Drive Shaft Bicycle

Keaton Glaser - Drive Shaft
Kyle Rechel - Frame
Robby Elkin - Gearing

Problem Statement

We plan to design a more efficient way of transportation through an advanced chainless bike system. 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). There are bicycles currently on the market that can raise that efficiency up to 80, 90, and even as high as 99% efficiency, however these kinds of bikes can range into the tens of thousands of dollars, making them unobtainable to the average consumer.

Background

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. Since this invention, the bicycle has remained mostly the same, only advancing in lighter materials and cheaper cost of production (2) with some exceptions such as electric, hydraulic, and pneumatic bikes.

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). This goes to show the constant growth in the amount of people that are using bicycles for transportation, enjoyment, or even for races.

Existing Technology

There is a company named CeramicSpeed who has made a drive shaft system that uses ceramic ball bearings to reduce friction between the gears, input pedals, and wheels. This allows for a remarkable 99% efficiency. This invention could be the future of the bicycling industry; however, the company is still in the prototype phase and has not released the price, but is estimated to cost the average consumer over $5,000.

Existing Technology Cont.

Modern chain driven bikes can also reach high efficiency levels into the the mid 90% range, but this is heavily dependent on what gear you are in, the quality of your chain and gears, and requires proper lubrication. Bikes of this quality can also easily soar above the $5,000 price mark.

These bikes require more maintenance, and also have the issue of “dropping chains” when in some gear combinations.

Customer Features

What is important to the customer?

1. Lightweight Design
2. High Efficiency
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

Product Objectives

Based on Customer Surveys, the product objectives are weighted as follows:

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 Parameters and Conditions

Top Speed Goal: 25 mph

Weight Goal: 30 lbs (25 lbs was initial goal for frame only)

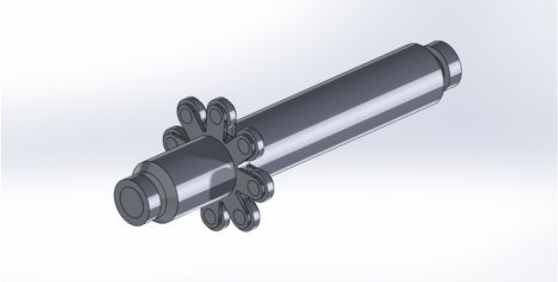
Design Budget: $1,500

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

Material Selection: Aluminum 6061-T6 frame, 316L Stainless shaft, SCM415 steel gears

Maintenance: General maintenance and lubrication 1-2 times a year

Shaft Design Options



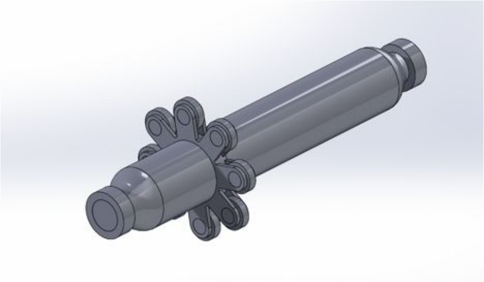
Concept 1

Concept 1 - Solid Shaft

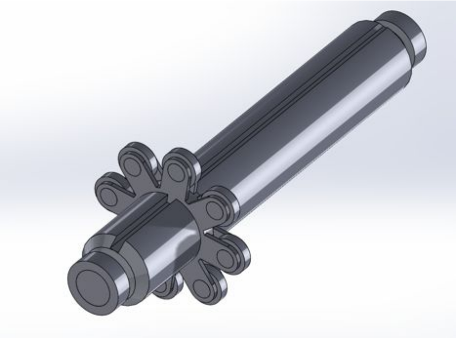
Concept 2 - Smooth Shaft

Concept 3 - Sliding Shaft

Concept 2



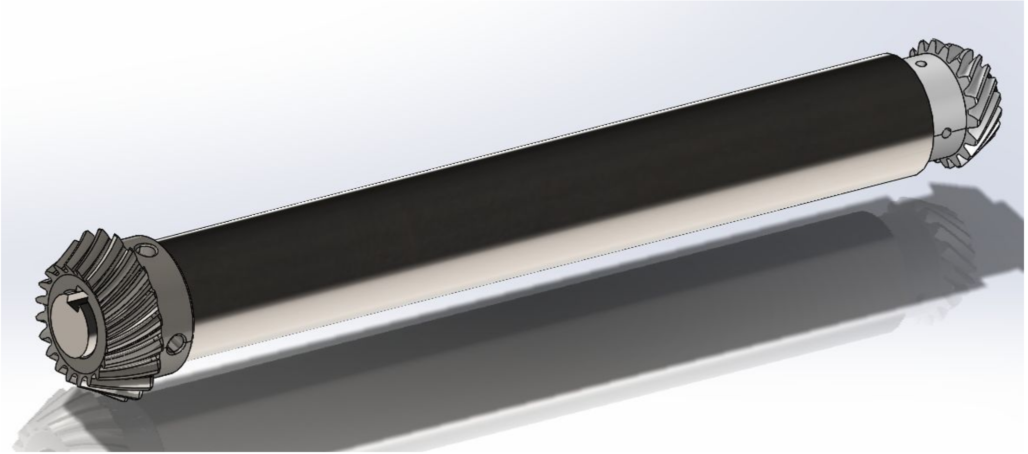
Selection: Concept 1



Concept 3

Shaft Solid Model

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 gears can be used with an internal gear hub for multiple gear combinations.



Factors of Safety/Calculations

Assumptions: 275 lb rider can exert 350 lbs of force, Design Factor should be 6 for impact rating and fatigue, 316L Stainless should be used for shaft material, crank shaft length of 170 mm, Factor of Safety should be 10-12 for heavy duty shafts

σ = Stress M = Moment n_d = Design Factor n = Factor of Safety
S = Yield Strength d = Shaft Diameter

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

$$M = Fd = 350\ lbs * \left[\left(170\ mm * \frac{1\ in}{24\ mm}\right) * \frac{1\ ft}{12\ in}\right] = 195.21\ lb * ft$$

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

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

ϕ = Angle of Twist T = Torque L = Length
J = Polar Moment of Inertia G = Shear Modulus

$$\phi = \frac{TL}{JG} \qquad J = \frac{\pi d^4}{32} = \frac{\pi * 1.5^4}{32} = .4970\ in^4$$

$$\phi = \frac{TL}{JG} = \frac{780.84 * 12.042}{11893000 * .4970} = .0253\ rad * \frac{180}{\pi} = 0.09°$$

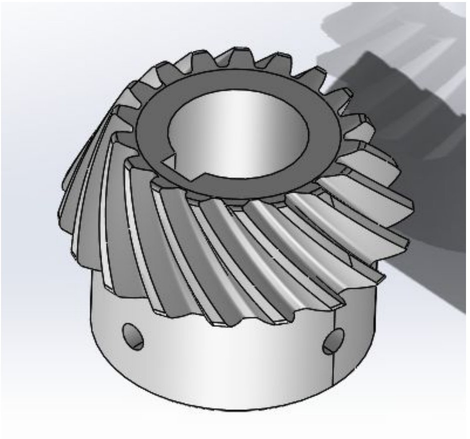
Industry Standards

Per industry standards, 0.52 inches for a shaft diameter would be a custom and specialized diameter. Thus, the next standard size up would be .625 inches, or ⅝ in. This is the minimum shaft diameter, which is where gear 2 is mounted.

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

For ease of connection to the gears that are currently selected, as well as to meet angle of twist concerns, the shaft diameter will be increased to 1.5 inches throughout the center of the shaft. This will allow an even higher safety factor, and low angle of twist (< 0.01 degrees/inch).

