work as walking (1). This means that if you were to expend the energy to walk 1km, you could spend the same amount of energy to ride 3km. In today's market, the average consumer's bike (If well taken care of and properly oiled) is roughly 74.5% efficient due to the inefficient gearing systems that are the standard (1). Taking this into account, if you were to expend energy walking 1km, the average bike would take you 2.235km. There are bicycles currently on the market that can raise that efficiency up to 80, 90, and even as high as 98% efficiency, however these kinds of bikes can range into the tens of thousands of dollars, making them unobtainable to the average consumer.

Research

Background of the Problem

Back in the 1870's, an Englishman by the name of John Kemp Starly created what we know as the chain drive system for bicycles. This was one of the most important advancements in the history of bikes, as it not only made it so that the back wheel provided the torque, but the front wheel could be used for steering. Since this invention, the bicycle has remained mostly the same, only advancing in lighter materials and cheaper cost of production with some exceptions such as electric, hydraulic, and pneumatic bikes; however most of these types of bikes are not as practical to the average consumer over a traditional mechanical bike (2). Today, the bicycle is widely used amongst many people throughout the world. While it is hard to get an exact number on biking statistics, several studies show that in the US alone there were roughly 4 billion bike trips made in 2009, doubling that from the year 2000 (3).

The people who are impacted by this lack of efficiency are the daily bike commuters. People who must bike as their main means of transportation most likely do not have the expendable income for a performance bike costing thousands of dollars. This would also apply to people who wish to join the competitive biking scene as performance is of top priority.

As mentioned in the above problem statement, according to Stanford University, the average consumer's bike (If well taken care of and properly oiled) is roughly 74.5% efficient due to the standard inefficient gearing systems. Even with the knowledge of this inefficiency, there have been very few advancements to the bicycle in the modern age. There is one company named CeramicSpeed who has made a drive shaft system that uses ball bearings to reduce friction between the input petals to the actual wheels, boasting a remarkable 99% efficiency. This invention could be the future of the bicycling industry; however, this advancement currently could cost the average person over $2,500. We won't be able to reach that level of efficiency, but we are hoping to produce a bike with impressive efficiency at a cost that is affordable to the average consumer, with features that put the bike into the modern era.

State of the Art– Frame

Marin Presidio 1

There are currently a few items on the market that solve our problem statement. The first is a bike known as the Marin Presidio 1. This bike was chosen as it is called the "best bang for your buck" bike. This bike features a 6061-aluminum frame, handlebar shift crank, and a few customizable features all for a price of $650. This bike may not be on the cutting edge of technology, but it is by far the most affordable bike on this list and provides a great comparison point.

Pros:

- Affordable

Cons:

- Less customizable
- Lacks efficiently

SuperSix EVO

Another bicycle worth looking at is the SuperSix EVO. There are several different versions of this model, however the main features stay mostly the same. This bike boasts to be the fastest road bike on the market with a lightweight frame and hardware, narrow body to cut down on drag, and a stiff professional feel. This bike also has many other quality of life improvements over a standard bicycle with a built in speedometer, an app, and many adjustable features so that the bike can be tailored to the users' preferences. This bike would be purchased by people who bike for sport, hobbies, and competition. This also offers many advantages over a typical bicycle and the cost reflects that higher level of quality. The cheapest model without all of the fancy bells and whistles is roughly $2000 dollars and up to $9,000 for carbon fiber. While this bike is certainly one of the most impressive bikes on the market, it is almost exclusively for competition and extreme hobbyists.

Pros:

- Very efficient
- High Quality
- Lightweight

Cons:

- Very Expensive

The Lux

Next, is the bicycle that will most likely change the industry of biking within the next few years. This bike is known as "The Lux". Developed by CeramicSpeed industries, this bike is the first to successfully remove the standard chain gear system and replace it with a drive train system. This bike boasts an incredible 99% efficiency by using a ball bearing drive train and a geared hub removing 49% of friction from the standard chain and gear system. This bike is on the cutting edge of the industry, and while pricing has not been official released due to there being no production yet, it is expected that this bike may cost above $5,000 or even $10,000. This means that its availability for the average biker is very out of reach and only obtainable for competitions, hobbyist, and bicycle enthusiasts.

Pros:

- Extreme Efficiency
- High Quality
- Lightweight

Cons:

- Price expected to be very high
- Nonstandard parts

SRAM NX Eagle

Finally, it is important to look at the SRAM NX Eagle Groupset. This innovation is not actually a bicycle; however, it is an efficient gear hub system that can be attached to almost any bike to increase performance. This is considered to be state of the art as it allows for an average consumer to be able to upgrade their existing bike's efficiency rather than replacing their existing bike. The cost to upgrade their bike with this system is around $375 and this includes a feature that allows the bike to be better suited to off road navigation.

Pros:

- Affordable
- Mostly Universal
- Increases Efficiency
- Quality

Cons:

- Heavier than a performance bike gear hub
- Requires knowledge of bike assembly
- Not as efficient as performance bike gear hubs

State of the Art – Power Transmission

Chain driven (traditional)

The main advantages to chain driven bicycles are cost, they can transmit large loads, and they allow for easy gear shifting (4). In addition to this, chains are compatible with all bicycle frames and are easier to find. The main disadvantages of chain driven bicycles are that they produce noise, the chain can be dropped, they are relatively heavy, and they require regular maintenance and lubrication (4).

Toothed belt driven

The main advantages of toothed belt driven bicycles are that they have low wear, require minimal maintenance, run silently, are relatively light, and have a longer life span (4). The disadvantages of toothed belt driven bicycles are that they are weather sensitive, are expensive, are very wide, and are manufactured by fewer companies (4). The larger width requires special mounting onto the bicycle frame making them not compatible on all bicycle frames.

Shaft driven

Drive shafts are different from chains and toothed belts have to be specially mounted to the bicycle frame on bearings. Their advantages are they are well protected from weather, they last a very long time, and they have a higher efficiency (4). The main disadvantages of drive shafts are they are the most expensive upfront cost, have the highest weight, and require extra gears to change the working angle of energy being transmitted. To make a drive shaft work you will also have to select a gearing system. This method also doesn't directly allow for different gear ratios unless an internal gear hub or similar device is used.

State of the Art – Transportation Methods

We live in a world where alternative forms of transportation have become a necessity. Walking to work every day would be impossible for many people. Partially due to the enormous number of cars in the world today, global warming has become a serious issue. This has caused a significant increase in the number of people that choose to use alternative methods of transportation to get to work. While our project will focus on how to create a more efficient form of bicycle utilizing a drive shaft, there are other eco-friendly alternatives to help people to get around as well, or even simply to ride for fun. The primary contenders of our proposal consist of chain driven bicycles, motorcycles, and electric bicycles.

The closest to our design, is the commonly known multi-speed chain bicycle. It is the most efficient and eco-friendly among these top contenders. Despite this, the average bike (If well taken care of and properly oiled) is only roughly 74.5% efficient (1). This leaves a lot of room for improvement. The chain driven bike requires no charging or form of fuel other than the work that the operator does on it. This can be considered both a positive and a negative. Since the movement of the bike is solely reliant upon the operator, they expend a large amount of energy using this means of transportation. Despite this, since it requires no electricity or fuel, it is the cheapest form of transportation and can also be a great form of exercise for the operator.

Next on the list is the motorcycle. While there are many different types of motorcycle, it has the ability to be economically friendly as well. They allow the rider to still enjoy the freedom of an agile and fun vehicle, without any of the work! The negatives to a motorcycle are that while they are often more fuel efficient than a car, they still require fuel as well as more basic maintenance from the owner when compared to a normal bicycle. Even when using fuel, internal combustion engines are largely inefficient. Motorcycles also utilize a chain driven system, which as previously mentioned, is also inefficient. Motorcycles also obviously cost thousands of dollars. They are typically cheaper than cars, but certainly more expensive than a bicycle as well. While they may be a lot more convenient for the rider, it is a lot less beneficial for their health, bank account, and for overall emissions.

A more recent trend is the use of electric bicycles, often called e-bikes. While many still prefer a traditional bike, others have opted for the easier version that can use an electric motor to propel them. Riding an e-bike, the operator uses minimal effort, as the motor will be able to handle most terrains on its own, and pedaling is not always necessary. The problem with this technology is the short operation distance. While it is nice that they require electricity instead of fuel, their trip range is very limited. This is dependent on how fast you ride, how much you pedal to help the motor, what the terrain is like, etc. The average e-bike will get anywhere from 20-50 miles on a single charge, based on speeds ranging from 10-20 mph. This does not take into account harsh conditions, such as going up hills, sandy or rocky ground that may be uneven, wind, or degradation of the battery and motor performance over time. However, the e-bike market is ever growing. According to an experiment conducted in the UK, 80 participants were loaned an e-bike for 6-8 weeks. Across the sample, average usage was in the order of 15–20 miles per week, and was accompanied by an overall reduction in car mileage of 20%. At the end of the trial, 38% of participants expected to cycle more in the future, and at least 70% said that they would like to have an e-bike available for use in the future, and would cycle more if this was the case (2). Due to this increase in demand, e-bikes have been increasing in price, and remain limited in their ability to travel longer distances.

Our drive shaft driven bicycle will include the best parts of each of these alternative forms of transportation. Similar to a regular chain driven bike, our drive shaft bike will not require any fuel or energy source other than the rider, but will have an optional electric assist. It will still provide riders with a better experience than a chain driven bike as it will be more efficient and require less effort to operate. The drive shaft bike will also be more reliable as there is no chain to drop along the side of the road, and it may require less lubrication and overall maintenance. The addition of the electric motor assist to the bike will give users a boost when desired, however will not be necessary for normal operation of the bike. Overall, the drive shaft bike is 100% state of the art.

End User

The end user of our drive shaft bike design is the general population of children and adults who enjoy riding bikes on occasion for joyrides, daily commuters, and even people who want high performance while riding or racing their bike.

No one product that currently exists encompasses all of these customer features. There is a multi-speed driveshaft bike currently being made by “Ceramic Speed” that is the closest to our design. It is designed for racing, so it is extremely lightweight and efficient. This high performance means it would also be fun to ride and the safety is up to par for adults, but wouldn’t be suitable for children. It features an all black carbon fiber design which is widely appealing, but it does not come in any other colors or designs, especially for children. The main part that they failed though is the cost efficiency. The bike is projected to be several thousand dollars, which makes it way more than most people would be willing to pay.

Customer Features:

What is important to the customer?

1. Lightweight Design
2. Highly Efficient Design
3. Cost Efficient (Doesn’t Break the Bank)
4. Safe and Fun to Operate
5. Sufficient Number of Gears
6. Highly Reliable
7. Low Maintenance Required
8. Visually Appealing

Engineering Characteristics:

How will you meet the customer features?

1. Will be designed of aluminum as it is lightweight and doesn’t rust.
2. A drive shaft bike system can reach up to 99% efficiency; which is 49% better than the leading chain driven bike system (Dura Ace Components).
3. Aluminum is a cheap material when compared to other alternatives. We will also minimize the number of bearings used and can choose bearings and materials that offer the highest quality for the lowest prices.
4. Our product needs to be safe. The frame and gear design will be created with not only efficiency and being lightweight in mind, but also keeping it safe to operate and use on a regular basis. Covers can be designed to fit over the gears to avoid injury as well as debris from entering the system. Performance will help to make it more fun for the user.
5. Painting and designing of the frame and drive shaft system will help to make the bike more visually appealing to different types of people. Different colors or designs could be offered.

Summary of Research

In conclusion, the ideal solution to this problem does not exist. There are no bikes that currently exist that are highly efficient, lightweight, multi-speed, low maintenance, and with an electrical assist, let alone while still being at a reasonable price range. Our end user ranges from daily commuters and joy riders, all the way to performance cyclists. Studies indicate that this population of end users is only growing over time, while standard bicycle technology has done little to keep progressing. We will design and create a drive shaft bike that will encompass all of these features and more, putting the bike back into the modern era.

Quality Function Deployment

Based on a survey conducted on the 30th of September 2020, using google surveys completed by regular bicycle users, questions of cost, safety, efficiency, etc. were answered. Based on over thirty completed surveys of which a sample has been attached below, clear product objectives were devised.

Customer Survey Sample

Customer Survey

Bicycle Alternative Designs

This survey will be used to prioritize various features to maximize customer satisfaction. The system in question will address issues for creating a more efficient bicycle that is driven by a direct drive shaft.

Name: ________________________ Date: ______________

What are the primary reasons that you bike?

a) Recreation b) Commuting/Travel c) Exercise d) Competition e) Other (please type)

How many times per month do you ride your bike?

a) <5 b) 5-10 c) 10-15 d) 15+

What is the brand of your current bike? (Optional, please type)

What type of bicycle do you currently have?

Mountain Bike Street/Road Bike Racing Bike Other (please type)

How important is each feature to you in a regular bicycle?

Please circle your answer. 1 = Low Importance 5 = High Importance

Initial Investment Cost:	**1**	**2**	**3**	**4**	**5**	**N/A**
Efficiency:	**1**	**2**	**3**	**4**	**5**	**N/A**
Safety:	**1**	**2**	**3**	**4**	**5**	**N/A**
Weight:	**1**	**2**	**3**	**4**	**5**	**N/A**
Number of Gears:	**1**	**2**	**3**	**4**	**5**	**N/A**
Reliability:	**1**	**2**	**3**	**4**	**5**	**N/A**
Maintenance:	**1**	**2**	**3**	**4**	**5**	**N/A**

Bike Esthetics/Looks: 1 2 3 4 5 N/A

How satisfied are you with current bicycle technology?

Please circle your answer. 1 = Low Importance 5 = High Importance

Initial Investment Cost: 1 2 3 4 5 N/A

Efficiency: 1 2 3 4 5 N/A

Safety: 1 2 3 4 5 N/A

Weight: 1 2 3 4 5 N/A

Number of Gears: 1 2 3 4 5 N/A

Reliability: 1 2 3 4 5 N/A

Maintenance: 1 2 3 4 5 N/A

Bike Esthetics/Looks: 1 2 3 4 5 N/A

How much would you be willing to invest in new and/or more efficient bicycle technology?

a) $0-$300 b) $300-$600 c) $600-$900 d) $900-$1200 e) $1200-$1500 f) $1500+

Customer Features

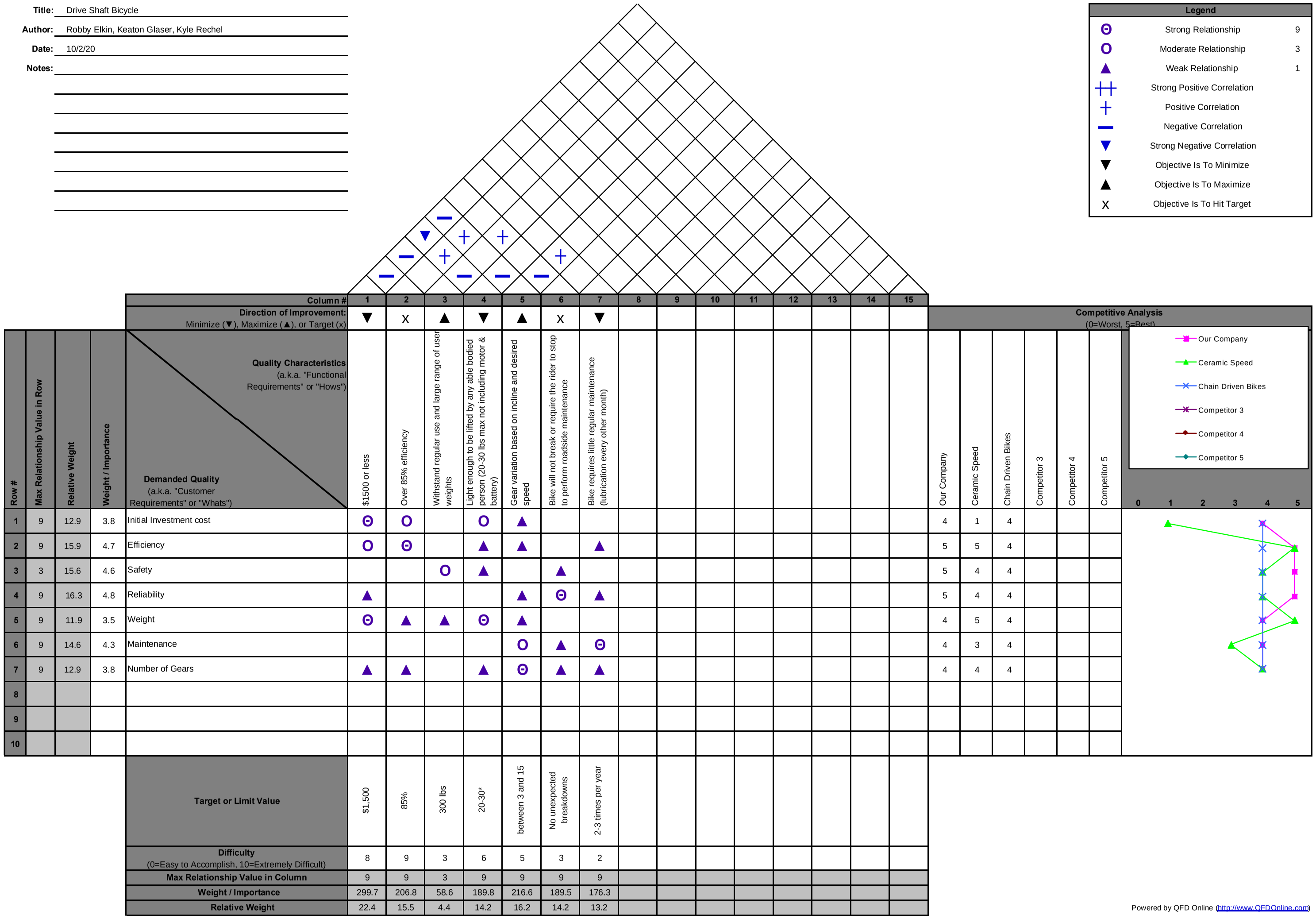
Customer Features:

1. Lightweight Design
2. Highly Efficient Design
3. Cost Efficient (Doesn't Break the Bank)
4. Safe and Fun to Operate
5. Sufficient Number of Gears
6. Highly Reliable
7. Low Maintenance Required
8. Visually Appealing

Engineering Characteristics

1. Aluminum Frame – Will be designed of aluminum as it is lightweight and doesn't rust.
2. High Quality/Efficient Components – A drive shaft bike system can reach up to 99% efficiency; which is 49% better than the leading chain driven bike system (Dura Ace Components). We are aiming for at least 85% efficiency.
3. Material Selection – Aluminum is a cheap material when compared to other alternatives. We will also minimize the number of bearings used and can choose bearings and materials that offer the highest quality for the lowest prices.
4. High Factor of Safety (FOS) and Reliability – Our product needs to be safe. The frame and gear design will be created with not only efficiency and being lightweight in mind, but also keeping it safe to operate and use on a regular basis. Covers can be designed to fit over the gears to avoid injury as well as debris from entering the system. Performance will help to make it more fun for the user.
5. Proper Gear Ratios – Has enough gears to enable the user to easily ride on different terrain and elevation types.
6. Low Maintenance – The bike will require low maintenance intervals, requiring little lubrication and care throughout regular use.
7. Design Appearance – Painting and designing of the frame and drive shaft system will help to make the bike more visually appealing to different types of people. Different colors or designs could be offered.

House of Quality



Title: Drive Shaft Bicycle
Author: Robby Elkin, Keaton Glaser, Kyle Rechel
Date: 10/2/20
Notes:

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▼	x	▲	▼	▲	x	▼								
Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	$1500 or less	Over 85% efficiency	Withstand regular use and large range of user weights	Light enough to be lifted by any able bodied person (20-30 lbs max not including motor & battery)	Gear variation based on incline and desired speed	Bike will not break or require the rider to stop to perform roadside maintenance	Bike requires little regular maintenance (lubrication every other month)								

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Our Company	Ceramic Speed	Chain Driven Bikes	Competitor 3	Competitor 4	Competitor 5
1	9	12.9	3.8	Initial Investment cost	Θ	O		O	▲											4	1	4			
2	9	15.9	4.7	Efficiency	O	Θ		▲	▲		▲									5	5	4			
3	3	15.6	4.6	Safety			O	▲		▲										5	4	4			
4	9	16.3	4.8	Reliability	▲				▲	Θ	▲									5	4	4			
5	9	11.9	3.5	Weight	Θ	▲	▲	Θ	▲											4	5	4			
6	9	14.6	4.3	Maintenance					O	▲	Θ									4	3	4			
7	9	12.9	3.8	Number of Gears	▲	▲		▲	Θ	▲	▲									4	4	4			
8																									
9																									
10																									

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target or Limit Value	$1,500	85%	300 lbs	20-30*	between 3 and 15	No unexpected breakdowns	2-3 times per year								
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	8	9	3	6	5	3	2								
Max Relationship Value in Column	9	9	3	9	9	9	9								
Weight / Importance	299.7	206.8	58.6	189.8	216.6	189.5	176.3								
Relative Weight	22.4	15.5	4.4	14.2	16.2	14.2	13.2								

Competitive Analysis (0=Worst, 5=Best)

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Powered by QFD Online (http://www.QFDOnline.com)

Figure 1 – House of Quality

Product Objectives

Reliability (16.3%)

The bike will not break down or malfunction during normal operation, causing the user to stop and perform critical maintenance.

Efficiency (15.9%)

Drive shaft bikes are widely accepted as more efficient than chain driven bikes. We plan to achieve an efficiency of at least 85%.

Safety (15.6%)

Our bike will need to remain safe for a variety of different users, being different shapes and sizes. Our bike should be safe for users up to 275 lbs.

Maintenance (14.6%)

The bike will have low maintenance intervals, requiring little lubrication and care throughout regular use. The bike may require general maintenance or lubrication 1-2 times per year.

Initial Investment Cost (12.9%)

We want our product to be readily available to a larger consumer base, so we will keep our total cost around $1500.

Number of Gears (12.9%)

Has enough gears to enable the user to easily ride on different terrain and elevation types. This should allow the user to expend less effort when encountering difficult conditions.

Weight (11.9%)

The bike should remain within the 20-30 lb range, utilizing lightweight materials. This does not include the additional weight of a motor or battery that would be optional attachments.

Design – Frame

Design Alternatives and Selection

There were several design alternatives that were considered during the span of the design process. Mainly the shape, size, and material for the final product. For the actual size of the frame, the team opted to design the frame for an average height user (5'8") as opposed to an above average height user. The above average sized user design consideration was only on the table as our group consists of members who are above average height. Our team did however design the bike for an above average weight to include anyone who wants to use the bike for weight loss. This means that the diameter of the bicycle members is thicker than the members of other bikes of the same size to accommodate the added weight and to avoid any flex in the rear forks which could result in a misalignment of the gears. For the material, the bike needed a lightweight and strong frame, but because of our limited resources it also needed to be cheap. The two options that were considered were 6061 T6 aluminum and galvanized steel. Both materials are strong enough to handle the capacity and both are corrosion resistant however each had some advantages over the other. Galvanized steel had the advantage of being cheaper, our group has access to free galvanized steel. The frame was the most expensive costs to the project, cutting out material costs would save the project a lot of money. 6061 T6 Aluminum has the advantage of being lighter and stronger than galvanized steel and it is relatively cheap to obtain. In the end it was decided that the quality of the bike outweighed the cost savings that the galvanized steel could bring.