Component and Material Selection



Aluminum 6061-T6 is a very common Aluminum alloy that is typically used in bike frames and other applications due to its toughness and corrosion resistance, while still being fairly light. This was not strong enough for the shaft, but 316L Stainless was up to the challenge, while maintaining the corrosion resistance.

We currently have gears selected from KHK that will have a 2.5:1 gear ratio at the front of the bike from spur to pinion, a 1:2 ratio in the back, making a 1.25:1 ratio for the bike as a whole.

We used a Shimano Alfine 8 series internal gear hub, due to its high efficiency and gear range.

Fabrication and Assembly

There are no specialized methods that were used in order to fabricate the drive shaft. We purchased 316L Stainless stock material in order to create the piece. Once obtained, it was machined using a standard lathe and milling machine.

The spiral bevel gears were purchased from a supplier, rather than trying to machine them ourselves. These came in sets of two upon purchase. Material selection and shipping time was greatly impacted by price.

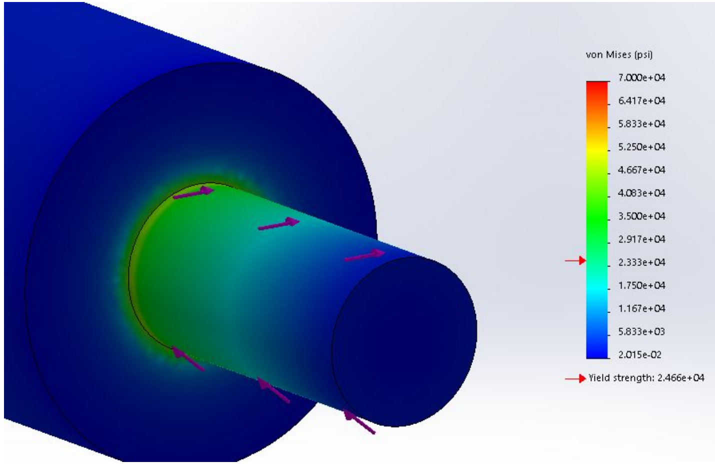
The internal gear hub and other bike components (brakes, wheels, etc) were purchased or used from old bicycles. The internal gear hub that was chosen was the Shimano Alfine 8.

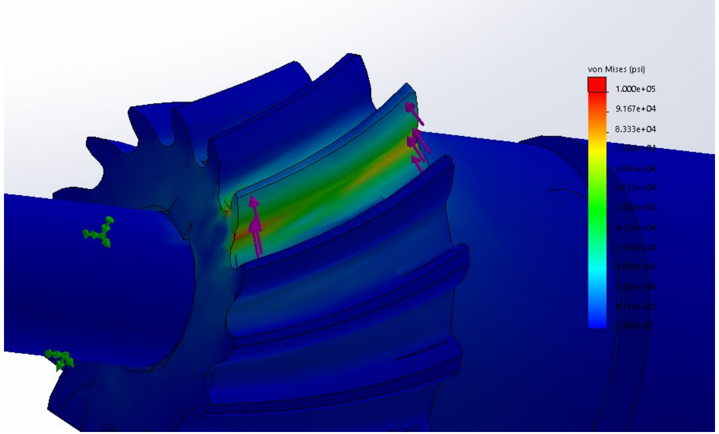
There was no specialized equipment required for assembly.

Testing Methods - Shaft FEA

After conducting analysis using Solidworks simulations on the shrink fitting, key slots, and spiral bevel gears, it was determined that the design and materials of choice were able to withstand the forces and stress that they will be under during worst case conditions. For example, we can assume that the force will be distributed across two teeth on the gear, rather than just one, as shown in the analysis.

Note: Shaft is 316L Stainless and the Spiral Bevel Gear is SCM415 Steel

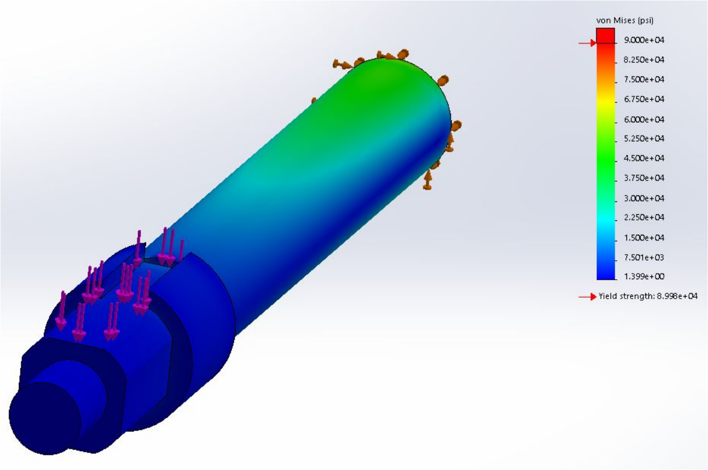




New Pedal Shaft

To accommodate for a wider back fork on the bike frame, we also needed a longer shaft to connect the pedals to avoid hitting the frame while pedaling.

While the shaft would be longer (and therefore have a larger moment), we matched the initial shaft diameter, and chose a nicer steel to handle the additional stress. A medium carbon steel shaft was used from the VPC shop to fabricate the replacement shaft.

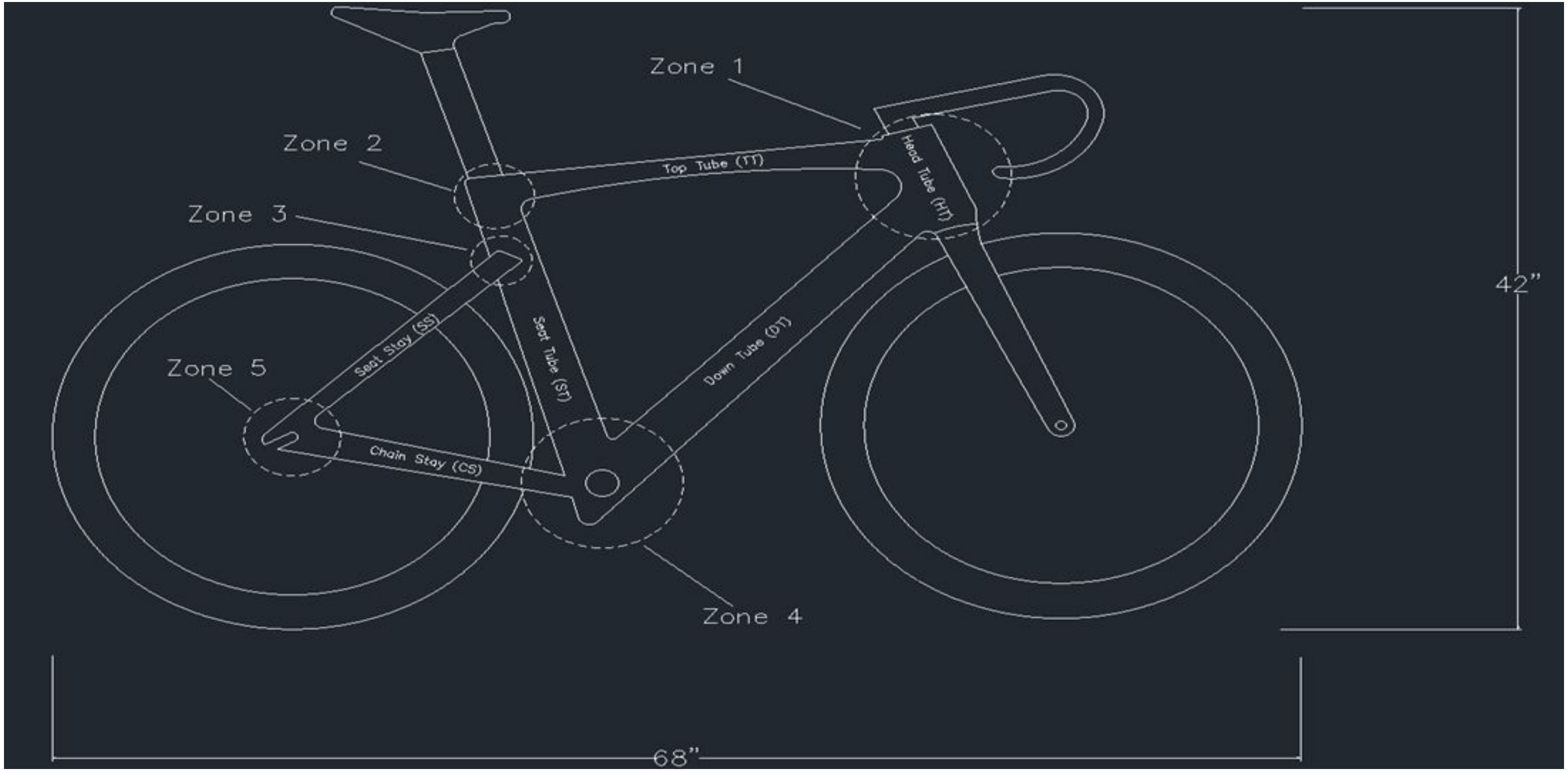


Frame Design and Analysis

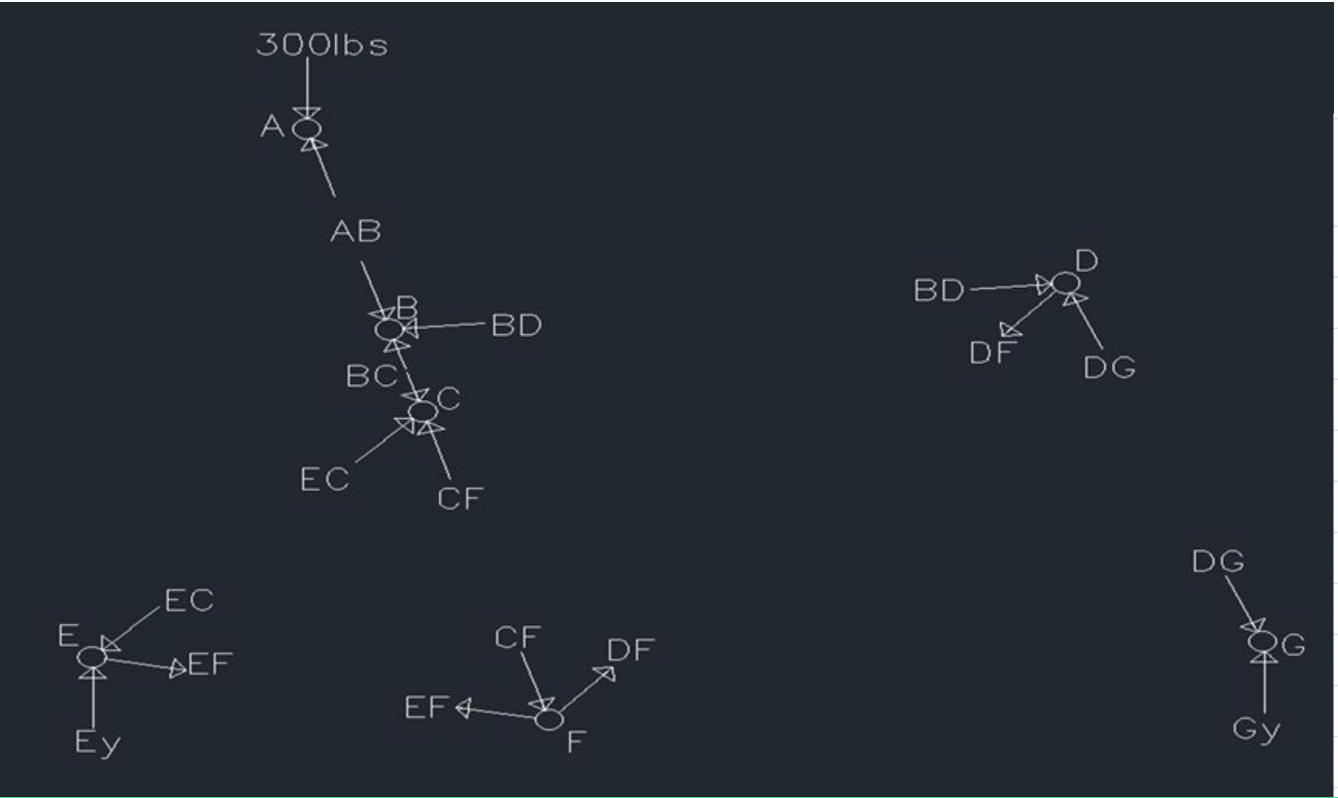
Frame Design Goals and Features

- Frame designed to handle a 300lb rider
- Must be able to handle that 300lb rider driving off of a 1ft curb
- Frame goal weight 25lbs
- Final frame weight 28.5lbs
- 6061 T6 Aluminum tube Construction

Original 2D Concept Drawing



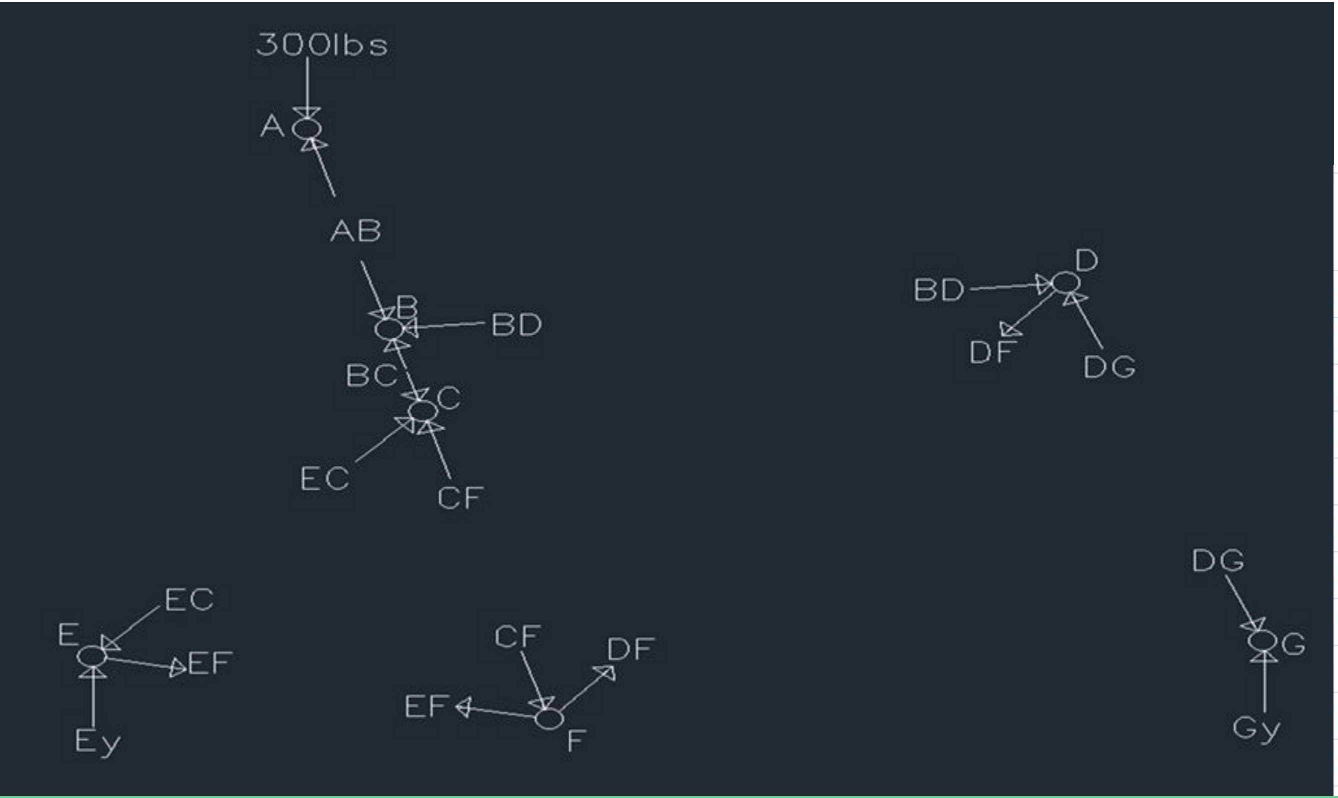
Tension/Compression FBD and Member Force Analysis