Figure 2 – Initial Frame Design

This preliminary design was made based off of the 2D drawing and was quickly scrapped due to its complex geometry.

Figure 3 – Bent Pipe Frame Design

This version was the intended to be what the finished product would look like, however the team could not acquire the tools necessary to make the bends in the rear fork accurately.

Figure 4 – Cut Pipe Frame Design

This model is the version that was accepted as our groups final model. This version features cut members to avoid bending and a redesigned wheel mounting system.

Design – Gears

Design Alternatives and Selection

Concept 1: Bevel Gears

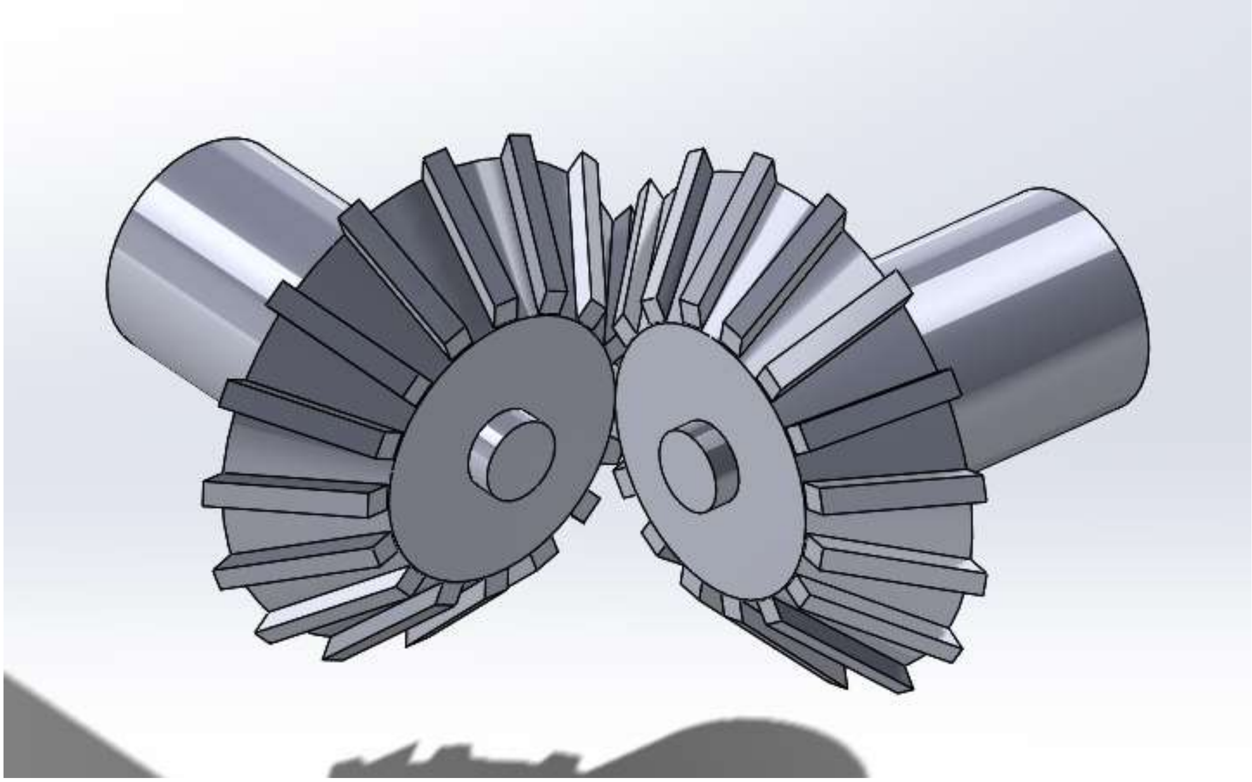


Figure 5 – Bevel Gear Concept Drawing

Bevel gears are good because they allow you to change the operating angle and are simpler gears to manufacture. Bevel gears' axes intersect instead of being offset. Regular bevel gears have an efficiency of 93-97% (5). For the bicycle, these would be used on both ends of the drive shaft to transmit the power from the pedals to the rear wheel. Once at the back of the drive shaft it will go through an internal gear hub. This is how multiple gear speeds will be achieved while having a fixed drive shaft.

Concept 2: Spiral Bevel Gears

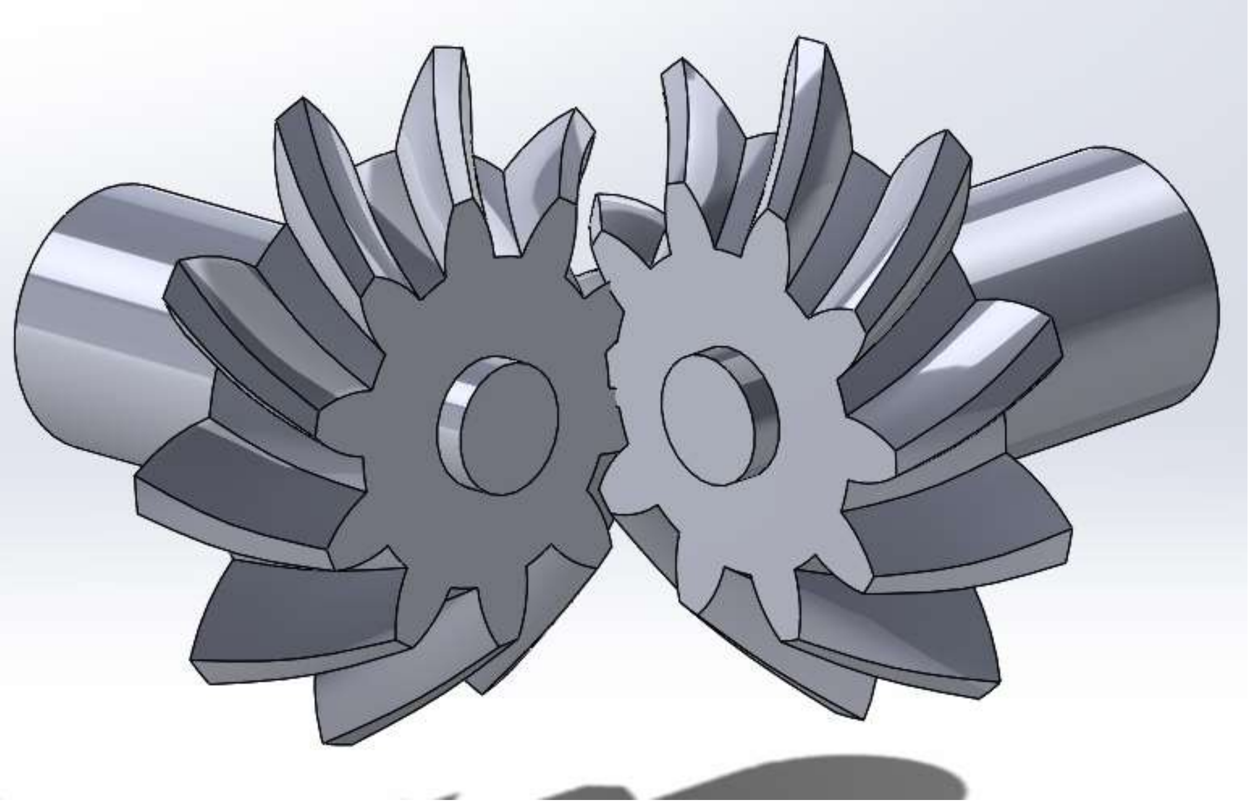


Figure 6 – Spiral Bevel Gear Concept Drawing

Spiral bevel gears are bevel gears with spirally cut teeth. They produce less noise and less vibrations that traditionally cut bevel gears and spur gears (5). Like a traditional bevel gear, the spiral bevel gears' axes intersect instead of being offset. Spiral bevel gears are also more efficient than straight cut bevel gears. Spiral bevel gears have an efficiency of 95-99% (5). For the bicycle, these would be used on both ends of the drive shaft to transmit the power from the pedals to the rear wheel. Once at the back of the drive shaft it will go through an internal gear hub. This is how multiple gear speeds will be achieved while having a fixed drive shaft.

Concept Selection

Spiral bevel gears were selected for their high efficiency and greater strength.

Concept 3: Gear and Bearings

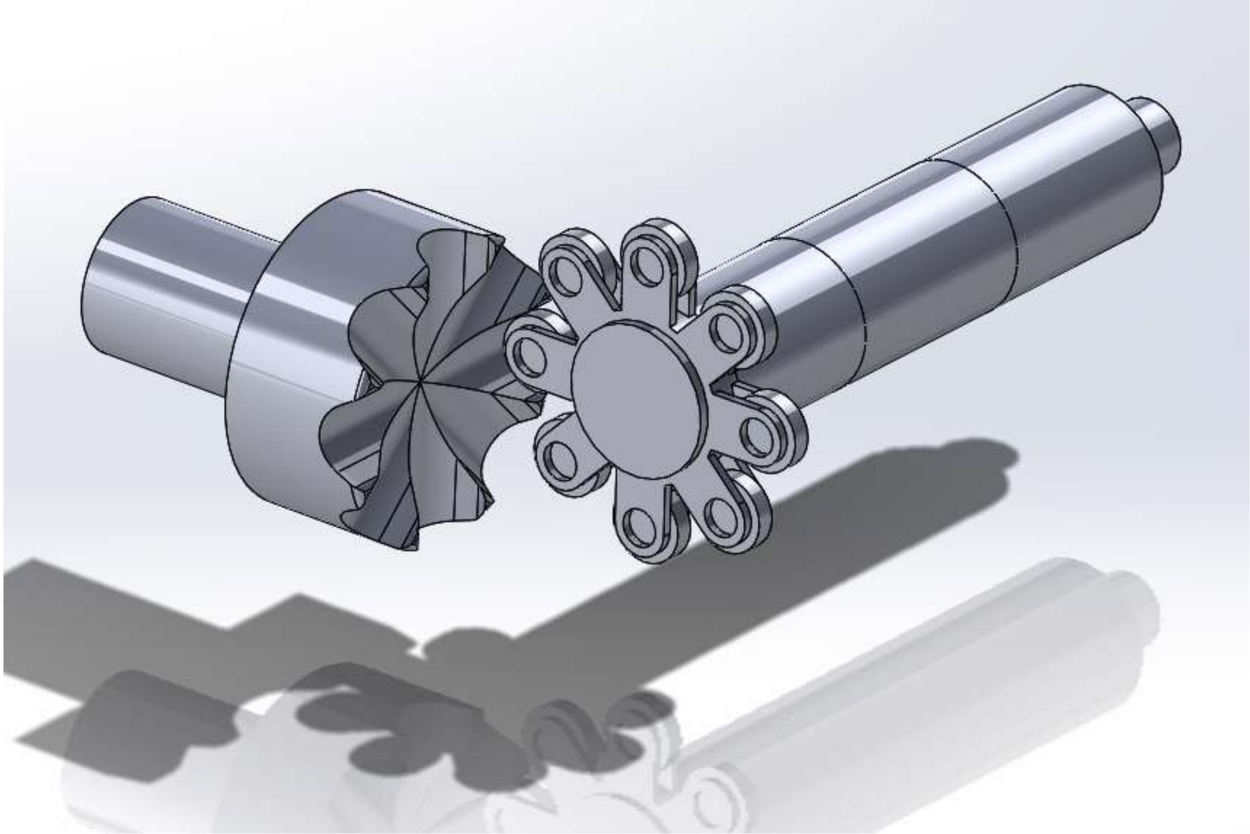


Figure 7 – Gear and Bearings Concept Drawing

Bevel gears that include bearings have an efficiency of 98-99% (6). Gears with bearings aren't able to transmit as much torque but have higher efficiencies. The difficulty with this is in the design of the gear that mates up to the bearings. The downside to this is the added cost of high efficiency bearings and you also need to select the type of bearings you want. This design would be used in the same application as the bevel gears on the bicycle.

Design – Shaft

Design Alternatives and Selection

Figure 8 – Solid Shaft

Concept 1 – Solid Shaft

This concept is a simple solid shaft design. It would be mounted into the bike frame at either end via the bearings shown. This will allow the shaft to spin freely, as it will be securely fastened into the frame of the bike. There is a ring of bearings that can be seen, that is directly attached to and would spin along with the shaft. These bearings will rotate against a prototype gear that is attached to the rear axle. Using this design, there would be an internal gear hub system in the rear wheel for shifting that is connected to the prototype gearing system. There would be a matching ring of bearings on the opposite end of this shaft to connect the shaft to the pedals.

This design would be relatively easy and cheap to manufacture. It would be a sturdy design that could withstand some abuse. The drawbacks to this concept is that it would be a heavier product, and that there could be high stress points near the ends where the diameter is reduced for mounting to the frame.

Figure 9 – Smooth Shaft

Concept 2 – Smooth Shaft

This concept has several similarities to Concept 1. As before, it is mounted into the bike frame via bearings, and is also a solid shaft design. This would also be used along with an internal gear hub for shifting and a prototype gearing system. There would also be a matching ring of bearings on the opposite end of this shaft to connect the shaft to the pedals. Where this shaft differs, is in the shape and material. The idea behind this design is to have no corners on the shaft. Having a fully smooth profile, there would be no key stress points throughout the shaft. Ideally, there would be chamfers and fillets to smooth every corner of the shaft. Through stress analysis, the shape could be altered and slimmed down to reduce the overall size and weight of this shaft.

Due to the reduced amount of stress, a cheaper or lighter material could be used for the shaft.

Being able to have a smaller profile and reduced weight would be a large benefit of this design. The drawbacks to this design would be the large increase in manufacturing time, along with the amount of prototype parts that would need to be created for both destructive and non-destructive stress analysis testing.

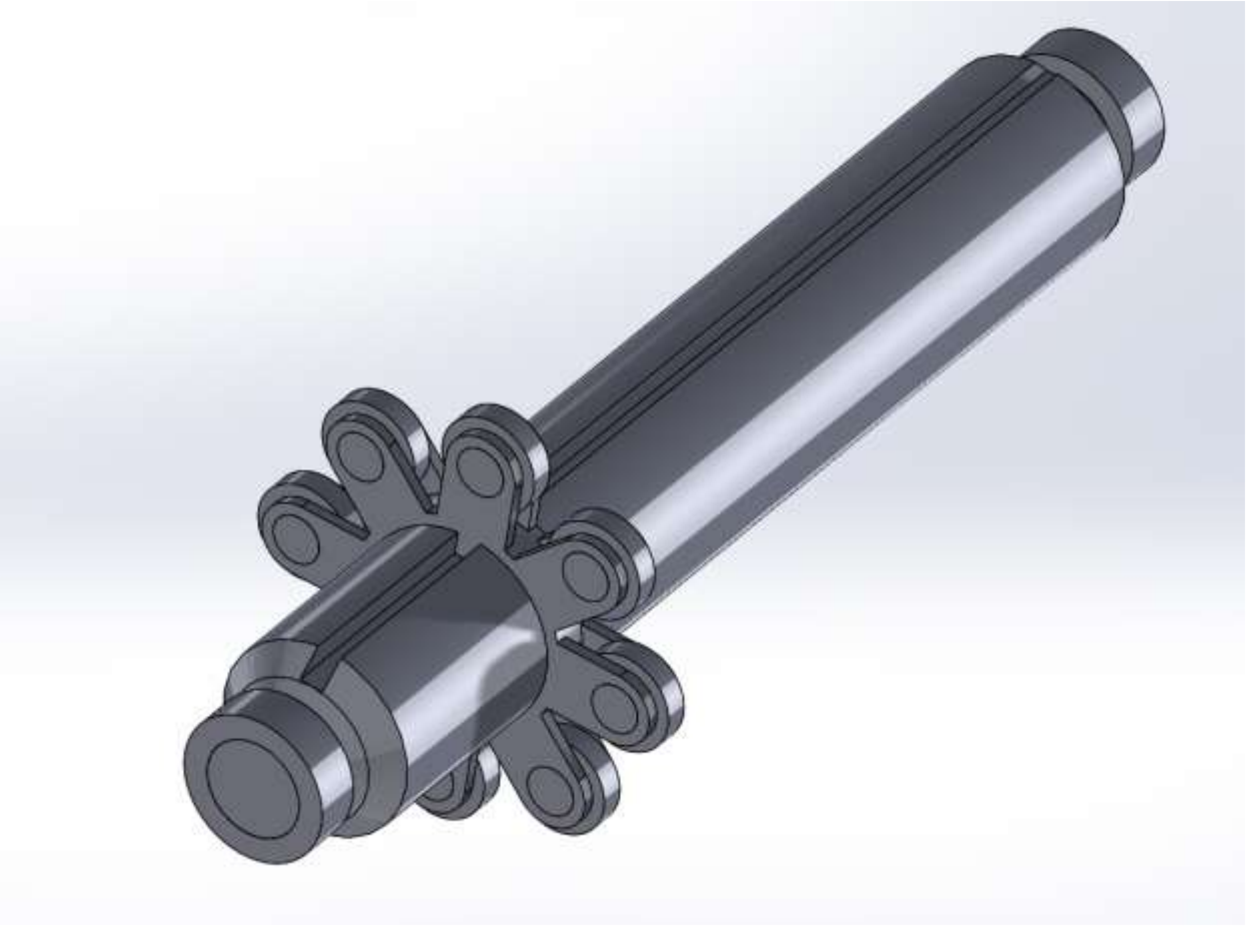


Figure 10 – Sliding Shaft

Concept 3 – Sliding Shaft

This concept would utilize a sliding shifting system. Mounted to the frame via the bearings shown, it would be well held in place. There would be a matching ring of bearings on the opposite end of this shaft to connect the shaft to the pedals. On the rear axle of the bike, a separate prototype gearing system would be required. This gearing system would have several rows of teeth similar to a normal bicycle, but they would be facing 90 degrees outwards from the bike, and would be flat instead of angled. The ring of bearings would rotate along with the shaft, but would be able to slide along the key slot to shift in between gears. This shifting would be accomplished using a separate worm or other gearing system.

Using this design, the shifting mechanism has the possibility of being more efficient than an internal gear hub. The drawback is that it is no easy feat. Getting this mechanism to shift properly would be quite difficult. The shaft and associated rear gear would be extremely complex and expensive to manufacture. On top of this, the key slot would be under very high stress.

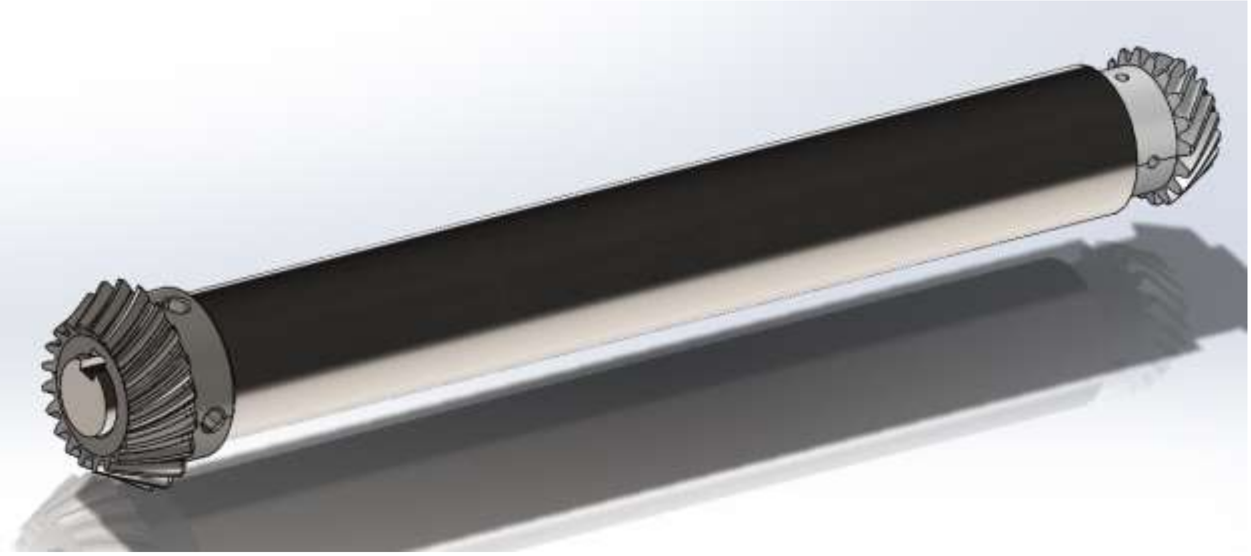


Figure 11 – Concept Selection

Concept Selection – Solid Shaft

The final selection is based off of Concept 1. This shaft has a high factor of safety, is easy to manufacture, and should be able to withstand all stresses. At the ends, after further consideration, we decided to move away from bearings, and selected spiral bevel gears instead, as they offer similar efficiency levels of 95-99%, require less general maintenance, and can be purchased instead of needing to fabricate a mounting mechanism for bearings. These were attached using a key slot (gear 3) or shrink fitting (gear 2), and can be used with an internal gear hub to allow for multiple gear ratios when riding on different inclines.

With this design, we pair high durability with a very simple design, making it cheap and easy to manufacture. Any hard edges from the machining process were rounded and tapered, and thus minimized any possible high stress concentration areas or sharp corners.