Standing 300lb force analysis

	300lbs Force(lbs)	Tension/ Compression
AB	300	Compession
BD	306	Compression
BC	328	Compression
EC	293	Compression
CF	261	Compression
EF	258	Tension
DF	486	Tension
DG	53	Compression
Gy	53	
Ey	247	
F	300	

Tension/Compression FBD and Member Force Analysis

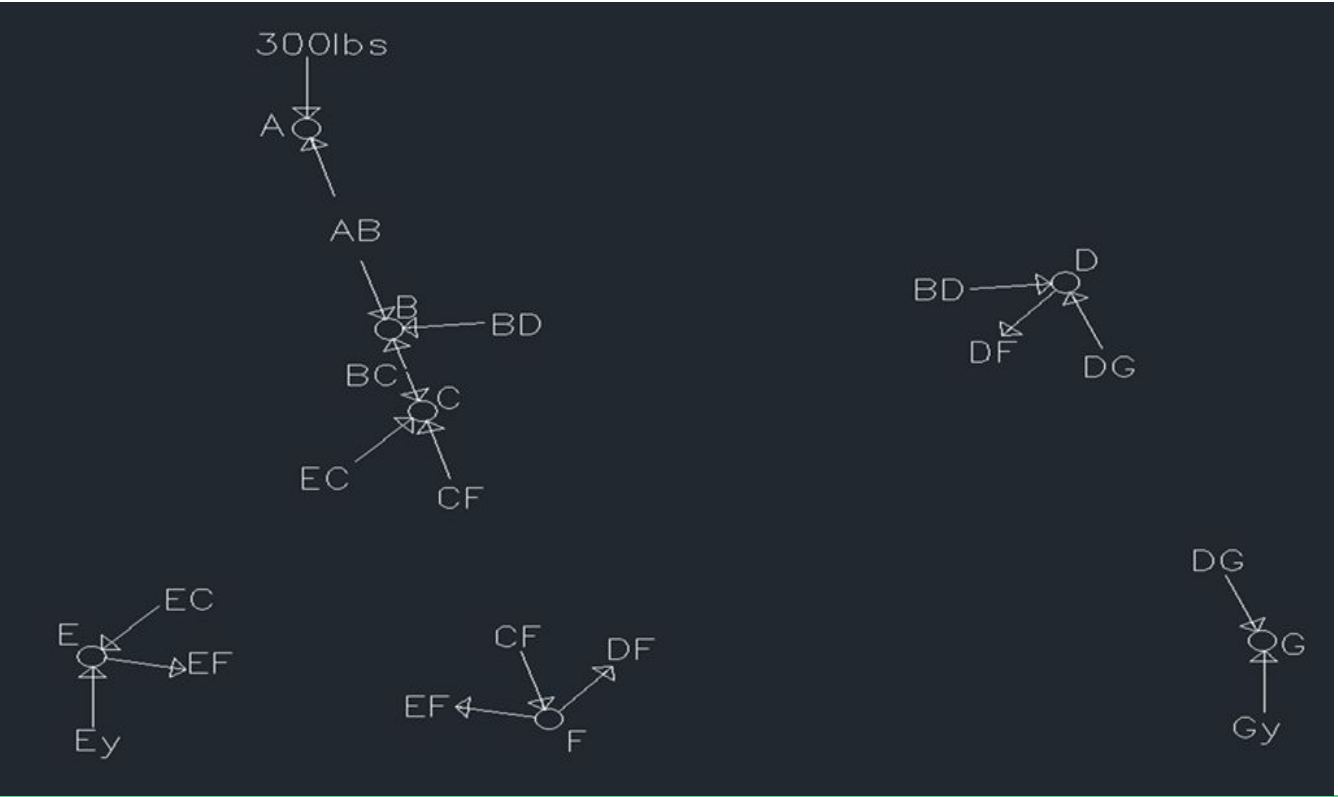


300lbs one foot drop

Force Analysis

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

Tension/Compression FBD and Member Stress Analysis



300lbs Stress Analysis (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

3D Models

Original 3D model based off 2D design

- Bulky
- Complicated Design

3D Models

Basic 3D model of a standard bike

- Standard
- Good starting point

3D Models

Modified version V16

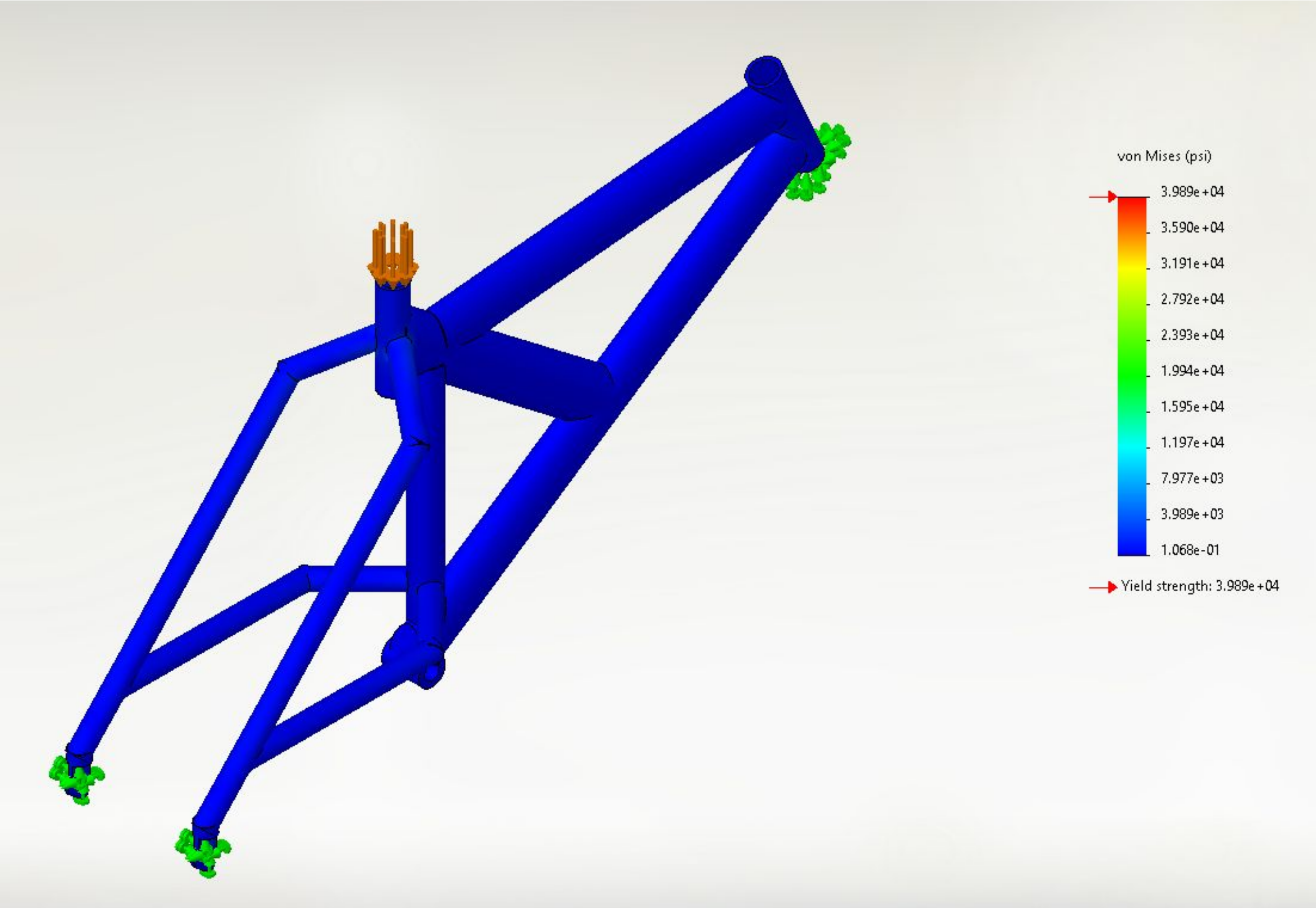
- Widened rear forks
- Offset fork
- Thicker members

3D Models

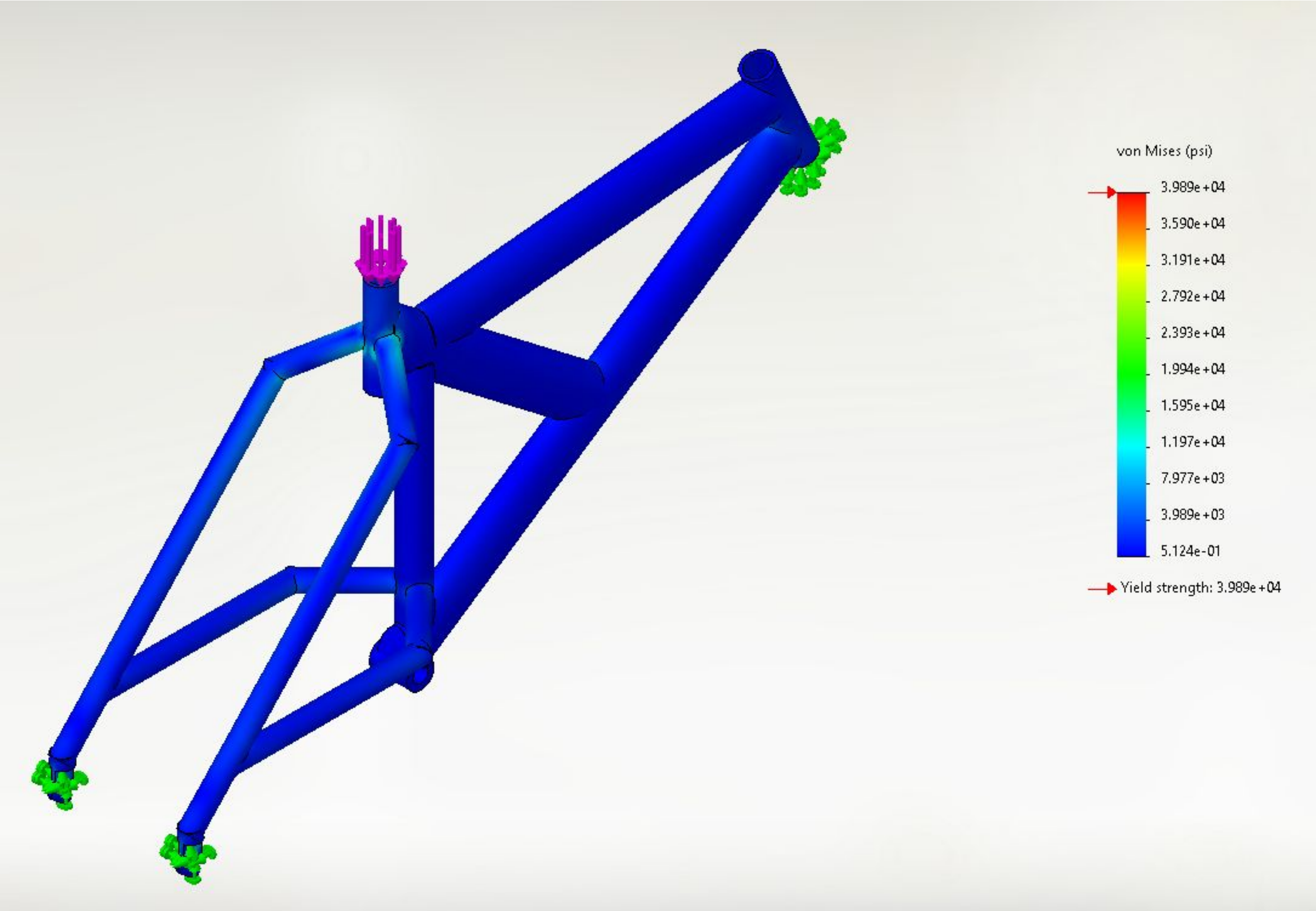
Final version

- Cut members rather than bend
- More stable rear wheel mounting

6061-T6 Aluminum Under 300 lbs of Force

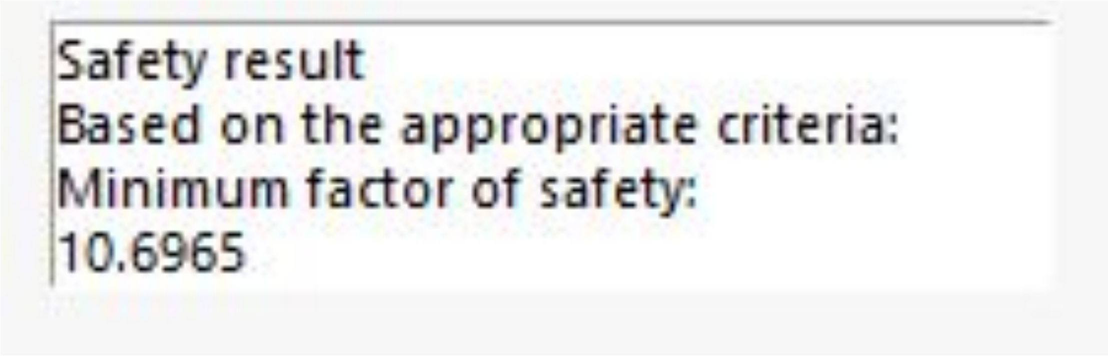


6061-T6 Aluminum Under 1,440 lbs of Force



Factor of Safety

Solidworks simulations show that the recommended factor of safety is 10, meaning that the frame by itself can handle up to 3207 lbs of force before catastrophic failure.