Engineering Calculations – Frame

List of equations

$$\tau = rF\sin\theta$$

τ = torque
r = radius
F = force
θ = angle between F and the lever arm

$$F = m \cdot a$$

F = force
m = mass of an object
a = acceleration

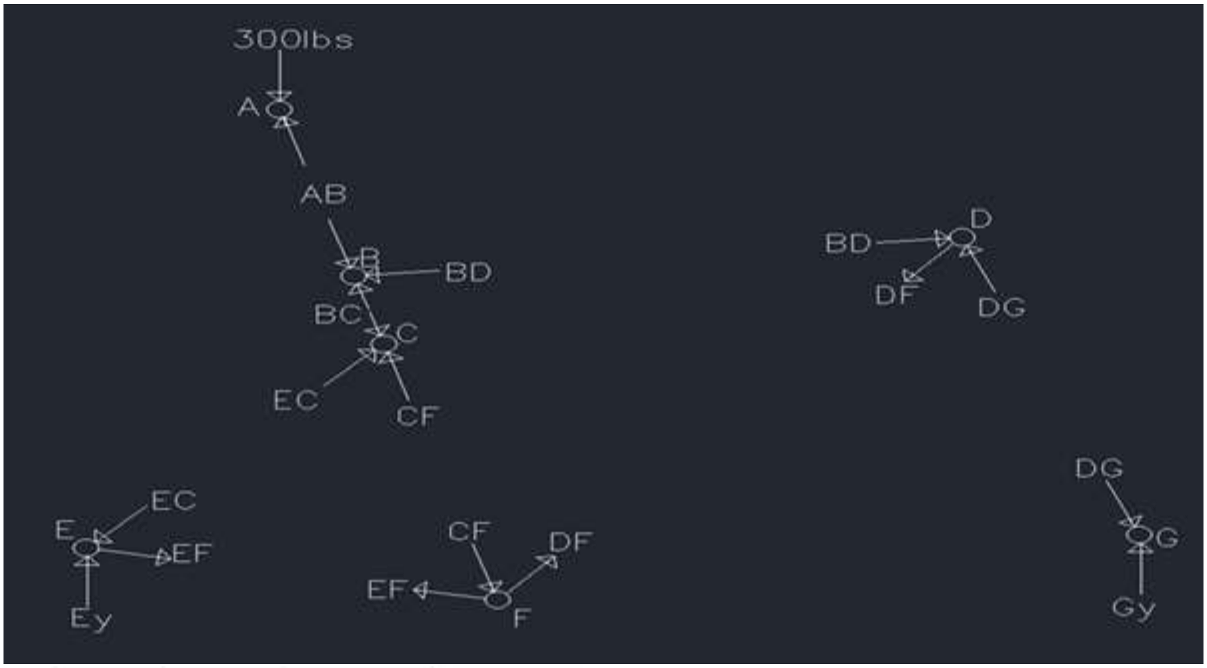
$$\sum \vec{F} = 0$$

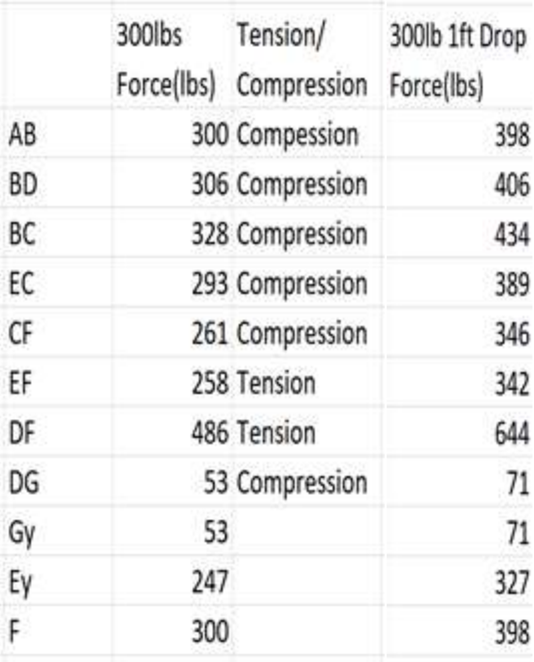
$$\sum F_x = 0 \quad \sum F_y = 0$$

***Fx* =** force in the x direction

Fy = force in the y direction

Loading Conditions – required yield and tensile strength of material.





	300lbs Force(lbs)	Tension/ Compression	300lb 1ft Drop Force(lbs)
AB	300	Compession	398
BD	306	Compression	406
BC	328	Compression	434
EC	293	Compression	389
CF	261	Compression	346
EF	258	Tension	342
DF	486	Tension	644
DG	53	Compression	71
Gy	53		71
Ey	247		327
F	300		398

In psi

Compressive/Tensional Stress		
	Standing	1ft Drop
AB	543	3827
BD	2495	18408
BC	594	3663
EC	2387	14646
CF	472	3224
EF	1206	15662
DF	687	520
DG	302	2083

Figure 12 – Bicycle Frame Free Body Diagram

Material Selection

6061-T6 Aluminum was chosen over galvanized steel as it provided 35 ksi of yield strength and was much lighter than its competition. It is slightly more expensive as our group has access to free galvanized steel, however the properties of 6061-T6 aluminum is well worth the slight increase in price.

Finite Element Analysis (FEA) – Frame

6061-T6 Aluminum under 1440 lbs. of force at seat tube (Worst Case Scenario)

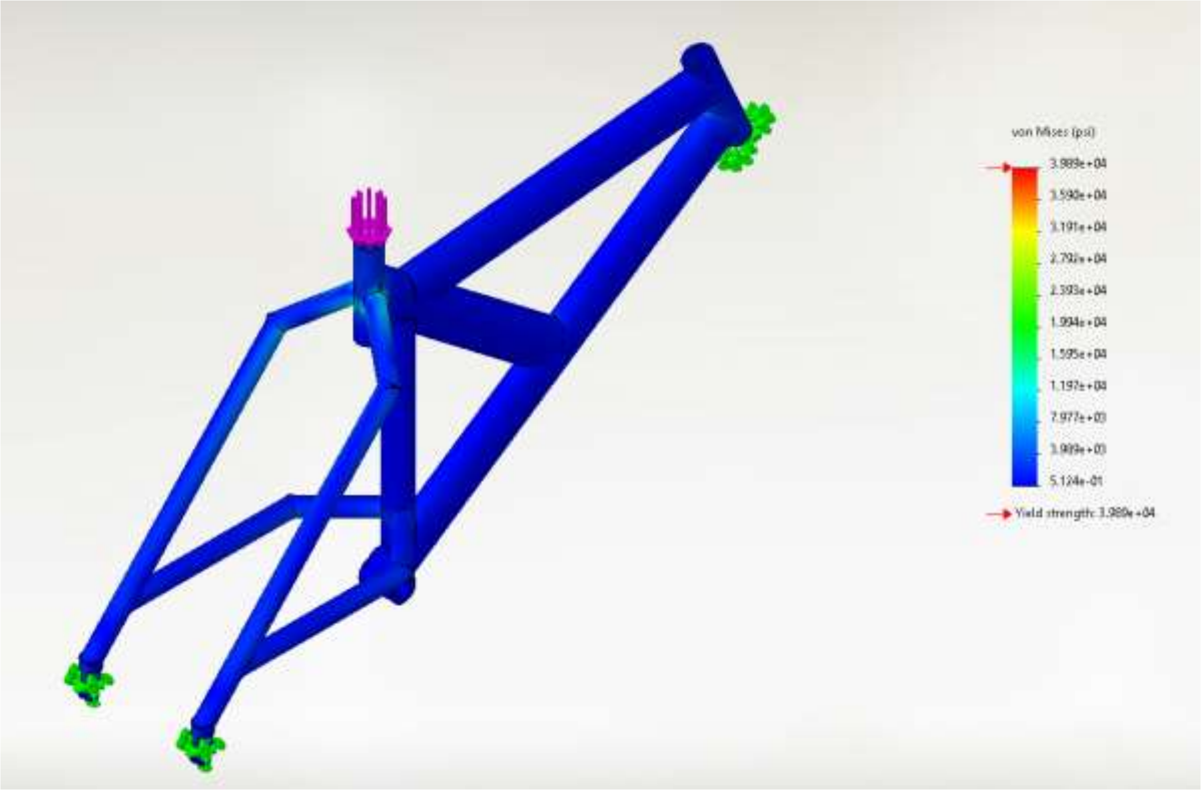


Figure 13 – Frame FEA with 1 foot drop

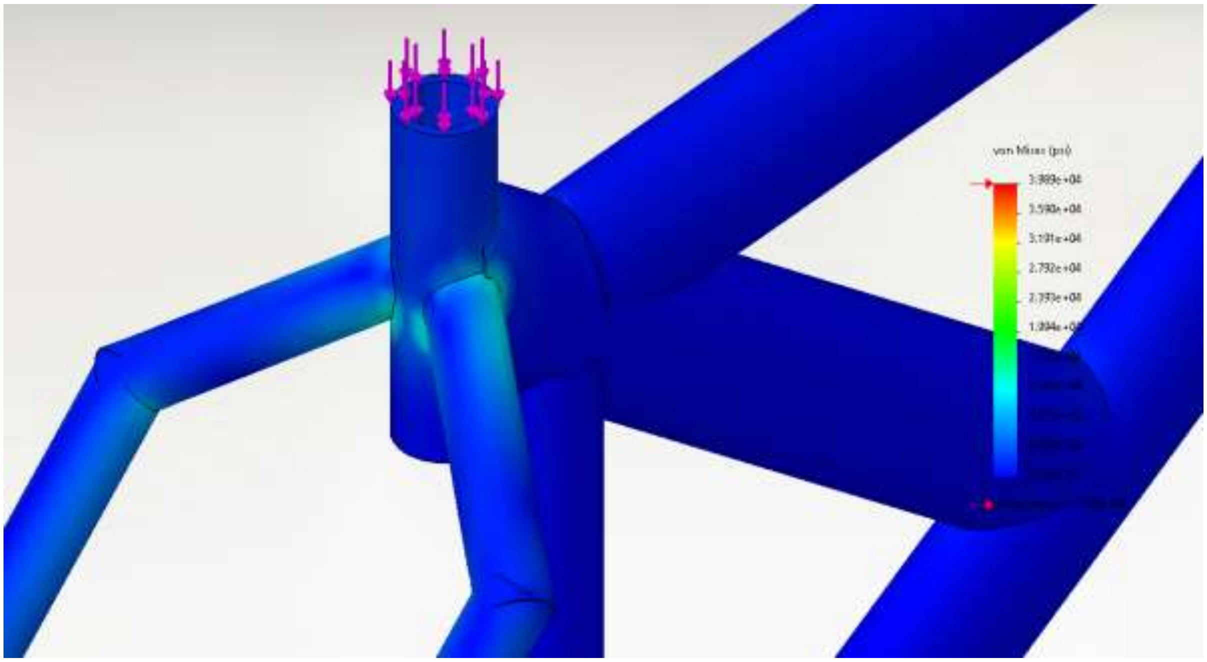


Figure 14 – Zoomed in Frame FEA with 1 foot drop

6061-T6 Aluminum under 300lbs of force at seat tube (Typical operating force)

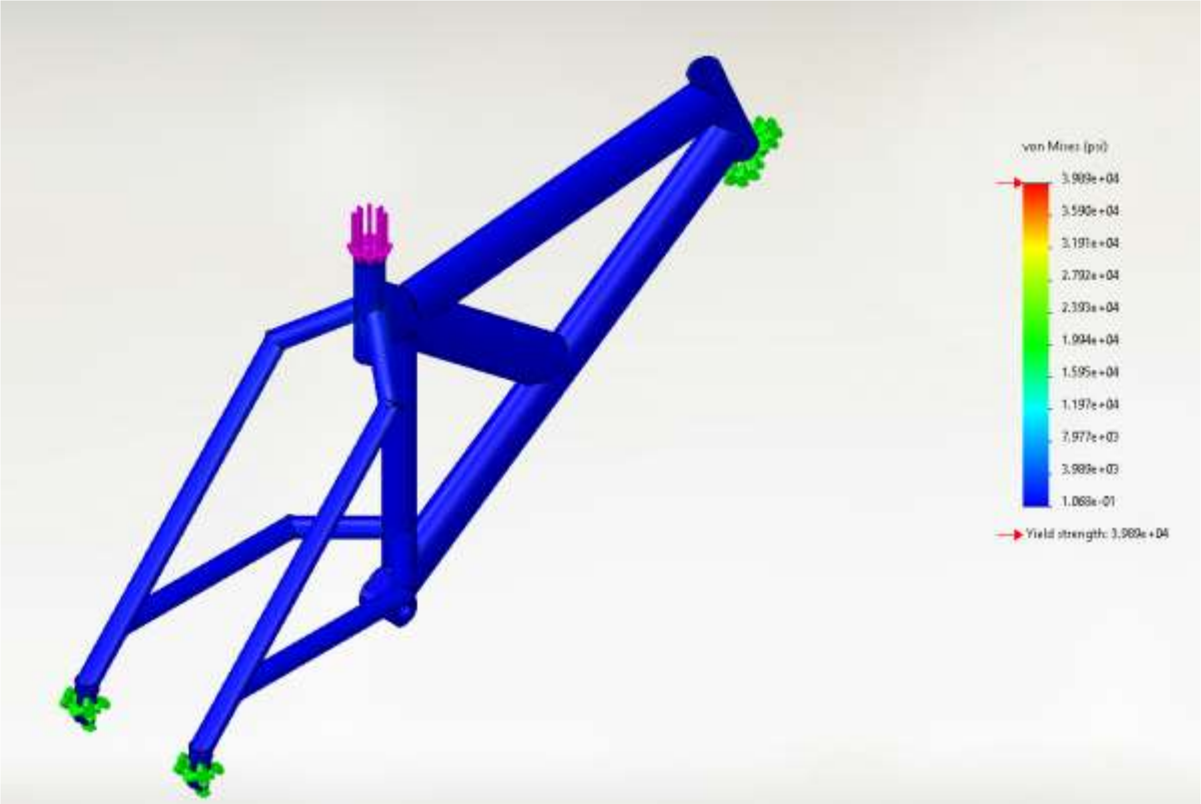


Figure 15 – Frame FEA under rider's weight

Factors of Safety

Safety results based on the appropriate criteria: The frame by itself has a safety factor of 10 and can handle up to 3000 lbs. on seat tube before frame failure.

Engineering Calculations – Gears

Figure 16 – Gear Layout

For brevity, the gears are numbered in the order they transmit the force from the crankshaft and pedals to the back wheel.

AGMA and AISI are the standards that will be used.

List of equations

$$T = Force * distance * \sin(\theta)$$

$$w^T = \frac{T}{r_P}$$

$$v_T = \mathrm{pi} * d_P * \frac{n_P}{12}$$

$$B = 0.25 * (12 - Q_V)^{\frac{2}{3}}$$

$$A = 50 + 56 * (1 - B)$$

$$K_V = \left(\frac{A + v_T^{\frac{1}{2}}}{A}\right)^B$$

$$C_S = 0.5 \mid F < 0.5$$

$$C_S = 0.125 * F + 0.4375 \mid 0.5 \le F \le 4.5$$

$$C_S = 1 \mid F > 4.5$$

$$K_S = 0.4867 + \frac{0.2132}{P_d} \mid 0.5 \le P_d \le 16$$

$$K_S = 0.5 \mid 16 < P_d$$

$$K_m = K_{mb} + 0.0036 * F^2$$

$$C_L = 2 \mid 10^3 \le N_L < 10^4$$

$$C_L = 3.4822 * N_L\hat{}(-0.0602) \mid 10^4 \le N_L \le 10^{10}$$

$$K_L = 2.7 \mid 10^2 \le N_L < 10^3$$

$$K_L = 6.1515 * N_L^{-0.1192} \mid 10^3 \le N_L < 3 * 10^6$$

$$K_L = 1.3558 * N_L^{-0.0178} \mid 3 * 10^6 \le N_L \le 10^{10}$$

$$B1 = 0.00898 * \frac{H_{BP}}{H_{BG}} - 0.00829 \mid 1.2 \le \frac{H_{BP}}{H_{BG}} \le 1.7$$

$$C_H = 1 + B1 * \left(\frac{N}{n} - 1\right) \mid 1.2 \le \frac{H_{BP}}{H_{BG}} \le 1.7$$

$$B2 = 0.00075 * \exp(-0.0122 * f_P) \mid 48\ HRC < H_{BP}\ \&\ 180 \le H_{BG} \le 400$$

$$C_H = 1 + B2 * (450 - H_{BG}) \mid 48\ HRC < H_{BP}\ \&\ 180 \le H_{BG} \le 400$$

$$K_R = 0.50 - 0.25 * \log(1 - R) \mid 0.99 \le R \le 0.999$$

$$K_R = 0.70 - 0.15 * \log(1 - R) \mid 0.90 \le R < 0.99$$

$$C_R = K_R^{\frac{1}{2}}$$

$$C_P = 2290 \mid given\ value\ for\ steel$$

$$H_B = H_{BG} \mid H_{BG} < H_{BP}$$

$$H_B = H_{BP} \mid H_{BP} \le H_{BG}$$

$$S_{ac} = 341 * H_B + 23620 \mid Material\ is\ Grade\ 1$$

$$S_{ac} = 363.6 * H_B + 29560 \mid Material\ is\ Grade\ 2$$

$$S_{at} = 44 * H_B + 2100 \mid Material\ is\ Grade\ 1$$

$$S_{at} = 45 * H_B + 5980 \mid Material\ is\ Grade\ 2$$

$$S_C = C_P * (\frac{w^T}{F * d_P * I} * K_O * K_V * K_m * C_S * C_{XC})\hat{}(\frac{1}{2})$$

$$S_{wc} = \frac{S_{ac} * C_L * C_H}{S_H * K_T * K_R}$$

$$Contact\ Factor\ of\ Safety = \frac{S_{wc}}{S_C}$$

$$S_t = \frac{w^T}{F} * P_d * K_O * K_V * \frac{K_S * K_m}{K_X * J}$$

$$S_{wt} = \frac{S_{at} * K_L}{S_F * K_T * K_R}$$

$$Bending\ Factor\ of\ Safety = \frac{S_{wt}}{S_t}$$

Loading Conditions – required Yield and Tensile Strength of Material

$$Average\ Cadence = 60\ rpm$$

$$Force = 350\ lbs$$

$$K_T = 1 \mid 32°F < Temperature < 250°F$$

$$K_O = 1 \mid Already\ using\ maximum\ force$$

$$K_{mb} = 1.25 \mid the\ gears\ on\ the\ shaft\ are\ not\ straddle\ mounted$$

$$For\ K_L\ the\ general\ failure\ equation\ will\ be\ used, not\ the\ critical\ failure\ equation$$

$$S_H = 1.5$$

$$S_F = 1.5$$

Material Selection

The spiral bevel gears will be made out of SCM 415 (carburized to 55-60 HRC). The expected weight of all 4 gears is less than 2.5 lbs.

Material	Yield Strength	Ultimate Tensile Strength
AISI 1045 cold rolled	76,870 psi	90,648 psi
AISI 4340 normalized	103,000 psi	161,000 psi
SCM 415 Carburized	60,190 psi	95,000 psi

Table 1 – Material Strengths

Power and Torque Calculations

$$T1 = 350\, lbs * 170mm * \frac{1in}{25.4mm} * \frac{1ft}{12in} = 195.2\, ft * lbs$$

$$T2 = \frac{T1}{2.5} = 78.08\, ft * lbs$$

$$T3 = T2 = 78.08\, ft * lbs$$

$$T4 = T3 * 2 = 156.16\, ft * lbs$$

Finite Element Analysis (FEA)