Gear Design and Analysis

Let’s switch gears…

Gear Layout Overview

Gear Diameters

Gear 1 = 90mm ≈ 3.54”

Gear 2 = 40mm ≈ 1.57”

Gear 3 = 53mm ≈ 2.10”

Gear 4 = 101mm ≈ 4”

Assumptions

- ➢ AGMA standards (American Gear Manufacturers Association)
- ➢ AISI standards (American Iron and Steel Institute)
- ➢ Maximum applied force of 350 lbf (based on 275 lb rider starting from complete stop)
- ➢ Average cadence of 60 rpm
- ➢ Spiral bevel gear area is approx. equal to a straight bevel gear area (hand calculations)
- ➢ Ko (overload factor) is equal to 1 (hand calculation)
- ➢ 2 gear teeth will be supporting the load at all times (FEA analysis)

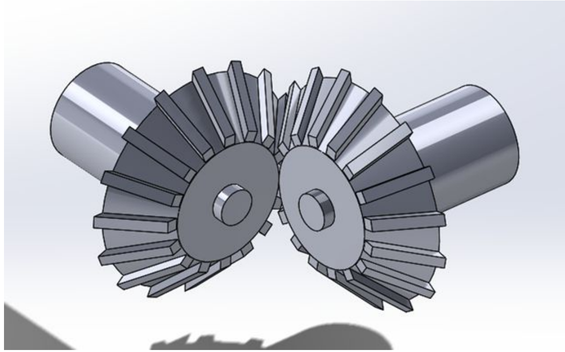
Gear Design Options

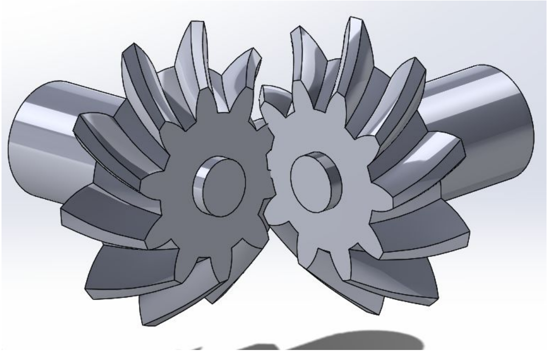
Type of gear

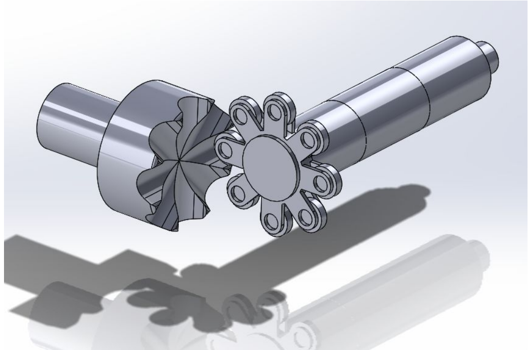
- ❖ Bevel gear
- ❖ Spiral bevel gear
- ❖ Rotating bearing gearing

Material

- ❖ AISI 1045 Cold rolled steel
- ❖ AISI 4140
- ❖ AISI 4340 normalized
- ❖ SCM 415







Gear Specifications

SCM415

Carburized - 55-60 HRC (560-627 HB)

Yield Strength - 60.19 ksi

Ultimate Tensile Strength - 95.0 ksi

Front gear ratio of 2.5:1, back gear ratio of 1:2, overall gear ratio of 1.25:1

Helix angle = 35°, Pressure angle = 20°

Tooth depth = 4.8mm

*Based on specs from KHK gears (KHKGears.us)

Loading Conditions

350 lbf on 170mm crank shaft (at 90° angle)= 195.2 lb-ft torque

Gear 1 torque = 195.2 lb-ft

Gear 2 torque = 77 lb-ft (2.5:1 gear ratio)

Gear 3 torque = 77 lb-ft (same as gear #2)

Gear 4 torque = 154 lb-ft (1:2 gear ratio from gear 3)

Bending Factors of Safety - Solidworks FEA

AISI 1045

- ➢ Gear 1 FoS = 0.76
- ➢ Gear 2 FoS = 0.82
- ➢ Gear 3 FoS = 0.99
- ➢ Gear 4 FoS = 0.76

AISI 1045 Cold Rolled

- ➢ Gear 1 FoS = 1.3
- ➢ Gear 2 FoS = 1.4
- ➢ Gear 3 FoS = 1.7
- ➢ Gear 4 FoS = 1.3

SCM415

- ★ Gear 1 FoS = 2.0
- ★ Gear 2 FoS = 2.4
- ★ Gear 3 FoS = 3.0
- ★ Gear 4 FoS = 2.0

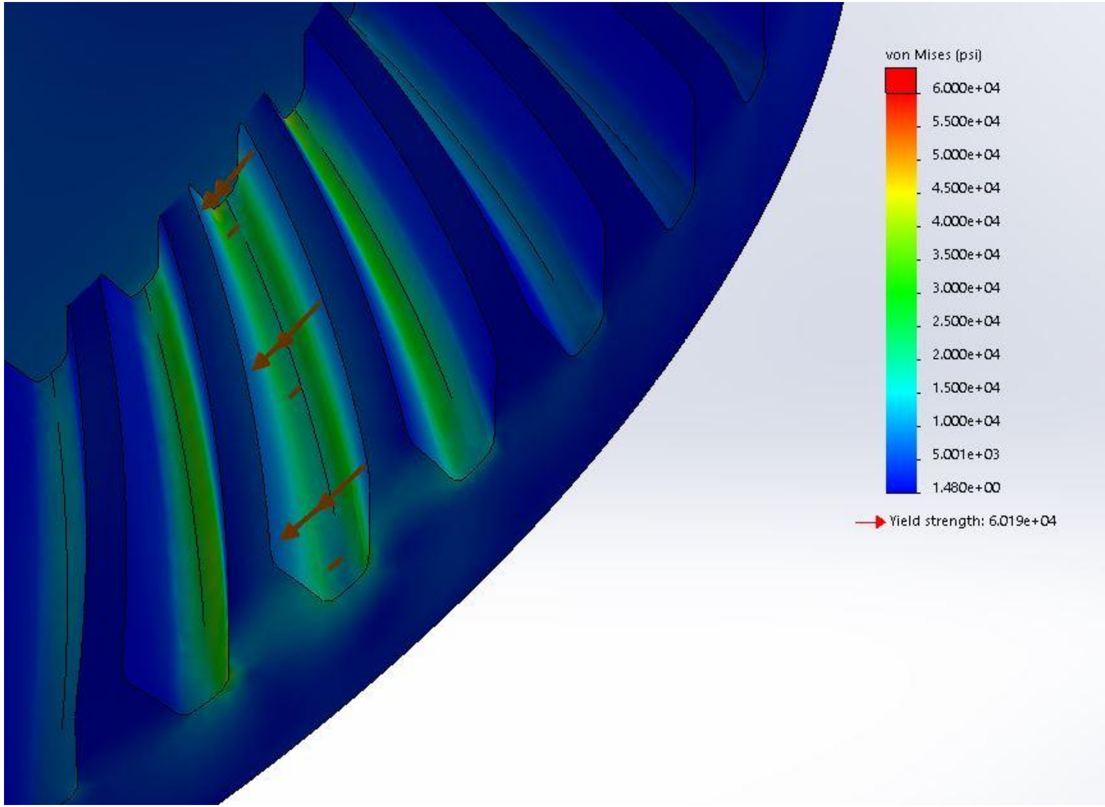
AISI 4140

- ➢ Gear 1 FoS = 1.03
- ➢ Gear 2 FoS = 1.11
- ➢ Gear 3 FoS = 1.34
- ➢ Gear 4 FoS = 1.03

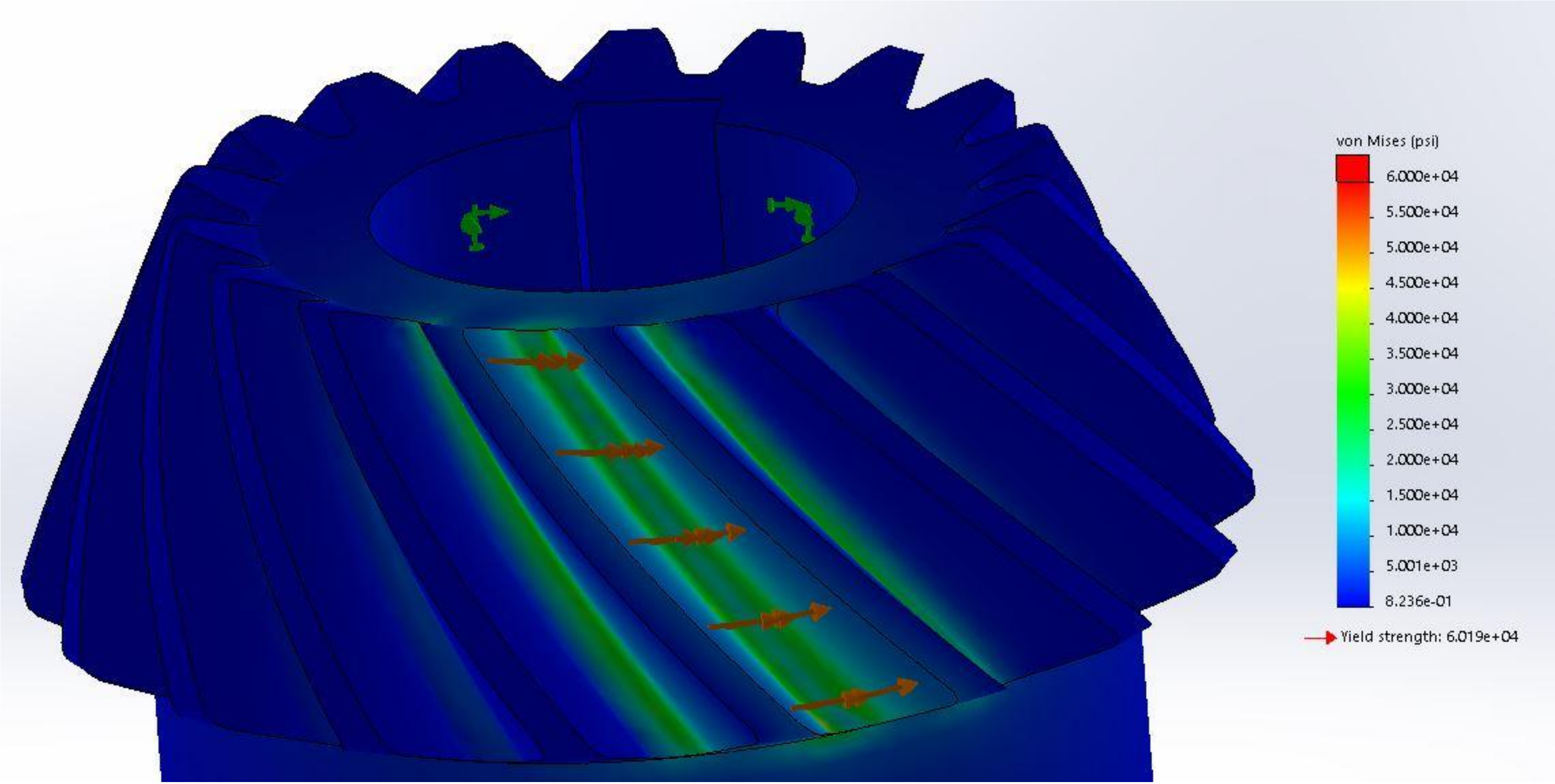
AISI 4340 normalized

- ➢ Gear 1 FoS = 2.0
- ➢ Gear 2 FoS = 2.1
- ➢ Gear 3 FoS = 3.0
- ➢ Gear 4 FoS = 2.0