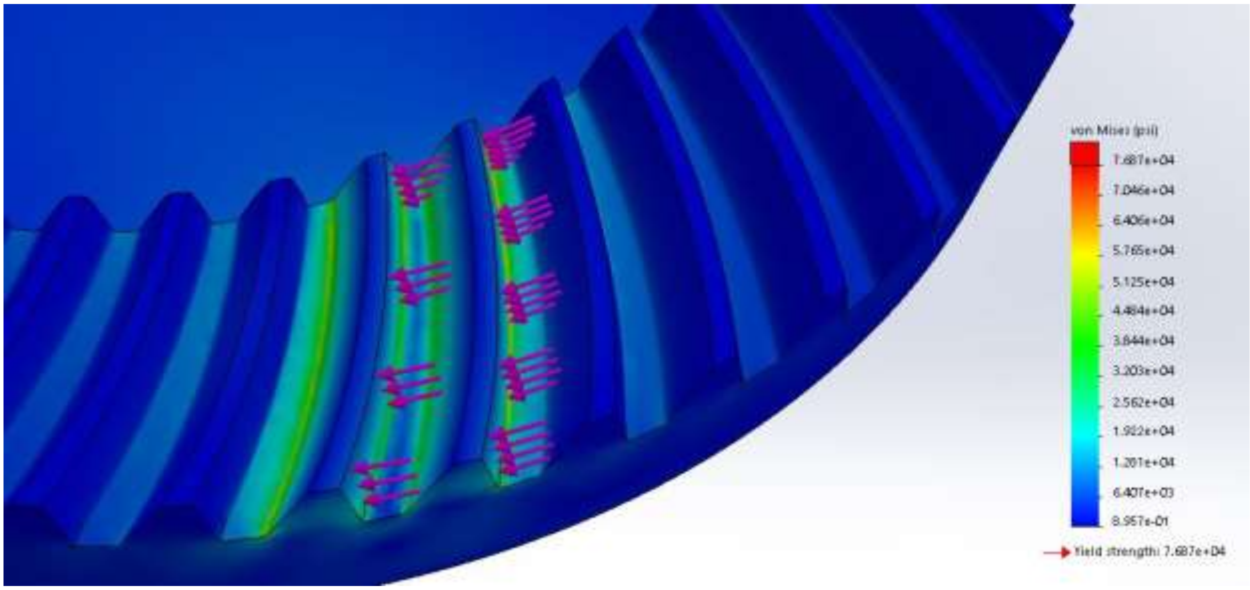


Figure 17 – Gear 1 AISI 1045 cold rolled

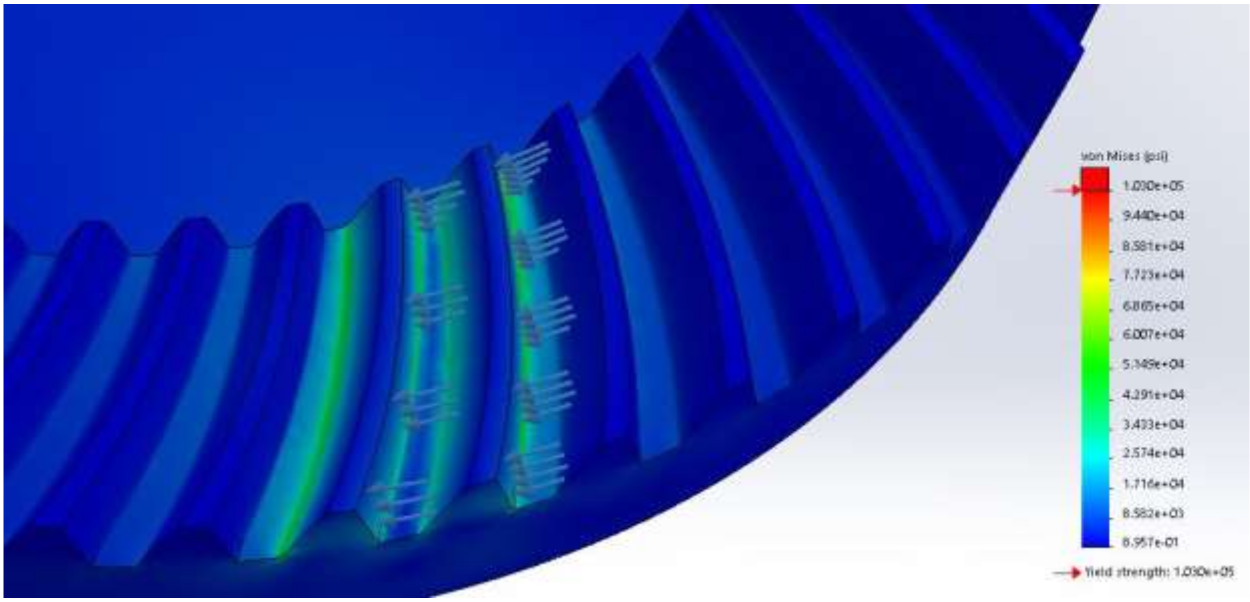


Figure 18 – Gear 1 AISI 4340 normalized

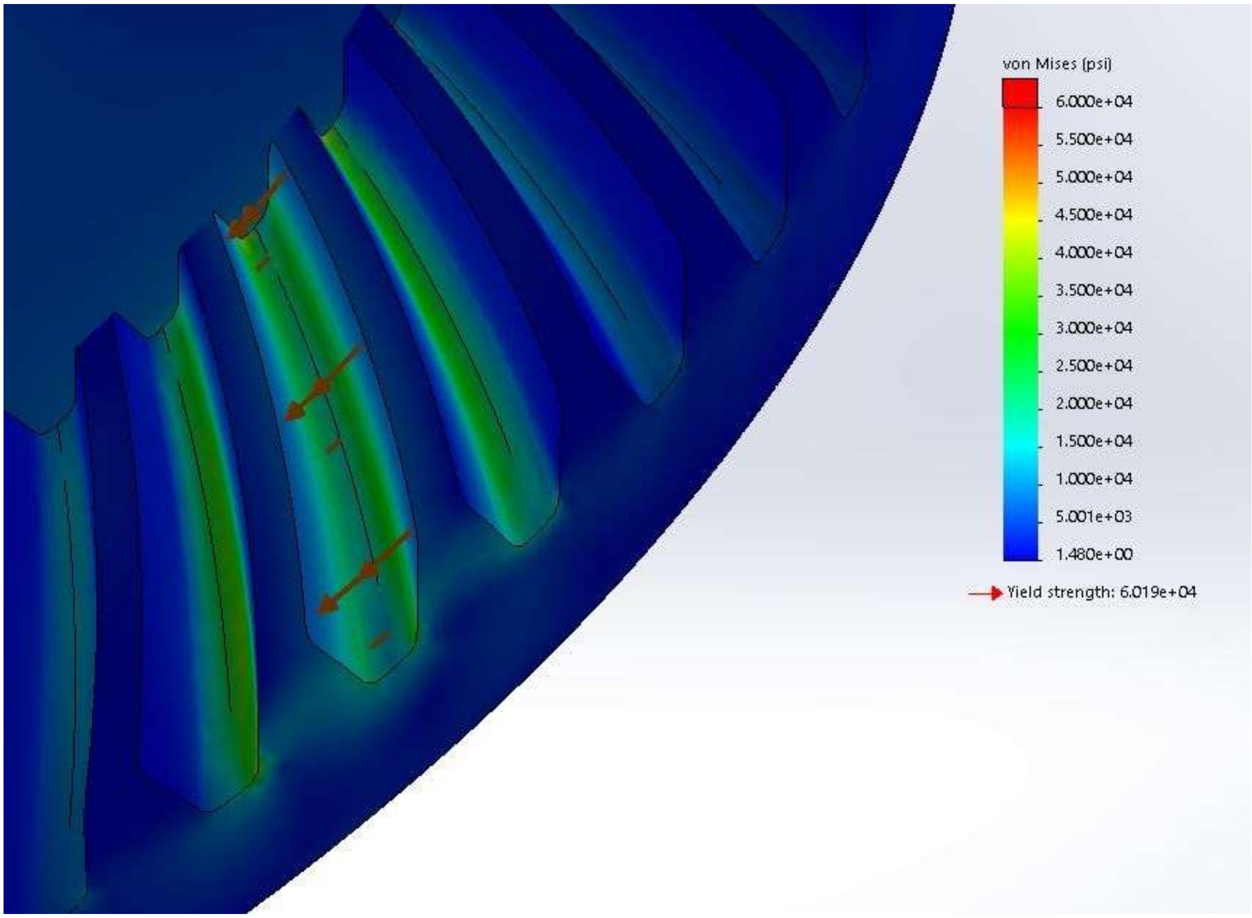


Figure 19 – Gear 1 SCM 415 carburized

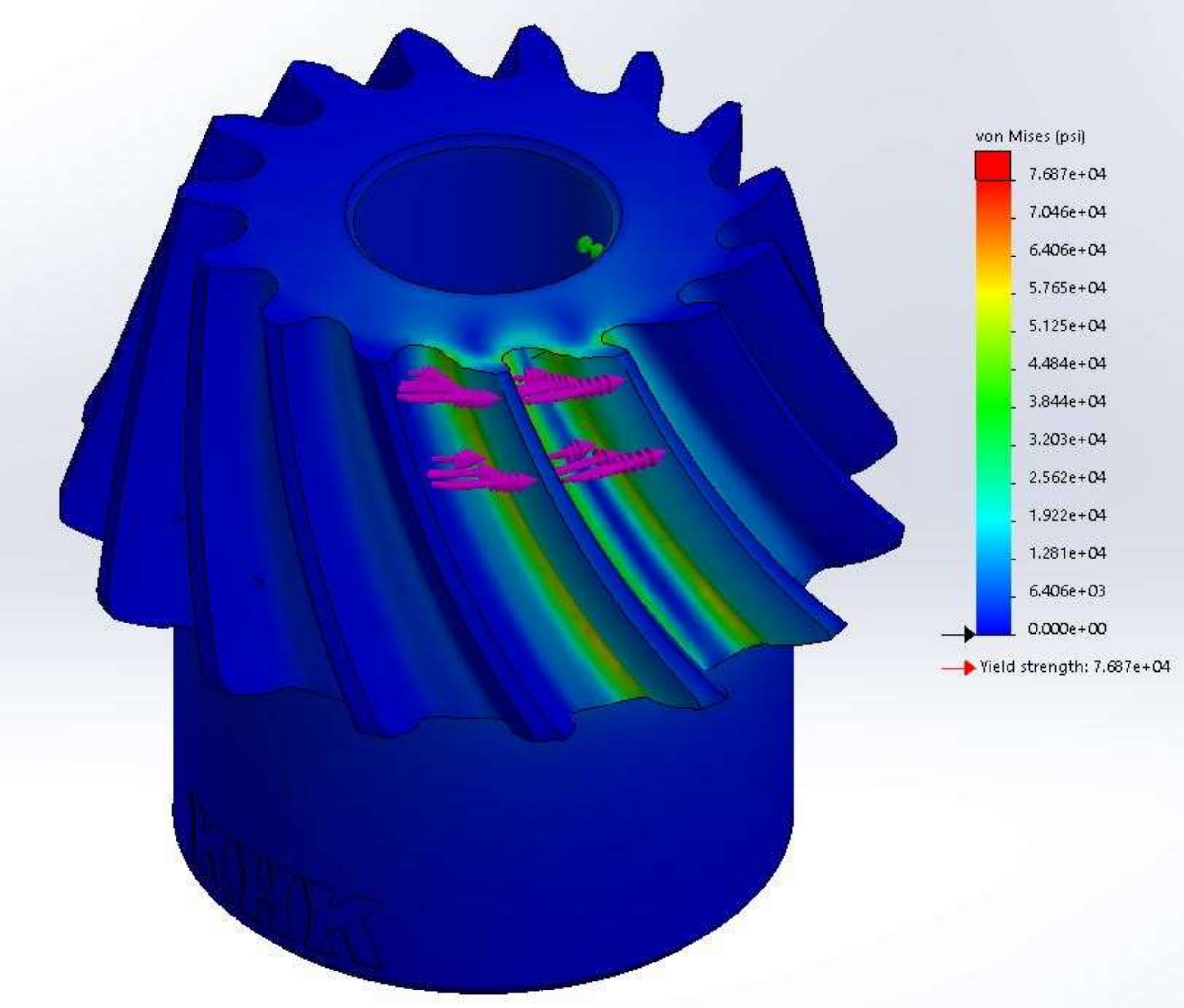


Figure 20 – Gear 2 AISI 1045 cold rolled

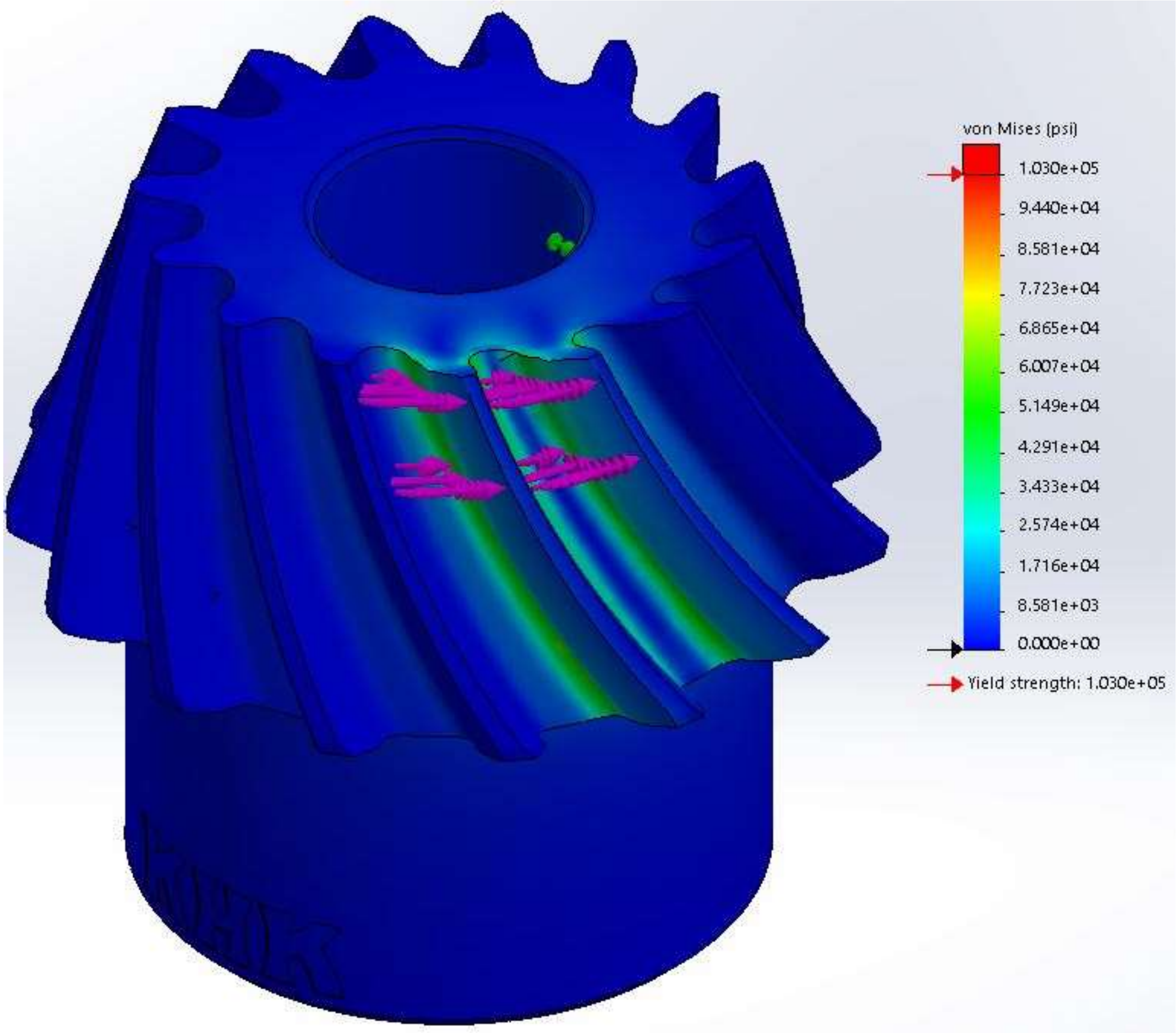


Figure 21 – Gear 2 AISI 4340 normalized

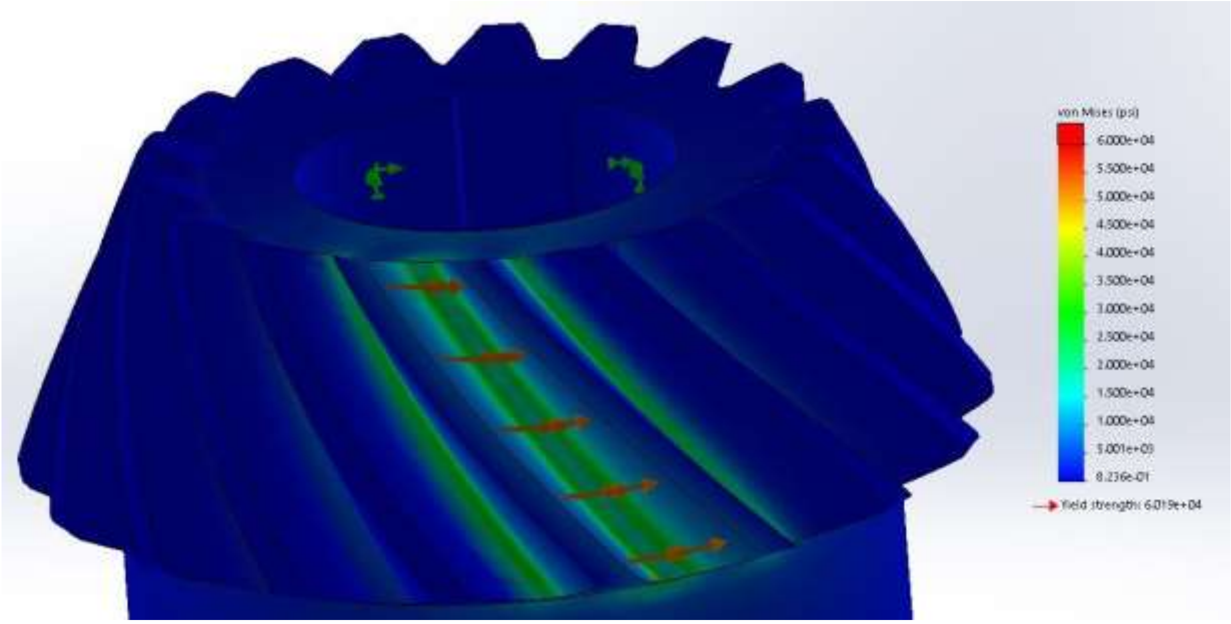


Figure 22 – Gear 2 SCM 415 carburized

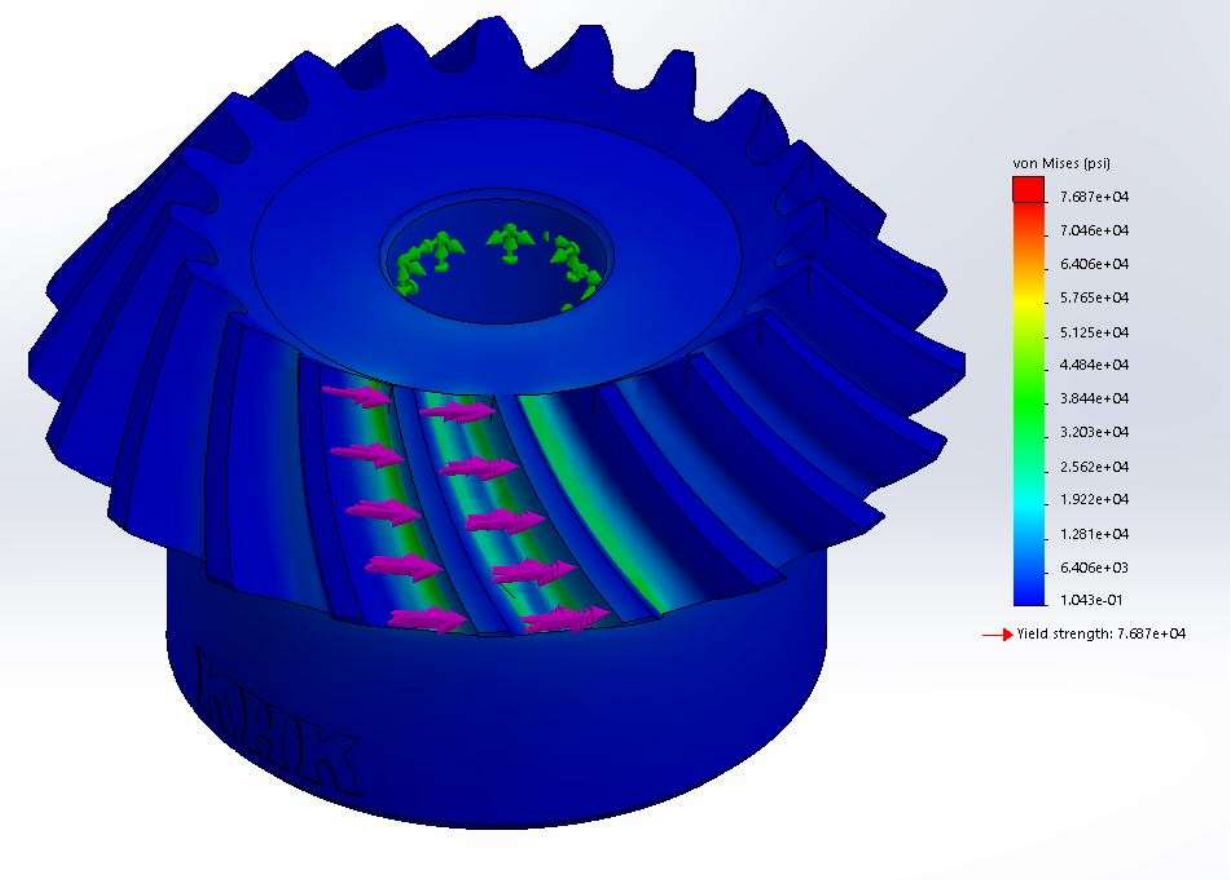


Figure 23 – Gear 3 AISI 1045 cold rolled

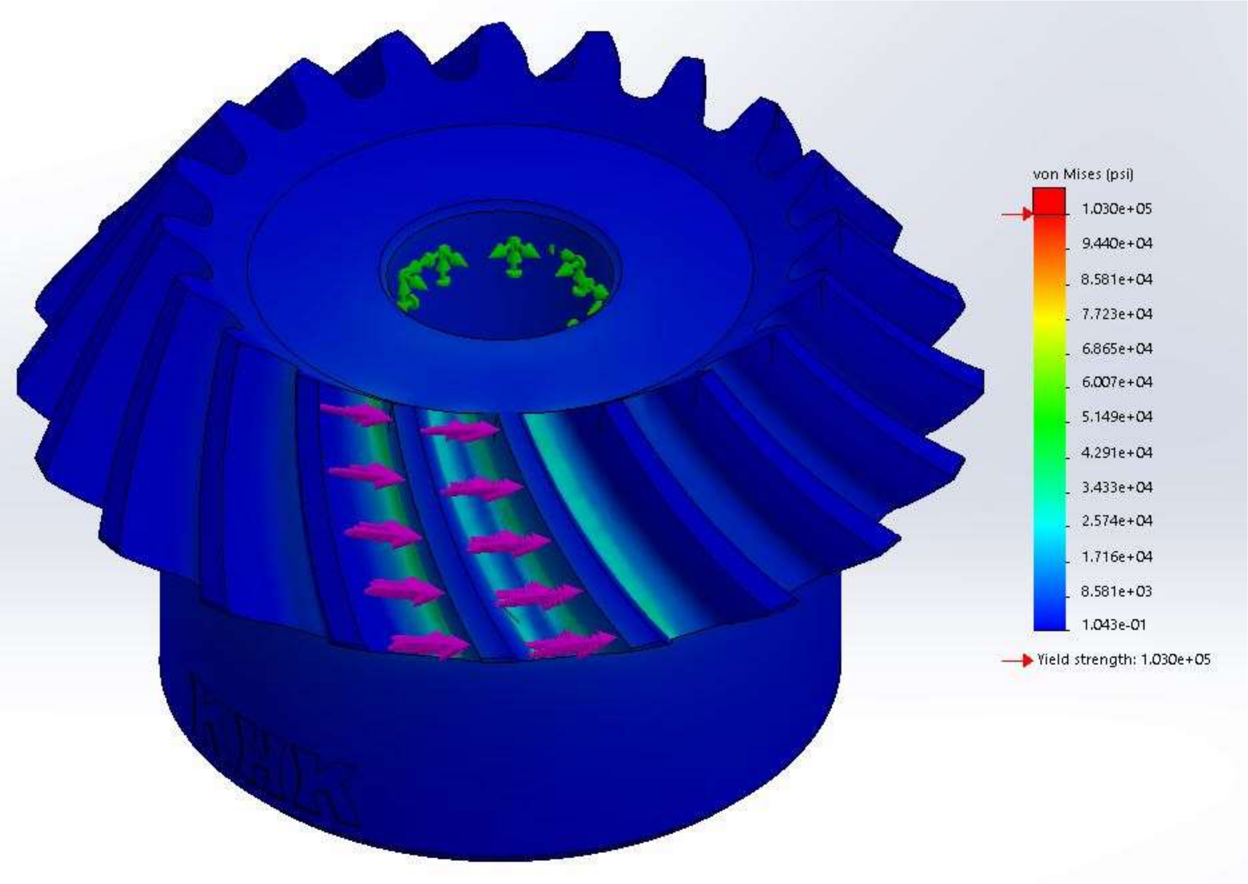


Figure 24 – Gear 3 AISI 4340 normalized

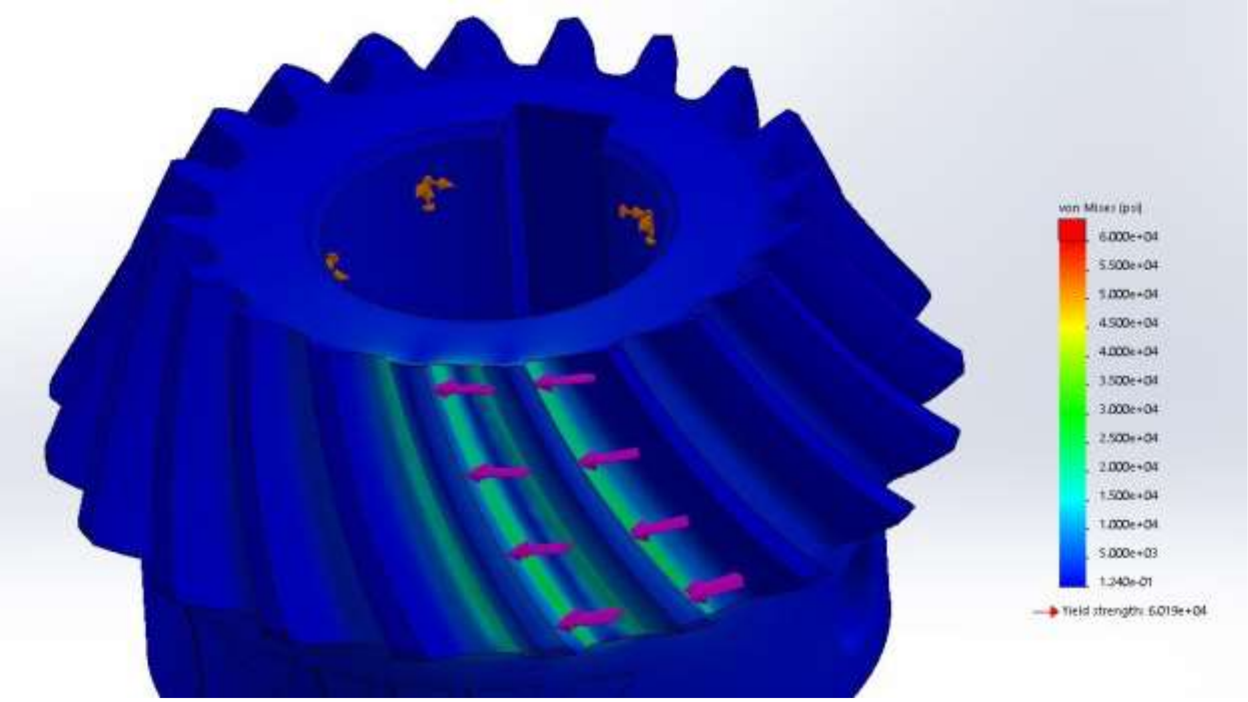


Figure 25 – Gear 3 SCM 415 carburized

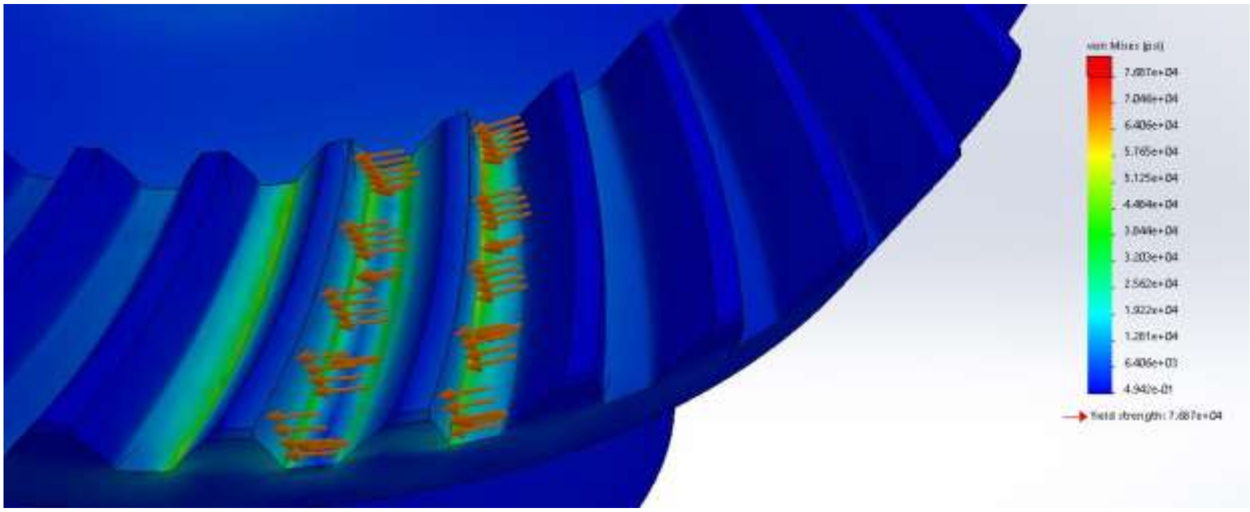


Figure 26 – Gear 4 AISI 1045 cold rolled

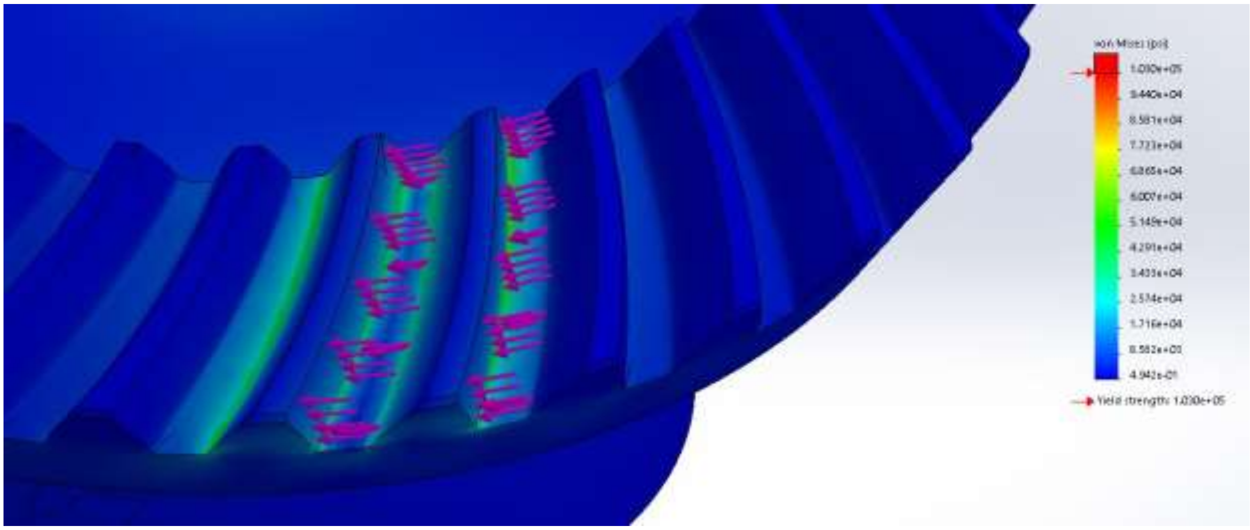


Figure 27 – Gear 4 AISI 4340 normalized

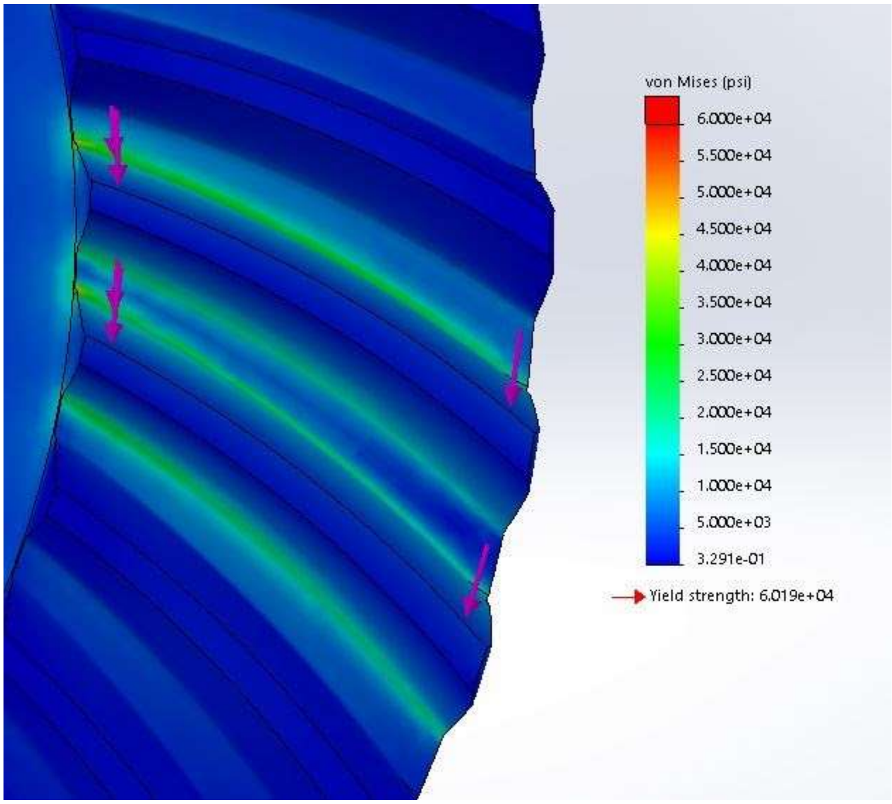


Figure 28 – Gear 4 SCM 415 carburized

Factors of Safety

The desired factor of safety for bending is 1-1.25 since the force being used is the maximum possible force.

The following values were obtained using FEA within SolidWorks and confirmed with MatLab calculations. These calculations represent the worst case scenario which is a person putting full force (350 lbs) on the pedal while the bicycle is stationary.

Gear #	AISI 1045 cold rolled FoS (bending)	AISI 4340 normalized FoS (bending)	SCM 415 Carburized FoS (bending)
1	1.3	2.0	2.0
2	1.4	2.1	2.4
3	1.7	3.0	3.0
4	1.3	2.0	2.0

Table 2 – Bending Factors of Safety

Gears	Bending FoS	Contact FoS
1 & 2	0.85	0.26
3 & 4	1.14	0.31

Table 3 – Factors of Safety from MatLab Code

Engineering Calculations – Shaft

List of Equations

$$T = F * D * \sin\theta \qquad W = \Delta K_E = FD\mu$$

$$\sigma = \frac{16M}{\pi d^3} = \frac{S}{n_d} \rightarrow d = \left(\frac{16Mn_d}{S\pi}\right)^{\frac{1}{3}}$$

$$n = \frac{\pi S d^3}{16M} \qquad M = FD \qquad K = \frac{1}{2}mv^2 \qquad F = PA$$

$$\phi = \frac{TL}{JG} \qquad J = \frac{\pi d^4}{32} \qquad w = mg \qquad A = l * w$$

Loading Conditions, Parameters, and Assumptions

Top Speed Goal: 25 mph

Weight Goal: 25 lbs (no motor or battery), 65 lbs (with optional electrical assist)

Max Load: 275 lbs (can exert up to 350 lbs of force on pedals)

Maximum Force Angle: Angle of crankshaft where maximum force will be applied is 90°

Material Selection: Aluminum 6061-T6 frame, 316L Stainless Steel shaft, SCM415 Steel Gears

Operating Temperature: The bicycle will be ridden in temperatures of 32-250 °F ($K_T = 1$)

Shaft Diameter: Diameter will be increased to 1.5 inches for gear mounting and increased strength to resist torsion and twisting (angle of twist is not to exceed .01 degrees/inch). Minimum shaft diameter is 0.625 inches (5/8) at gear 2 mounting area.

Gear Tooth Forces: Torsional force will be applied to at least 2 teeth faces at all times

Stopping Distance: Distance of 50 ft (10 ft per 5 mph)

Brake Pad Friction Coefficient: $\mu = .4$

Material Selection

For the material selection of the shaft, 316L Stainless Steel was chosen due to its corrosion resistance and high strength. This is a common Stainless Steel that should be able to handle the torsional stresses without exceeding the angle of twist required. While 6061-T6 Aluminum was also a debated shaft material, it did not appear that it could withstand the torsional forces without sustaining permanent deformation.

Calculations

Shaft:

$$T = F \ast D \ast sin\,\theta = 350\ lbs \ast \left[\left(170\ mm \ast \frac{1\ in}{24\ mm}\right) \ast \frac{1\ ft}{12\ in}\right] \ast \sin(90) = 195.21\ lb \ast ft$$

$$d = \left(\frac{16Mn_d}{S\pi}\right)^{\frac{1}{3}} = \left(\frac{16 \ast 195.21 \ast 6}{42{,}000 \ast \pi}\right)^{\frac{1}{3}} = .52\ in\ \rightarrow\ .625\ in\ \text{or}\ \frac{5}{8}\ in$$

$$J = \frac{\pi d^4}{32} = \frac{\pi \ast 1.5^4}{32} = .4970\ in^4$$

$$\phi = \frac{TL}{JG} = \frac{780.84 \ast 12.042}{11893000 \ast .4970} = .00159\ rad \ast \frac{180}{\pi} = 0.091°$$

Braking System:

$$w = mg \rightarrow m = \frac{w}{g} = \frac{275\ lbs}{32.2\frac{ft}{s^2}} = 8.54\ slugs$$

$$K = \frac{1}{2}mv^2 = .5 \ast 8.54\ slugs \ast \left(25\ mph \ast \frac{3600\ sec}{5280\ ft}\right)^2 = 1240.64\ ft \ast lbs$$

$$W = \Delta K_E = FD\mu \rightarrow 1240.64\ ft \ast lbs = F \ast 50\ ft \ast .4 \rightarrow F = \frac{62.03\ lbs}{2} = 31.02\frac{lbs}{1\ brake}$$

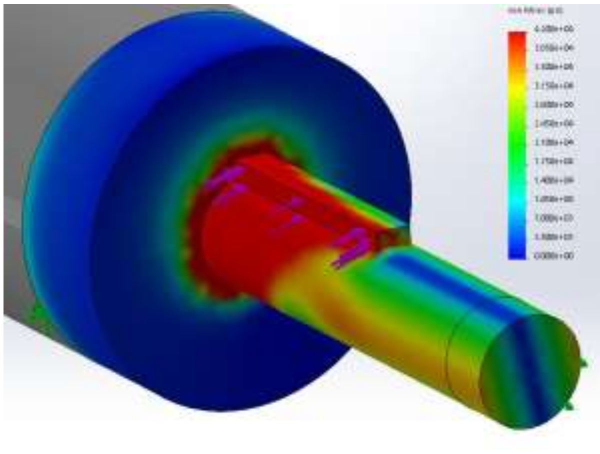
$$A_{brake\ pad} = l \ast w = \frac{1.5\ in}{12\ ft} \ast \frac{.25\ in}{12\ ft} = .002604\ ft^2 = .375\ in^2$$

$$F = PA \rightarrow P = \frac{F}{A} = \frac{31.02\ \frac{lbs}{1\ brake}}{2 \ast .375\ in^2} = 41.35\frac{psi}{1\ brake}$$

Factor of Safety

$$n = \frac{\pi S d^3}{16M} = \frac{\pi \ast 42{,}000 \ast .625^3}{16 \ast 195.21} = 10.31$$

Finite Element Analysis (FEA)



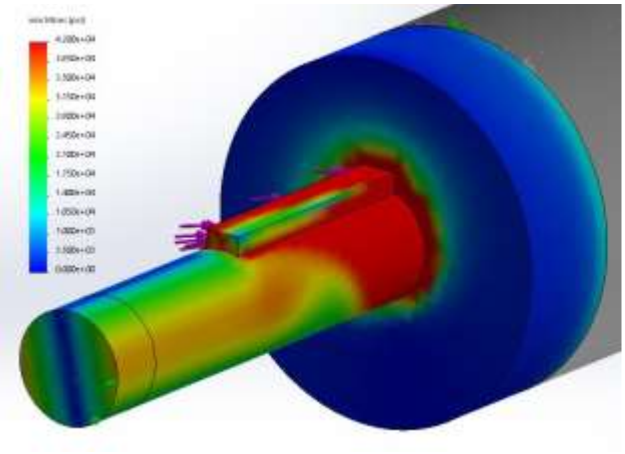


Figure 29 – Gear 2 Key Slot Concerns Pic 1 (Left)

Figure 30 – Gear 2 Key Slot Concerns Pic 2 (Right)

With the shaft fixed about the center and a maximum torsional force applied evenly across the key slot, the analysis showed that the maximum force exerted on the shaft at gear 2 would certainly break. Due to this, it was decided that the gear's inner diameter should be increased, and then would be welded onto the shaft.

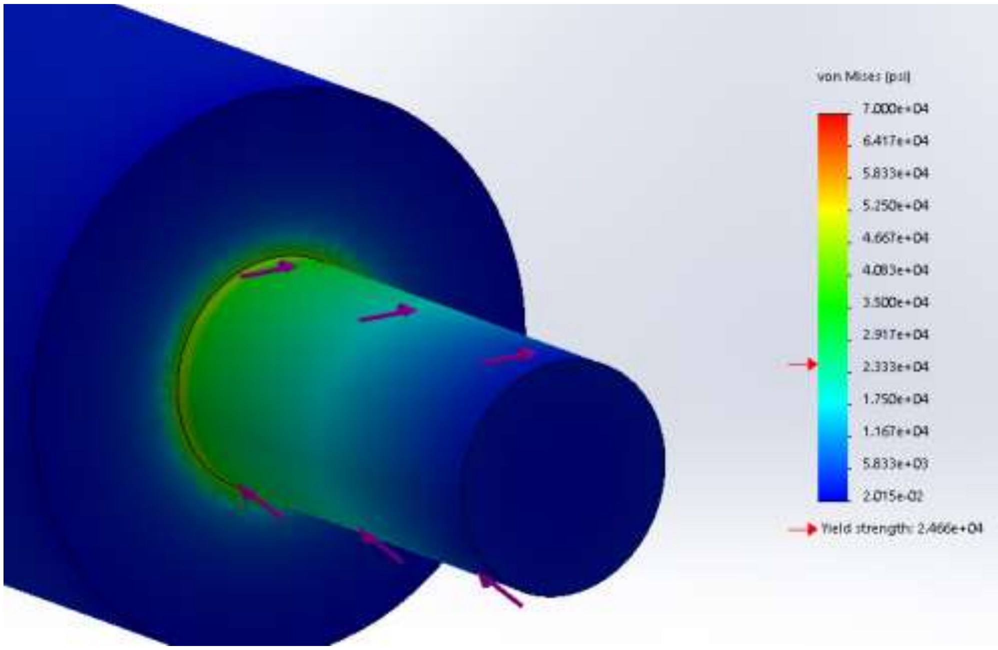


Figure 31 – Gear 2 Heat Shrink Fitted Shaft

After further consideration, it was decided to do a heat shrink fit for gear 2 onto the shaft once the inner diameter was increased. This allowed for a greater surface area to spread the force across, and resulted in an analysis that showed no failure or key concerns.

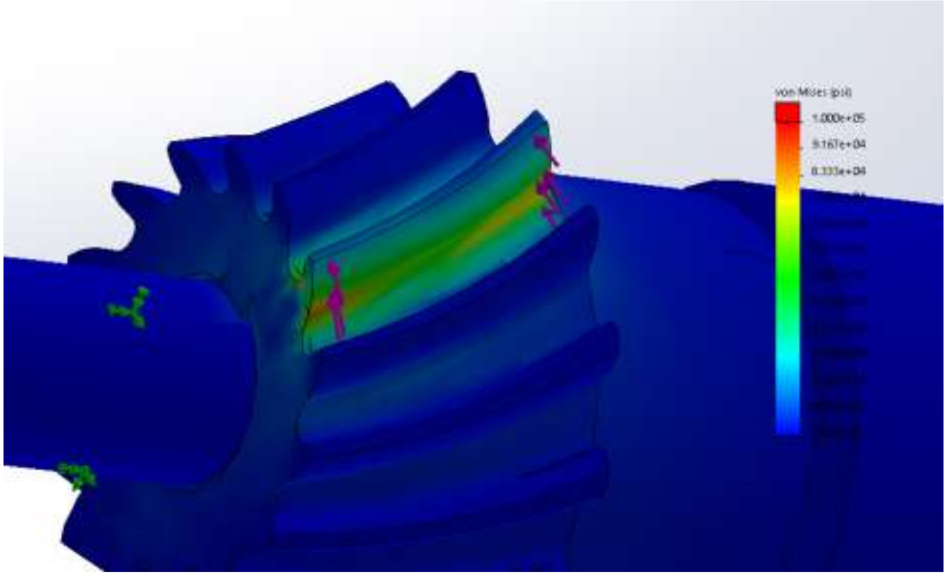
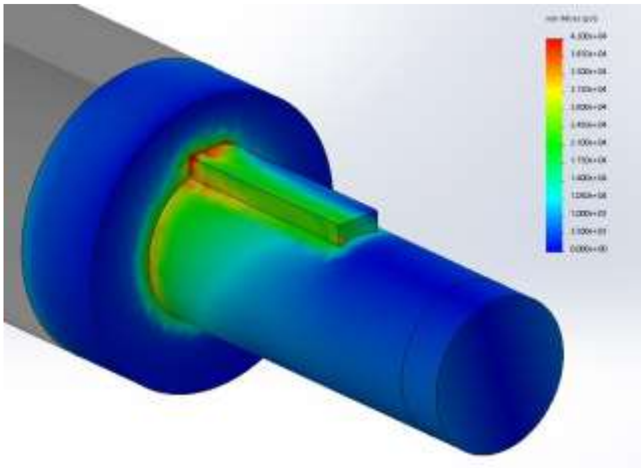


Figure 32 – Gear 2 on Shaft FEA

With the shaft fixed about the center, and a maximum torsional force applied to a single tooth, the analysis showed some possible signs of failure. After further consideration, it was found that a reasonable assumption to make would be that the torsional force would be distributed on at least 2 teeth at all times. After reanalyzing, there were no points of failure shown on the teeth.



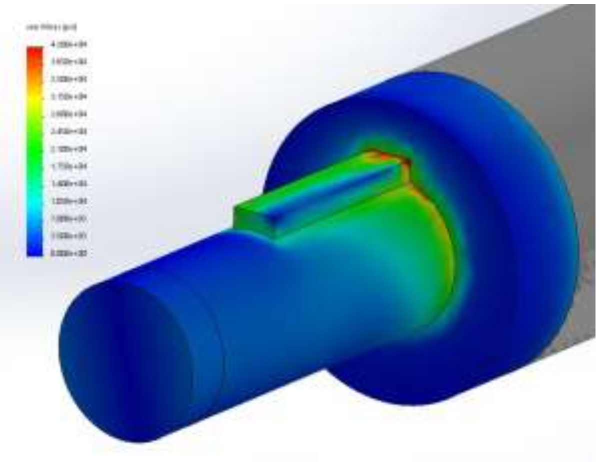


Figure 33 – Gear 3 Key Slot Pic 1 (Left)

Figure 34 – Gear 3 Key Slot Pic 2 (Right)

With the shaft fixed about the center and a maximum torsional force applied evenly across the key slot, the analysis showed that the maximum force exerted on the shaft at gear 3 would be of slight concern, but would be sufficient given factor of safety calculation. Due to this, it was decided not to machine or alter gear 3 in any way. This would also allow for removing of the shaft from the bicycle with greater ease.

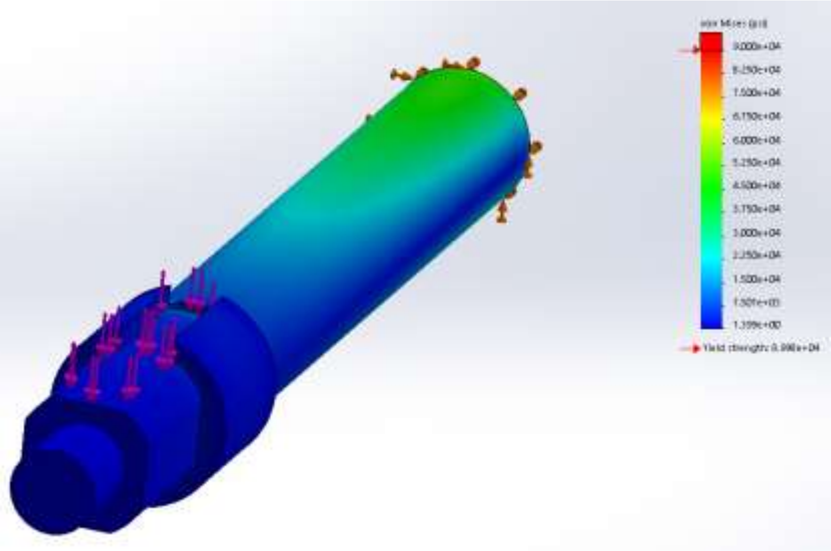


Figure 35 – Pedaling Shaft

To accommodate for a wider back fork on the bike frame, a longer shaft to connect the pedals was needed to avoid hitting the frame while pedaling. While the shaft would be longer (and therefore have a larger moment), the replacement matched the initial shaft diameter, and a nicer steel was chosen to handle the additional stress. A medium carbon steel shaft was used from the VPC shop to fabricate the replacement shaft. FEA showed no major concerns for this piece.