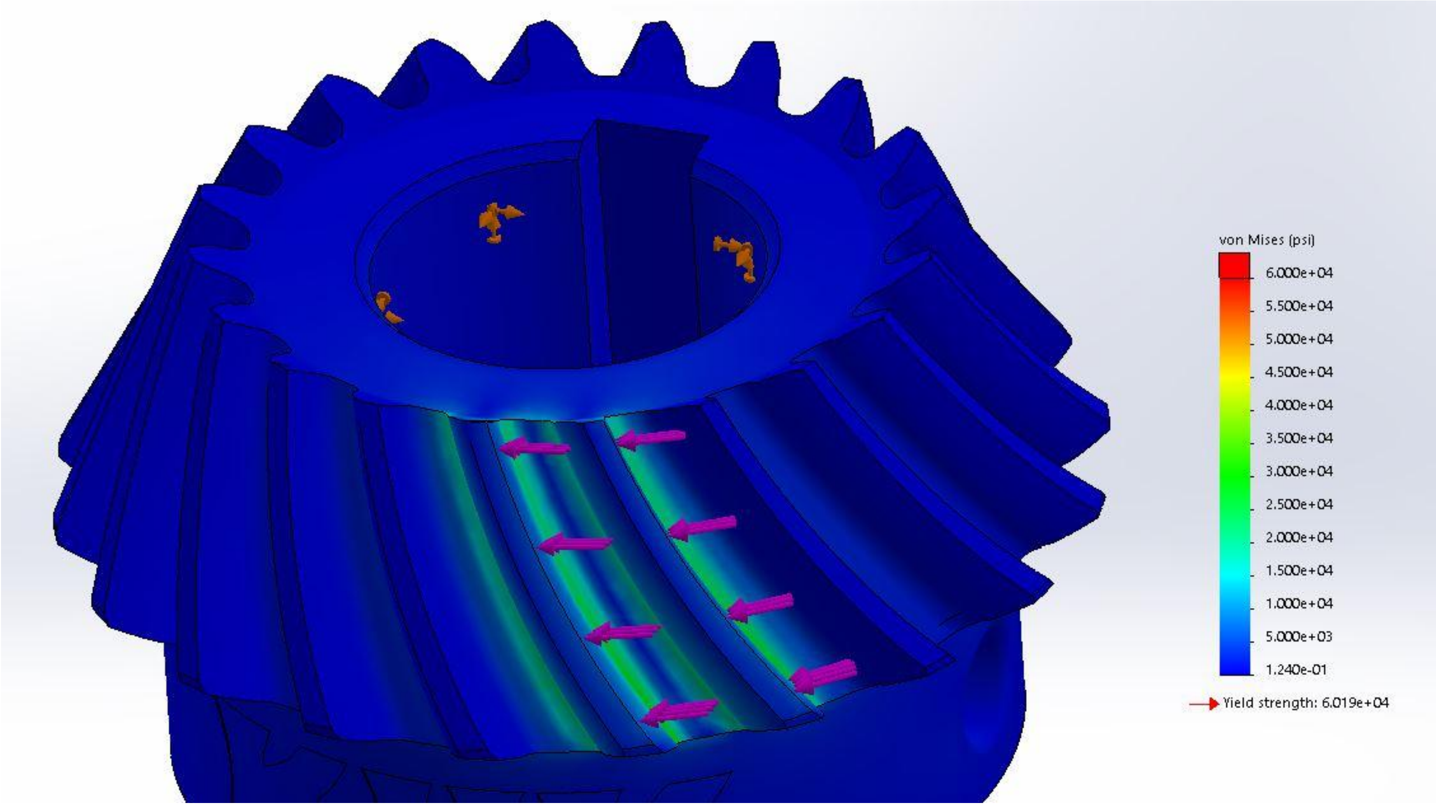
FEA Analysis - Gear 1 SCM415



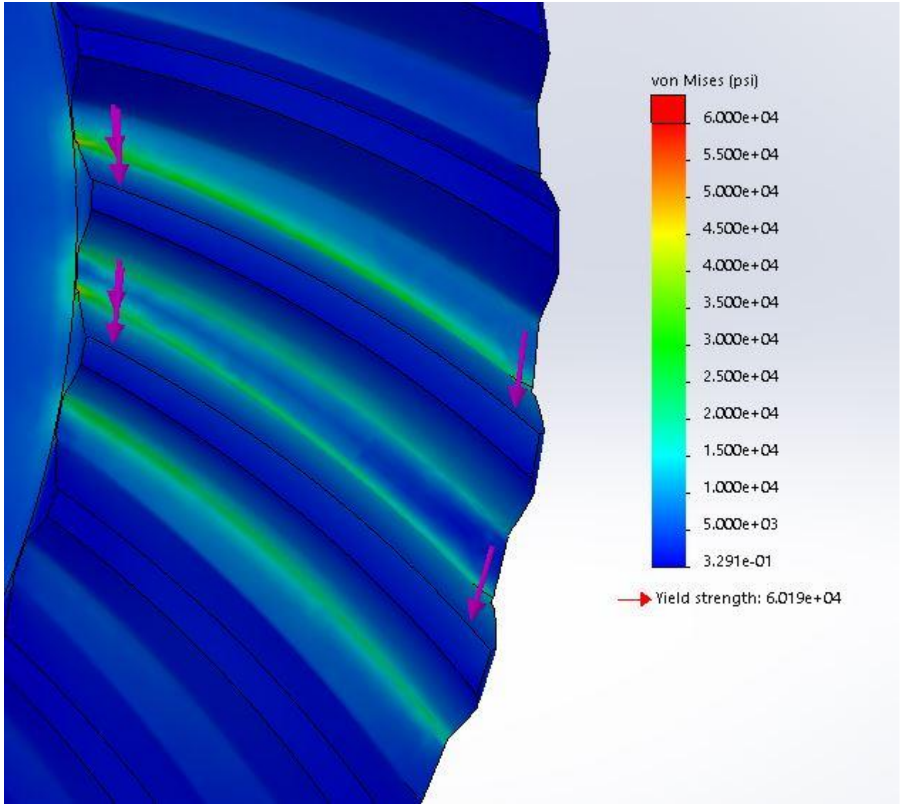
FEA Analysis - Gear 2 SCM415



FEA Analysis - Gear 3 SCM415



FEA Analysis - Gear 4 SCM415



Gear Costs

Gear 1 = $118.09

Gear 2 = $60.76

Gear 3 = $57.86

Gear 4 = $107.05

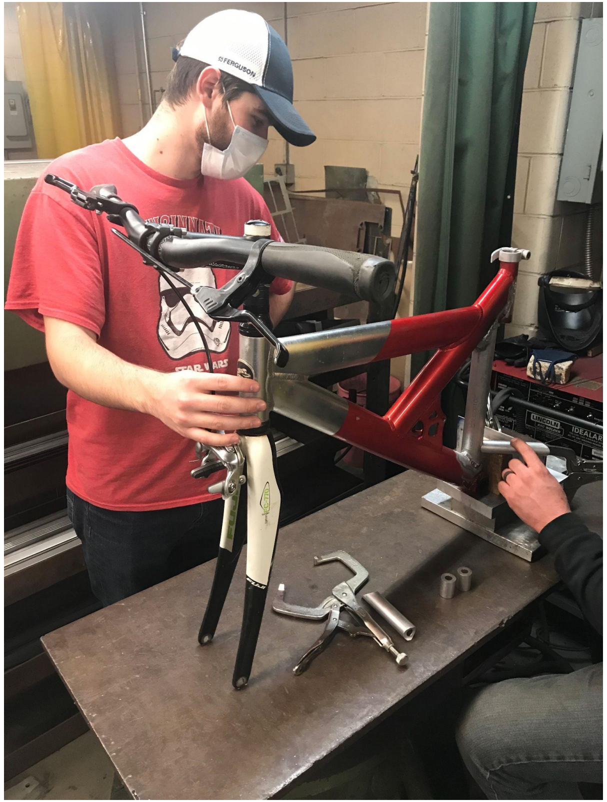
Total cost = $362.23 (+ tax & shipping)

*Prices and models obtained from KHK Gears (KHKGears.us)

Fabrication and Assembly

Fabrication and Assembly Cont.

Fabrication and Assembly Cont.



Fabrication and Assembly Cont.

Fabrication and Assembly Cont.

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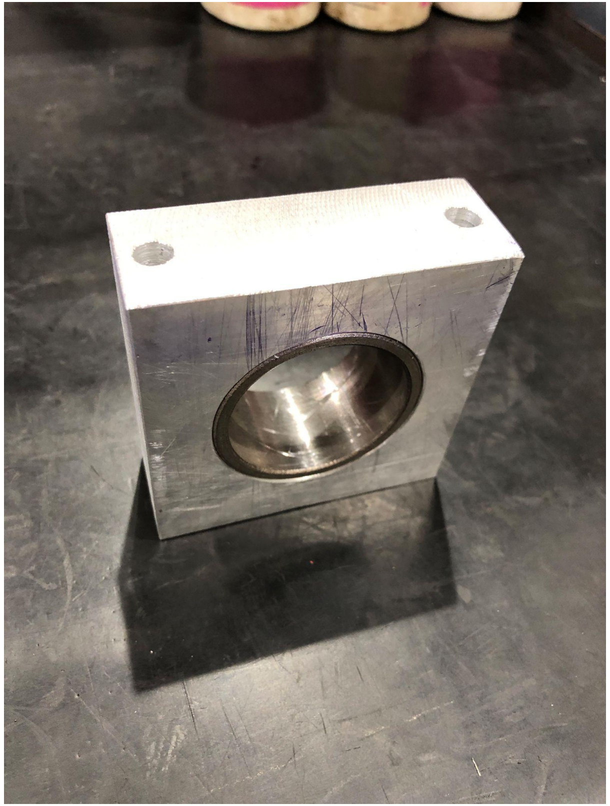

Fabrication and Assembly Cont.

Fabrication and Assembly Cont.

Fabrication and Assembly Cont.

Production Methods and Cost Per Unit

Personal Material Costs: $1,464.83 (of $1,500 budget)

Hourly Cost Assumed: $4,600 (230 hrs @ $20.00/hr)

Production Tools Required: Vertical Mill, Lathe, TIG Welder and Filler Material, Fixtures to Hold Pipe while Welding, Wire EDM Machine, Pipe Bender and Die

Estimated Production Cost: 700+1000= **$1,700** (50% Materials Cost + 50 hrs)

Extremely rough estimation if being mass produced

Testing and Proof of Design

Strength Test: Able to withstand a 275 lb rider

Total Bike Weight: 41.0 lbs

Frame Weight: 28.61 lbs

Efficiency Test: Compared to a high performance bike; assumed efficiency of 0.85

Overall efficiency = 74.8% efficiency across whole system

Could be improved with ball bearings & improved gear alignment

Recommendations

Things we would do different

- Order material extra early to avoid shipping complications due to Covid-19
    - Follow up with shipping companies more often
    - Lost 3 weeks of time on what was supposed to be 2 weeks of shipping time
- Bend pipe rather than cutting it for welding the frame together
- Ball Bearings rather than bushings
- Use a Dyno to measure efficiency more accurately

Project Timeline

Proposed

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																																				

Actual

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																	

Project Budget

Initial Budget = $1500 ± 20% = $1200-1800
Bike Frame - < $500 ➔ Dependent on material purchasing vs. frame modification
Internal Gear Hub – $200-400 ➔ Dependent on Shimano Alfine 8 or 11 selection
Components - < $200-300 ➔ Based on purchasing or reuse from old bicycles
Wheels/Tires - $200 ➔ Dependent on wheel and tire quality
Gears - $100-250 ➔ Dependent on gear material selection
Shaft - < $100 ➔ Dependent on material purchasing cost
Battery and Motor - Leftover Budget ➔ Optional addition
Total = $1300-1750

Proposed

Actual

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

References:

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. **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.]

5. **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.]

6. **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.

Thank You!

Questions?