Manufacturing Drawings

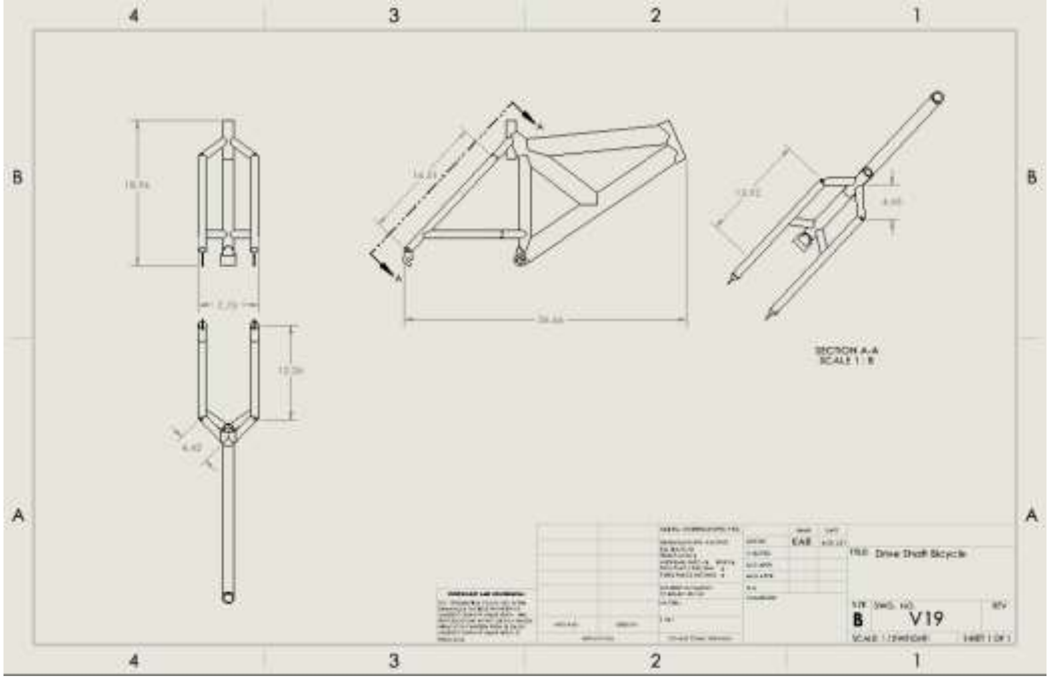


Figure 36 – Bicycle Frame Drawing

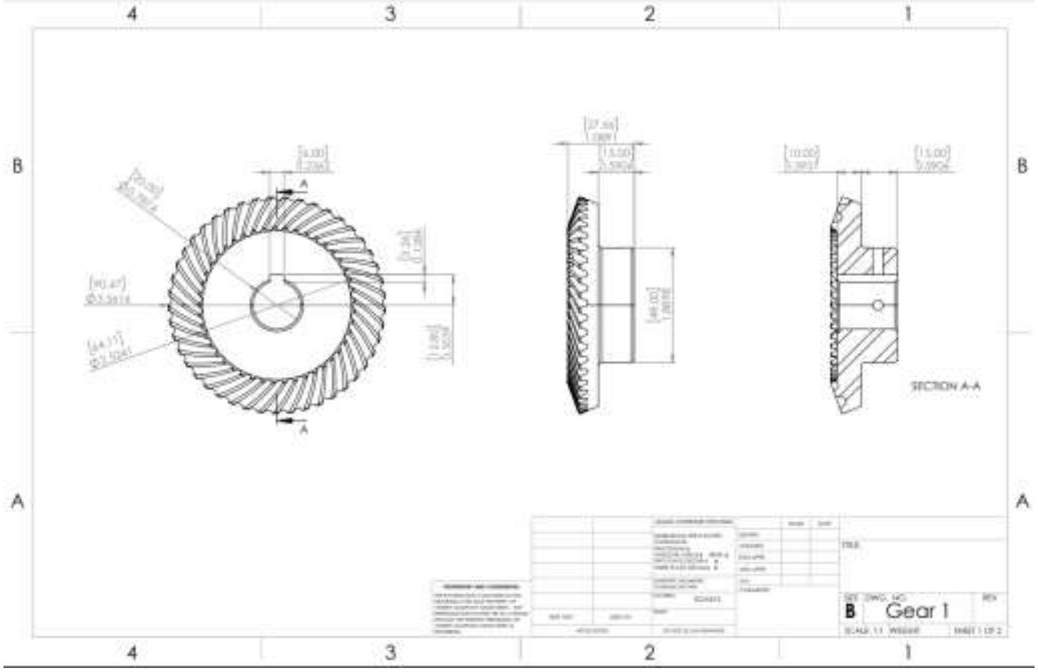


Figure 37 – Gear 1 Stock Drawing

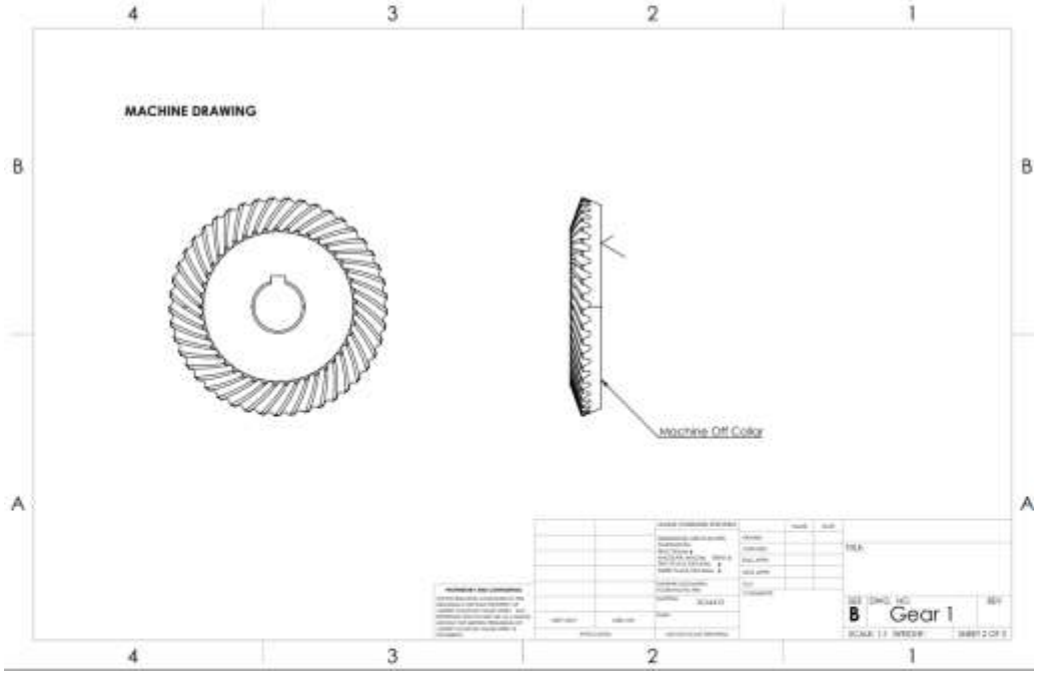


Figure 38 – Gear 1 Machine Drawing

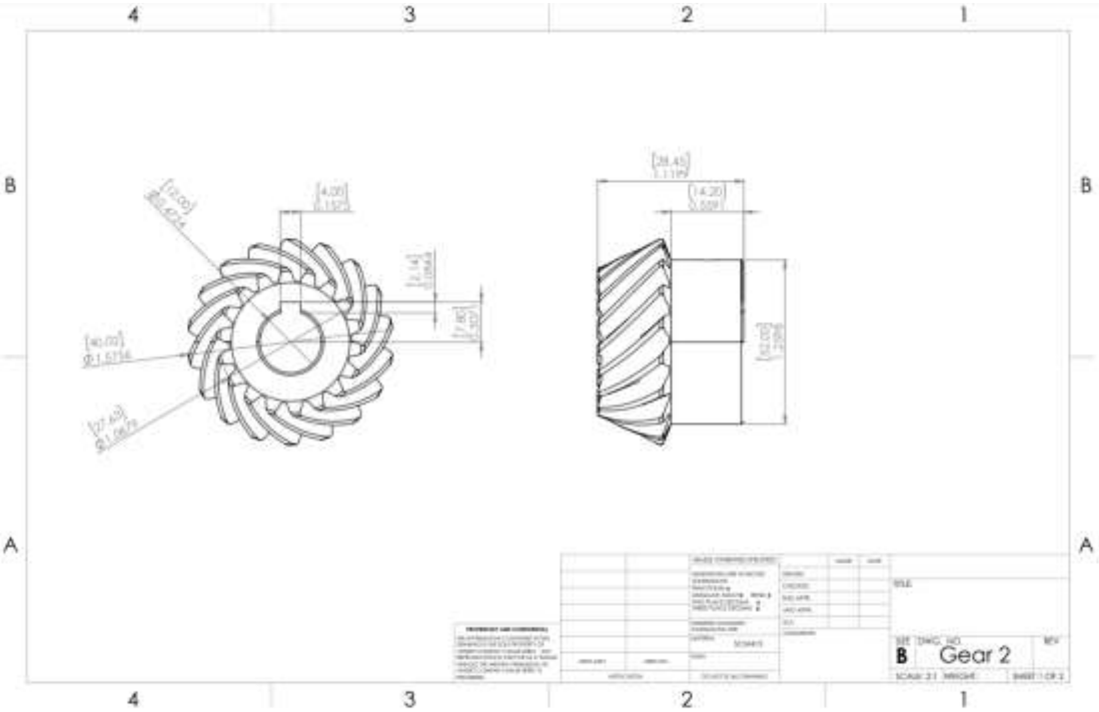


Figure 39 – Gear 2 Stock Drawing

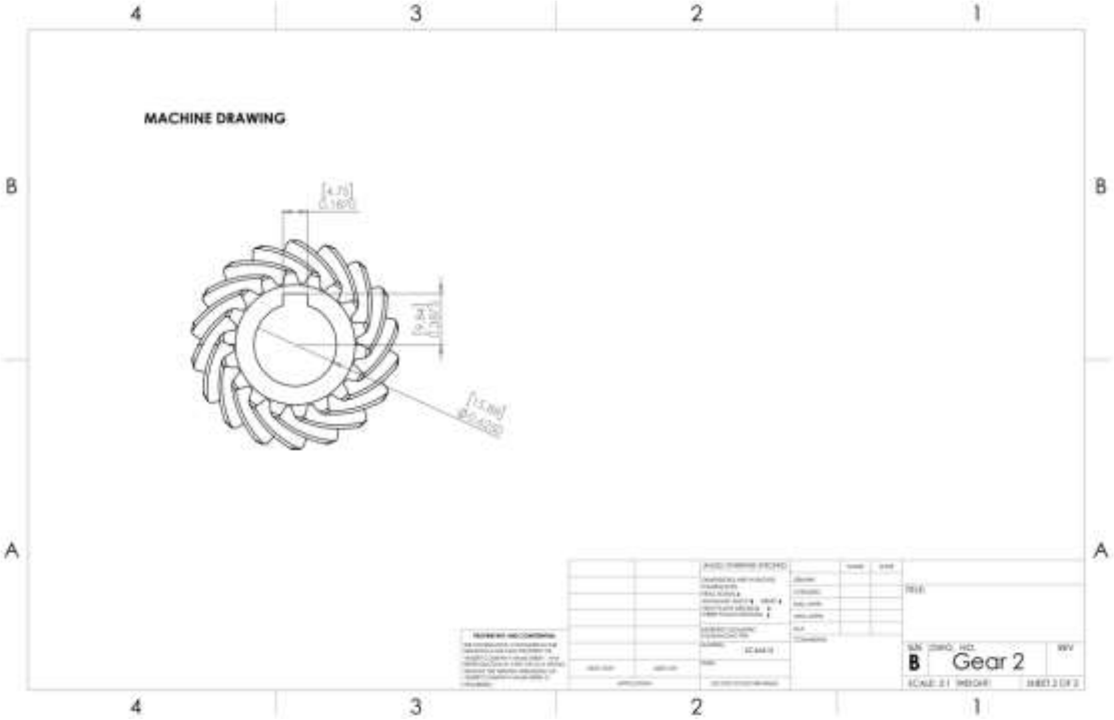


Figure 40 – Gear 2 Machine Drawing

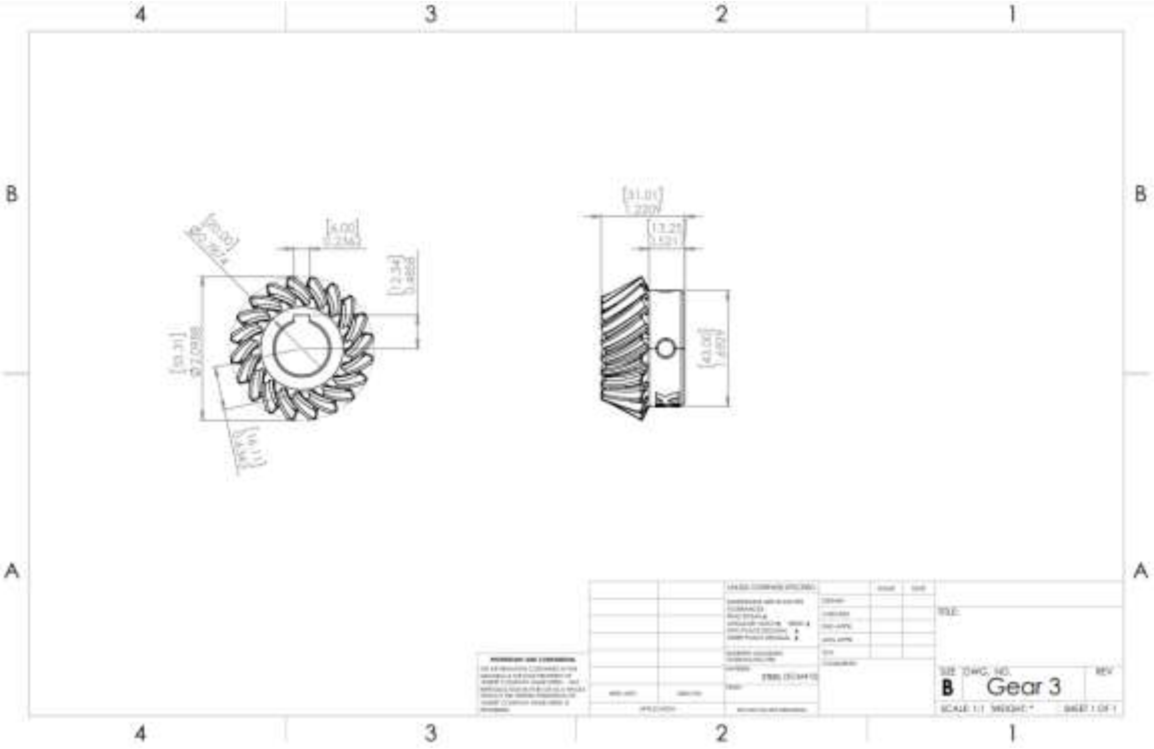


Figure 41 – Gear 3 Stock Drawing

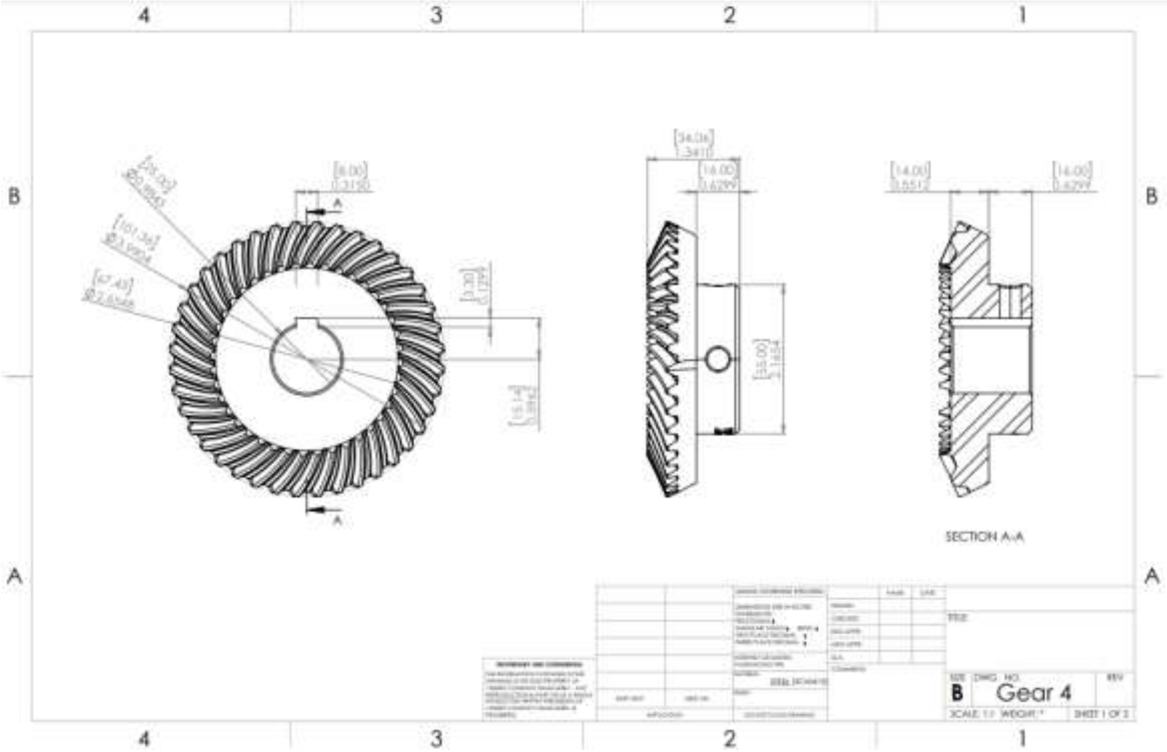


Figure 42 – Gear 4 Stock Drawing

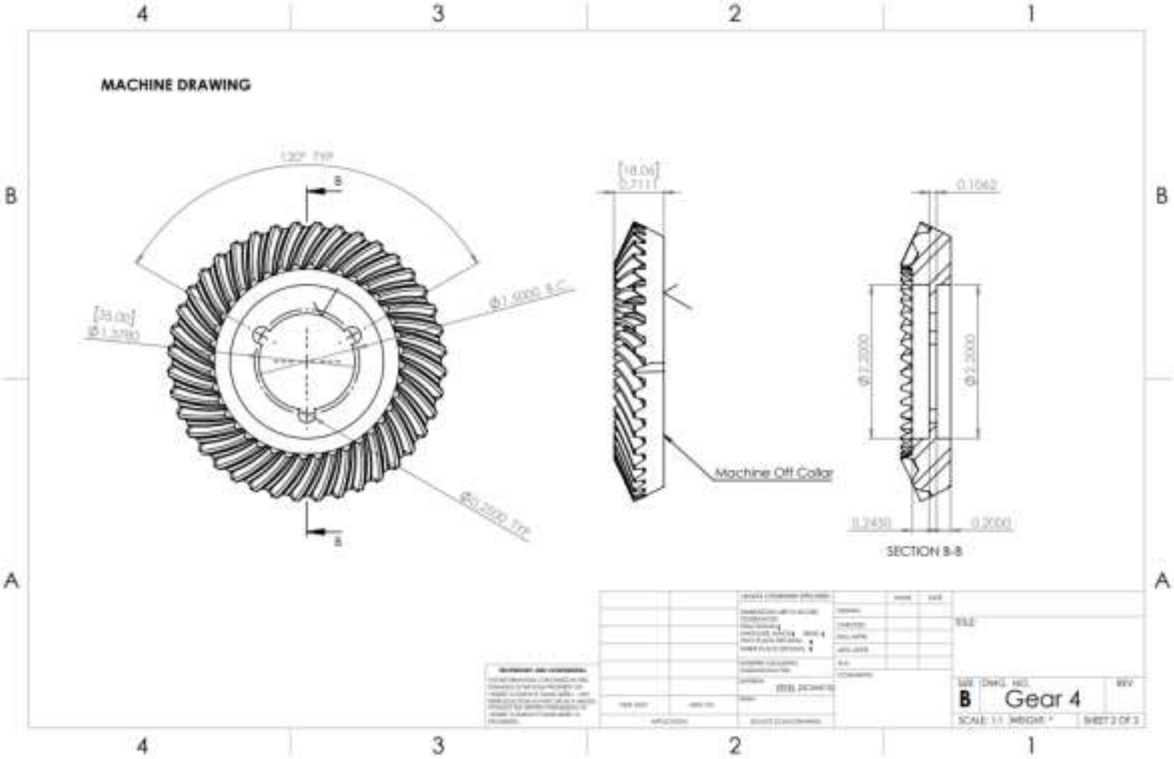


Figure 43 – Gear 4 Machine Drawing

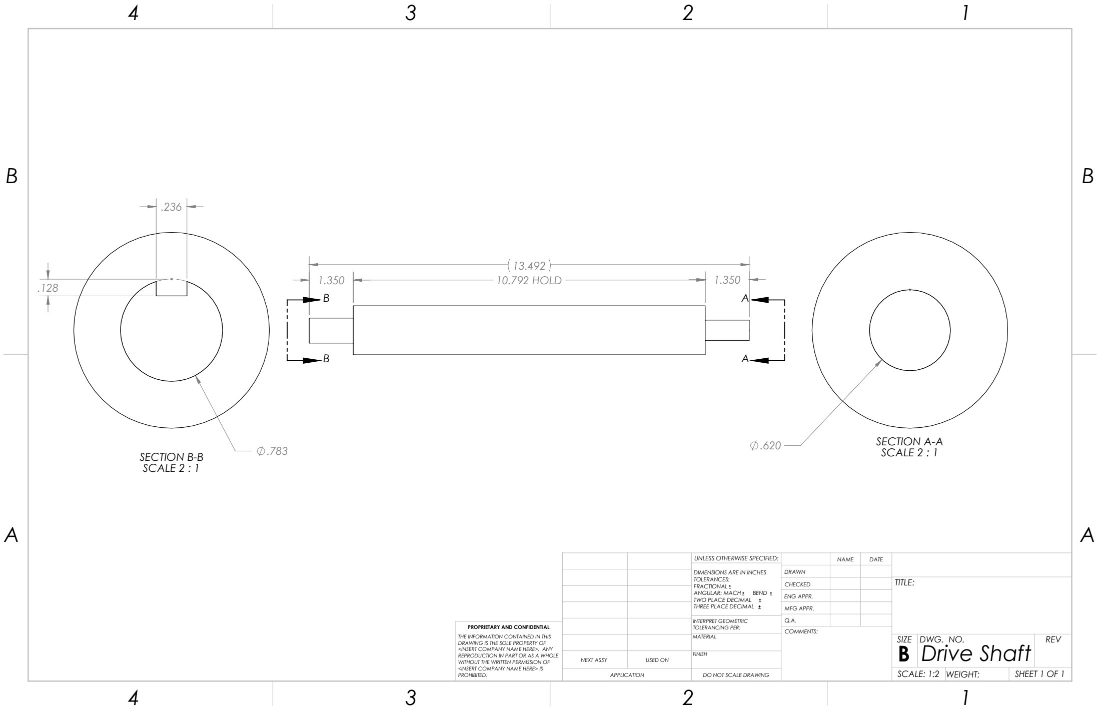


Figure 44 – Drive Shaft Drawing

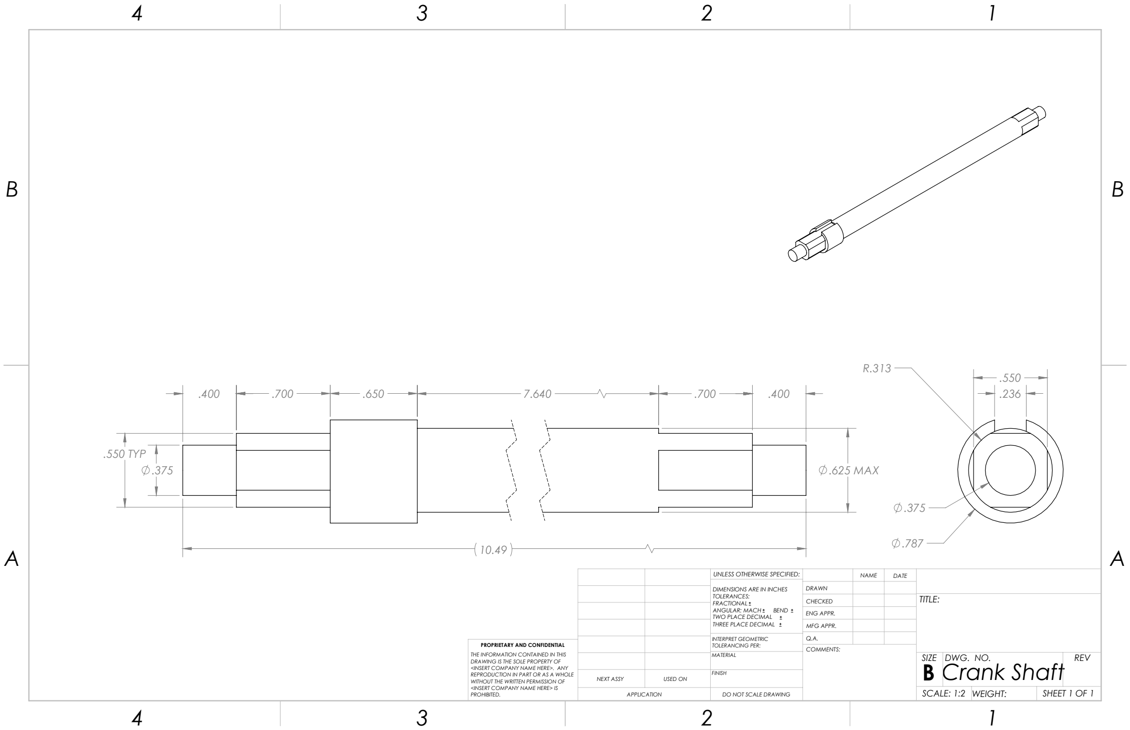


Figure 45 – Pedaling Shaft Drawing

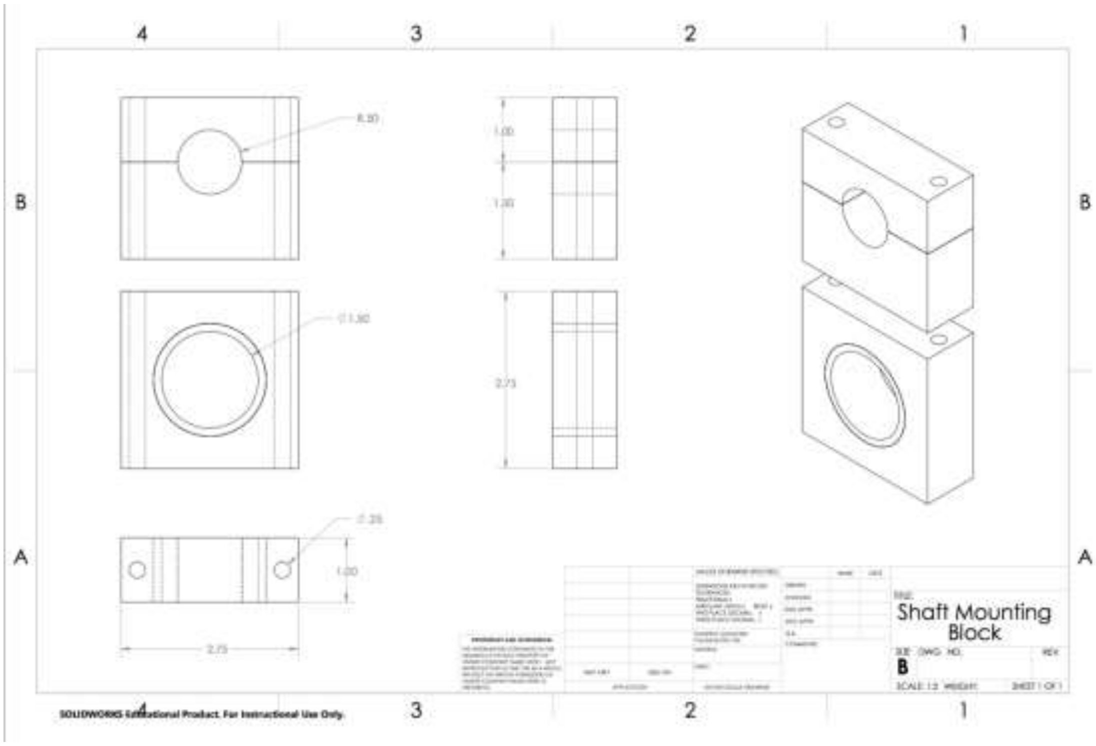


Figure 46 – Drive Shaft Mounting Block Assembly Drawing

Bill of Materials

Bike Part	Quantity	Comments
Internal Gear Hub	1	Shimano Alfine 8, pre-mounted in back wheel
Front Wheel	1	Standard front wheel
Tires and Innertubes	2	700C x 23mm
316L Stainless Steel 1.5” Bar Stock	2 ft	Drive Shaft raw material
Low Friction Bushings (Normal and Flange)	2 Normal/ 2 Flange	Flange bushings for pedal shaft Normal bushings for drive shaft
6061-T6 1” Aluminum Piping with 1/4” Walls	12 ft	Bicycle Frame back fork material
6061-T6 1.5” Aluminum Piping 1/4” Walls	3 ft	Bicycle Frame center support material
Gears 1+2 (45 - 18 teeth)	Set of 2	Purchased from KHK Gears US
Gears 3+4 (20 - 40 teeth)	Set of 2	Purchased from KHK Gears US
Assorted Washers/Spacers	As Necessary	Used as necessary for gear alignment from back wheel to pedals

Table 4 – Bill of Materials

Build and Test

The process of building the bike first started with the frame. Originally our team had planned to build the whole frame from scratch, however due to an issue with getting materials, our team was forced to pay more for local materials rather than wait for the more cost-effective materials to arrive from out of state. In addition, this caused a 3 week loss of time.

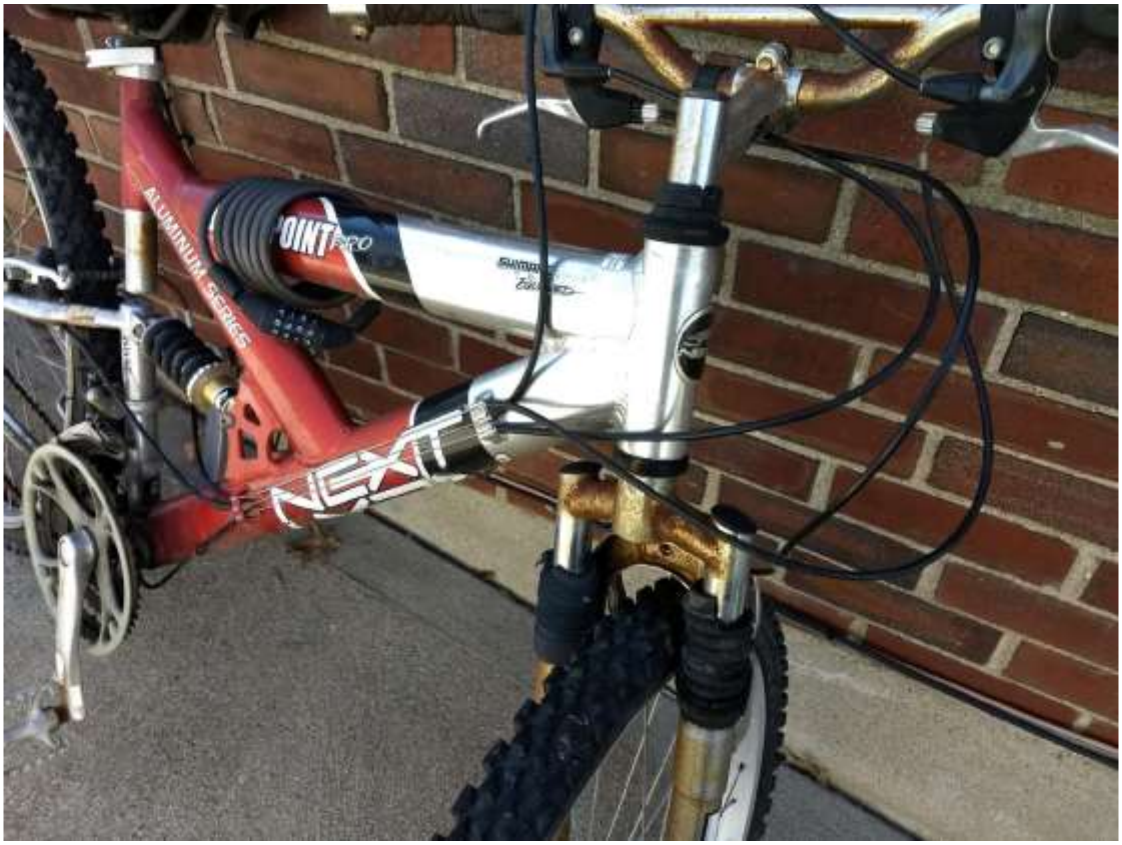


Figure 47 – Starting Bicycle

This change meant that our team had less money for the materials and needed to find a suitable starting frame as a base for our build. Our team disassembled the rear fork of the base bicycle and began fabrication on the members that would make up the new rear forks. While the bike was disassembled, our team added some of our aftermarket parts like breaks, racing seat, and a new front fork.

Figure 48 – Base Frame with Vertical Support

Each of the members had to be cut and machined on the ends for better contact area between the members allowing for a sturdier weld. To prep for welding the weld areas needed to be stripped of paint and then cleaned thoroughly with alcohol. First member to be added was a support tube that would reinforce the frame as well as provide an area to weld the lower half of the rear forks.

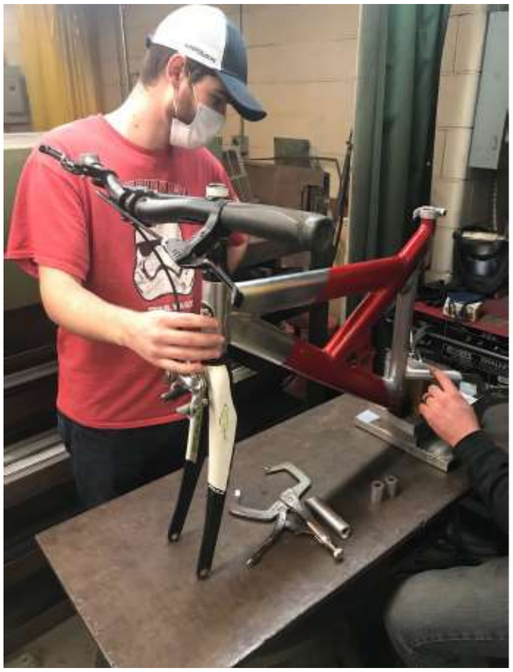


Figure 49 – Lower Rear Fork Welding (Left)

Figure 50 – Upper Rear Fork Welding (Right)

The next members to be welded on were the short lower and upper forks. The lower forks were welded onto the support tube and the upper forks were welded to the existing seat tube. Welding the members accurately was a difficult process and our team had to get creative in our ways to position the members in the correct orientation. The long members of the rear frame needed to have more intricate cuts into their ends to allow the frame to line up better and to accommodate the rear wheel mounts.

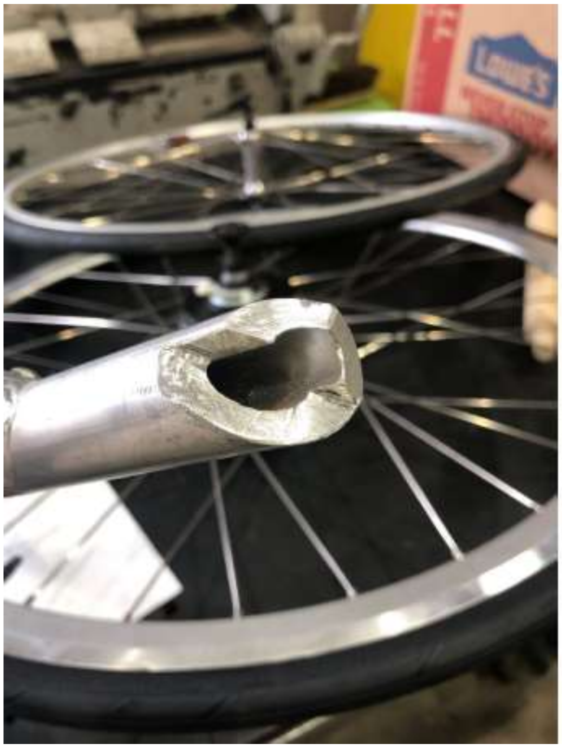


Figure 51 – End of Lower Rear Fork (Left)

Figure 52 – Wheel Mounting Block (Right)

With the short members of our back fork in place and our custom machining, our team was then able to weld the long members into place. At this point most of the rear frame was assembled and the wheel mounting plates can be welded. For the rear wheel mounting plates, it was crucial for them to be parallel as this would effect the wheel alignment.

Figure 53 – Welded Bicycle Frame

After the frame was fully welded, the wheels were attached. Thankfully the bicycle rolled in a straight line.

Figure 54 – Machined Pedaling Shaft (Left)

Figure 55 – Pedaling Shaft on Bicycle (Right)

With the bike frame widened, our team noticed that the pedal crankshaft would no longer work. This led to using some medium carbon steel to manufacture our own shaft that is wider than the original.



Figure 56 – Gear 4 Before Machining (Left)

Figure 57 – Gear 4 Machined Front (Center)

Figure 58 – Gear 4 Machined Back (Right)

Our gears were purchased from KHK Gears US and made of SCM415. Most of the gears required some minor modifications. Gear 4, which attaches to the rear wheels internal gear hub, required extensive modifications. The gears thickness was taken down on each side and the inner diameter was enlarged to accommodate the internal gear hub. Next there were three holes drilled into the gear that lined up with holes in the internal gear hub. This allowed for the placement of 3 pins to hold gear 4 in place.

Figure 59 – Gear 4 with Pins on Internal Gear Hub

With gear 4 completely machined, our team was able to install the gear onto the internal gear hub and secure it in place with the three pins and a locking ring.

Figure 60 – Gear 2

Gear 2 received a minor amount of modification. Our team used a wire EDM machine to enlarge the center hole so that the shaft would be able to fit inside the gear.

Figure 61 – Gear 1 Back

Gear 1 required a small amount of modification as the gear originally had a collar that needed to be machined off for mounting onto the pedal shaft.

Figure 62 – Gears on Wooden Model Shaft

To determine the length of our shaft, our team made a mock shaft out of wood to test the fit before committing our only piece of bar stock to the lathe.

Figure 63 – Gear 2 Heat Shrink Fitting

With our shaft turned down to size, it was decided that gear 2 would be better off being heat shrunk onto the shaft rather than going with our original plan to place a key slot into the shaft or welding it on.

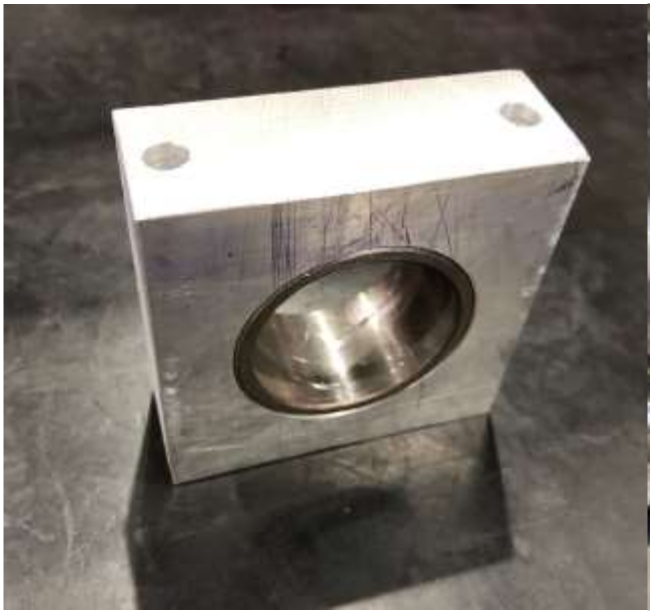


Figure 64 – Drive Shaft Mounting Blocks

Figure 65 – Drive Shaft Mounting Blocks Assembled on Bicycle

Custom mounting blocks were designed to be mounted off of the horizontal back fork member on the right side. These were adjustable to allow for optimized gear alignment. These allowed the shaft to spin by using oil impregnated bushings.

Figure 66 – Finished Bicycle

Once the shaft was lined up with gear 1 and gear 4, the testing was able to start.

Manufacturing Processes

This project encompassed many different manufacturing processes. Many of the parts that were ordered needed some form of machining performed to them. The gears required the vertical mill, lathe, CNC, and a wire EDM machine. Components such as the shafts were turned on the lathe and then needed some minor milling to be performed to make key slots. The frame needed its members to be cut to size on the bandsaw, then the ends needed to be milled to the proper geometry, and then lastly they needed to be TIG welded together.

Testing Procedures and Criteria

Figure 67 – Finished Bicycle with a good looking 6'2" Engineer

Testing the frame for structural stability was a simple matter. Our team had a member ride the bike. This tested the bike at 275lbs. During this time, our team also tested the ease of use and overall feel of the bicycle to determine if the added weight affected the riding quality. Our testing found that the bicycle rode very smooth and was easy to control even with the added weight.

Figure 68 – Drive Shaft Bicycle mounted on Bicycle Trainer

Finding the efficiency of the bicycle was a more complicated task. For testing, our team fixed both our bicycle, a high-performance bicycle, and a unmaintained bicycle onto a bike trainer and attempted to turn the wheels at the same force the same number of times and counted how many rotations the wheel would spin.

Test Results and Findings

Figure 69 – High Performance Bicycle mounted on Bicycle Trainer

During frame testing our team tested the bicycle at 275lbs. The bicycle frame showed no signs of flexing. While testing the efficiency of the bicycle, the teams' goal was to meet or exceed the efficiency of a standard bicycle. From the research conducted, a well-maintained chain bicycle is able to achieve roughly 74.5% efficiency. Data was gathered from the testing apparatus mentioned and was compiled and then analyzed. After factoring in the different gear ratios of each of the bicycles, it was assumed that the performance bicycle had an efficiency of approximately 85%. Based on this assumption, our bicycle had an approximate efficiency of 74.8%, and the unmaintained bicycle had an efficiency of 46.6%. Our testing shows that the team had managed to meet the goal of matching a standard bicycles efficiency, just barely beating the 74.5% efficiency goal. The team believes that if given more time and resources, the efficiency of the driveshaft bicycle could be raised further by replacing the bushings with higher efficiency bearings, and by applying a tighter meshing between the gears.

Project Management

Project Budget

Initial Budget = $1500 ± 20% = $1200-1800

Bike Part	Expected Cost	Comments/Conditions
Bike Frame	< $500	Dependent on material purchasing vs. frame modification
Internal Gear Hub	$200-400	Dependent on Shimano Alfine 8 or 11 selection
Bike Components	< $200-300	Based on purchasing vs. reuse from old bicycles
Wheels and Tires	$200	Dependent on wheel and tire quality
Gears	$100-250	Dependent on gear material selection
Drive Shaft	< $100	Dependent on material purchasing cost
Battery and Motor	Leftover Budget	Optional addition
Total	**$1300-1750**	Total estimated expenses

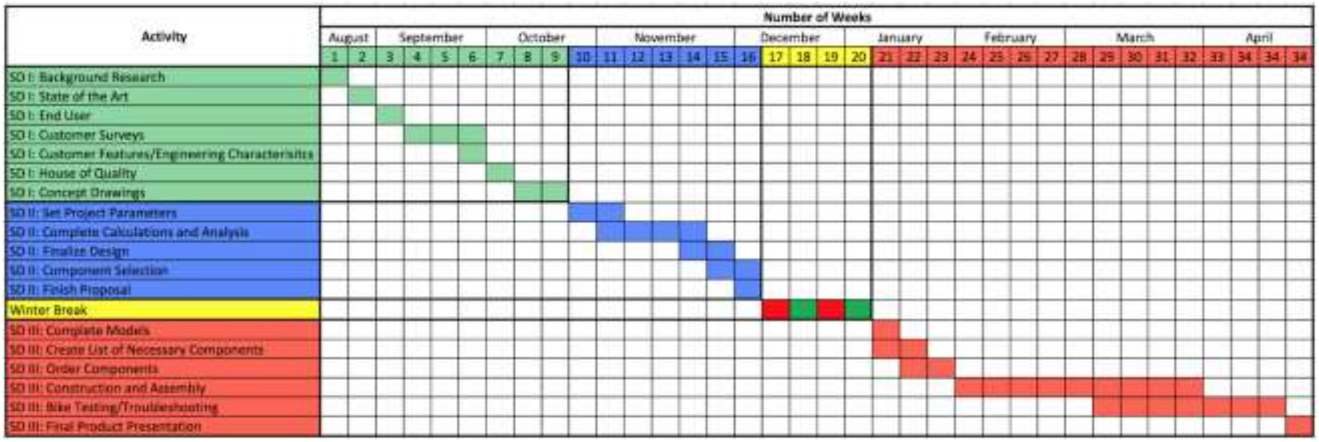
Table 5 – Initial Project Budget

Part	Qty/Amount	Expected Cost	Max Allotted Budget
🟩 1.5" solid 316 Stainless Steel	2 ft	$152.10	$100.00
🟩 6061-t6 piping (Large OD 1)	6 ft	$101.46	$250.00
🟩 6061-t6 piping (Small OD 2)	12 ft	$170.91	$250.00
🟩 Internal Gear Hub	1	N/A	$400.00
🟩 Gears	4	$362.23	$250.00
🟩 Bike Components (Brakes, crankshaft, seat, etc)	1	$0.00	$300.00
🟩 Wheels and Tires	2	$598.96	$200.00
🟩 Bushings/Collars	4/4	$57.27	$25.00
🟩 Washers and Spacers	lots	$21.90	$25.00
🟧 Battery and Motor (Optional)	N/A	$0.00	N/A
🟧 ER630 Weld Material	1 lb	$0.00	N/A
	Total	$1,464.83	$1,800.00

Table 6 – Final Project Budget

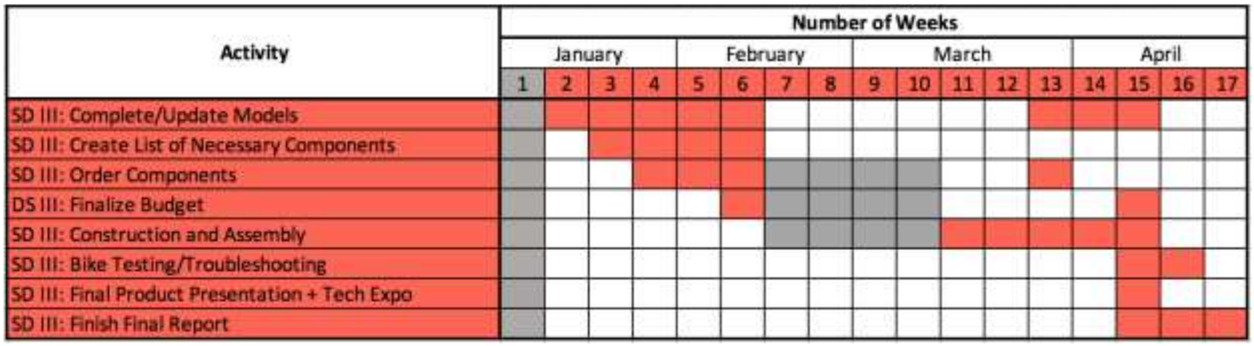
The total project budget was $1500 dollars, which was to be funded personally by the team, and split evenly at $500 per person. The final amount spent was $1,464.83 dollars. The total frame material costs added up to $424.47, which was under budget for that section. The gears and other small components including the bushings/collars, washers, and spacers, added up to $441.40, which was more than anticipated for the budget. The gears that were purchased were the only ones able to withstand the stresses required that were still remotely within the price range. We were able to use scrap materials from the old Hydraulic Team bicycles for the front brake, seat, and handlebar, as well as stock material from VPC for the crankshaft and shaft mounting blocks. The internal gear hub was purchased, having already been installed into a rear wheel. When adding the cost of the front wheel, innertubes, and tires, this amounted to $598.96, which was still within the allotted budget. Welding material was able to be used from VPC, and the decision was made to not add a battery and motor due to time and budgeting constraints.

Project Schedule



Activity	Number of Weeks																																		
	August		September				October			November							December				January			February				March					April			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	34	34
SD I: Background Research	🟩																																		
SD I: State of the Art		🟩																																	
SD I: End User			🟩																																
SD I: Customer Surveys				🟩	🟩	🟩																													
SD I: Customer Features/Engineering Characterisitcs						🟩																													
SD I: House of Quality							🟩																												
SD I: Concept Drawings								🟩	🟩																										
SD II: Set Project Parameters										🟦	🟦																								
SD II: Complete Calculations and Analysis											🟦	🟦	🟦	🟦																					
SD II: Finalize Design														🟦	🟦																				
SD II: Component Selection															🟦	🟦																			
SD II: Finish Proposal																🟦																			
Winter Break																	🟥	🟩	🟥	🟩															
SD III: Complete Models																					🟥														
SD III: Create List of Necessary Components																					🟥	🟥													
SD III: Order Components																						🟥	🟥												
SD III: Construction and Assembly																								🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥				
SD III: Bike Testing/Troubleshooting																													🟥	🟥	🟥	🟥	🟥	🟥	🟥	
SD III: Final Product Presentation																																			🟥

Figure 70 – Initial Project Schedule



Activity	Number of Weeks																
	January				February				March					April			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SD III: Complete/Update Models	▨	🟥	🟥	🟥	🟥	🟥							🟥	🟥	🟥		
SD III: Create List of Necessary Components	▨		🟥	🟥	🟥	🟥											
SD III: Order Components	▨			🟥	🟥	🟥	▨	▨	▨	▨			🟥				
DS III: Finalize Budget	▨					🟥	▨	▨	▨	▨					🟥		
SD III: Construction and Assembly	▨						▨	▨	▨	▨	🟥	🟥	🟥	🟥	🟥		
SD III: Bike Testing/Troubleshooting	▨														🟥	🟥	
SD III: Final Product Presentation + Tech Expo	▨														🟥		
SD III: Finish Final Report	▨														🟥	🟥	🟥

Figure 71 – Final Project Schedule

The project schedule changed a decent amount compared to what was anticipated. The key difference that can be seen is the grey area in the middle of the timeline. This was lost time due to a shipping complication when ordering the frame material. The company initially stated a two week shipping period. After 3-4 weeks, and calling weekly to check in with the company, the team was informed that they had shipping issues due to Covid-19, and hadn't started filling the order yet. A local vendor company had to be contacted to try ordering the material again with accelerated 2 day shipping times at an increased fee. There were also later late components ordered, which were the bushings, collars, washers, and spacers. The 3D models were updated towards the end of the project once final dimensions were confirmed.

Sustainability and Material Usage

The frame was constructed from 6061-T6 Aluminum piping with ¼ inch walls. This material will be able to withstand the forces without breaking down over the years to rust or other forms of wear. The shaft material was 316L Stainless steel, which is a heavy duty steel that will also not rust or degrade over time. The gears are made of SCM415, which is a medium carbon stainless steel. They should be resistant to rust, and strong enough to not have any of the teeth break under maximum stress assumptions and conditions. The bushings are oil impregnated brass. These were used for both the mounting of the drive shaft, as well as the pedaling shaft. These are the only components that are expected to need to be replaced every few years.

Conclusions

With a tested efficiency of 74.8%, the drive shaft bicycle has shown similar efficiency levels as the average chain driven bicycle, averaging 74.5% efficiency (1). As a forerunner for this type of bicycle, the team was pleased to be able to achieve this level of efficiency. The budget was the main limiting factor on this project, as it was self-funded by the team. The gears that were purchased were the only ones that were within budget and able to withstand the stresses required, but were smaller in diameter than desired, and did not provide an ideal gear ratio. Due to this gear selection causing reduced space availability, in addition to the low budget, bushings were used in place of ball bearings, which was a large source of efficiency loss. The second largest source of efficiency loss was in gear alignment. In the initial 3D model, the shaft and horizontal section of the back fork were meant to be perfectly level and parallel with a flat floor, allowing for the best possible gear meshing. This was difficult to achieve in the real world without welding fixtures, and thus there is a slight angle to the shaft, which causes a misalignment and extra friction in the gear mesh. Due to this misalignment, gears 1 and 2 slip when experiencing larger forces exerted by the rider.

Aside from the level of efficiency achieved, the drive shaft bicycle was a success. It is easily able to withstand all forces as expected from a 275 lb rider. The internal gear hub functions properly, and is able to shift between its 8 gear ratios, allowing for greater ease of riding on different elevation levels. The assembled bicycle is a bit heavier than was anticipated at 41 lbs over our 25 lb goal, but our frame weight was only 28 lbs, and the assumed shaft material was changed, causing an unexpected increase in weight. The bicycle rides straight and smoothly, without feeling off center due to the weight of the drive shaft system.

Bibliography/Reference Material

1. Kozlov, K., Belogusey, V., Egorov, A. and Syutov, N. Development Of Method To Evaluate Friction Losses Of Chain Drives. Engineering for Rural Development. *SCOPUS.* [Online] 2018. [Cited: 9 2, 2020.]

2. Transport Research Laboratory/University College London, United Kingdom. Electrically-Assisted Bikes: Potential Impacts On Travel Behaviour. *Google Scholar - Science Direct.* [Online] 2020. [Cited: 9 2, 2020.] https://www.sciencedirect.com/science/article/pii/S096585641.

3. Joachim GÖBEL, J. Multi-Speed Internal Gear Hub For A Bicycle. *Google Scholar.* [Online] 2011. [Cited: 9 2, 2020.] https://patents.google.com/patent/US20110130242A1/en.

4. E., Levarda. Bicycle Transmissions. *Materials Science and Engineering.* 2018, Vol. 444, 5.

5. Max Power Gears. [Online] 11 21, 2017. [Cited: 10 15, 2020.]

6. Efficiency of Small Machine Elements. *Engineering Toolbox.* [Online] 2018. [Cited: 10 15, 2020.] https://www.engineeringtoolbox.com/efficiency-small-machine-elements-d_2076.html.

7. Davis, R. and Hull, M. Design Of Aluminum Bicycle Frames. Journal of Mechanical Design, Transactions of the ASME. *SCOPUS.* [Online] 1981. [Cited: 9 2, 2020.]

8. Hull, M. and Bolourchi, F. Contributions Of Rider-Induced Loads To Bicycle Frame Stress. The Journal of Strain Analysis for Engineering Design, 23. *SCOPUS.* [Online] 2020. [Cited: 9 2, 2020.]

9. Budynas, Richard G. and Keith Nisbett, J. *Shigley's Mechanical Engineering Design.* Chennai : McGraw Hill Education (India) Private Limited, 2016. 978-93-392-2163-8.

10. *KHK Gears US.* [Online] [Cited: 4 25, 2021.] https://www.khkgears.us/catalog/product/MBSA2-4518R.

11. *KHK Gears US.* [Online] [Cited: 4 25, 2021.] https://www.khkgears.us/catalog/product/MBSA2-1845L.

12. *KHK Gears US.* [Online] [Cited: 4 25, 2021.] https://www.khkgears.us/catalog/product/MBSA2.5-2040L.

13. *KHK Gears US.* [Online] [Cited: 4 25, 2021.] https://www.khkgears.us/catalog/product/MBSA2.5-4020R.

Appendix A – Common Abbreviations

AISI = American Iron and Steel Institute

AGMA = American Gear Manufacturing Association

FEA = Finite Element Analysis

FoS = Factor of Safety

H_B = Hardness in Brinell

HoQ = House of Quality

HRC = Hardness in Rockwell C

SCM = Steel Composite Material (In Japanese Classification System)

QFD = Quality Function Deployment

Appendix B – AGMA Standard Variable Names (Gears)

$C_H = Hardness\,ratio\,factor\,for\,pitting\,resistance$

$C_L = Stress\,cycle\,factor\,for\,pitting\,resistance$

$C_P = \ Elastic\,coefficient\,for\,pitting\,resistance$

$C_R = Reliability\,factor\,for\,pitting$

$C_S = Size\,factor\,for\,pitting$

$C_{XC} = Crowning\,factor\,for\,pitting\,resistance$

$d_G = Diameter\ of\ gear$

$d_P = Diameter\ of\ pinion$

$E_G = Young's modulus\ of\ elasticity\,for\,the\,gear$

$E_P = Young's modulus\ of\ elasticity\,for\,the\,gear$

$F\ = net\,face\,width$

$f_P = Pinion\,surface\,roughness$

$H_B = Brinell\,hardness\,for\,allowable\,contact\,stress\,(smaller\ of\ H_{BG}\ \&\ H_{BP})$

$H_{BG} = Minimum\,Brinell\,hardness\,for\,gear\,material$

$H_{BP} = Minimum\,Brinell\,hardness\,for\,gear\,material$

$I = Geometry\,factor\,for\,pitting\,resistance$

$J = Geometry\,factor\,for\,bending\,strength$

$K_L = Stress\,cycle\,for\,bending\,factor$

$K_M = Load\,distribution\,factor$

$K_{mb} = \ Straddle - mounting\,factor$

$K_O = Overload\,factor$

$K_R = Reliability\,factor\,for\,bending$

$K_T = Thermal\,factor$

$K_V = Dynamic\,factor$

$K_X = Lengthwise\,curvature\,factor\,for\,bending\,strength$

$N = Number\ of\ gear\ teeth$

$n = Number\ of\,pinion\,teeth$

$N_L = Number\ of\ load\ cycles$

$n_P = Pinion\,speed$

$P_d = Outer\ transverse\ diametral\ pitch$

$Q_V = Transmission\ accuracy\ number$

$R = Reliability\ factor$

$r_G = Radius\ of\ gear$

$r_P = Radius\ of\ pinion$

$S_{ac} = Allowable\ contact\ stress\ number$

$S_{at} = Bending\ stress\ number\ (allowable)$

$S_C = Calculated\ contact\ stress\ number$

$S_F = Bending\ safety\ factor$

$S_H = Contact\ safety\ factor$

$S_t = Calculated\ bending\ stress\ number$

$S_{wc} = Permissible\ contact\ stress\ number$

$S_{wt} = Permissible\ contact\ stress\ number$

$T = Torque$

$v_t = Pitch - line\ velocity\ at\ outer\ pitch\ circle$

$w^T =$

Appendix C – Shaft Standard Variable Names

σ = Stress

M = Moment

n_d = Design Factor

n = Factor of Safety

S = Yield Strength

d = Diameter

ϕ = Angle of Twist

T = Torque

L = Length

J = Polar Moment of Inertia

G = Shear Modulus

F = Force

D = Distance

θ = Angle

W = Work

w = Weight

K = Kinetic Energy

ΔK_E = Change in Kinetic Energy

P = Pressure

m = Mass

A = Area

μ = Friction Coefficient

g = Gravitational Constant

Appendix D – MatLab code for Front Gears

```
% Robby Elkin
% Drive Shaft Bicycle Senior Design Project
% MET Class of 2021
% IN AGMA standards and AISI standards

%% Inputs
clear; close all; clc;

% Number of teeth on GEAR
N=45

% Number of teeth on PINION
n=18

% Diameter of the GEAR
dg=77.289/25.4

% Speed of the PINION (feet per minute)
np=6*(2.5/1)*2*pi*30*(1/25.4)*(1/12)

% Outer transverse diametral pitch Teeth per inch
Pd=45/90

% Diameter of the PINION (Np/Pd)
dp=33.826/25.4

% net contact area
F=(4.79*14)/(25.4^2)

% Trasmission accuracy #
Qv=4

% adjustments for strength
Sh=1.5
Sf=1.5

% Straddle mounting of gears
Kmb=1.25

% Crowning Factor
Cxc=1.5

% Overload factor (assume 1)
Ko=1
```

```
% Lengthwise curvature factor for bending strength (assume 1)
Kx=1

% Contact geometry factor
I=0.11

% Bending factor
J=0.39

% Temperature K factor
Kt=1

% Life cycle *****not stated on website
Nl=10^6

% Reliablility factor
R=0.90

% Hardness in Brinell
HBP=17.515*55-401
HBG=17.515*55-401

% Pinion surface roughness
fp=1

% Metal Grade quality (1 or 2)
Grade=1

% Youngs modulus for the GEAR
Eg=27577000

% Youngs modulus for the PINION
Ep=27577000

% Torque on PINION?
T=78.08

%% Calculate other factors

% Load sharing ratio
mN=1

% radii
r1=dg/2
r2=dp/2
```

```
% transverse pressure angle
PhiT=(2*(1/dp+1/dg))/(1/r1+1/r2)

% Speed ratio
mG=N/n

% Transmitted load
Wt=T/(14.4725/25.4/12)

% Dynamic Factor
Vt=pi*dp*np/12
B=0.25*(12-Qv)^(2/3)
A=50+56*(1-B)
Kv=((A+Vt^(1/2))/(A))^B

% Size factor for pitting
if F<0.5
    Cs=0.5
elseif 0.5<=F && F<=4.5
    Cs=0.125*F+0.4375
else
    Cs=1
end

% Size factor for bending
if 0.5<=Pd<=16
    Ks=0.4867+0.2132/Pd
elseif 16<Pd
    Ks=0.5
end

% Load distribution of gears
Km=Kmb+0.0036*F^2

% Stress-cycle factor for pitting resistance
if 10^3<=Nl && Nl<10^4
    Cl=2
end

if 10^4<=Nl && Nl<=10^10
    Cl=3.4822*Nl^(-0.0602)
end

% Stress-cycle factor for bending strength
if 10^2<=Nl && Nl<10^3
    Kl=2.7
end
```

```
if 10^3<=Nl && Nl<3*10^6
    Kl=6.1515*Nl^(-0.1192)
end

if 3*10^6<=Nl && Nl<=10^10
    Kl=6.1515*Nl^(-0.1192)
end

% Hardness ratio factor
if 1.2<=HBP/HBG && HBP/HBG<=1.7
    B1=0.00898*(HBP/HBG)-0.00829
    Ch=1+B1*(N/n-1)
else
    B2=0.00075*exp(-0.0122*fp)
    Ch=1+B2*(450-HBG)
end

% Reliability factors
if 0.99<=R && R<=0.999
    Kr=0.50-0.25*log(1-R)
end

if 0.50<R && R<0.99
    Kr=0.70-0.15*log(1-R)
end

Cr=Kr^(1/2)

% Elastic coefficient for pitting resistance (2290 psi/190 N/m
for steel)
Cp=2290   %(1/(pi*((1-Vp^2)/Ep+(1-Vg^2)/Eg)))^(1/2)

% Allowable contact stress
if HBG<HBP
    Hb=HBG
else
    Hb=HBP
end

% Sac = allowable contact stress
% Sat = allowable bending stress
if Grade==1
    Sac=341*Hb+23620
    Sat=44*Hb+2100
elseif Grade==2
    Sac=363.6*Hb+29560
```

```
    Sat=45*Hb+5980
end

%% Final Contact Equations

% Fundamental contact stress
Sc=Cp*((Wt/(F*dp*I))*Ko*Kv*Km*Cs*Cxc)^(1/2)

% Permissible contact stress
Swc=(Sac*Cl*Ch)/(Sh*Kt*Kr)

% Factor of safety for contact
Contact_FoS=Swc/Sc

%% Final Bending Equations

% Bending stress
St=(Wt/F)*Pd*Ko*Kv*((Ks*Km)/(Kx*J))

% Permissible bending force
Swt=(Sat*Kl)/(Sf*Kt*Kr)

% Factor of safety for bending
Bending_FoS=Swt/St
```

Appendix E – MatLab code for Back Gears

```
% Robby Elkin
% Drive Shaft Bicycle Senior Design Project
% MET Class of 2021
% IN AGMA standards and AISI standards

%% Inputs
clear; close all; clc;

% Number of teeth on GEAR
N=40

% Number of teeth on PINION
n=20

% Diameter of the GEAR
dg=84.395/25.4

% Speed of the PINION (feet per minute)
np=6*(2.5/1)*2*pi*30*(1/25.4)*(1/12)

% Outer transverse diametral pitch Teeth per inch
Pd=40/101

% Diameter of the PINION (Np/Pd)
dp=42.765/25.4

% net contact area
F=(4.79*17)/(25.4^2)

% Trasmission accuracy #
Qv=4

% adjustments for strength *****check spur gear section
Sh=1.5
Sf=1.5

% Straddle mounting of gears
Kmb=1.25

% Crowning Factor
Cxc=1.5

% Overload factor (assume 1)
Ko=1
```

```
% Lengthwise curvature factor for bending strength (assume 1)
Kx=1 % for straight bevel gear

% Contact geometry factor
I=0.1025

% Bending factor
J=0.385

% Temperature K factor
Kt=1

% Life cycle *****not stated on website
Nl=10^6

% Reliablility factor
R=0.90

% Hardness in Brinell
HBP=17.515*55-401
HBG=17.515*55-401

% Pinion surface roughness
fp=1

% Metal Grade quality (1 or 2)
Grade=1

% Youngs modulus for the GEAR
Eg=27577000

% Youngs modulus for the PINION
Ep=27577000

% Torque on PINION?
T=78.08

%% Calculate other factors

% Load sharing ratio
mN=1

% radii
r1=dg/2
r2=dp/2
```

```
% transverse pressure angle
PhiT=(2*(1/dp+1/dg))/(1/r1+1/r2)

% Speed ratio
mG=N/n

% Transmitted load
Wt=T/(14.4725/25.4/12)

% Dynamic Factor
Vt=pi*dp*np/12
B=0.25*(12-Qv)^(2/3)
A=50+56*(1-B)
Kv=((A+Vt^(1/2))/(A))^B

% Size factor for pitting
if F<0.5
    Cs=0.5
elseif 0.5<=F && F<=4.5
    Cs=0.125*F+0.4375
else
    Cs=1
end

% Size factor for bending
if 0.5<=Pd<=16
    Ks=0.4867+0.2132/Pd
elseif 16<Pd
    Ks=0.5
end

% Load distribution of gears
Km=Kmb+0.0036*F^2

% Stress-cycle factor for pitting resistance
if 10^3<=Nl && Nl<10^4
    Cl=2
end

if 10^4<=Nl && Nl<=10^10
        Cl=3.4822*Nl^(-0.0602)
end

% Stress-cycle factor for bending strength
if 10^2<=Nl && Nl<10^3
        Kl=2.7
end
```

```
if 10^3<=Nl && Nl<3*10^6
        Kl=6.1515*Nl^(-0.1192)
end

if 3*10^6<=Nl && Nl<=10^10
        Kl=6.1515*Nl^(-0.1192)
end

% Hardness ratio factor
if 1.2<=HBP/HBG && HBP/HBG<=1.7
        B1=0.00898*(HBP/HBG)-0.00829
        Ch=1+B1*(N/n-1)
else
    B2=0.00075*exp(-0.0122*fp)
    Ch=1+B2*(450-HBG)
end

% Reliability factors
if 0.99<=R && R<=0.999
        Kr=0.50-0.25*log(1-R)
end

if 0.50<R && R<0.99
        Kr=0.70-0.15*log(1-R)
end

Cr=Kr^(1/2)

% Elastic coefficient for pitting resistance (2290 psi/190 N/m
for steel)
Cp=2290   %(1/(pi*((1-Vp^2)/Ep+(1-Vg^2)/Eg)))^(1/2)

% Allowable contact stress
if HBG<HBP
    Hb=HBG
else
    Hb=HBP
end

% Sac = allowable contact stress
% Sat = allowable bending stress
if Grade==1
    Sac=341*Hb+23620
    Sat=44*Hb+2100
elseif Grade==2
    Sac=363.6*Hb+29560
```

```
    Sat=45*Hb+5980
end

%% Final Contact Equations

% Fundamental contact stress
Sc=Cp*((Wt/(F*dp*I))*Ko*Kv*Km*Cs*Cxc)^(1/2)

% Permissible contact stress
Swc=(Sac*Cl*Ch)/(Sh*Kt*Kr)

% Factor of safety for contact
Contact_FoS=Swc/Sc

%% Final Bending Equations

% Bending stress
St=(Wt/F)*Pd*Ko*Kv*((Ks*Km)/(Kx*J))

% Permissible bending force
Swt=(Sat*Kl)/(Sf*Kt*Kr)

% Factor of safety for bending
Bending_FoS=Swt/St
```